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Bees from an island in the Delta of the Americas (Maranhão state, Brazil) and their floristic interactions

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Abstract

Surveys of the bee fauna on islands are scarce due to the difficult access to the study area. Thus, the current study intended to establish the species of bees present in an island of the Delta of the Americas, called Grande do Paulino, Tutóia, Maranhão. Together with the bees, the plants visited by these insects were recorded, in order to document the relationships between these organisms. Between July 2017 and June 2018, once a month, 1,095 individuals, distributed in 16 tribes, 30 genera, and 48 species, were collected with active (entomological net) and passive (bowl traps) sampling methods. Data from plants and their visiting bees are presented in an interaction network in the form of a bipartite graph, showing *Xylocopa cearensis* as the most collected bee species, and *Chamaecrista ramosa* as the most visited plant by bees. In addition to providing information about the bee fauna of the state of Maranhão and, consequently, from the Brazilian northeast, this study explores the apifauna of a place never before explored and, because it is an island, of difficult access, also providing information about the floristic interactions of these insects.

Introduction

For the Brazilian territory, 1.678 known species of bees belonging to 207 genera are documented (Moure et al., 2007), and together of the different regions of the world, the number of species is estimated at 25 to 30 thousand, divided into 4.000 genera responsible for the pollination of, approximately, 60% of higher plants (Michener, 2007).

In the state of Maranhão, Brazil, there are about 230 species of bees recognized in biological collections (Rêgo & Albuquerque, 2012; Ferreira et al., 2020) and many of these records occur on the coast. A massive number of works on the apifauna of the state of Maranhão were carried out, exploring different environments such as restinga (Silva et al., 2009; Gostinski et al., 2016), brazilian savanna (Albuquerque & Mendonça, 1996; Rebêlo & Cabral, 1997; Mendes et al., 2008), dunes (Gottsberger & Silberbauer-Gottsberger, 1988;

Albuquerque et al., 2007; Serra et al., 2009; Oliveira et al., 2010), Amazon (Silva & Rebêlo, 1999; Ferreira et al., 2019), as well as secondary vegetation regions (Gonçalves et al., 1996; Albuquerque et al., 2001; Brito & Rêgo, 2001) and islands (Silva & Rebêlo, 2002).

Although the bee fauna is well represented in the state, some places do not have information about the species. In the Brazilian coast, few islands have data on bee fauna (Zanella et al., 1998) due to their distance from the continent and/or the researchers' difficult access. We can mention as an example Grande do Paulino Island, the study area of this work, located on the coast of State of Maranhão.

One of the fundamental factors for the survival of bees is the plants, which provide resources for these insects and, consequently, are pollinated (Michener, 2007). Bees and plants have coevolved since the Cretaceous to form a beneficial relationship that lasts to the present day (Grimaldi, 1999).

Parallel to these factors, we have the historical records of the disappearance and loss of several bee colonies, and the causes of this great episode are still discussed. Some say they are motivated by parasitic interactions with mites (Eliash & Mikheyev, 2020) and climate changes (Lima & Marchioro, 2021; Raven & Wagner, 2021), but the most accepted reason today is the use of toxic substances in crops (Almasri et al., 2020; Faita et al., 2020).

Thus, we find ourselves in a situation of aggravating loss of the diversity of bees, and we do not even know many of the species in the national territory. Although research on the diversity of Brazilian bee fauna has occurred frequently in recent years (Viana & Lourenço, 2020; Almeida et al., 2019), the vastness of the Brazilian territory prevents all areas from being covered with this type of work, thus leaving some regions lacking such information, mainly restricted access regions, such as islands off the Brazilian coast, for example.

Thus, the current study intended to establish the species of bees and their floristic interactions in an island of the Delta of the Americas, called Grande do Paulino, Tutóia, Maranhão, an area devoid of apifaunistic sampling. With the information obtained, we can contribute to the removal of Wallacean (species distribution data), Prestonian (abundance data) and Eltonian (interactions data) biodiversity shortfalls (Hortal et al., 2015).

Material and Methods

Sampling area

This study was conducted on Grande do Paulino Island (42°11'23.4"S, 02°43'58.2"W,), which is 40.5 km^2 and is located in the Parnaíba Delta, also known as the Delta of the Americas. This island belongs to the municipality of Tutóia, State of Maranhão, and is 2 km from the continental coast. The vegetation of the island is predominantly characterized by the presence of mangrove and restinga ecosystems, the latter characterized by the coastal location and the presence of undergrowth, shrub and tree vegetation (Marques et al., 2015). According to the Köppen-Geiger classification, the climate of the locality is type Aw, with two well-defined seasons: a rainy season from January to June, and a drought from July to December (Alvares et al., 2013).

The area used for the collection has about 4.940m^2 (42°11'23.929"S, 2°44'0.877"W; 42°11'12.570"S, 2°43'57.112"W) and consists of an open restinga composed of a sandy field with creeping plants and shrubs, with the presence of flooded environments. Temperature and humidity data were obtained on the collection days using a thermo-hygrometer and rainfall information was obtained by consulting the INMET digital platform database.

Sampling of the bees

The collections were performed between July 2017 and June 2018, once a month, from 6h to 18h, by two collectors, totaling 288 hours of sampling. Bees were collected using an entomological net to capture the bees while visiting the flowers, when at rest, or in flight (Sakagami et al., 1967). The insects collected by entomological net were placed in paper bags with identification of the plant on which the bee was collected.

