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Taxonomic Diversity of Soft-Bottom Ichthyofauna in the Lagoon of La Paz, B.C.S., México

Acosta-Rodríguez Isaac [a], Barjau-Gonzalez Emelio [a*], Lopez-Vivas Juan Manuel [a], Castillo-Rosas Bruma Rachel [a], Romero-Piñera Abril Karim [a] and Armenta-Quintana Jose Angel [b]

[a] Departamento Académico de Ciencias Marinas y Costeras, Universidad Autónoma de Baja California Sur, La Paz, B.C.S., Mexico.
[b] Departamento Académico de Ciencia Animal y Conservación del Hábitat, Universidad Autónoma de Baja California Sur, La Paz, B.C.S., Mexico.

Authors' contributions

This work was carried out in collaboration among all authors. Authors ARI and BGE wrote the manuscript. Authors BGE, ARI, CRBR collected and identified fish samples and analyzed the data. Authors RPAK, LVJM and AQJA revised the manuscript. All authors read and approved the final manuscript.

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ABSTRACT

The lagoon of La Paz has been affected by different anthropogenic activities, such as wastewater discharge and construction of marinas, which affect the local and transient ichthyofauna. Between august 2016 and June 2017, 2,763 organisms belonging to 72 species grouped in 51 genera were

Corresponding author: Email: ebarjau@uabcs.mx;

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collected using an experimental trawl net. Temperature and dissolved oxygen presented a temporal variation, with August being the warmest month (28.17°C) and the lowest in oxygenation (12.44 mg*L), contrary to February (21.42°C) and June (21.9 mg*L). α-Fisher diversity was highest in Zacatecas (S=10.9); Las Palmas obtained the lowest (S=3.898). Alpha and average alpha diversities were highest in April (37, 11), beta diversity in August (3.4); lowest beta diversity was recorded in April (1.9), and lowest alpha during august (21). Taxonomic distinctness and average Taxonomic distinctness were highest in February (Δ^*=85.95) and December (Δ^+=65.399); August recorded the lowest values (Δ^*=50.55; Δ^+=55.079). Variation in Taxonomic distincntess was highest in April ($\wedge^+$=304.02) and lowest in august ($\wedge^+$=304.02). Variability in such indices corresponds to the seasonal cycle of the Lagoon, with well-marked increases during the warm season, indicating stability in the conditions of the lagoon during the past years.

Keywords: Coastal lagoon; anthropogenic impact; taxonomic diversity; taxonomic distinctness; ichthyofauna.

1. INTRODUCTION

Given its great extension, Mexico holds the twelfth biggest marine territory in the world, which, in addition to its geographical and geological history gives it an extraordinary marine life diversity [1].

The Gulf of California is recognized as an important ecological region, since it is used by a great variety of tropical and subtropical fish as a primary feeding and growth area [2]. however, only a few species carry out their entire life cycle within this kind of ecosystem (Frontier and Leggette, 1982).

A total of 21723 fish species have been described, comprising almost half of the vertebrates in the world [3] Mexican ichthyofauna is comprised of 2,171 species, grouped in 792 genera [4]. La Paz bay is home for 533 of these fish species, making it an ecosystem of great ecological importance [5].

The stability of a community within a lagoon-estuarine system can be attributed to the distribution associated to environmental gradients, migratory movements, dominance of a few species in the system and a stable food chain [6].

Fish play a fundamental role in aquatic ecosystems; hence, a knowledge of the relationship and importance of species within an ecosystem, as well as the number and distribution of such species is essential, for communities with a greater heterogeneity are capable of a superior biomass production [7].

Anthropogenic activities like indiscriminate fishing, construction of marinas and wastewater discharge can decrease fish population drastically, as evidenced by a recent study in Kapaleswari River, India. Researchers found 17 very high risk, 23 high risk, and eight moderately risk species, accounting for 71.42% of the fish species inhabiting the river. Therefore, studies like the present are of great importance for the management and conservation of the fish diversity of natural ecosystems [8].

2. METHODS

2.1 Area of study

The lagoon of La Paz is a body of water found between the parallels 24°10', 24°06', and the meridians 110°19', 110°25'. It is limited on its north end by a 12 Km sand barrier, which separates it from La Paz bay (Fig. 1) [9] the lagoon has an anti-estuarine circulation, causing a rise on salinity levels in its interior [10].

