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Space-time patterns and drivers of migrant bird communities in coastal Piauí State, Brazil

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ABSTRACT

Introduction: Migration is a natural phenomenon that includes annual movements of many bird species in response to seasonal cycles. With approximately one third of all living bird species, South America has an important avifauna, and many migrants land in Brazil at stopping points and wintering sites.

Objective: To identify associations between migrant birds and coastal vegetation, and environmental influence of on migration.

Methods: At 10 points along the coast of Piauí State, Brazil, we made visual censuses and mist net captures, between April 2009 and February 2016.

Results: We identified 82 migrant bird species (13 orders; 28 families) that represented 41 intracontinental migrating species, 26 northern visiting species, 14 nomad species and one vagrant species. The richness peaks were at the beginning and end of both dry and rainy seasons, matching insolation and atmospheric pressure. There were spatial pattern differences among vegetation complexes. *Chrysolampis mosquitus* is an indicator of caatinga vegetation, *Numenius phaeopus* of wetland, *Charadrius collaris* of non-flooding fields, *Rostrhamus sociabilis* of forest-grassland transition, and *Columbina picui* of orchards. Despite differences in number and species composition within vegetation types, the temporal pattern in species richness was similar among flooded fields, non-flooded fields, and transition grassland categories.

Conclusions: Migrant birds occupy specific environments during their permanence along the coast of Piauí State, with richness matching insolation and atmospheric pressure.

Key words: climatic variables; environment; movements; migration chronology; stopover.

RESUMEN

Patrones y factores espacio-temporales de comunidades de aves migratorias en el estado costero de Piauí, Brasil

Introducción: La migración es un fenómeno natural que incluye los movimientos anuales de muchas especies de aves en respuesta a los ciclos estacionales. Con aproximadamente un tercio de todas las especies de aves conocidas, América del Sur tiene una avifauna importante y muchas aves migratorias tienen puntos de parada e invernada en Brasil.
Objetivo: Identificar asociaciones entre las aves migratorias y la vegetación costera, y la influencia del medio ambiente en la migración.
Métodos: En 10 puntos a lo largo de la costa del Estado de Piauí, Brasil, realizamos censos visuales y capturas con redes de niebla, entre abril 2009 y febrero 2016.
Resultados: Identificamos 82 especies de aves migratorias (13 órdenes; 28 familias) que representaron 41 especies migratorias intracontinentales, 26 especies visitantes del norte, 14 especies nómadas y una especie vagante. Los picos de riqueza se dieron al principio y al final de las estaciones seca y lluviosa, coincidiendo con la insolación y la presión atmosférica. Hubo diferencias en el patrón espacial entre los complejos de vegetación. *Chrysolampis mosquitus* es un indicador de vegetación de caatinga, *Numenius phaeopus* de humedales, *Charadrius collaris* de campos que no se inundan, *Rostrhamus sociabilis* de transición bosque-pastizales y *Columbina picui* de huertos. A pesar de las diferencias en el número y composición de especies dentro de los tipos de vegetación, el patrón temporal en la riqueza de especies fue similar entre las categorías de campos inundados, campos no inundados y pastizales de transición.
Conclusiones: Las aves migratorias ocupan ambientes específicos durante su permanencia a lo largo de la costa del estado de Piauí, con una riqueza acorde con la insolación y la presión atmosférica.

Palabras clave: variables climáticas; ambiente; movimientos; cronología migratoria; escala.

INTRODUCTION

In total, 1 971 bird species are distributed in the Brazilian territory, based on the Brazilian Committee of Ornithological Records, also known as CBRO (Pacheco et al., 2021). The National Research Center for Wild Birds Conservation, also known as CEMAVE, often published the Annual Report of Migrant Birds Routes and Concentration Sites in Brazil. Based on this report, coastal Piauí State (BR) holds two migratory routes; this state is pointed out as concentration site for shorebirds and migrant birds in the country; it also emphasizes the important role played by this site for these species' conservation (CEMAVE, 2020). Oftentimes, these birds get to the wintering sites by late August and early September; they stay in this location until April, when they once more return to their breeding grounds (Cabral et al., 2006; Silva & Rodrigues, 2015; Somenzari et al., 2018).

Several localities along the coast of Piauí State (BR) are wintering sites for migrant birds. Guzzi et al. (2012) reported 17 migrant species in Parnaíba River Delta; 7 species were observed at Parnaíba International Airport - they were identified as Nearctic migrants belonging to families Charadriidae, Scolopacidae and Hirundinidae (Cardoso et al, 2013). Guzzi et al. (2015) reported 16 Nearctic migrant species at Pedra do Sal Beach (in Parnaíba River Delta), as well as three austral migrants and one partially Nearctic migrant species.

Some factors have influenced the distribution and abundance of migrant birds; among them, one finds habitat conditions and the availability or food resources. (Neima et al., 2020; Rodrigues et al., 2015). Studies carried out in neotropic areas, for example, have shown the importance of migrant birds in tropical bird communities, with emphasis on the fact that this group cannot be taken as element external to these communities because they showed domination over and segregation patterns of habitats inside a wintering site (Kelsey, 1992). However, they can be particularly vulnerable to climate changes, either in wintering sites or in breeding grounds (Sanderson et al., 2006).

Climate changes can also influence individual behaviors, breeding success and the population dynamics of migrant birds, a fact that can change the patterns and connections between specific summer and winter populations (Webster & Marra, 2005). Breeding locations are linked to wintering sites by the movements of individuals belonging to any migratory organism (Webster et al., 2002). Many different connectivity patters are possible to happen, in other words, connectivity is strong if most individuals who reproduce in a given site also spend winter together in a given location (Salomonsen, 1995).