Simultaneously, plastic bowl traps (Moerike traps, 15 cm wide, 5 cm high, 300 ml of water and drops of dishwashing detergent) were used (Portman et al., 2020). Bowls had different non-fluorescent colors (blue, green, red, white and yellow) and were deployed monthly for 24 h (total effort: 1.440 h). The bowls were placed on the ground (five groups with one bowl from each color) at 5 m intervals with interspersed colors. The collected insects were preserved and stored in 70% alcohol (Krug & Alves-dos-Santos, 2008).

All bees were mounted on pins and deposited in the Bee Collection of the Laboratory of Bee Studies (LEACOL/ Universidade Federal do Maranhão – UFMA). They were identified to the morphospecies and species level by comparison with the reference collection, the assistance of taxonomists and the aid of taxonomic keys (Silveira et al., 2002). Michener's classification scheme was used to identify bees (Michener, 2007).

Sampling of melittophilous flora

The plants that received visits from the inventoried bees were collected with the help of pruning shears and placed in a plastic bag for later herborization according to the usual techniques of Peixoto and Maia (2013). Identification was performed with the aid of analytical keys and comparison with exsiccates from Maranhão Herbarium (MAR), Department of Biology, Federal University of Maranhão, in which all the collected material was processed and deposited.

Descriptive community analysis

The Shannon-Wiener Index (H') was applied to calculate diversity using Past software version 3.13 (Hammer et al., 2016). The abundance distribution for each species was analyzed using the Whittaker diagram (rank/abundance).

Determination of the sample sufficiency was evaluated through the creation of the species accumulation curve with randomized samples. Additionally, using EstimateS version 9.10 software (Colwell, 2013), three non-parametric estimators (ACE, Jackknife, and Bootstrap) were used to infer an approximation of the real richness of the community. The use of these estimators is justified by their complementarity, in which they relate the parameters: rarity, abundance and total wealth, respectively for the construction of the species accumulation curve, bees collected in both sampling methods were counted.

Occurrence frequency (OF = number of samples with species i / number of samples x 100) and dominance (DM = abundance of species i / total abundance x 100) classes were calculated for bees collected with entomological net. If OF ≥ 50%, then is considered a very frequent species (VF); OF <

50% and > 25% is considered frequent (F); and OF ≤ 25% is considered infrequent (IF). If DM > 5% = dominant species (D); DM ≤ 5% and > 2.5% = accessory species (A) and DM ≤ 2.5% = occasional species (OC). The OF + DM combination divides the species into three groups: common species (VF or F + D), rare species (IF + OC), and intermediate species (other combinations) (Aguiar & Gaglianone, 2012).

Interaction networks

A bipartite weighted interaction network of bees and visited plants was created using R software (The R Project for Statistical Computing), version 3.5.1, with the *bipartite* package (Dormann et al., 2018). A bipartite network displays members of a trophic level connected to members from another trophic level (e.g., flowers and bees) (Pigozzo & Viana, 2010). Among the available metrics for the description of a qualitative interaction network, the metrics were used to calculate the connectivity, the average degree for plants and animals.

Connectance (C), which measures the proportion of connections that are actually observed, is the ratio between the number of observed interactions (E) and the number of possible interactions, which in turn is given by the product of the number of plants (P) and animals (A) from the network: C = E/A.P (Pigozzo & Viana, 2010). For percentage values, the value of C was multiplied by 100. The average degree of plants and animals was obtained from the arithmetic mean of the degrees of all plant/animal species, the degree being the number of interactions in which each species was involved. (Pigozzo & Viana, 2010).

The average degree of plants, corresponding to the number of interactions, was obtained from the arithmetic mean of all interactions performed by botanical species in relation to bees. The same principle was used to establish the average degree of animals. The distribution of the degree was performed graphically, in a vertical bar representation, in which the number of established interactions (degree) is represented on the *x* axis, while the *y* axis represents the number of species that presented a certain degree, either of plants or bees (Pigozzo & Viana, 2010).

Results

Species richness and diversity

A total of 1,095 individuals were collected, distributed in 16 tribes, 30 genera, and 48 species, belonging to the Andrenidae, Apidae, Colletidae, Halictidae, and Megachilidae families. Specifically, with the entomological net, 1,089 individuals were collected (Table 1), while in the bowl traps, only six bee specimens were collected (five bees from the blue bowls and one from the yellow bowls. The other bowls colors did not have the presence of bees) (Table 2).

Table 1. Families, tribes, and bee species collected in Grande do Paulino Island, using entomological net. n = Relative abundance; DM = Dominance (D = Dominant; A = Accessory; OC = Occasional); FO = Frequency of occurrence (VF = Very frequent; F = Frequent; IF = Infrequent); CL = Classification (C = Common; I = Intermediate; R = Rare).

