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Aquatic avifauna in a subtropical estuarine system, a World Heritage site (Paraná, southern Brazil)

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ABSTRACT

The Paranaguá Estuarine Complex (PEC) is internationally recognized for its economic, social, and environmental relevance. It is designated as a World Heritage site and part of selected wetland areas that protect and conserve biodiversity, especially waterbirds. However, it has historically been under pressure from human activities, and the information about waterbirds that use the region is fragmented. Thus, with this study, we sought to establish a baseline for the waterbirds using the bays of the PEC, considering aspects such as species richness, abundance, and conservation status. On board a boat, we conducted monthly surveys from March 2020 to February 2021 along 36 transects equally distributed among the three main bays of the PEC. We recorded 46 species distributed across 17 families and eight orders. The order Charadriiformes displayed the highest number of species, totaling 19. Among them, the Neotropic Cormorant, identified as *Nannopterum brasilianum*, stood out with the highest number of occurrences. Furthermore, we documented eight migratory species from the Northern Hemisphere, including *Calidris pussilla*, the Semipalmated Sandpiper, considered near threatened by the International Union for Conservation of Nature Red List. Additionally, we observed seven other species classified under some threat of extinction. Our results revealed that the PEC harbors a rich and diverse assemblage of waterbirds consisting of resident and migratory species, many of which are at some risk of population decline. Therefore, we reinforce the importance of continuous monitoring in the region, which can serve as a basis for public policies, supporting management and conservation strategies focused on waterbirds and the wetlands on which they depend.

Keywords: Baseline, Estuary, Management, Waterbirds, Wetlands

INTRODUCTION

Wetlands are experiencing rapid and alarming loss and degradation, surpassing the rate of decline observed in any other global ecosystem (Millennium Ecosystem Assessment, 2005; United Nations, 2015). These hydrological changes in wetlands, coupled with the degradation of coastal and marine habitats and the depletion of food resources, have had a detrimental impact on various waterbird populations (Kushlan et al., 2002; Millennium Ecosystem Assessment, 2005; United Nations, 2015). Consequently, many waterbird species are undergoing significant population declines and face the risk of extinction (Wetlands International, 2012; Studds et al., 2017; Amano et al., 2018; Wang et al., 2022). Therefore, implementing measures recognizing the importance of waterbird richness and abundance is a priority to support the conservation of wetlands. The ecological measures qualify the identification of wetlands as internationally significant areas and contribute to define priority

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sites for management, restoration, conservation, and protection. (Stroud et al., 2004; Amano et al., 2018; Aguilar et al., 2021).

Waterbirds, whose life cycles are intricately linked to wetlands environments, have developed remarkable adaptations such as interdigital membranes, specialized beaks for filtration or fishing, and exceptional diving abilities (Weller, 1999; Pough et al., 2003). The RAMSAR Convention (1971) defines them as species that depend, either wholly or partially, on wetlands and are seldom sighted outside these areas. Due to their spatial and temporal mobility, waterbirds exhibit two distinct assemblages in subtropical wetlands: wintering assemblages consisting of migratory species that utilize the region for foraging and resting between migrations, and breeding assemblages composed of species reliant on these regions for reproduction and nesting (Webster and Marra, 2005; Zurell et al., 2018).

These avian inhabitants of the interface between aquatic and terrestrial ecosystems play a pivotal role in assessing wetland health (Şekercioglu, 2006; Whelan et al., 2008; Green and Elmberg, 2014). Their significance lies in the execution of multiple ecosystem functions, including regulating animal populations as predatory regulators, positively influencing species richness and abundance, facilitating plant seed dispersion during feeding, and promoting connectivity among various wetlands and ecosystems due to their high mobility (Green and Elmberg, 2014; Green et al., 2016; Martín-Vélez et al., 2020).

Estuaries, recognized as highly productive wetlands (Nagelkerken et al., 2015; Whitfield, 2017), are complex ecosystems that foster remarkable biological diversity. Their abundant resources and environmental variability provide ideal habitats for many species across different life stages (Nagelkerken et al., 2015; Whitfield, 2017). In particular, waterbirds thrive in estuaries due to the favorable conditions that these ecosystems offer, such as vast opportunities for foraging, areas for reproduction, nesting sites, overnight resting places, and stopover locations during migration (Krul, 2004; Tavares et al., 2015; Dias et al., 2017; Arruda Almeida et al., 2018).

The Paranaguá Estuarine Complex (PEC) is located on the Paraná coast, southern Brazil, and is home to a diverse range of resident and migratory waterbirds (Krul, 2004; Krul et al., 2011). Recognized worldwide for its environmental and ecological significance, the PEC has been designated as a World Natural Heritage Site by UNESCO (1999) to protect areas of exceptional biological and landscape diversity. The complex comprises a mosaic of conservation units, with 14 designated for sustainable use and 30 for complete protection (Paula et al., 2018). In 2017, part of its area was recognized as a RAMSAR site and included in the List of Wetlands of International Importance (ICMBio, 2017; Ribeiro et al., 2020). These sites serve as living laboratories for developing and refining conservation and sustainable use strategies (Wetlands Convention, 2012). The PEC is particularly relevant as a natural laboratory due to its unique hydrological and oceanographic complexity and the numerous sub-estuaries comprising this complex estuary (Lana et al., 2001; 2018; Noernberg et al., 2006). However, the coast of Paraná, including the PEC, is historically under pressure from various anthropic activities (Miura and Noernberg, 2020). It has two ports installed in the Paranaguá and Antonina Bays, several potentially polluting industrial activities, and real estate expansion and tourism that has been growing in recent years (Pierri et al., 2006; Angeli et al., 2020; Mengatto and Nagai, 2022). Furthermore, despite the significant number of conservation units, only 16.3% have management plans (Paula et al., 2018), and baseline data on waterbirds in this region are scarce (Moraes and Krul, 1995; Mestre et al., 2007; Meijer and Disaró, 2018).