2.2 Sampling

Six bimonthly samplings were carried out between August 06 of 2016 and June 30 of 2017 in seven different locations within the lagoon of La Paz (Table 1). A nine-meter long experimental trawl net with a vertical opening of 4.5 meters, a 4.44 cm mesh size in the primary cone, and a 3.81 cm mesh size in the secondary cone was used. Samplings were performed on board of a 22 feet boat with a 75 HP four stroke outboard engine, a trawl speed of 3.5 km/h and an average sweep of 20 minutes in each sampling site. Samplings were carried out under the fishing permit number "PPF/DGOPA-026/22", issued by the Secretariat of Agriculture, Livestock, Rural development, Fishing and Food (SAGARPA), allowing fishing and extraction in the Lagoon of La Paz for research purposes.

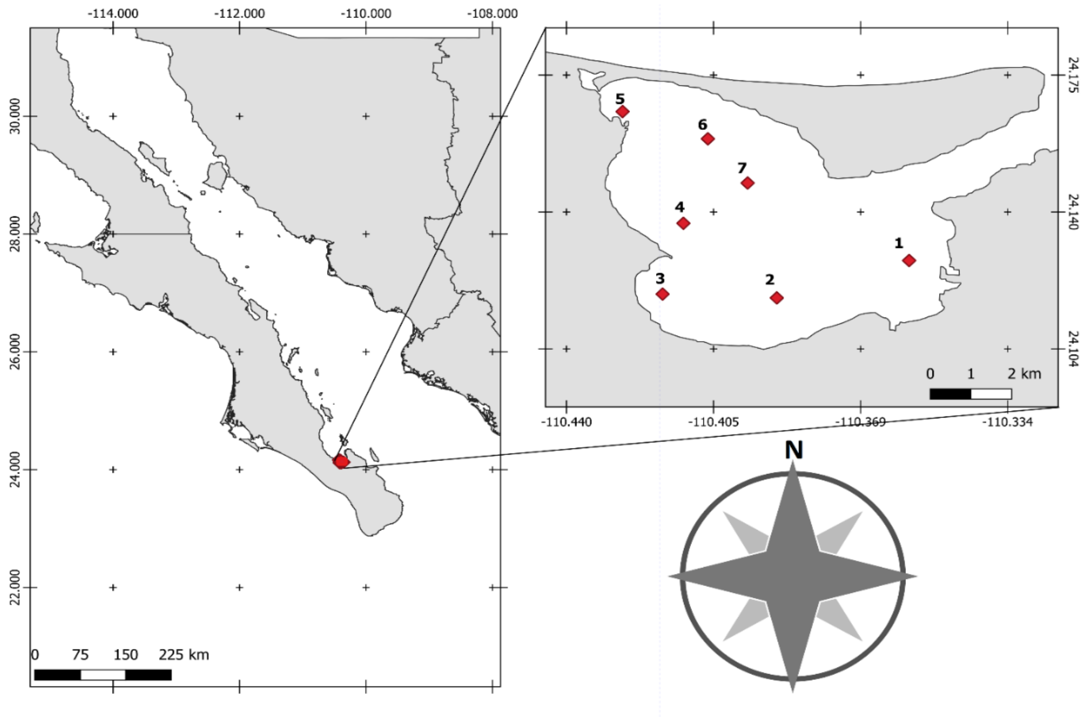

Fig. 1. Location of the lagoon of La Paz and sample sites

Table 1. Geographic coordinates of the seven sampling sites.

Site	N	W
1. Grand Plaza	24° 07' 38.8''	110° 21' 28.1"
2. Aeropuerto	24° 07' 03.9"	110° 23' 23.1"
3. Aripez	24° 07' 07.4"	110° 25' 02.3"
4. CIBNOR	24° 08' 13.5"	110° 24' 44.2"
5. Zacatecas	24° 09' 57.7"	110° 25' 37.1"
6. Las Palmas	24° 09' 32.3"	110° 24' 23.0"
7. Yate Hundido	24° 08' 51.0"	110° 23' 48.4"

Physicochemical variables (°C, UPS, OD) were recorded using an YSI 2030 Pro multiparameter instrument; each site was referenced with a Garmin GPS model Oregon 750.

All fish specimens were then analyzed in the coastal and reef fish ecology laboratory at the Autonomous University of Baja California Sur (UABCS). Morphometric measurements were carried out and weight was determined using an Ohaus Explorer Pro digital scale. Species identification Coordinatwas carried out using specialized literature.

2.3 Data Analysis

- Fisher's alpha [11]: Allows comparing species diversity levels between sites with differences in abundance.

$$S = \alpha \, ln(1 + N/\alpha) \quad (1)$$

- Alpha diversity (α) [12]: Expresses the species diversity of a population and its ecological relationships within a certain site and timeframe [13].