The conservation of migrant birds is closely associated with the identification and protection of sites used for resting, feeding and breeding, since the loss of some of these locations can be decisive for some species' survival. Continuity and expansion of monitoring procedures applied to Nearctic migrant birds visiting Brazil are essential for their survival (Graff et al., 2016; Somenzari et al., 2018). Thus, the aim of the present study was to investigate spatiotemporal patterns of migrant bird species richness and composition along the coast of Piauí State, Brazil, by correlating these community features to both local climate and vegetation features.

MATERIALS AND METHODS

Study site: Data were collected at 10 sites along the coast of Piauí State, Brazil (Fig. 1), one site in Ilha Grande County, two in Luis Correia County and seven sites in Parnaíba County. These sites were chosen because of previous knowledge on their occupation by migrant birds. Each site was classified based on its prevalent vegetation type, according to Santos-Filho et al. (2010). The points were classified into two main vegetation types, based on this scheme: "*caatinga*" (typical of dry inland areas) and "*restinga*" (typical of coastal regions). *Restinga* was divided into four subtypes: flooded fields (2 sites), non-flooded

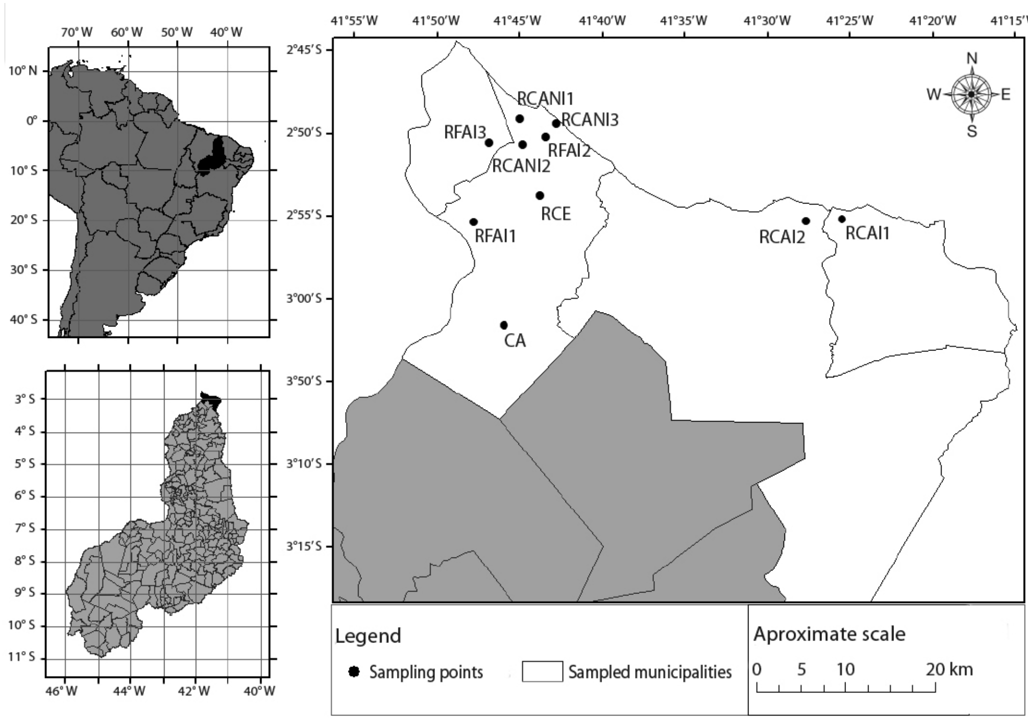

Fig. 1. Sampling points along the coast of Piauí State, Brazil.

fields (3 sites), transition grasslands (1 site) and orchards (3 sites).

Data collection: Quantitative survey on migrant birds was carried out between April 2009 and February 2016 based on visual observations (with binoculars) and mist net captures. Visual observations were performed in study sites, which were divided into transects that were surveyed at dawn and dusk with the aid of binoculars (10X50) and digital recorder equipped with directional microphone to capture and replay birds' vocalizations. Mist nets (2.5 m × 30 mm × 12 m) were used at dusk and dawn; they were visited every 20 min. The nets were extended near vegetation formations and/or aquatic sites. Stotz et al. (1996), Nunes and Tomas (2008), Pacheco et al. (2021) and Somenzari et al. (2018) were used as reference for birds' identification. Their conservation statuses were determined by following the classification by the International Union for Conservation of Nature (IUCN, 2022).