Despite the acknowledged ecological significance of the PEC, a dearth of primary data and fundamental biological assessments persists. Undertaking exhaustive fauna surveys and establishing foundational information can substantially bolster the formulation and execution of conservation-oriented management strategies pertaining to aquatic avifauna and their respective habitats, particularly in view of the ongoing global population decline (Silveira et al., 2010). Seeking a comprehensive approach, this study conducted a qualitative and quantitative survey of aquatic avifauna over the course of a year, encompassing the main bays of the PEC. The research encompassed the assessment of various ecological aspects, such as species diversity, relative abundance, and predominant conservation status. The resulting data is readily accessible to researchers and managers from a dedicated repository, with the specific aim of facilitating the preservation of both aquatic avifauna species and their essential habitats.

METHODS

Study Sites

The study was carried out in the Paranaguá Estuarine Complex (PEC) (48°25'W, 25°30'S). Defined as a subtropical estuary, the PEC comprises two main bodies of water, the bays of Laranjeiras and Pinheiros (200 km^2) on the north-south axis, and the bays of Paranaguá and Antonina (260 km^2) that make up the east-west axis (Noernberg et al., 2006; Lana et al., 2018) (Figure 1).

The mean annual rainfall is 2500 mm, with a well-defined rainy season during the summer and a dry season in the winter months (Lana et al., 2001; Vanhoni and Mendonça, 2008). Variations in the salinity gradient are well-marked, ranging from 0 to 34 (Lana et al., 2001). The tidal regime is semidiurnal, with a mean tidal amplitude of 2.2 m, a 12.6 km of intrusion, and a mean depth of 5.4 m (Lana et al., 2001).

The PEC comprises extensive mangroves, marshes, tidal flats, canals, streams, estuarine beaches, and rocky shores. It is surrounded by one of Brazil's last continuous remnants of the Atlantic Forest. (Noernberg et al., 2006; Lana et al., 2018). It has a mosaic of restricted and sustainable-use conservation units, including marine and terrestrial units (Paula et al., 2018). In addition, it houses two ports on the East-West axis – the port of Antonina and the port of Paranaguá. The latter is considered one of Brazil's largest grain ports, with one of the largest port infrastructures on the continent (Menem et al., 2019).

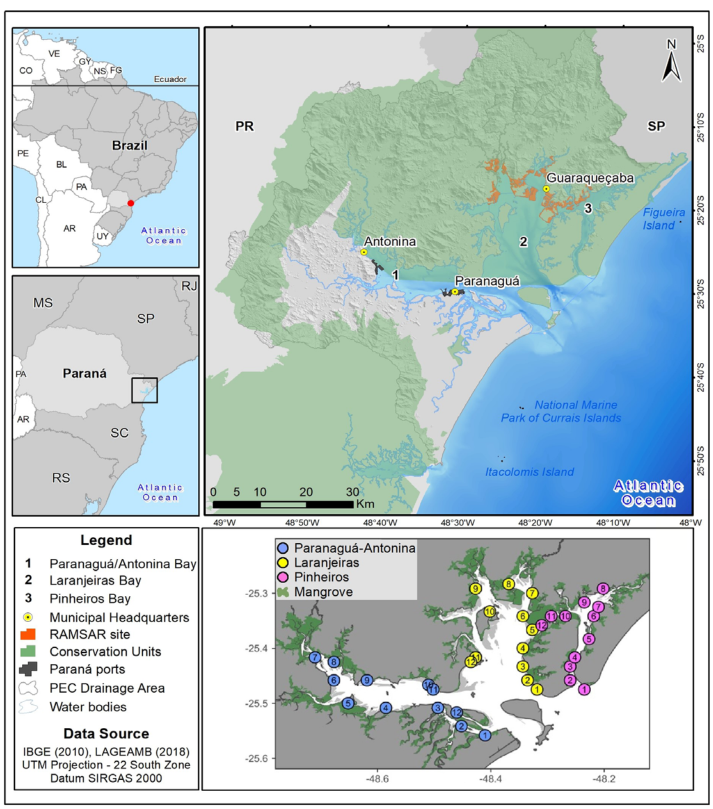

Figure 1. Map of the study area. The upper map illustrates the Paranaguá/Antonina Bay (1), Laranjeiras Bay (2), and Pinheiros Bay (3), with a focus on conservation units and the RAMSAR site. The lower map indicates the location of each transect within the Paranaguá Estuarine Complex (PEC) (Adapted from Miotto et al., 2023).

Sampling waterbirds and analyses

In the context of this study, waterbirds were defined according to the classification proposed by Wetlands International (2012) as species ecologically dependent and semi-dependent on wetland environments. Additionally, species with morphophysiological and behavioral characteristics adapted for the direct exploitation of resources in wetlands, as documented by Vieira (2017) and Arruda Almeida et al. (2018), were included in the study. Furthermore, species that show behaviors directly associated with the use of resources or habitats in wetlands, whether for feeding or reproductive purposes, were considered, even if they do not possess specific morphophysiological features for such purposes. Species with a more generalist nature, which may use these areas during specific stages of their life cycles or as transitional zones, were also incorporated into the study.