- Average Alpha diversity (α): It is the average value of the alpha diversities [14].

$$\alpha_{prom} = \frac{\Sigma_{i=1..n} a_i}{n} \quad (2)$$

- Beta diversity (β): Evaluates the species exchange between two sites, in different kinds of communities [13]. The Whittaker [12] species exchange index was used.

$$\beta = \frac{\gamma}{\alpha} \quad (3)$$

- Gamma diversity (γ): Product of the alpha diversity (α) of each community and the Beta diversity index (β) [12].

$$\gamma = (\beta)(\alpha) \quad (4)$$

- Taxonomic Distinctness index (Δ*) [15]: Taxonomic relationship between two random individuals taken from a sample [16].

$$\Delta^* = \frac{\sum_{i=1}^{n} \sum_{i<j} \omega_{ij} x_i x_j}{\sum_{i=1}^{n} \sum_{i<j} x_i x_j} \quad (5)$$

- Average Taxonomic Distinctness index (Δ^+) [17]: Average taxonomic distance among every pair of species within a given sample [16]:

$$\Delta^+ = \frac{\sum_{j=1}^{n} \sum_{i<j} \omega_{ij}}{S\,(S-1)/2} \quad (6)$$

- Variation in Taxonomic Distincntess index (Λ^+) [17]: Represents the variance of the taxonomic distance between every pair of species in a sample (Milošević *et al*., 2012).

$$\Lambda^+ = \frac{\sum_{j=1}^{n} \sum_{i<j} (\omega_{ij} - \Delta^+)^2}{S(S-1)/2} \quad (7)$$

Indices were calculated with PAST 4.09 software, the “vegan 2.6-4” package within the Rstudio 2021.09.2 platform, and Primer & Permanova V7.

3. RESULTS

3.1 Physicochemical Variables

Water temperature was statistically different between months (p = 0.0002), with August (28.17°C) being significantly different from April (23.04°C) (p = 0.001), December (22.71°C) (p = 0.0006), February (21.42°C) (p = 0.00002) and June (22.8°C) (p = 0.0007); average temperature in October (26.74°C) is different to April (p = 0.03), December (p = 0.01), February (p = 0.0008) and June (p = 0.02). No statistically significant differences were recorded between sampling sites; highest temperature was recorded in Gran Plaza (25.41°C), while the lowest was recorded in Zacatecas (23.28°C).

Salinity was not statistically different between months or sampling sites (p = 0.3053); p = 0.559). The lowest concentration was recorded in Grand Plaza (31.78 UPS), and the highest concentration in CIBNOR (33.68 UPS). Salinity was the lowest during the month of April (31.9 UPS) and highest during October (33.97 UPS) (Table 2).

Dissolved Oxygen (OD) recorded statistical differences between months (p = 0.0019), August being the lowest (12.44 mg*L) and June (21.92 mg*L) the highest (Table 2). August is different from the rest of the months; April (p = 0.000), December (p = $1e^{-7}$), February (p = $1e^{-7}$), June (p = 0.000) and October (p = 0.000). Oxygen concentration was not different among sampling sites (p = 0.4842). Yate Hundido recorded the highest concentration (21.25 mg*L), while Las Palmas recorded the lowest value (18.39 mg*L).

3.2 Community Structure

Two thousand seven hundred and sixty-three organisms, grouped in 73 species, 26 families and 51 genera were captured. Haemulidae was the most abundant family (13 species), representing 14.04% of the total; nevertheless, the most abundant species was *Diapterus peruvianus* (Gerreidae family), with 683 individuals (24.7% of the total). A single individual represented ten families (Achiridae, Clupeidae, Cynoglossidae, Dasyatidae, Engraulidae, Ephippidae, Mullidae, Nematistiidae, Rhinobatidae and Sparidae).

1) Alpha, average alpha, beta and gamma diversities

Alpha diversity (α) showed the highest value during April (37 species), while August recorded the lowest (21 species). Average alpha diversity ($\bar{\alpha}$) was the highest during April (11.1 species), while December recorded the lowest value (five species). Beta diversity (β) got the highest value during August (3.4) and the lowest in April (1.9) (Fig. 2).

Zacatecas got the highest alpha (42 species) and average alpha (13.5 species) values; Las Palmas was the lowest site for alpha (15 species) and average alpha (4.8 species). Beta diversity was highest in Las Palmas (4.8), while Zacatecas was the lowest (1.7) (Fig. 3).

Total or Gamma diversity in the lagoon of La Paz was 72 species (Fig. 2).