Data processing and analyses: The sampling effort among sites and months was first equalized through rarefaction analysis to determine the spatial and temporal patterns of migrant bird species' richness. The expected richness (i.e., the rarefied number of species) plus or minus twice its standard deviation was the calculation used to make the comparisons. Expected (rarefied) richness per month was regressed against monthly values recorded for five climatic variables to help explaining the temporal patterns, namely: mean temperature (ºC), total rainfall (mm), mean wind speed (m/s), mean insolation (W/m^2) and mean atmospheric pressure (Pa), which were collected from the Agrometeorological Bulletin of *EMBRAPA Meio-Norte*. An elastic net regression was used, since these five variables can be highly correlated and, consequently, hinder model interpretation and applicability. It was done by assuming the Gaussian error distribution and by estimating penalization (α) and shrinkage (λ) parameters via leave-one-out cross-validation, in order to select variables and regulate model coefficients (Zou & Hastie, 2005). Finally, spatial patterns were investigated through PERMANOVA by using a Bray-Curtis dissimilarity matrix of field campaigns grouped by vegetation type. Therefore, we investigated vegetation's likely influence on bird assemblies' composition in each sampling site. The IndVal test was used to identify potential indicator species for each vegetation type, among the migratory birds, in order to qualify these differences among communities. All statistical analyses were run in R software (R Core Team, 2019), in packages vegan 2.4-6 and glmnet 2.0-16 - values were considered statistically significant when $P < 0.05$. The trophic categories followed the classification proposed by Motta-Júnior (1990): granivores (GRAN), with ¾ or more grains; frugivores (FRU), with ¾ or more fruits; insectivores (INSET), with ¾ or more insects and other arthropods in the diet; omnivores (ONIV), with more than ¾ of insects, other arthropods and fruits, in similar proportions; aquatic invertebrates (INVAQ), diet with more than ¾ of aquatic invertebrates; carnivores (CARN) and scavengers (NECRO), living and dead vertebrates, respectively, at least in ¾ of the diet; malacophagi (MAL), with ¾ or more of mollusks and piscivores (PISC), with ¾ or more of fish.

RESULTS

Eighty-two migrant bird species were recorded along the coast of Piauí State. They belonged to 13 orders and 28 families, and represented 41 intracontinental migrant species (50 %) in South America, 26 species of Northern visitors (31.7 %), 14 nomad species (17.07 %) and 1 vagrant species (1.21 %). These species were distributed into 10 feeding guilds, with the prevalence of trophic guilds, namely: 22 species (26.8 %) feeding on aquatic arthropods; 19 species (23.2 %) of insectivorous birds; 16 omnivore species (19.5 %); 10 piscivorous species (12.2 %); 6 granivore species (7.3 %); three nectarivore species (3.7 %); 2 carnivore species (2.4 %); 2 molluscivorous species (2.4 %); one frugivore species (1.2 %);

and one insectivore/granivore species (1.2 %). With respect to sensitivity to environmental changes, 47 bird species (57.3 %) were classified as low-sensitivity species, 24 (29.3 %) as medium-sensitivity species, 6 (7.3 %) as high-sensitivity species; 5 (6.1 %) species did not record any sensitivity at all. As for dependence on forest environments, 61 species (74.4 %) were independent, 9 (10.1 %) were semi-dependent, 7 (8.5 %) were dependent, and 5 species (6.1 %) did not record any dependence. Finally, when it comes to conservation status, 80 species (97.56 %) were of least concern, whereas 2 species (2.44 %) were considered as close to endangering (*Calidris canutus* and *C. pusilla*) (Table 1).

TABLE 1
Migrant birds recorded along the coast of Piauí State, Brazil

TAXON NAME	STATUS	GUILD	SE	UH	SC	EN	FR
ANSERIFORMES Linnaeus, 1758							
ANATIDAE Leach, 1820							
DENDROCYGNINAE Reichenbach, 1850							
Dendrocygna viduata (Linnaeus, 1766)	INTRA	ONI	BAI	IN	LC	OS	17
ANATINAE Leach, 1820							
Amazonetta brasiliensis (Gmelin, 1789)	NO	PIS	BAI	IN	LC	OS	2
PODICIPEDIFORMES Fürbringer, 1888							
PODICIPEDIDAE Bonaparte, 1831							
Podilymbus podiceps (Linnaeus, 1758)	INTRA	PIS	MED	IN	LC		
Tachybaptus dominicus (Linnaeus, 1766)	INTRA	PIS	MED	IN	LC		
SULIFORMES Sharpe, 1891							
PHALACROCORACIDAE Reichenbach, 1849							
Nannopterum brasilianum (Gmelin, 1789)	INTRA	PIS	BAI	IN	LC	TG	98
PELECANIFORMES Sharpe, 1891							
ARDEIDAE Leach, 1820							
Ardea alba Linnaeus, 1758	INTRA	ONI	BAI	IN	LC	FF	89
Ardea cocoi Linnaeus, 1766	NO	ONI	BAI	IN	LC	FF	4
Bubulcus ibis (Linnaeus, 1758)	NO	INS	BAI	IN	LC	NF	152
Egretta caerulea (Linnaeus, 1758)	INTRA	ONI	MED	IN	LC	FF	30
ACCIPITRIFORMES Bonaparte, 1831							
PANDIONIDAE Bonaparte, 1854							
Pandion haliaetus (Linnaeus, 1758)	VN	PIS	MED	IN	LC	FF	16
ACCIPITRIDAE Vigors, 1824							
Elanus leucurus (Vieillot, 1818)	INTRA	CAR	BAI	IN	LC		
Rostrhamus sociabilis (Vieillot, 1817)	INTRA	MAL	BAI	IN	LC	TG	148
GRUIFORMES Bonaparte, 1854							
ARAMIDAE Bonaparte, 1852							
Aramus guarauna (Linnaeus, 1766)	INTRA	MAL	MED	IN	LC	TG	88
RALLIDAE Rafinesque, 1815							
Laterallus melanophaius (Vieillot, 1819)	NO	ONI	BAI	SD	LC	OS	2
Porphyrio martinica (Linnaeus, 1766)	INTRA	ONI	BAI	IN	LC	NF	4