To conduct visual surveys of waterbirds in the PEC, we implemented a monitoring program that covered 36 transects evenly distributed across the three estuarine bays, each spanning 1,400 meters in length, as detailed in Figure 1. We utilized a 7-meter boat equipped with a 60 HP engine and a draft of 30 centimeters. Monthly censuses were carried out from March 2020 to February 2021, employing the linear transect method as described by Bibby et al. (2000). During these surveys, we recorded all waterbirds observed within a 200-meter radius around the boat.

Each transect was surveyed once a month, with the boat maintaining a constant speed of 5 km/h over a 15-minute period. To minimize potential observer bias, data collection was consistently performed by a single observer using 10×50 binoculars positioned at the bow of the boat, providing comprehensive coverage of a 180-degree field of view. Mixed flocks of birds were identified and quantified, with the boat's speed reduced as needed. Whenever possible, photographic records were captured.

All sampling was conducted under favorable environmental conditions, specifically in the absence of rain and fog, ensuring precise observations. To mitigate potential influences from variations in time and tidal regimes, we employed a systematic approach, sequentially ordering the transects from 1 to 12 in each bay and alternated the starting and ending points of the census each month. Additional measures were taken to prevent the double-counting of birds in motion, whether within the same transect or between different transects. The selection of locations for each transects considered the representation of diverse habitats within the PEC, as well as navigational safety considerations, accounting for the presence of rocks and sandbanks in the region.

To evaluate the sample representativeness, a species accumulation curve was calculated (observed richness of species) compared with two curves of extrapolated richness indices (in addition to the richness of species), calculated with two methods, Jaccard and Bootstrap (Palmer, 1990; Colwell and Coddington, 1994; Ugland et al., 2003; Oksanen et al., 2022). Plotted accumulation curves of the observed richness of species and the extrapolated richness curves are compared using the indices values and confidence interval (95%) for random ordering of sampling units (Oksanen et al., 2022).

To calculate the relative abundance, we used the equation $(n/N)\times100$, where "n" represents the number of views of a given species, and "N" represents the total number of organisms counted. Occurrence rates were calculated by the formula $p\times100/P$, where "p" represents the number of censuses in which a species was sighted, and "P" represents the total number of censuses (Dajoz, 1978). We classified taxa based on their occurrence rates, categorizing them as dominant if present in over 50% of the samples, frequent if observed between 30% and 50%, rare if observed between 30% and 10%, and uncommon if observed at a frequency of 10% or less (Branco et al., 2010; Barbieri et al., 2013).

The nomenclature and type of occurrence of waterbirds in this study followed the list of the Brazilian Ornithological Records Committee (CBRO) (Pacheco et al., 2021). To classify the conservation status of the species, we referred to the list of the International Union for Conservation of Nature (IUCN) (BirdLife International, 2021), the Brazilian national list of threatened species: MMA (MMA, 2022), and the List of Bird Species belonging to the Wild Fauna Threatened with Extinction in the State of Paraná (Paraná, 2018).

RESULTS

During our study, we conducted 427 censuses and recorded 46 waterbird species from eight orders and 17 families. Of these, five species were classified as dominant (DM), three as frequent (FR), nine as rare (RR), and 29 as uncommon (UN) (Table 1). The order Charadriiformes was the most represented, accounting for 41.3% (n=19) of the total species sighted, followed by Pelecaniformes with 28.3% (n=13). Families Ardeidae, Scolopacidae, and Sternidae had the highest number of species sighted, with nine, six, and five species, respectively (Table 1).

Most sighted species had low occurrence rates, with 63% (n=29) uncommon. Only *Nannopterum brasilianum*, *Fregata magnificens*, *Egretta caerulea*, *Ardea alba*, and *Egretta thula* had occurrence rates greater than 50% (Table 1). Among the most abundant species, *N. brasilianum*, *E. caerulea*, and *Sula leucogaster* stood out for their large flocks and year-round presence, accounting for 83.5% of the relative abundance (Table 1). Although present throughout the year, we recorded a higher number of *N. brasilianum* sightings during the months of May to October (Figure 2).