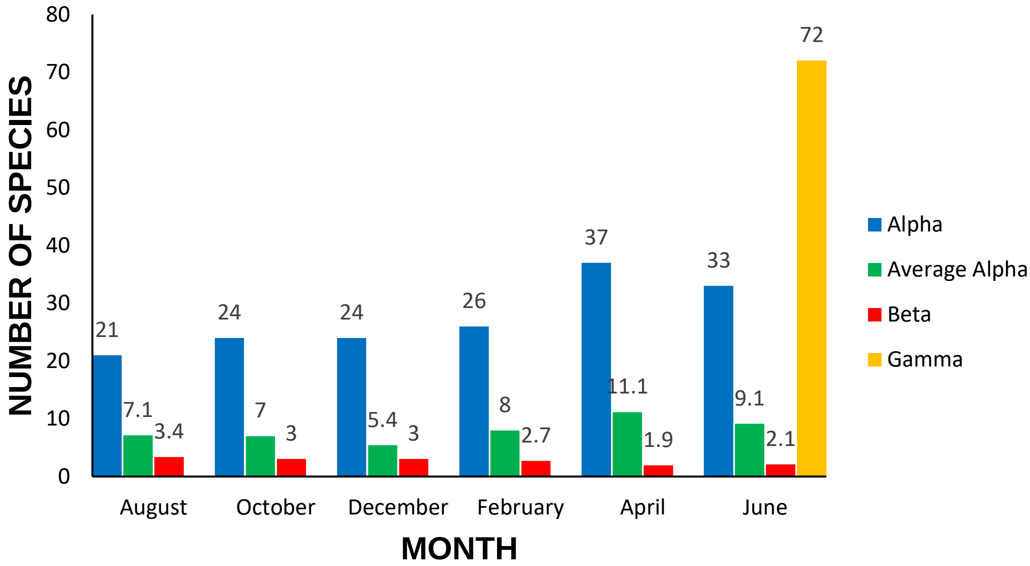

Fig. 2. Alpha (α), average alpha (ᾱ), beta (β) and gamma (γ) diversities during sample months

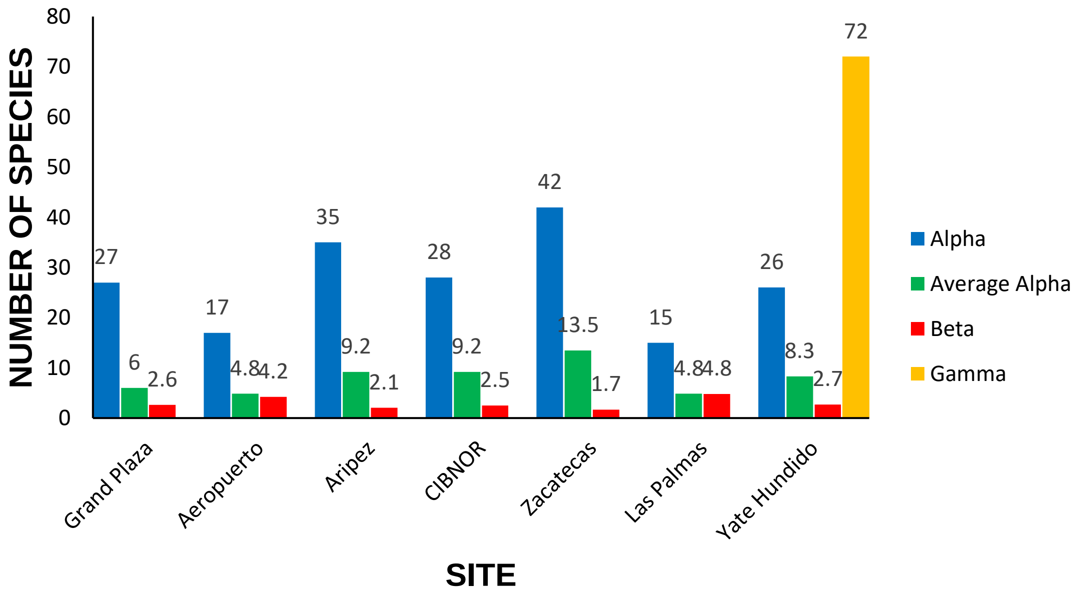

Fig. 3. Alpha (α), average alpha (ᾱ), beta (β) and gamma (γ) diversities in sampling sites

3.3 Taxonomic Diversity

i) α-Fisher diversity

α-Fisher was significantly different among sites ($p = 0.0114$). Zacatecas recorded the highest value (S = 10.996), Las Palmas recorded the lowest (S = 3.89). There was not a statistically significant difference among months ($p = 0.4033$). Highest value was found in June (S = 9.33), and the lowest in February (S = 4.913) (Table 2).

ii) Taxonomic Distinctness (Δ*)

Taxonomic distinctness was different between months ($p = 0.003$), being August the one with the lowest value ($\Delta^* = 50.55$), and February the one with the highest ($\Delta^* = 85.95$) (Table 2). December was significantly different from April (p

= 0.001), August (p = 0.0005), February (p = 0.02), June (p = 0.0007) and October (p = 0.011). Spatial analysis did not reveal any differences among sites (p = 0.8851); highest value was recorded in Las Palmas (Δ* = 53.63) and the lowest in CIBNOR (Δ* = 37.61) Table 2).

iii) Average Taxonomic Distincntess (Δ+)

Average taxonomic distincntess was different among months (p = 0.0267); the highest value was recorded during December (Δ+ = 65.399), while the lowest was recorded in August (Δ+ = 55.079) (Table 2). December shows differences with April (p = 0.0007), August (p = 0.001), February (p = 0.002), June (p = 0.001) and October (p = 0.008). Sampling sites were not statistically different (p = 0.87) (Table 2).