TAXON NAME	STATUS	GUILD	SE	UH	SC	EN	FR
CHARADRIIFORMES Huxley, 1867							
CHARADRII Huxley, 1867							
CHARADRIIDAE Leach, 1820							
Charadrius collaris Vieillot, 1818	INTRA	INVAQ	ALT	IN	LC	NF	150
Charadrius semipalmatus Bonaparte, 1825	VN	INVAQ	MED	IN	LC	NF	68
Pluvialis dominica (Statius Muller, 1776)	VN	INVAQ	ND	ND	LC	NF	6
Pluvialis squatarola (Linnaeus, 1758)	VN	INVAQ	BAI	IN	LC	FF	26
RECURVIROSTRIDAE Bonaparte, 1831							
Himantopus melanurus Vieillot, 1817	VN	INVAQ	MED	IN	LC	NF	25
Himantopus mexicanus (Statius Muller, 1776)	VN	INVAQ	MED	IN	LC	FF	7
SCOLOPACI Steijneger, 1885							
SCOLOPACIDAE Rafinesque, 1815							
Actitis macularius (Linnaeus, 1766)	VN	INVAQ	BAI	IN	LC	NF	27
Arenaria interpres (Linnaeus, 1758)	VN	INVAQ	ALT	IN	LC	FF	25
Calidris alba (Pallas, 1764)	VN	INVAQ	ND	ND	LC		
Calidris bairdii (Coues, 1861)	VN	INVAQ	ND	ND	LC		
Calidris canutus (Linnaeus, 1758)	VN	INVAQ	ALT	IN	AT	FF	13
Calidris fuscicollis (Vieillot, 1819)	VN	INVAQ	MED	IN	LC	FF	4
Calidris minutilla (Vieillot, 1819)	VN	INVAQ	MED	IN	LC	NF	8
Calidris pusilla (Linnaeus, 1766)	VN	INVAQ	MED	DP	AT	NF	30
Gallinago paraguaiae (Vieillot, 1816)	INTRA	INVAQ	BAI	IN	LC	TG	41
Limnodromus griseus (Gmelin, 1789)	VN	INVAQ	ALT	IN	LC	FF	12
Numenius hudsonicus Latham, 1790	VN	INVAQ	ND	ND	LC	FF	14
Numenius phaeopus (Linnaeus, 1758)	VA (N)	INVAQ	MED	DP	LC	FF	38
Tringa flavipes (Gmelin, 1789)	VN	INVAQ	BAI	IN	LC	NF	26
Tringa melanoleuca (Gmelin, 1789)	VN	INVAQ	BAI	IN	LC	NF	31
Tringa semipalmata (Gmelin, 1789)	VN	INVAQ	ND	ND	LC		
Tringa solitaria Wilson, 1813	VN	INVAQ	BAI	IN	LC	NF	24
LARI Sharpe, 1891							
LARIDAE Rafinesque, 1815							
Leucophaeus atricilla (Linnaeus, 1758)	VN	PIS	MED	IN	LC		
STERNIDAE Vigors, 1825							
Phaetusa simplex (Gmelin, 1789)	INTRA	PIS	ALT	IN	LC		
Sterna hirundo Linnaeus, 1758	VN	PIS	MED	SD	LC	NF	2
Sternula superciliaris (Vieillot, 1819)	INTRA	PIS	BAI	IN	LC	NF	23
RYNCHOPIDAE Bonaparte, 1838							
Rynchops Níger Linnaeus, 1758	INTRA	PIS	ALT	IN	LC	NF	5
COLUMBIFORMES Latham, 1790							
COLUMBIDAE Leach, 1820							
Columbina picui (Temminck, 1813)	NO	GRA	BAI	IN	LC	OS	128
Patagioenas picazuro (Temminck, 1813)	INTRA	FRU	MED	SD	LC	FF	14
CUCULIFORMES Wagler, 1830							
CUCULIDAE Leach, 1820							
CUCULINAE Leach, 1820							
Coccyzus americanus (Linnaeus, 1758)	VN	INS	MED	SD	LC		
Coccyzus euleri Cabanis, 1873	INTRA	INS	MED	SD	LC	CA	4