Family/Tribe/Species or morphospecies	Abbrev.	Specimen	n (%)	DM	FO	CL
ANDRENIDAE						
Protomeliturgini						
Protomeliturga turnerae (Ducke, 1907)	*Pt*	1	0,09%	OC	IF	R
APIDAE						
Apini						
Apis mellifera (Linnaeus, 1758)	*Am*	47	4,32%	A	F	I
Centridini						
Centris (Xanthemisia) bicolor (Lepeletier 1841)	*Cb*	1	0,09%	OC	IF	R
Centris (Centris) byrsonimae (Mahlmann & Oliveira, 2012)	*Cby*	2	0,18%	OC	IF	R
Centris (Centris) caxiensis (Ducke, 1907)	*Cc*	194	17,81%	D	VF	C
Centris (Centris) decolorata (Lepeletier, 1841)	*Cd*	55	5,05%	D	VF	C
Centris (Centris) flavifrons (Fabricius, 1775)	*Cf*	3	0,28%	OC	IF	R
Centris (Paracentris) hyptidis (Ducke, 1908)	*Ch*	1	0,09%	OC	IF	R
Centris (Melacentris) obsoleta (Lepeletier, 1841)	*Co*	41	3,76%	A	F	I
Centris (Hemisiella) tarsata (Smith, 1874)	*Ct*	3	0,28%	OC	IF	R
Centris (Hemisiella) trigonoides (Lepeletier, 1841)	*Ct*	1	0,09%	OC	IF	R
Epicharis (Epicharis) bicolor (Smith, 1854)	*Eb*	2	0,18%	OC	IF	R
Epicharis (Epicharis) sp.	*Ep*	11	1,01%	OC	F	I
Emphorini						
Melitoma segmentaria (Fabricius, 1804)	*Ms*	11	1,01%	OC	F	I

Table 1. Families, tribes, and bee species collected in Grande do Paulino Island, using entomological net. (Continuation)

Family/Tribe/Species or morphospecies	Abbrev.	Specimen	n (%)	DM	FO	CL
Ericrocidini						
Mesonychium asteria (Smith, 1854)	*Ma*	31	2,85%	A	VF	I
Eurytis funereus (Smith, 1854)	*Ef*	6	0,55%	OC	IF	R
Eucerini						
Florilegus sp.	*Fl*	13	1,19%	OC	IF	R
Euglossini						
Eulaema (*Apeulaema*) *nigrita* (Lepeletier, 1841)	*Em*	1	0,09%	OC	IF	R
Meliponini						
Frieseomelitta doederleini (Friese, 1900)	*Fd*	12	1,10%	OC	F	I
Melipona (*Melipona*) *subnitida* (Ducke, 1910)	*Msu*	63	5,79%	D	VF	C
Tapinotaspidini						
Paratetrapedia duckei (Friese, 1910)	*Pd*	1	0,09%	OC	IF	R
Paratetrapedia sp.	*Pa*	1	0,09%	OC	IF	R
Xylocopini						
Ceratina (*Crewella*) *pubescens* (Smith, 1879)	*Cp*	1	0,09%	OC	IF	R
Ceratina (*Crewella*) *rotundiceps* (Smith, 1879)	*Cr*	20	1,84%	OC	F	I
Ceratina (*Crewella*) *maculifrons* (Smith, 1854)	*Cm*	13	1,19%	OC	F	I
Ceratina (*Crewella*) *cf. asunciana* (Strand, 1910)	*Ca*	14	1,29%	OC	IF	R
Ceratina sp1	*Ce1*	5	0,46%	OC	IF	R
Ceratina sp2	*Ce2*	1	0,09%	OC	IF	R
Xylocopa (*Neoxylocopa*) *aurulenta* (Fabricius, 1804)	*Xa*	4	0,37%	OC	IF	R
Xylocopa (*Neoxylocopa*) *cearensis* (Ducke, 1910)	*Xc*	407	37,37%	D	VF	C
Xylocopa (*Neoxylocopa*) *frontalis* (Olivier, 1789)	*Xf*	2	0,18%	OC	IF	R
Xylocopa (*Schonnherria*) *muscaria* (Fabricius, 1775)	*Xm*	1	0,09%	OC	IF	R
COLLETIDAE						
Hylaeini						
Hylaeus sp.	*Hy*	1	0,09%	OC	IF	R
Diphaglossini						
Ptiloglossa sp.	*Pti*	24	2,2%	OC	F	I
HALICTIDAE						
Augochlorini						
Augochloropsis aff. vivax (Smith, 1879)	*Av*	10	0,92%	OC	IF	R
Augochlorini sp1	*Au1*	1	0,09%	OC	IF	R
Augochlorini sp2	*Au2*	1	0,09%	OC	IF	R
Augochlorini sp3	*Au3*	2	0,18%	OC	IF	R
Halictini						
Dialictus sp.	*Di*	1	0,09%	OC	IF	R
MEGACHILIDAE						
Anthidiini						
Dicranthidium arenarium (Ducke 1907)	*Da*	47	4,32%	A	F	I
Epanthidium tigrinum (Schrottky, 1905)	*Et*	18	1,65%	OC	VF	I
Megachilini						
Coelioxys sp.	*Coe*	2	0,18%	OC	PF	R
Hypanthidium maranhense (Urban, 1998)	*Hm*	4	0,37%	OC	F	I
Megachile sp1	*Me1*	5	0,46%	OC	F	I
Megachile sp2	*Me2*	3	0,28%	OC	IF	R
Megachilini sp1	*Meg*	1	0,09%	OC	IF	R
	Total	1089				

The Apidae family presented the highest abundance, with 88.58% of the collected specimens (970 individuals), of which *Xylocopa* (*Neoxylocopa*) *cearensis* (Ducke, 1910) was the most abundant species, with 407 collected individuals, representing 37.17% of the abundance. The next most abundant family was Megachilidae (7.4%, 81 individuals), followed by Colletidae (2.28%, 25 individuals), Halictidae (1.64%, 18 individuals), and Andrenidae (0.09%, 1 individual). The highest abundance of Apidae is mainly due to bees of the genera *Xylocopa* (414 individuals) and *Centris* (301 individuals), representing, respectively, 37.81% and 27.49% of the sampled specimens. Xylocopini and Centridini were the most abundant tribes, with 42.92% (470 individuals) and 28.68% (314 individuals). Apidae was the family with the greatest richness, comprising 30 sampled species (62.5%), followed by Halictidae (8 species, 16.67%), Megachilidae (7 species, 14.58%), Colletidae (2 species, 4.17%), and Andrenidae (1 species, 2.08%).