Every month except for August (sticking out in the lower region of the funnel plot) falls within the 95% confidence interval (Fig. 4). Sampling sites fall entirely within the confidence interval and close to the mean, except for Yate Hundido (Δ+ = 52.55) and Aripez (Δ+ = 51.01), where the lowest average taxonomic distincntess values were found (Fig. 5).

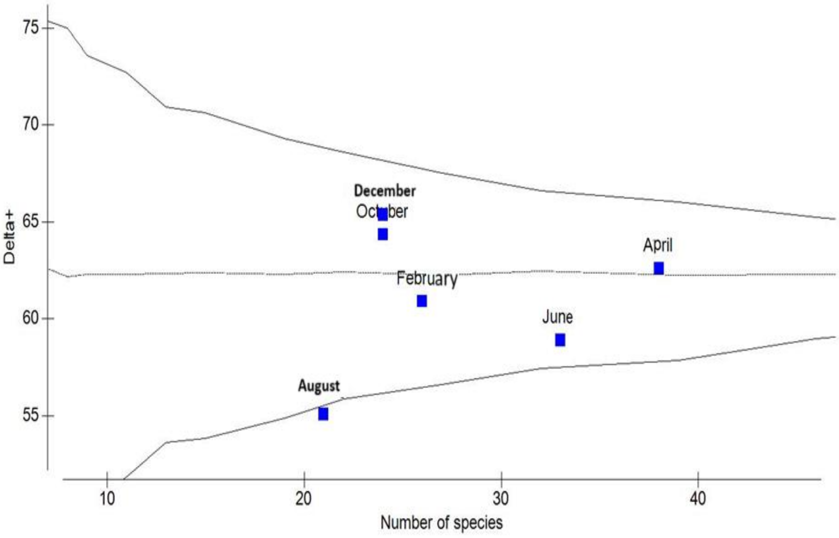

Fig. 4. Funnel plot of the average taxonomic distinctness (Δ+) during the sampling months with a 95% confidence interval

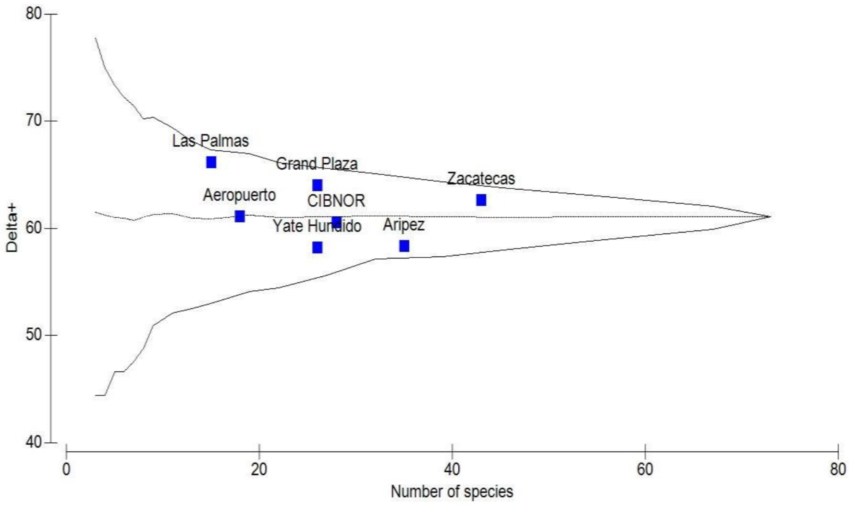

Fig. 5. Funnel plot of the average taxonomic distinctness (Δ+) in the sampling sites with a 95% confidence interval