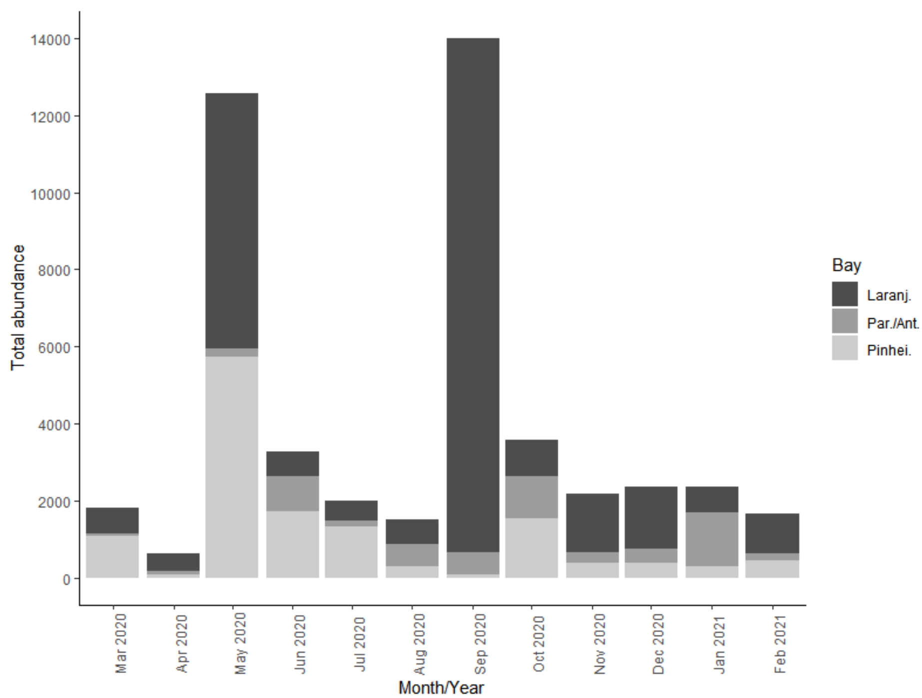

Figure 2. Total abundance of *Nannopterum brasilianum* categorized by month and year. The x-axis represents the month and year, while the y-axis indicates the total abundance of individuals. The color coding differentiates between the three bays: Laranjeiras (Laranj), Paranaguá/Antonina (Par./Ant.), and Pinheiros (Pinhei.).

We documented eight Northern Hemisphere migratory species, all belonging to the Charadriiformes order, specifically *Charadrius semipalmatus*, *Calidris alba*, *Calidris fuscicollis*, *Tringa flavipes*, *Tringa melanoleuca*, *Tringa solitaria*, *Sterna hirundo*, and *Calidris pusilla*, the latter of which is categorized as near-threatened (NT) by the IUCN (Table 1). The remaining species, whether migratory or resident, were classified as Least Concern (LC) by the IUCN (Table 1). These species were observed year-round, except for the months of June and July, with the highest records occurring in October and November (Figure 3).

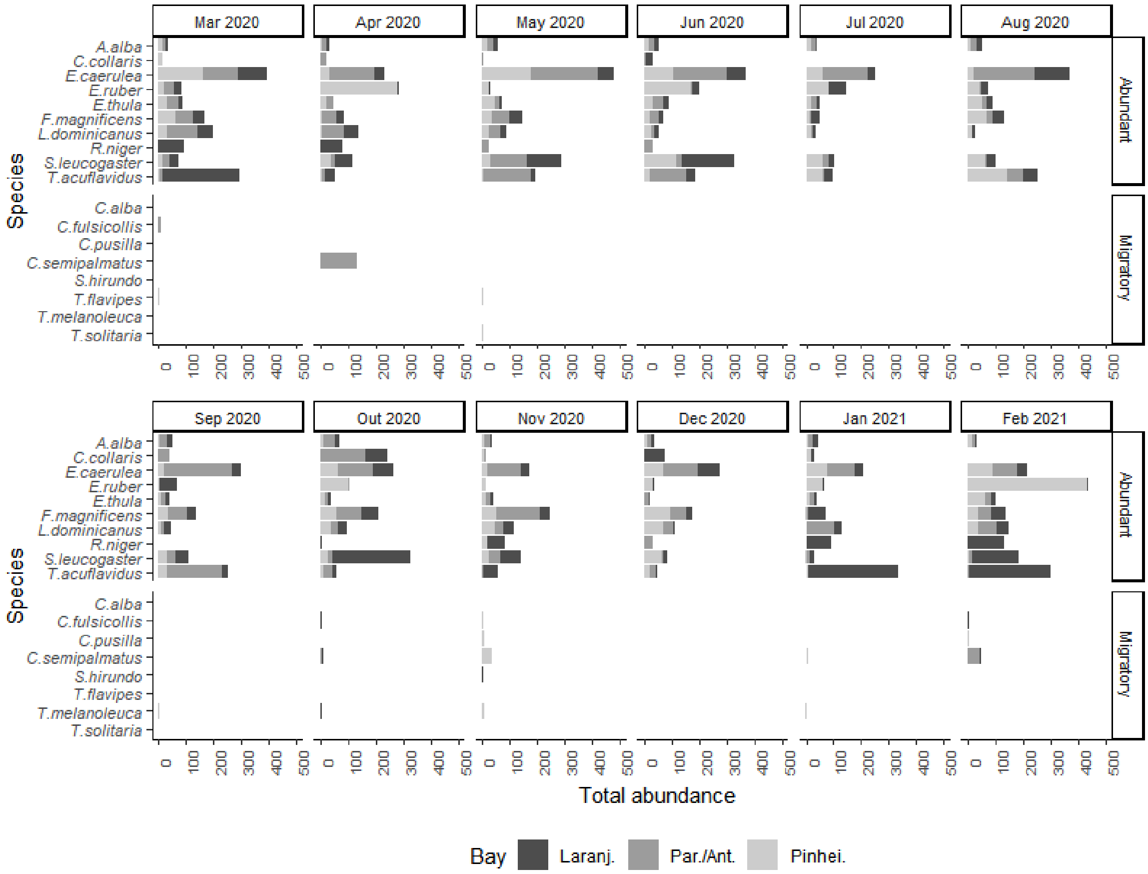

Figure 3. Total abundance of the ten most abundant species excluding *Nannopterum brasilianum* (*A. alba*, *C. collaris*, *E. caerulea*, *E. ruber*, *E. thula*, *F. magnificens*, *L. dominicanus*, *R. niger*, *S. leucogaster*, *T. acuflavidus*) and total abundance of migratory species (*C. semipalmatus*, *C. alba*, *C. fulsicollis*, *T. flavipes*, *T. melanoleuca*, *T. solitaria*, *S. hirundo*, *C. pusilla*) categorized by month and year. The x -axis represents the total abundance of the species, while the y-axis indicates the species names. The color coding distinguishes between the three bays: Laranjeiras (Laranj), Paranaguá/Antonina (Par./Ant.), and Pinheiros (Pinhei.).