Table 2. Families, tribes, and bee species collected in Grande do Paulino Island using bowl traps.

Family/Tribe/Species or morphospecies	Bowl trap color	Specimen
APIDAE		
Xylocopini		
Ceratina (*Crewella*) *maculifrons* (Smith, 1854)	Blue	1
Ceratina (*Crewella*) *pubescens* (Smith, 1879)	Blue	1
HALICTIDAE		
Augochlorini		
Augochlorella tredecim (Vachal, 1911)	Blue	1
Halictini		
Halictini sp1	Blue	1
Halictini sp2	Blue	1
MEGACHILIDAE		
Anthidiini		
Dicranthidium arenarium (Ducke 1907)	Yellow	1

Activity pattern

During all the months of collection, bees were captured with entomological net, while in the bowl traps, only in the months of July, November, December (2017) and April (2018): 551 specimens were collected in the dry period and 544 were collected in the rainy season. The month of February showed a peak of abundance (Fig 1b), with 214 bees collected (19.54% of the entire sample). The morning period demonstrated higher activity of individuals (Fig 1a), between 6:00 and 10:00. The occurrence of bees gradually decreased during the day, increasing again between 16:00 and 18:00 (Fig 1a).
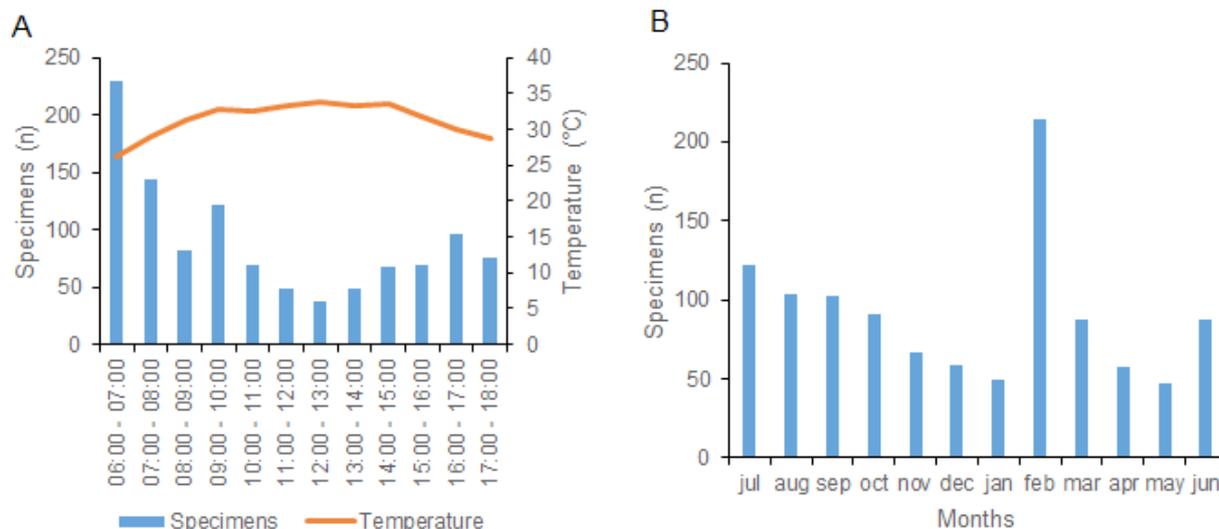

Fig 1. (a) Temperature and number of individuals collected per hour in the study area and (b) seasonal distribution (specimens per month).

Regarding the frequency of occurrence, six species (12.24%) were considered very frequent (VF), 11 (22.45%) frequent (F), and 32 (65.31%) infrequent (IF). *Centris* (*Centris*) *caxiensis* (Ducke, 1907), *C.* (*Centris*) *decolorata* (Lepeletier, 1841), *Melipona* (*Melipona*) *subnitida* (Ducke, 1910), and *Xylocopa* (*Neoxylocopa*) *cearensis* (Ducke, 1910) were considered dominant (D) species (8.16%), four species (8.16%) accessory (A), and 41 (83.67%) occasional (OC). Four species were considered common (8.16%), 13 intermediate (26.53%), and 32 rare (65.31%) (Table 1).

Few very abundant species and many species considered not abundant were represented in the rank/abundance graph (Fig 2), demonstrating an unevenness of the bee community collected in Grande do Paulino Island. The Shannon-Wiener diversity index (H') presented a value of 2.4. The species accumulation curve together with the ACE, Jackknife, and Bootstrap richness estimators are shown in Figure 3. For ACE, the samples correspond to 62,26% of the total richness of the location, while for Jackknife and Bootstrap, the values were, respectively, 70,41% and 84,45%.