TAXON NAME	STATUS	GUILD	SE	UH	SC	EN	FR
CAPRIMULGIFORMES Ridgway, 1881							
CAPRIMULGIDAE Vigors, 1825							
Chordeiles acutipennis (Hermann, 1783)	INTRA	INS	BAI	IN	LC	CA	9
Podager nacunda (Vieillot, 1817)	INTRA	INS	BAI	IN	LC	NF	12
APODIFORMES Peters, 1940							
APODIDAE Olphe-Galliard, 1887							
Tachornis squamata (Cassin, 1853)	NO	INS	BAI	IN	LC	NF	3
TROCHILIDAE Vigors, 1825							
POLYTMINAE Reichenbach, 1849							
Anthracothorax nigricollis (Vieillot, 1817)	INTRA	NEC	BAI	SD	LC		
Chrysolampis mosquitus (Linnaeus, 1758)	NO	NEC	BAI	IN	LC	CA	10
TROCHILINAE Vigors, 1825							
Thalurania furcata (Gmelin, 1788)	NO	NEC	MED	SD	LC	CA	4
FALCONIFORMES Bonaparte, 1831							
FALCONIDAE Leach, 1820							
Falco peregrinus Tunstall, 1771	VN	CAR	MED	IN	LC		
PASSERIFORMES Linnaeus, 1758							
TYRANNIDA Wetmore & Miller, 1926							
TITYRIDAE Gray, 1840							
Xenopsaris albinucha (Burmeister, 1869)	INTRA	INS	MED	IN	LC	CA	1
TYRANNIDAE Vigors, 1825							
ELAENIINAE Cabanis & Heine, 1860							
Elaenia cristata Pelzeln, 1868	INTRA	ONI	MED	IN	LC	CA	7
Elaenia mesoleuca (Deppe, 1830)	NO	INS	BAI	DP	LC	CA	2
Elaenia spectabilis Pelzeln, 1868	INTRA	ONI	BAI	DP	LC	CA	1
Phaeomyias murina (Spix, 1825)	INTRA	ONI	BAI	IN	LC		
Suiriri suiriri (Vieillot, 1818)	INTRA	INS	MED	IN	LC	OS	4
TYRANNINAE Vigors, 1825							
Myiarchus swainsoni Cabanis & Heine, 1859	INTRA	INS	BAI	IN	LC	FF	4
Myiodynastes maculatus (Statius Muller, 1776)	INTRA	ONI	BAI	DP	LC		
Myiozetetes cayanensis (Linnaeus, 1766)	INTRA	INS	BAI	DP	LC		
Myiozetetes similis (Spix, 1825)	INTRA	ONI	BAI	SD	LC	CA	4
Tyrannus melancholicus Vieillot, 1819	INTRA	INS	BAI	IN	LC	FF	100
FLUVICOLINAE Swainson, 1832							
Arundinicola leucocephala (Linnaeus, 1764)	NO	INS	MED	IN	LC		
Fluvicola albiventer (Spix, 1825)	NO	INS	MED	IN	LC	NF	6
Fluvicola nengeta (Linnaeus, 1766)	NO	INS	BAI	IN	LC	OS	11
PASSERI Linnaeus, 1758							
CORVIDA Wagler 1830							
VIREONIDAE Swainson, 1837							
Vireo olivaceus (Linnaeus, 1766)	VN	ONI	BAI	DP	LC	CA	5
PASSERIDA Linnaeus, 1758							
HIRUNDINIDAE Rafinesque, 1815							
Hirundo rústica Linnaeus, 1758	VN	INS	BAI	IN	LC	NF	10
Progne chalybea (Gmelin, 1789)	INTRA	INS	BAI	IN	LC		
Progne tapera (Linnaeus, 1766)	INTRA	INS	BAI	IN	LC		

TAXON NAME	STATUS	GUILD	SE	UH	SC	EN	FR
Tachycineta albiventer (Boddaert, 1783)	INTRA	INS	BAI	IN	LC		
TURDIDAE Rafinesque, 1815							
Turdus amaurochalinus Cabanis, 1850	INTRA	ONI	BAI	SD	LC	CA	21
MOTACILLIDAE Horsfield, 1821							
Anthus chii Vieillot, 1818	INTRA	INS/GRA	BAI	IN	LC	NF	76
PASSERELLIDAE Cabanis & Heine, 1850							
Ammodramus humeralis (Bosc, 1792)	NO	GRA	BAI	IN	LC	CA	12
ICTERIDAE Vigors, 1825							
Chrysomus ruficapillus (Vieillot, 1819)	INTRA	ONI	BAI	IN	LC	OS	10
Molothrus bonariensis (Gmelin, 1789)	NO	ONI	BAI	IN	LC		
Leistes superciliaris (Bonaparte, 1850)	INTRA	ONI	BAI	IN	LC	OS	74
THRAUPIDAE Cabanis, 1847							
Sporophila caerulescens (Vieillot, 1823)	INTRA	GRA	BAI	IN	LC	CA	1
Sporophila lineola (Linnaeus, 1758)	INTRA	GRA	BAI	IN	LC		
Sporophila nigricollis (Vieillot, 1823)	INTRA	GRA	BAI	IN	LC	CA	2
Volatinia jacarina (Linnaeus, 1766)	INTRA	GRA	BAI	IN	LC	OS	9

STATUS: INTRA (intracontinental migrants); NO (nomads); VN (Northern visitors); VA(N) (vagrant species originating from the Northern hemisphere). GUILDS: ONI (omnivores); PIS (piscivores); INS (insectivores); CAR (carnivores); MAL (molluscivores); ONI (omnivores); INVAQ (aquatic invertebrates); GRA (granivores); FRU (frugivores); NEC (necrophagic); INS/GRA (insectivore and granivore). SE (sensitivity): ALT (high); BAI (low); MED (medium); ND (not determined). UH (habitat use): IN (independent); SD (semi-dependent); DP (dependent); ND (not determined). SC (conservation status): LC (little concern); AT (almost endangered). EN (Environment): CA (*Caatinga*); FF (Flooding Fields); NF (Non-Flooding Fields); TG (TRANSITION GRASSLANDS); OS (Orchard Sites). FR (frequency).

Migrant birds were recorded over the year. However, richness peaks, which were estimated by rarefying the sampling effort of each month, were mainly observed during season transitions after major changes in weather conditions in the assessed region, mainly at the beginning of the rainy season, or in the beginning and at the end of the dry season - this pattern was observed in all three classes of migrants, i.e., intracontinental, Northern visitors and nomads (Fig. 2).

The elastic net regression led to a model capable of explaining 30.6 % of species richness variance based on only two of the five original climatic variables, namely: insolation and atmospheric pressure. These two variables had negative and positive influence on the number of migrant bird species at the coast of Piauí State, respectively. This finding suggested the preference of some species for the easy weather conditions observed in the region, namely: little rain and low wind speed (as reflected by the barometric trend), without excessive solar radiation - represented by insolation. (Fig. 3).