At a national level, we have identified three species under some level of threat (MMA, 2022). These species include *Haematopus palliatus* and *Sterna hirundinacea*, classified as vulnerable (VU), and *Thalasseus maximus*, classified as endangered (EN), all belonging to the order Charadriiformes (Table 1). We have also recorded three species listed as near threatened (NT), namely *Chloroceryle aenea* from the order Coraciiformes, *Aramides mangle* from the order Gruiformes, and *Eudocimus ruber* from the order Pelecaniformes (Table 1). Lastly, *C. pusilla*, listed as endangered on a national scale, lacks sufficient data for the state of Paraná, and thus it is listed as data deficient (DD) (Table 1).

The number of species recorded in the bays was quite similar, with 36 species in Laranjeiras Bay, 37 in Paranaguá and Antonina Bays, and 38 in Pinheiros Bay (Table 1). The composition of dominant species was also similar among the bays (Table 1; Figure 3), with *N. brasilianum* as the most abundant species, accounting for 83.9% of the relative abundance in Laranjeiras Bay, 73.5% in Pinheiros Bay and 48.1% in Paranaguá and Antonina Bays. On the other hand, *S. leucogaster* and *E. ruber* showed abundance higher than 5% in Pinheiros Bay. The first had 6.6% of the relative abundance, whereas the second had 5.5% of abundance. In Paranaguá and Antonina Bays, *E. caerulea* had for 15.7% of the relative abundance, *F. magnificens* had 5.5%, and *T. acuflavidus* had 5.3% of the total species abundance. Except for *N. brasilianum*, no species represented more than 5% of the relative abundance in Laranjeiras Bay (Supplementary Material, Table S1).

Table 1. List of species recorded in the Paranaguá Estuarine Complex between March 2020 and February 2021, indicating the number of individuals recorded in each bay, where L represents Laranjeiras Bay, P represents Pinheiros Bay, and PA represents Paranaguá and Antonina Bays. Total constancy values (C%) are followed by the classification as follows: Dominant (DM) ≥ 50%, Frequent (FR) between 50% and 30%, Rare (RR) between 30% and 10%, and Uncommon (UN) ≤ 10%. The relative abundance of species is represented by A%. The conservation status at the international (IUCN), national (MMA), and state (PR) levels includes categories such as Least Concern (LC), Near Threatened (NT), Vulnerable (VU), Endangered (EN), and Data Deficient (DD). The occurrence of species (Oc.) is classified according to Pacheco et al., 2021, where (BR) denotes resident migrants or breeders (with evidence of reproduction in the country), and (VI(S)) non-reproductive seasonal visitor, originating from the south.

Orders/Families/Species	IUCN/ MMA/PR	L (n)	P (n)	PA (n)	C%	Class.	A%	Oc.
Anseriformes								
Anatidae								
Anas bahamensis Linnaeus, 1758	LC/-/-	-	-	24	0.7	UN	< 0.1	BR
Cairina moschata (Linnaeus, 1758)		1	-	-	0.2	UN	< 0.1	BR
Charadriiformes								
Charadriidae								
Charadrius collaris Vieillot, 1818	LC/-/-	13	40	178	3.7	UN	0.3	BR
Charadrius semipalmatus Bonaparte, 1825	LC/-/-	191	43	234	3.9	UN	0.6	VI(S)
Vanellus chilensis (Molina, 1782)	LC/-/-	26	23	116	12.8	RR	0.2	BR
Haematopodidae								
Haematopus palliatus Temminck, 1820	LC/-/VU	7	14	117	7.2	UN	0.2	BR
Laridae								
Chroicocephalus maculipennis (Lichtenstein, 1823)	LC/-/-	9	2	16	1.8	UN	< 0.1	BR
Larus dominicanus Lichtenstein, 1823	LC/-/-	336	319	523	42.1	FR	1.7	BR
Recurvirostridae								
Himantopus melanurus Vieillot, 1817	LC/-/-	2	-	195	3.5	UN	0.3	BR
Rynchopidae								
Rynchops niger Linnaeus, 1758	LC/-/-	458	18	90	3.8	UN	0.8	BR
Scolopacidae								
Calidris alba (Pallas, 1764)	LC/-/-	-	2	-	0.2	UN	< 0.1	VI(S)
Calidris fuscicollis (Vieillot, 1819)	LC/-/-	5	11	8	1.6	UN	< 0.1	VI(S)
Calidris pusilla (Linnaeus, 1766)	NT/EN/DD	-	8	-	0.4	UN	< 0.1	VI(S)
Tringa flavipes (Gmelin, 1789)	LC/-/-	2	3	-	0.9	UN	< 0.1	VI(S)
Tringa melanoleuca (Gmelin, 1789)	LC/-/-	6	12	2	1.9	UN	< 0.1	VI(S)
Tringa solitaria Wilson, 1813	LC/-/-	-	2	-	0.2	UN	< 0.1	VI(S)
Sternidae								
Sterna hirundinacea Lesson, 1831	LC/VU/VU	4	1	18	1.6	UN	< 0.1	BR
Sterna hirundo Linnaeus, 1758	LC/-/-	1	-	-	0.2	UN	< 0.1	VI(S)