Interactions network

Of the 1,089 bees sampled from the active search, 984 were collected during flower visits, while 105 were collected in flight and were not included in the construction and calculation of the interaction network metrics. Bees were collected from 19 plant species, corresponding to 14 botanical families (Tab 3). The most commonly visited plants were *Chamaecrista ramosa* (Vogel) H.S Irwin & Barneby (357 bees), *Byrsonima crassifolia* (L.) Kunth (144 bees), *Borreria verticillata* (L.) G.Mey. (141 bees), and *Euploca polyphylla* (Lehm.) J.I.M. Melo & Semir (133 bees). Of the 14 families, only three were visited by one species, while the others interacted with four or more bee species. During the dry
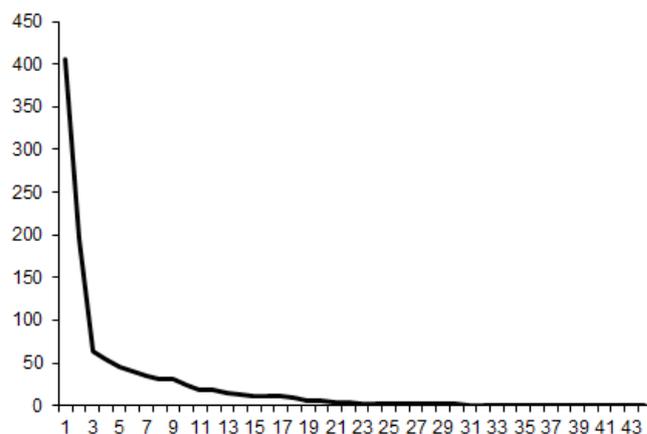

Fig 2. Rank/abundance graph of bee species collected on Grande do Paulino Island.

season, eight plant species were visited by bees, in contrast to 16 botanical species visited in the rainy season.

The interaction network presented in the study area (Fig 4) consisted of 44 bee species and 19 plant species, theoretically resulting in 836 possible interactions. However, only 118 interactions were observed between mellitophilous fauna and associated flora, equivalent to 14.11% of possible interactions.

About 50% (59) interactions observed were concentrated in only eight bee species, which together made up 18.18% of all apifauna present in the network: *Xylocopa* (*Neoxylocopa*) *cearensis* (Ducke, 1910) (12 interactions; 10.17%), *Centris* (*Centris*) *caxiensis* (Ducke, 1907) (9; 7.63%), *Apis mellifera* (Linnaeus, 1758) (8; 6.78%), *Dicranthidium arenarium* (Ducke 1907) (7; 5.93%), *Epanthidium tigrinum* Schrottky, 1905 (7; 5.93%), *Centris* (*Centris*) *decolorata* (Lepeletier, 1841) (6; 5.08%), *Centris* (*Melacentris*) *obsoleta* (Lepeletier, 1841) (5; 4.24%), and *Melipona* (*Melipona*) *subnitia* (Ducke, 1910) (5; 4.24%).
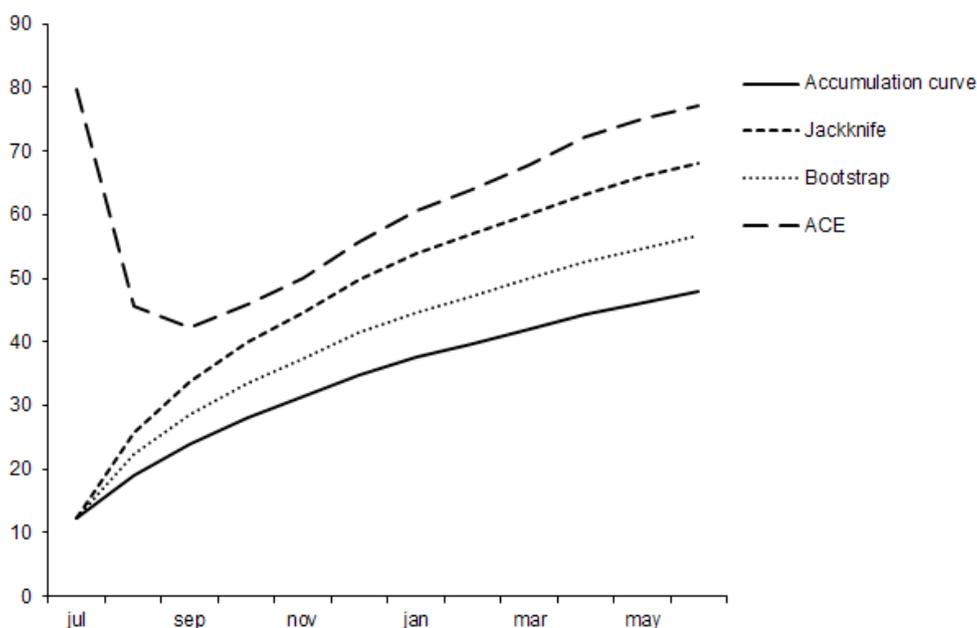

Fig 3. Species accumulation curve with richness estimators.

Table 3. Botanical families and species with their respective visiting bee species in the study area on Grande do Paulino Island, Tutóia, MA. N = Nectar; P = pollen; O = Oil. Abbreviations for visiting bee species are presented in Table 1.