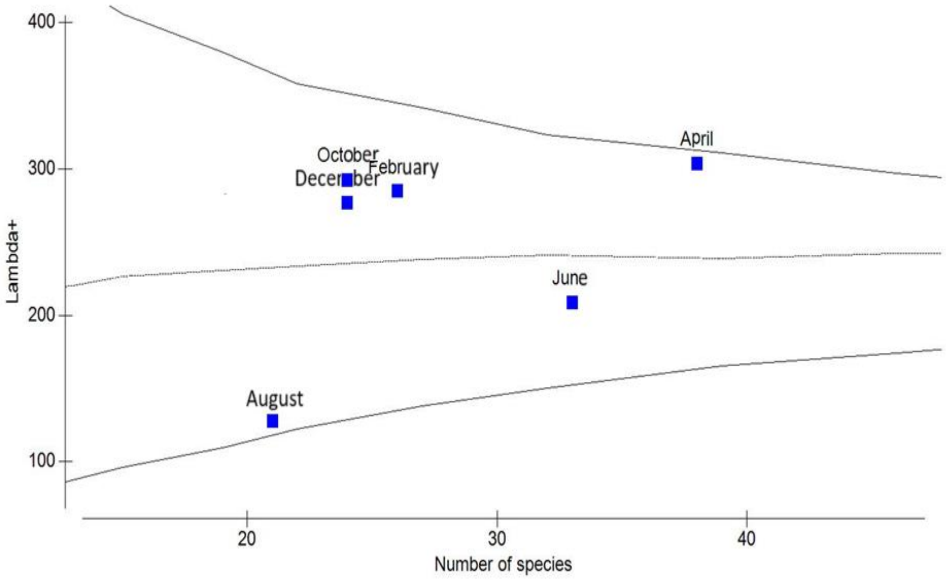

Fig. 6. Funnel plot of the variation in taxonomic distinctness (^+) during the sampling months with a 95% confidence interval

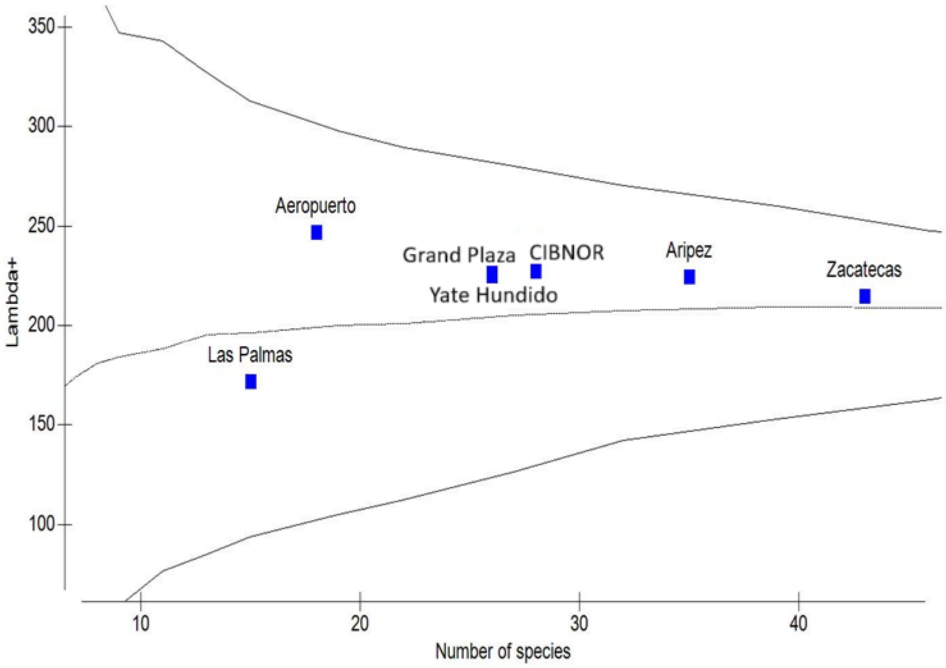

Fig. 7. Funnel plot of the variation in taxonomic distinctness (^+) in the sampling sites with a 95% confidence interval

i) Variation in taxonomic distincntess (^+)

Variation in taxonomic distinctness was statistically different among months ($p = 0.04$); December recorded differences with April ($p = 0.023$) and February ($p = 0.014$). The lowest value was recorded in August (^+ = 127.64), while the highest was recorded in April (^+ = 304.02) (Table 2). Sampling sites did not show any significant differences ($p = 0.86$) (Table 2).

Monthly data fell entirely within the 95% confidence interval, with June (^+ = 209.1) and August being the only two sites with values lower than the mean. Sampling sites were also within the 95% confidence interval with Las Palmas being the only one above the mean value (Fig. 7).

4. DISCUSSION

4.1 Physicochemical Variables

Physicochemical variables recorded no significant differences among sampling sites. However, months showed an inverse relationship between temperature and dissolved oxygen; due to the collisions between water molecules and dissolved oxygen, the oxygenation of any given aquatic system depends greatly on its thermal regime [18].