[continued]

Orders/Families/Species	IUCN/ MMA/PR	L (n)	P (n)	PA (n)	C%	Class.	A%	Oc.
Sternula superciliaris (Vieillot, 1819)	LC/-/-	4	1	-	0.4	UN	< 0.1	BR
Thalasseus acuflavidus (Cabot, 1847)	LC/-/-	1173	321	648	29.2	RR	3	BR
Thalasseus maximus (Boddaert, 1783)	LC/EN/EN	138	135	142	14	RR	0.6	BR
Coraciiformes								
Alcedinidae								
Chloroceryle aenea (Pallas, 1764)	LC/-/NT	-	1	1	0.5	UN	< 0.1	BR
Chloroceryle amazona (Latham, 1790)	LC/-/-	14	16	12	7.7	UN	< 0.1	BR
Chloroceryle americana (Gmelin, 1788)	LC/-/-	4	7	3	3	UN	< 0.1	BR
Megaceryle torquata (Linnaeus, 1766)	LC/-/-	49	73	73	29	RR	0.9	BR
Falconiformes								
Falconidae								
Caracara plancus (Miller, 1777)	LC/-/-	21	29	24	10	RR	0.1	BR
Milvago chimachima (Vieillot, 1816)	LC/-/-	55	29	45	20	RR	0.2	BR
Gruiformes								
Rallidae								
Aramides mangle (Spix, 1825)	LC/-/NT	1	-	2	0.5	UN	< 0.1	BR
Aramides cajaneus (Statius Muller, 1776)	LC/-/-	7	19	13	4.2	UN	< 0.1	BR
Pelecaniformes								
Ardeidae								
Ardea alba Linnaeus, 1758	LC/-/-	145	138	250	54.5	DM	0.7	BR
Ardea cocoi Linnaeus, 1766	LC/-/-	75	78	87	33.7	FR	0.3	BR
Bubulcus ibis (Linnaeus, 1758)	LC/-/-	1	-	-	0.2	UN	< 0.1	BR
Butorides striata (Linnaeus, 1758)	LC/-/-	-	5	8	2.6	UN	< 0.1	BR
Egretta caerulea (Linnaeus, 1758)	LC/-/-	721	898	1925	73.5	DM	5.1	BR
Egretta thula (Molina, 1782)	LC/-/-	156	315	247	52.2	DM	1	BR
Nyctanassa violacea (Linnaeus, 1758)	LC/-/-	68	134	67	12.4	RR	0.4	BR
Nycticorax nycticorax (Linnaeus, 1758)	LC/-/-	12	31	86	8.7	UN	0.2	BR
Syrigma sibilatrix Temminck, 1824)	LC/-/-	-	1	-	0.2	UN	< 0.1	BR
Threskiornithidae								
Eudocimus ruber (Linnaeus, 1758)	LC/-/NT	223	1261	52	13.6	RR	2.2	BR
Phimosus infuscatus (Lichtenstein, 1823)	LC/-/-	-	9	46	4.9	UN	< 0.1	BR
Platalea ajaja Linnaeus, 1758	LC/-/-	12	108	117	13.8	RR	0.3	BR
Plegadis chihi (Vieillot, 1817)	LC/-/-	-	-	1	0.2	UN	< 0.1	BR

[continued]

Orders/Families/Species	IUCN/ MMA/PR	L (n)	P (n)	PA (n)	C%	Class.	A%	Oc.
Podicipediformes								
Podicipedidae								
Podicephorus major (Boddaert, 1783)	LC/-/-	-	-	2	0.5	UN	< 0.1	BR
Suliformes								
Fregatidae								
Fregata magnificens Mathews, 1914	LC/-/-	466	489	671	75.1	DM	2.3	BR
Phalacrocoracidae								
Nannopterum brasilianum (Gmelin, 1789)	LC/-/-	28629	16978	5909	89.9	DM	74.1	BR
Sulidae								
Sula Leucogaster (Boddaert, 1783)	LC/-/-	1071	1518	339	42.8	FR	4.2	BR
Total of individuals of each bay		34106	23092	12291				
Species richness of each bay		36	38	37				

In addition to the waterbirds species listed in Table 1, we also recorded the red-tailed parrot (*Amazona brasiliensis*, n=171) and ten species of hawks, such as: *Amadonastur lacernulatus* (n=8), *Buteo brachyurus* (n=1), *Buteogallus aequinoctialis* (n=1), *Elanoides forficatus* (n=1), *Elanus leucurus* (n=1), *Geranospiza caerulescens* (n=1), *Leptodon cayanensis* (n=1), *Pseudastur polionotus* (n=9), *Rupornis magnirostris* (n=6) and *Urubitinga urubitinga* (n=9) (Table S1).

The species accumulation curves (observed richness and the extrapolated richness indices) did not overlap the confidence intervals at the beginning of their stabilization, indicating that a more significant number of samplings is necessary to sight unusual species (Figure 4).