Family/Species	Abbrev.	Visiting bee species	Visits. (*n*)
AIZOACEAE			
*Sesuvium portulacastrum (*L.) L.	*Sp*	*Am* (2), *Av* (9), *Fd* (5), *Msu* (1)	17
AMARANTACEAE			
Alternanthera brasiliana (L.) Kuntze	*Ab*	*Au3* (1), *Da* (9), *Di* (1), *Et* (1), *Hm* (2)	14
ANACARDIACEAE			
Anacardium occidentale L.	*Ao*	*Cb* (1), *Cc* (12), *Cd* (2), *Ct* (1), *Co* (1), *Ep* (1), *Et* (1), *Msu* (2), *Xc* (10)	31
BORAGINACEAE			
Euploca polyphylla (Lehm.) J.I.M. Melo & Semir	*Epo*	*Am* (3), *Cc* (11), *Cd* (1), *Cm* (1), *Cr* (2), *Da* (5), *Et* (3), *Fl* (7), *Msu* (2), *Pt* (1), *Xa* (1), *Xc* (96)	133
CONVOLVULACEAE			
Ipomoea maurandioides Meisn.	*Im*	*Am* (1), *Ce1* (5), *Cm* (11), *Cp* (1), *En* (1), *Ms* (8), *Xc* (7)	34
Jacquemontia tamnifolia (L.) Griseb.	*Jt*	*Au1* (1), *Au2* (1), *Cc* (3), *Fl* (1), *Me2* (1), *Xc* (1)	8
EUPHORBIACEAE			
Jatropha mollissima (Pohl) Baill.	*Jm*	*Am* (1)	1
FABACEAE			
Ancistrotropis peduncularis (Fawc. & Rendle) A. Delgado	*Ap*	*Xc* (10)	10
Andira surinamensis (Bondt) Splitg. ex Pulle	*As*	*Xc* (1)	1
Canavalia sp.	*Can*	*Xf* (1)	1
Chamaecrista ramosa (Vogel) H.S Irwin & Barneby	*Cra*	*Am* (4), *Au3* (1), *Av* (1), *Cby* (1), *Cc* (35), *Cd* (23), *Ch* (1), *Cm* (1), *Co* (26), *Ct* (2), *Da* (4), *Ef* (3), *Et* (3), *Fl* (3), *Hm* (1), *Ma* (1), *Msu* (36), *Pti* (24), *Xc* (187)	357
Zornia reticulata Sm.	*Zr*	*Da* (5), *Et* (3), *Fl*(1), *Hm* (1), *Me1* (1)	11
LOGANIACEAE			
Spigelia anthelmia L.	*Sa*	*Xa*(1)	1
MALPIGHIACEAE			
Byrsonima crassifolia (L.) Kunth	*Bc*	*Cc* (91), *Cd* (25), *Cf* (3), *Co* (9), *Eb* (2), *Ep* (8), *Fd* (2), *Pa* (1), *Pd* (1), *Xc* (2)	144
OCHNACEAE			
Ouratea hexasperma (A.St.-Hil.) Baill	*Oh*	*Cc* (2), *Cd* (2), *Msu* (3), *Xc* (7), *Xm* (1)	15
RUBIACEAE			
Borreria verticillata (L.) G. Mey.	*Bv*	*Am* (2), *Cc*(30), *Cd* (2), *Co* (2), *Cr* (1), *Da* (19), *Et* (3), *Ep* (1), *Hy* (1), *Me1* (3), *Me2* (1), *Msu* (8), *Xa* (2), *Xc* (66)	141
Mitracarpus strigosus (Thunb.) P.L.R. Moraes, De Smedt & Hjertson	*Mst*	*Am*(3), *Cby*(1), *Cc*(1), *Da* (1), *Ma*(1)	7
SAPOTACEAE			
Manilkara triflora (Allemão) Monach.	*Man*	*Xc*(1)	1
TURNERACEAE			
Turnera melochioides Cambess.	*Tm*	*Am* (1), *Ca* (14), *Cc* (4), *Ce2* (1), *Cr* (17), *Co* (2), *Da* (2), *Ef* (2), *Ep* (1), *Et* (2), *Ma* (2), *Meg* (1), *Xc*(8)	57

About plant species, 68 interactions (57.63%) were concentrated in five species, which together corresponded to 26.32% of the entire mellitophilous flora of the network: *Chamaecrista ramosa* (Vogel) H.S Irwin and Barneby (19; 16.1%), *Borreria verticillata* (L.) G.Mey. (14; 11.86%), *Turnera melochioides* Cambess. (13; 11.02%), *Euploca polyphylla* (Lehm.) J.I.M. Melo & Semir (12; 10.17%), and *Byrsonima crassifolia* (L.) Kunth (10; 8.47%).