The thermal flow of the sediment is higher in smaller and shallower bodies of water [19] hence, La Paz lagoon favors a higher saline concentration during the warmer months, as well as a decrease in the oxygenation levels [20].

After studying the variables in the lagoon of La Paz, two climatic seasons were identified, a warm season (June-October) and a cold season (December-April). Castillo-Rosas et al., [21] agree that the variability on environmental variables corresponds with a well-defined temporal cycle. Barjau-González et al., [22] reported similar temperature conditions in the lagoon, as well as Hernández-Villasana and Barjau-González [23], with rises in temperature between August and October, and decreases during December-February.

Salinity is directly related with the humidity of an ecosystem; Sánchez-Bernal et al., [24] for “La Salina” coastal lagoon, Oaxaca, Mexico, reported differences between the humid and dry seasons. The weather in La Paz is predominantly dry, with a short humid season [9] allowing for stable salinity levels in the lagoon of La Paz throughout the year.

Dissolved oxygen plays a great role in determining fish behavior, since fish can suffocate when oxygen is not enough to meet the minimum energy requirements [25]. Maes et al., [26] showed that oxygen represents an effective barrier for fish migration, being increasingly uncommon to find individuals in relation to the depletion of oxygen in the water column. The collected data in the lagoon of La Paz shows a decrease in oxygen concentration during August (12.44 mg*L) (Table 2), which corresponds with de lower diversity indices during this season.

4.2 Species Richness

4.2.1 Alpha (α), beta (β) and gamma (γ) diversities

Alpha (α) and average alpha ($\bar{\alpha}$) diversities showed their lowest values during April (α = 37 species; $\bar{\alpha}$ = 11.1) (Table 2) (Fig. 2). Barjau-González [27] also reports a higher alpha diversity during the warm season in the San José Island. Riofrío-Lazo et al., [28] shows a rise in species richness during the warm season in coastal habitats near the southeast of Galapagos archipelago. Although no differences were found among sites, Zacatecas showed the highest values (α=42; $\bar{\alpha}$=13.5) (Fig. 2). Such values could be due to a higher algae coverage in the zone, allowing a greater amount of fish to use the zone as a feeding area [29].

Assuming an overlap in the distribution range of the species, beta diversity allows for an effective mapping of the species richness in an ecologically important site [30]. Whenever organisms are capable of moving freely, beta diversity tends to be higher [31]. hence, the beta diversity decrease observed during April-June (Fig. 2) points to a greater homogeneity among communities during the warm season, allowing us to assume that the physicochemical conditions in the lagoon of La Paz permit an easier migration between sampling sites.

4.3 Taxonomic Diversity

4.3.1 α-Fisher diversity

α-Fisher diversity index does not depend on the sample size or masks the importance of uncommon species, making it one of the best biologically founded indices [27]. No differences among sampling sites have been reported in the lagoon of La Paz before the present study [22,32], on a study in the San Ignacio lagoon, Southern Baja California, emphasizes the possibility of differences among sites being due to substrate differences. Aripez (S = 9.94) and Zacatecas (S = 10.99) recorded the highest values, which could be due to a greater vegetation presence in the zone, serving as a food source for fish inhabiting the area [29].

Our results contrast with those reported by Cota-Ortega et al., [33] who found higher values for fisher’s alpha during the warmer months (August-October) instead of the transition season (April-June); however, the substrate differences

Table 2. Summary of the values of the physicochemical variables and indices

Variation in taxonomic distinctness (VTD)	Average Taxonomic Distinctness (ATD)	Taxonomic Distinctness (TD)	α Fisher	Dissolved Oxygen (DO)	Salinity (UPS)	Temperature (∘C)	Site/Month
226.49	59.36	45.54	7.64	19.32mg*L	31.78 UPS	25.41°C	Grand Plaza
246.91	56.95	50.99	4.72	19.13mg*L	33.6 UPS	23.7°C	Aeropuerto
224.4	51.01	45.4	9.94	19.18mg*L	33.31 UPS	24.16°C	Aripez
227.53	54.64	37.61	5.98	19.68mg*L	33.68 UPS	24.06°C	CIBNOR
214.98	56.86	50.2	10.99	18.39mg*L	32.01 UPS	23.28°C	Zacatecas
171.73	59.78	53.63	3.89	20.46mg* L	33.33 UPS	24.23°C	Las Palmas
224.98	52.55	37.45	5.42	21.25mg*L	33.66 UPS	24.18°C	Yate Hundido
127.64	55.07	50.55	6.32	12.44mg*L	33.3 UPS	28.17°C	August
292.64	64.37	68.84	6.61	21.6mg *L	33.97 UPS	26.74°C	October
277.18	65.39	69.29	5.66	20.28mg*L	33.18 UPS	22.71°C	December
284.96	60.98	85.95	4.91	20.31mg*L	32.77 UPS	21.42°C	February
304	62.61	83.38	8.68	21.22mg*L	31.9 UPS	23.04°C	April
209.1	58.9	59.4	9.33	21.92mg*L	33.21 UPS	22.8°C	June

between Conquista Agraria (Rocky) and the lagoon of La Paz (Sandy) must be taken into consideration.