Vegetation type was a good predictor of migrant birds' spatial distribution, since the habitats were occupied by each species (PERMANOVA$F_{4,472}$ = 16.5, R^2 = 0.12, P = 0.001). Thus, there were significant differences in bird assemblies' composition among different vegetation types observed in coastal Piauí State (Fig. 4). Despite such a statistical significance, based on many superpositions observed in Fig. 4, some species seem to be found in more than one habitat, or at least in transition sites among them.

These differences in avifauna can be represented by different bird species that can work as indicators for each vegetation type; i.e., some species were more closely associated with certain habitats, such as the ruby-topaz humming bird (*Chrysolampis mosquitus*), which was associated with *caatinga* sites; the whimbrel (*Numenius phaeopus*) species, which was associated with flooded fields; the collared plover (*Charadrius collaris*) species, which was correlated to non-flooded fields; the snail kite

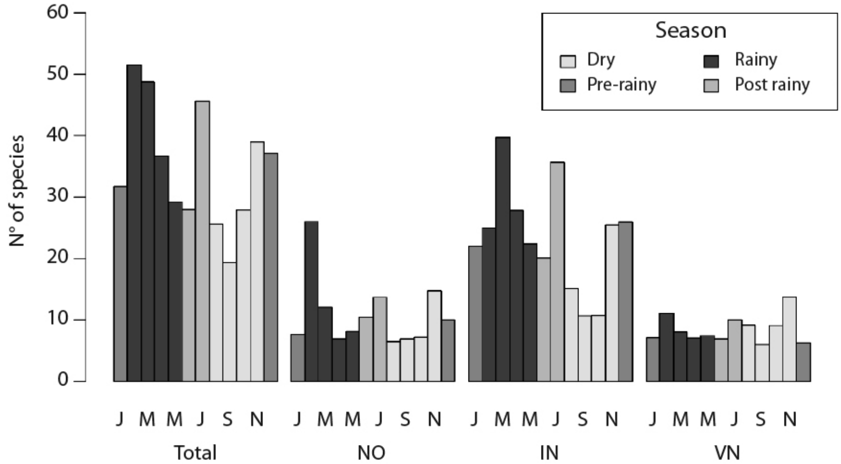

Fig. 2. Barplot of the expected (i.e., rarefied) number of migrant bird species per month at the coast of Piauí State, Brazil. Groups of bars indicate migratory status: NO (nomad species); IN (intracontinental migrants); VN (Northern visitor species). Bar colors indicate different seasons often observed in the site.

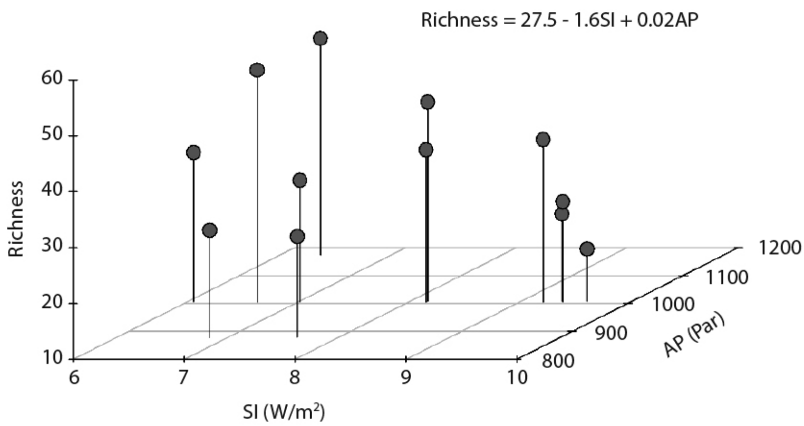

Fig. 3. Scatterplot depicting the association among monthly migrant bird species richness, mean insolation (SI) and mean atmospheric pressure (AP) at the coast of Piauí State, Brazil. The model's equation derived from an elastic net regression.

(*Rostrhamus sociabilis*) species, which was associated with transition grasslands; and the Picui ground dove (*Columbina picui*) species, which was mostly related to orchards (Table 1).

It is noteworthy that transition grasslands were the only vegetation type sampled in 2 discontinuous periods (between 2009-2011 and 2015-2016); they presented differences in bird assemblies between these two-time intervals: TG1 and TG2, respectively (Fig. 4). However, both intervals seemed consistently different from those of other vegetation types. Thus, snail kite was the main indicator-species between 2009-2011, whereas white-browed meadowlark (*Sturnella superciliaris*) became more abundant between 2015 and 2016. This finding suggests that other factors, besides vegetation - although associated with it -, may influence the wintering site of migrant birds at the coast of Piauí State.