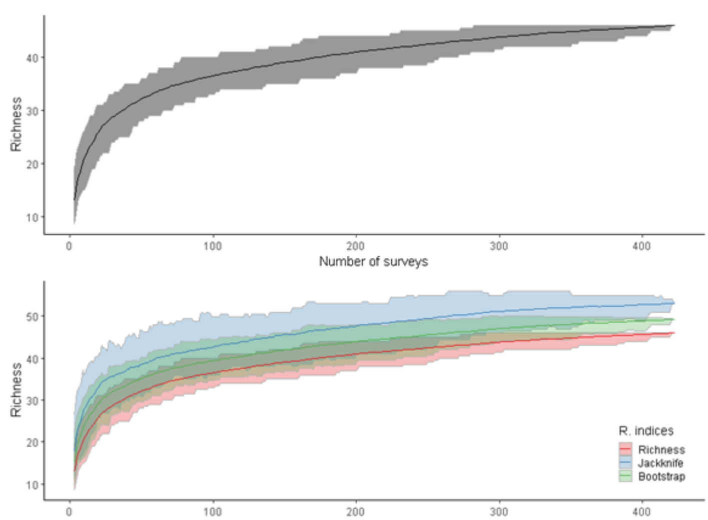

Figure 4. Aquatic avifauna species–accumulation curves for randomized samples of the PEC (Paraná, Brazil) generated to assess observed richness (top) or calculated richness (bottom) along the survey effort. The graph displays the observed richness species–accumulation curve. On the bottom, the species–accumulation curves based on observed richness (the bottom curve, depicted in red) and those calculated using extrapolated richness (using the first-order Jackknife method in blue, the top curve; and the bootstrap method in green, the middle curve) are compared.

DISCUSSION

The information regarding the assemblages of waterbirds in the PEC is fragmented and lacks systematic organization. In this context, this study contributes to addressing these knowledge gaps, standing out due to a robust monitoring conducted over a year, resulting in the identification of 46 species of waterbirds in the three central bays of the PEC. Of these species, 38 were classified as residents, whereas eight were identified as migratory. Note that, despite most species exhibiting low occurrence rates, five stood out as dominant in the study area.

Previous studies conducted over two decades ago also documented the diversity of waterbirds in the PEC and its surrounding areas. Moraes and Krul (1995) conducted a study concerning the avifauna associated with marine-influenced ecosystems along the coast of the state of Paraná. The previous study identified 59 species in estuaries, oceanic waters, sandy beaches, and rocky shores. Remarkably, 28 species they reported were also sighted during our monitoring efforts. Additionally, more than a decade ago, a complementary study by Mestre et al. (2007) recorded 23 species of waterbirds in the mangroves of Paranaguá Bay, with 22 of these species matching our observations. More recently, Meijer and Disaró (2018) documented the presence of 36 estuarine bird species in Paranaguá, Antonina, and Guaraqueçaba regions, with 32 of them also appearing in our records. However, our monitoring efforts resulted in the exclusive identification of six additional species: *Calidris pusilla*, *Sterna hirundo*, *Syrigma sibilatrix*, *Plegadis chihi*, and *Podicephorus major*. This increase in observed species richness can be partly attributed to the increased sampling effort and the coverage of a more diversified range of habitats.

The Neotropic Cormorant (*N. brasilianum*) exhibited the highest occurrence rate, accounting for approximately 90% of the observations and representing around 70% of the total counted individuals. This dominance has also been observed in previous studies (Moraes and Krul, 1995; Mestre et al., 2007) within the PEC, as well as in other regions of Brazil (Branco, 2007; Dias et al., 2017;; Rubert et al., 2020; Roselli and Barbieri, 2022). Such high abundance in certain areas raises concerns about potentially impacting economically valuable fish populations and negative interactions with other waterbird species (Kirby et al., 1996; Wisz et al., 2013). In this study, the largest flocks of *N. brasilianum* were observed along Laranjeiras Bay, indicating that this area is the most utilized for roosting and foraging by the species (Miotto et al., 2023). This is attributed to the gregarious nature of *N. brasilianum* (Sick, 1997), its fidelity to specific feeding sites (Barquete et al., 2008), and its daily movements restricted to a few kilometers between resting and foraging areas (Quintana et al., 2004). Although Moraes and Krul (1995) documented a higher abundance of this species during the rainy season, spanning from November to April, associating these seasonal fluctuations with reproductive changes, our results reveal a discrepancy – the highest number of sightings of this species occurred between May and October, during the dry season. These findings raise two possibilities: seasonal variations in the reproductive period or the potential for the species to have initiated reproductive activities within the PEC. However, we must emphasize that the understanding of the temporal variations, reproductive cycles, and migratory behaviors of *N. brasilianum* is still incomplete (Barquete et al., 2008). Therefore, further research is essential to comprehensively elucidate the seasonality of occurrence movement patterns and the local parameters of behavior ecology of this species.

Another prominent resident species in the PEC is the Blue Heron, known scientifically as *Egretta caerulea*. The frequent observation of the species follows the trend previously documented by Moraes and Krul (1995), who reported the common presence of *E. caerulea* in the PEC. However, they noted the absence of sightings in February, August, November, and December. During our observations, we verified the presence of *E. caerulea* during all months, with sightings of adult and young individuals based on plumage characteristics, suggesting that reproduction may have been a relatively recent addition to the ecological dynamics of the region. Notably, in addition to *E. caerulea*, the species *F. magnificens* and *S. leucogaster* were also recorded as dominant and frequent in the PEC. The latter, in particular, is among the three most abundant species in the region. Both *F. magnificens* and *S. leucogaster* nest on the coast of Paraná in mixed colonies located in the archipelago of the Currais Islands Marine National Park, where reproductive activities occur continuously throughout the year (Krul, 2004).