4.3.2 Taxonomic Distinctness (Δ*)

Taxonomic distinctness (Δ*) can be used to infer on the anthropogenic impact in a certain ecosystem due to its independence of the sample size and the use of systematic hierarchical information. The results obtained can be contrasted with Barjau-González et al., [22] who found the highest values during April and June in the lagoon of La Paz. On the other hand, the results concur with those of Contreras-Romero et al., [34] in "El Faro", Conquista agraria, Southern Baja California, who reported the highest value during February (Δ* = 150), which leads us to believe the homogeneity of the populations is higher during the colder months [15]. The dissimilarity with the aforementioned study [22] despite being carried out in the same area could be due to the regime change between the El Niño southern oscillation and La Niña events between the years of 2016-2017, leading to colder conditions in the lagoon which could affect the distribution of the local ichthyofauna [35].

4.3.3 Average taxonomic distinctness (Δ+)

The highest value for the average taxonomic distinctness (Δ^+) was recorded in December (Δ^+ = 65.39) while the lowest was found in August (Δ^+ = 55.07) (Table 2). Contreras-Romero *et al*., [34] reports the highest values during the warmer months (June), as well as Barjau-González *et al*., [36]. Such contrast can be related to the transition months (April-June) conferring the lagoon of La Paz with the ideal conditions to maintain a higher fish diversity.

The average taxonomic distinctness (Δ^+) index can also accurately assess the water quality and habitability of an ecosystem, since a decrease on the values indicates a rise in the eutrophication [37]. The similarity between our results and those reported by Barjau-González *et al*., [22] as well as the results falling within the 95% confidence interval point to the ecological health of the ecosystem being stable during the past years.

4.3.4 Variation in taxonomic distinctness (Λ+)

The variation in taxonomic distinctness (Λ+) index allows differentiating among populations with very diverse genera, while a single individual can represent higher hierarchy taxa [16]. Although no statistical differences were found among sites, higher values are characteristic of island fauna [17] and coincide with Juaristi-Videgaray [32] in San Ignacio Lagoon, Southern Baja California.

The variation in taxonomic distinctness (Λ+) index tends to increase with depth because the number of species per family decreases and homogenizes [38]. Since the lagoon of La Paz is a shallow body of water with a maximum depth of eight meters, the similarity among sites (p = 0.86) is to be expected.

Variation in this index and the general distribution of fish species closely relates with salinity and temperature. Due to the extreme weather conditions in the lagoon of La Paz, a wide variation in temperature, salinity and dissolved oxygen are expected, causing important fluctuations in the index values (Instituto Nacional de Estadística, Geografía e Informática, 1996; [39]. The aforementioned is illustrated in Fig. 6 with a close grouping of the colder months and a wider distribution of the warmer months, demonstrating a higher heterogeneity of the fish communities during the warmer months in the lagoon of La Paz. In addition, Hu and Zhang [40-42]. in the Bohai Bay, northern China reported wider fluctuations in such index values among climatic seasons, hence, the local variations in the index values could be due to the extreme temperature changes between the warm and cold seasons in the lagoon of La Paz.

5. CONCLUSION

Two climactic seasons were found, a cold one (December-April), and a hot one (June-August). The seasonal variability directly affects the α-Fisher diversity and the average alpha ($\bar{\alpha}$), which presented the highest values during April, indicating the local species preference for warmer weather throughout the year.

Beta diversity (β), taxonomic distinctness (Δ*) and average distinctness (Δ+), were highest during December and February, evidencing a higher species replacement and heterogeneity among populations during the cold season. Since not all of the species are residents of the La Paz Lagoon throughout the year, the season in which the abundance of species is lower (December-February) results in an increased Taxonomic diversity due to the prevalence of species that are better adapted to the fluctuating conditions of the Lagoon.

According to the presented results, we infer the Lagoon of La Paz is currently in good ecological conditions, with no evidence of anthropogenic impact in recent years. However, it is important to keep monitoring the lagoon status in order to avoid possible negative impacts in the near future.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Authors hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

DATA AVAILABILITY

The datasets generated during the current study are available on https://drive.google.com/drive/folders/1RlkLbK8UptSH235AYYqFuv-MQ-kSGuxP?usp=sharing and from the corresponding author on reasonable request.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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