Besides the composition of assemblies, the species richness of migrant birds also differed

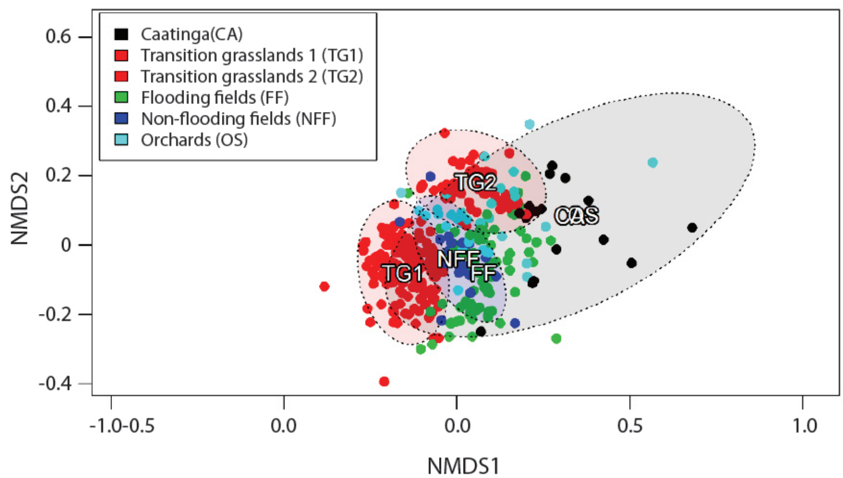

Fig. 4. Biplot of Non-metric Multidimentional Scalling (NMDS) generated from the Bray-Curtis dissimilarity of sampling campaigns; it depicts differences in species composition of migrant bird assemblies from different vegetation types at the coast of Piauí State.

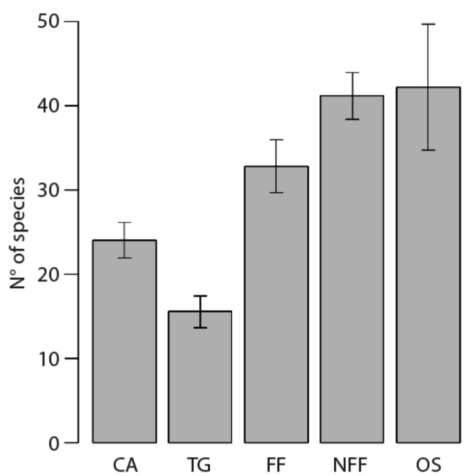

Fig. 5. Barplots depicting the expected (i.e., rarefied to equalize sampling effort) number of migrant bird species in each vegetation type along the coast of Piauí State, Brazil. Lines represent 2x the standard deviation of the expected richness. CA = *Caatinga*; TG = Transition grasslands; FF = Flooding Fields; NFF = Non-flooding Fields; OS = Orchards.

among vegetation types - orchards and non-flooded fields were the richest ones, and transition grasslands were the poorest categories (Fig. 5).

Despite differences in number and composition of species among vegetation types, the temporal pattern recorded for species richness was relatively similar among flooded fields, non-flooded fields and transition grassland categories - which were the only categories with samples collected in all assessed months (Fig. 6).

This temporal pattern was also similar to the one observed when the whole site was taken into account, including the different types of migrant species, namely: intracontinental, Northern visitors and nomads.

DISCUSSION

In order for shorebirds to survive the annual migration from the Southern hemisphere to breeding sites in the Artic, they count on a series of locations throughout their route. These places provide them with food for them to replace the energy lost during the flight (Clark, 2015). The coastal region of Piauí State has the potential to house a large number of migrant shorebirds because it is an estuarine environment (Putra et al., 2017). Muddy habitats in these locations provide a broader source of food, and it can be observed from the large number of bird species foraging on them (Silva & Rodrigues, 2015).

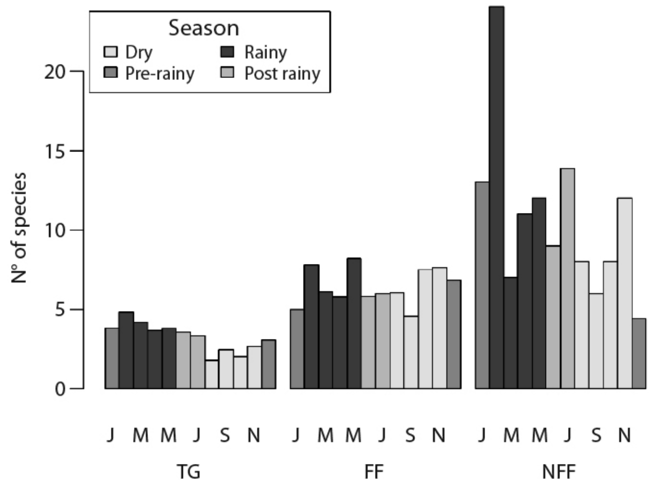

Fig. 6. Barplots depicting monthly variation in the expected (i.e., rarefied to equalize sampling effort) number of migrant bird species in each vegetation type along the coast of Piauí State, Brazil. TG = transition grasslands, FF = flooding fields, NFF = non-flooding fields. Bar colors represent different seasons.

It is essential highlighting that sites are influenced by tides and habitat physiognomy at different times of the year, a fact that makes food available for birds throughout the whole seasonal cycle. This feature reduces the need of these species to move to other physiognomies in order to find food (Cabrera-Cruz et al., 2020; Palacín et al., 2017). Species may not finish their trajectory if only one of these sites is compromised (Clark, 2015).

Migrant species are notably consistent in terms of their wintering sites, since they systematically visit habitats known for their food-resource availability to satisfy their feeding needs and foraging strategies (Nunes & Tomas, 2008). These requirements help explaining the significant differences observed in species compositions between different analyzed sites, as well as why some species are found in very specific sites - therefore, they are considered indicator species. Different sites present different resources, and they determine species compositions among migrant birds. On the other hand, despite the generally observed differences among environments, the coast of Piauí State is a dense mosaic of different landscapes (Santos-Filho et al., 2010); thus, it is not surprising that several superpositions take place in it. Therefore, at least some species can be distributed in transition zones, or even in more than one habitat; eventually, it results in complex patterns at species level.