The degree of bees ranged from 1 to 12 plant species (Fig 5a), with the average bee community degree being 2.68. It is noteworthy that 15 bee species (34.09%) visited more plants than the average, and 22 species (50%) depended on or preferred only one plant species. For the plants, the degree ranged from 1 to 19, with a mean degree of 6.21 (Fig 5b). Seven plant species (36.84%) received above average visits, and six species (31.58%) received only one bee species as visitors.
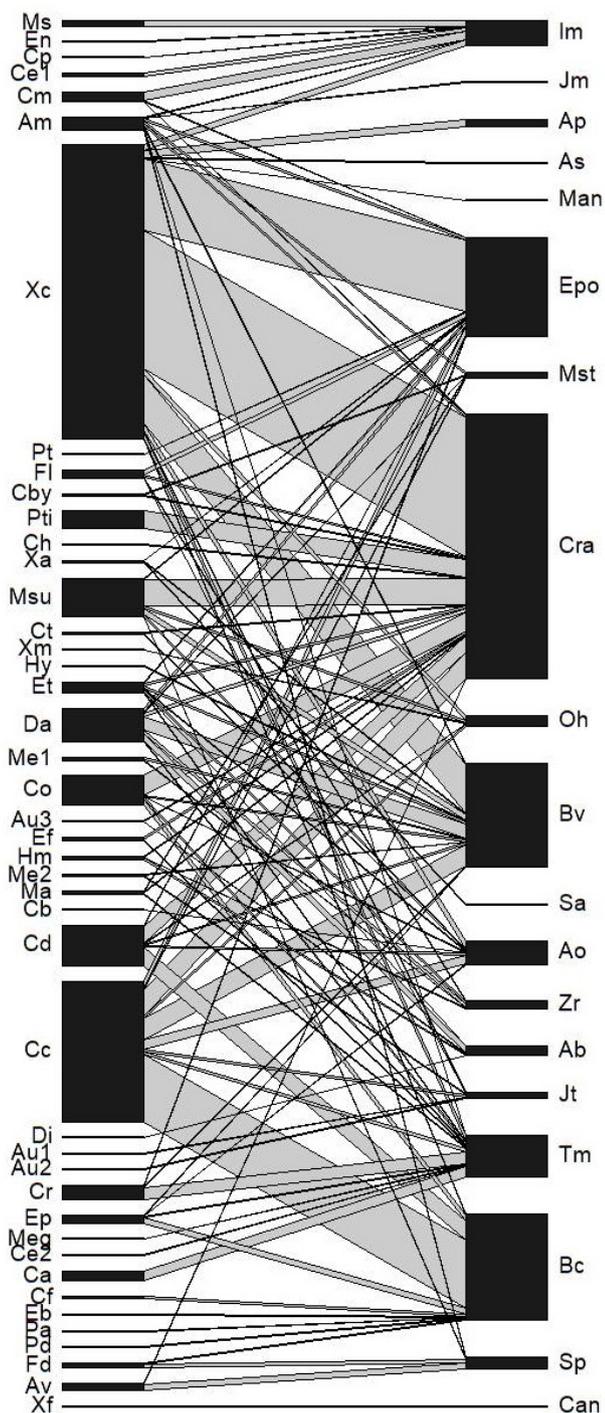
Fig 4. Bipartite interaction network: interactions between bees (left) and plants (right) of Grande do Paulino Island. The vectors represent the interactions between these species. The thickness of the vectors is proportional to the relative abundance of visiting bees. Abbreviations of species names are given in Tables 1 and 2.
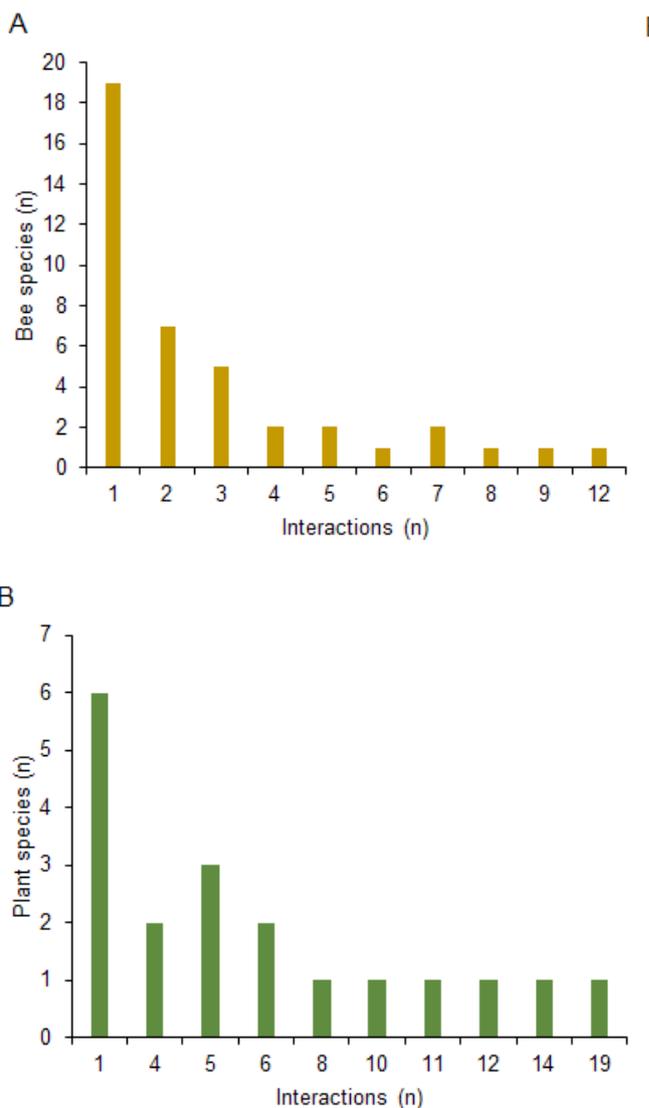
Fig 5. Degrees of bee species (A) and plant species (B) involved in the interactions of Grande do Paulino Island.

Discussion

In this pioneering survey on Grande do Paulino Island, 48 species of bees were collected with entomological net and trap dishes, three of which were new records for the State of Maranhão. The data collected on Grande do Paulino Island contribute to the removal of Wallacean (species distribution data), Prestonian (abundance data) and Eltonian (interactions data) shortfalls (Hortal et al., 2015) present in the State of Maranhão and, consequently, in Brazil.

The Apidae family presented the highest abundance in this study. This was expected, as commonly documented in apicultural surveys in different regions and/or ecosystems of the Brazilian territory, such as dunes (Oliveira et al., 2010; Gostinski et al., 2016), restinga (Madeira-da-Silva & Martins 2003; Kamke et al., 2011), Caatinga (Lopes et al., 2010), the Amazon (Albuquerque et al., 2001), and Atlantic Forest (Mouga et al., 2015, Somavilla et al., 2018).

The genera *Xylocopa* and *Centris* were represented in most of the months of collection, probably due to the availability of floral resources and nesting sites (Schlindwein et al., 2003; Aguiar & Gaglianone, 2003). Bees of the genus *Xylocopa* have a cosmopolitan distribution, presenting greater diversity in the tropical and subtropical regions of the New and Old World (Gerling et al., 1989). These bees are described by Viana and Alves-dos-Santos (2002) as abundant in open environments of dunes and beaches of northeastern Brazil.