As documented in our study, *Eudocimus ruber*, commonly known as the Scarlet Ibis, is a rare resident species in the PEC. In the past, this species was even considered extinct in the mangroves of the south and southeast of Brazil (Fink and Cremer, 2015; Chupil and Monteiro-Filho, 2018; Paludo et al., 2018), due to anthropogenic factors such as mangrove degradation (Hass, 1996), hunting, and egg collection (Lago-Paiva, 1994; Rodrigues, 1995); the last documented record of the species in the PEC before its supposed extinction dates back to 1977 (Teixeira and Best, 1981). However, the species reappeared with the observation of groups of juvenile individuals around 2011 (Krul et al., 2009). Population estimates conducted between October 2012 and September 2013 counted 1,559 individuals, with a predominance of adults (Vigário et al., 2020). Our observations confirm the remarkable recovery and reestablishment of the *E. ruber* population in the PEC, with an emphasis on Pinheiros Bay as the most attractive habitat for the species, as previously reported by Krul et al. (2011) and Vigário et al. (2020). Nevertheless, note that the species is still classified as Near Threatened (NT) on the Red List of the State of Paraná (Paraná, 2018), emphasizing the importance of implementing management and conservation measures to ensure its protection.

We also recorded the presence of *Sterna hirundinacea*, the South American tern, and *Thalasseus maximus*, the royal tern, in all monitored bays of the PEC. Both birds belong to the order Charadriiformes and are protected by the National Plan for the Conservation of Threatened Species (MMA, 2022). Whereas *S. hirundinacea* is classified as vulnerable (VU), *T. maximus* is listed as an endangered species (EN) (MMA, 2022). Along the coast of Paraná, *S. hirundinacea* nests on specific islands, including the Itacolomis and Figueira islands, located to the south and north of the PEC, respectively, and in the Currais Islands Marine National Park (Krul, 2004). However, due to the lack of systematic monitoring, data on the reproductive activities of these birds on these islands over the years is limited (Krul, 2004).

Throughout the year, we documented eight Nearctic migratory species that travel to the Southern Hemisphere in search of food and find suitable places to rest and feed in the PEC (Krul et al., 2011; Miotto et al., 2023). All migratory species recorded belong to the order Charadriiformes, which helps to explain the significant representation of this order in our study. Seven of the eight migratory species are included in the exclusive list of species identified by the National Action Plan for Coastal Migratory Birds, namely *Calidris pusilla*, *Charadrius semipalmatus*, *Calidris alba*, *Calidris fuscicollis*, *Tringa flavipes*, *Tringa melanoleuca* and *Tringa solitaria* (ICMBio No. 491, September 10, 2019). Among migratory species, *C. pusilla* stands out for its worrying conservation status, internationally classified as Near Threatened (NT) by the IUCN, Endangered (EN) in Brazil by the MMA (2022) and with Deficient Data (DD) in the state level. Note that, with the exception of *C. semipalmatus*, most sightings of these migratory species occurred in the Pinheiros bay, which presents habitats with less anthropogenic impact and a continuous mangrove forestry. This highlights the crucial role of environmental conservation in supporting these species occurrence and abundance.

Our results show variations in the composition of waterbird communities across the PEC. Although the total number of species is similar among bays, differences in relative abundances and the presence of dominant species indicate local dynamic processes such as tidal variations, prey availability and ecological interactions may be influencing the composition of waterbirds (Miotto et al., 2023). The species *N. brasilianum* was dominant in all bays, but variations in abundance rates suggest local influences that deserve further investigation. The abundance of this species can limit the coexistence of others with similar characteristics by competitive exclusion (Luck and Smallbone, 2001; Wisz et al., 2013). Furthermore, we observed differences in the abundance of species such as *S. leucogaster*, *E. ruber*, *E. caerulea*, *F. magnificens*, and *T. acuflavidus*, indicating different responses to the specific conditions of each location (Miotto et al., 2023). These variations in community composition reflect short-term behavioral, distributional, or demographic adjustments, influencing species turnover and maintaining a dynamic balance (Dias et al., 2017; Deus et al., 2020; Miotto et al., 2023).

Although our monitoring period has been relatively short, our combined analyses of observed and extrapolated richness curves confirm the representativeness of the data. These results highlight the remarkable diversity of the aquatic avifauna in the PEC. This region combines the ecological significance typical of a RAMSAR site and the economic importance of hosting one of Latin America's largest ports. Our findings underscore the critical role of the PEC as essential habitats for feeding, resting, nesting, and stopovers during the life cycle of various species of aquatic birds, including both resident and migratory ones, many of which face population decline risks. Furthermore, with our results, we aim to bridge a significant gap in the region by establishing an open-access database. The database might contribute to multiple stakeholders in assessing and mitigating environmental impacts, both at the local and global levels, thereby strengthening the conservation of the local avifauna's rich diversity and the entire marine life on a global scale

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AUTHOR CONTRIBUTIONS

M.L.M.: Conceptualization; Data curation; Investigation; Methodology; Resources; Validation; Writing – original draft; Writing – review & editing.

C.D.: Conceptualization; Funding acquisition; Methodology Supervision; Validation; Visualization; Writing – review & editing.

G.D.M.: Data curation; Methodology; Formal Analysis; Visualization; Writing – review & editing.

M.D.D.: Conceptualization; Data curation; Funding Acquisition; Investigation; Methodology; Project Administration; Resources; Supervision; Validation; Visualization; Writing – review & editing.

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