According to the classification system by Santos-Filho et al. (2010), the study site includes non-flooding, flooding and grassland fields, as well as orchards. The first two site types are basically covered by herbaceous vegetation, and they mainly differ from each other because of their water accumulation during the rainy season. These differences in vegetation are followed by differences in avifauna, as expressed by the indicator-species. Wet environments seasonally received more water birds (such as *Numenius phaeopus* and *Rostrhamus sociabilis*) than dry environments, for example. Although birds always return to the same wintering sites, severe changes in these environments can induce species to search for other, and more favorable, locations. Assumingly, it happened in sites TG1 and TG2, which recorded significant differences in their species compositions overtime. These observations corroborated Sick (1997), who emphasized the importance of habitat conservation for species conservation and noticed that birds are totally dependent on their environments; therefore, habitat losses have negative impact on migrant bird populations (Howard et al., 2018).

Other determining factors regarding migratory movements lie on climatic influences. Certain environmental variables are related to the arrival and departure of intercontinental migrants, mainly to insolation and atmospheric pressure. At first, both variables can emerge as uncommon biodiversity pattern drivers in tropical regions; however, Romero et al. (2000); Panuccio et al. (2010) and Ben-Hamo et al. (2013) considered climatic factors as determinant for migrant birds' flight paths. They emphasized that weak winds and high barometric pressure represented ideal climatic conditions for migrant birds' high-altitude flights. On the other hand, de Carvalho Melo (2017) reported that the number of adult marine birds in their focal species was positively related to mean wind velocity and negatively associated with atmospheric pressure. Results in the current study seem to be following those recorded by the aforementioned authors, when it comes to atmospheric pressure. According to the positive association with atmospheric pressure and to the negative correlation to solar radiation, at least some species prefer milder weather conditions when they get to Piauí State. The Brazilian equatorial coast is notoriously energetic due to its high temperatures over the year, intense (but highly variable) rainfall during the wet season and strong winds in the dry season (Soares et al., 2021). Accordingly, some species may adjust their arrival timing to transition times between seasons, and it forms the herein observed richness peaks.

It is noteworthy that although insolation and atmospheric pressure were selected by the model-building algorithm, they only explained a small portion of variations in migrant bird species' richness. This finding reflects the complexity of the probable species-specific processes driving the arrival of migrant bird species in the Brazilian equatorial coast. Therefore, caution is advisable at the time to take into consideration the model presented in Fig. 3. It should be regarded as no more than preliminary assessment on how weather clues can be important to migrant bird species' arrival in Piauí State - this subject should be more thoroughly investigated in future studies. Howard et al. (2018) commented that climatic changes would most likely increase the effective migration distances crossed by many migrant species, a fact that would force them to travel longer distances, to increase the numbers of stopovers and, consequently, the total duration of their long-distance migrations – this factor is not commonly considered in studies on climate change. Furthermore, lack of correlation between migratory movements and climatic factors, other than insolation and atmospheric pressure, can be related to the presence of some migrant individuals throughout the year. Sick (1997) noticed that birds who are not able to accumulate sufficient energy resources to return to their breeding grounds may remain in the wintering sites and only return during the next migratory cycle.

Additional factors also need to be considered; for example, there was remarkable coincidence of bird richness peaks and plant fructification peaks nearby *restinga* vegetation sites (Ribeiro, 2011). This coincidence is noteworthy because only one of the bird species recorded in the present study was classified as frugivore. Thus, increased fructification cannot be the direct cause of higher avifauna diversity. Therefore, other mechanisms should be investigated in order to clarify the association between food availability and bird migration in coastal Piauí State, such as the case of plant-insect phenological synchrony or spatiotemporal variations in benthic fauna composition.

Only two species were classified as nearly endangered: *Calidris canutus* and *C. pusilla*. Rosenberg et al. (2017) noticed that resources available for conservation purposes are usually quite limited, and that the recognition of vulnerable species (or of endangered ones) is an essential component for effective conservation planning. Surveys can identify and compare population trends recorded for focal species during different seasons of the year; these results can be used to identify proximal factors accountable for population changes.

Information gathered during long-term bird populations' monitoring can be used to guide and optimize management activities critical to maintain or reestablish viable avian populations (Lynn et al., 2017). Up-to-date knowledge about the origin and destination sites of migrant birds, as well as environmental details of each wintering site, will be essential to maintain viable populations.

It was never so urgent taking conservation actions, and actions to avoid climate changes given the large volume of migrant bird species suffering with the drastic decline in their populations in the last few years, since these changes can have impact on migrant shorebirds who breed in the Artic, and change their breeding locations and conditions (Wauchope et al., 2017). Some evidence suggest that the magnitude of migratory movements taken by these species can influence their vulnerability to environmental changes (Webster & Marra, 2005). Although it is not fully understood, the decline in migrant species is a constant concern (Hardesty-Moore et al., 2017). However, a study on migratory movements has shown that greater population variability within these movements leads to higher resilience towards environmental changes (Gilroy et al., 2016). Data in the present study reinforced the observation that migrant birds occupy specific environments during their permanence along the coast of Piauí State and that these birds are seen at higher concentrations during the most humid months of the year.

Ethical statement: the authors declare that they all agree with this publication and made significant contributions; that there is no conflict of interest of any kind; and that we followed all pertinent ethical and legal procedures and requirements. All financial sources are fully and clearly stated in the acknowledgements section. A signed document has been filed in the journal archives.

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