Viana and Alves-dos-Santos (2002) presented similar results to the present study regarding the abundance of *Xylocopa cearensis*, in a survey carried out in a coastal dune area in Abaeté, BA, where the authors obtained a total of 42.7% of the total collected individuals. In the same work, the species is cited as documented in the states of Maranhão, Paraíba, and Bahia. It is noteworthy that *X. cearensis*, together with *Centris caxiensis*, was a dominant and constant species in the restinga area of the Lençóis Maranhenses National Park (Gostinski et al., 2016), information also observed in other restinga areas of the Brazilian Northeast (Viana & Kleinert, 2006; Oliveira et al., 2010), in agreement with our results.

Among the sources of floral resources for *X. cearensis*, the species *Chamaecrista ramosa*, abundant in our study area, is also reported by Viana et al. (2002) as the most commonly visited plant, with the same authors interpret the vibrating behavior of poricidal anthers as evidence of specialization between these organisms. This botanical species is recognized as an important pollen source for bee fauna in tropical environments (Gottsberger & Silberbauer-Gottsberger, 1988).

Bees of the Centridini tribe visit flowers to obtain oil, pollen, nectar, essential products for their maintenance and reproductive activity (Aguiar et al., 2017; Santos et al., 2020). Studies point to the essential role of these bees as pollinating agents of various neotropical species (Gottsberger & Silberbauer-Gottsberger, 1988), which include oil producing plants (Rêgo & Albuquerque, 1989), such as *Byrsonima crassifolia*, which attracts a large number of bees to its inflorescences, the Centridini tribe being the main pollinators (Mendes et al., 2011). This species has a dependency link with its visitors, since its self-incompatibility was reported by Rêgo and Albuquerque (1989). To meet their energy needs and to collect material for nest building and provisioning, bees of the Centridini tribe visit many flowers during their flight. Apparently, in the collection area, *B. crassifolia* was the only source of floral lipids for these bees.

The species of the Centridini tribe represented in the current study, *C. caxiensis*, *C. byrsonimae*, *C. flavifrons*, *C. decolorata*, *C. trigonoides*, *C. tarsata*, *C. obsoleta*, *C. bicolor*, and *Epicharis bicolor*, were also documented in the survey by Gostinski et al. (2016) in a restinga area of the Lençóis Maranhenses National Park. Rêgo and Albuquerque (2012) point to bees of the Centridini tribe, along with the Tetrapediini and Tapinotaspidini tribes, as subsamples in the state of Maranhão. The occurrence of *C. hyptidis* was documented for the first time at this study site (Neves Jr et al., 2020).

Ceratina pubescens and *Cer. rotundiceps* are recorded for the first time in Maranhão territory in the present study. *Cer. pubescens* had been described only for the states of Amazonas and Pará; *Cer. rotundiceps* was considered to occur only in the state of Pará (Silveira., et al., 2002).

Contrary to what previous studies point out (Krug & Alves-dos-Santos, 2008, Gostinski et al., 2016), few bees were collected in the bowl traps due here to use of non-UV colors. The low occurrence of bees in the trap dishes may be due also to the proximity of the flower dishes from the place, causing a loss of attractiveness to the bees, even though there is still no evidence to show this correlation (Portman et al., 2020). This methodology tends to be selective for certain groups and should not be used in isolation in inventories (Gostinski et al., 2016). Although this method still has a low incidence of use in Brazilian surveys, it is included in many of the traditional techniques of sampling Hymenoptera fauna in North America and Europe (Pinheiro-Machado & Silveira 2006). For this method, usually the colors used are yellow, blue and white. Here in this study we decided to include the colors green and red to test the possibility of attraction to bees. However, only the yellow and blue colors were attractive.

Still, three species were collected exclusively using this method. Like the others caught in bowl traps, these species are small and hardly seen by the collector in active collection. Bowl trap sampling can be useful when testing the sampling effort of collections, as no sampling bias by the collector is demonstrated and the results will not be influenced by the ease and/or difficulty of catching some species (Gostinski et al., 2016). In this way, passive collection methods help standardize differences in catch rates between species.

The bees demonstrated higher activity in the morning, between 6:00 and 10:00. It is possible to relate the greater activity observed during the morning period due to the supply of pollen and nectar at that time, limited resources that, once collected from a flower, are only offered again the other day (Kuppler et al., 2021).

The Shannon-Wiener diversity index found (H'= 2.4) was similar to those found in the dune and restinga areas of Intermares Beach, Cabedelo, PB (H' = 2.45; Madeira-da-Silva & Martins, 2003) and Lençóis Maranhenses National Park, Barreirinhas, MA (H'= 2.41; Gostinski et al., 2016) and it was higher than the indices obtained in dune areas of Panaquatira beach, São José de Ribamar, MA (H '= 2.28; Oliveira et al., 2010), São Marcos beach, São Luís, MA (H' = 2.05; Albuquerque et al., 2007), and Abaeté Beach, BA (H'= 1.99; Viana & Kleinert, 2006).

The species accumulation curve together with the ACE, Jacknife, and Bootstrap richness estimators demonstrate that there was a sample insufficiency, showing no stabilization after the twelve months of collection. This indicates that in the collection area there are probably still unregistered species. The ACE, Jacknife, and Bootstrap richness estimators suggested that between 70% and 84% of the collection site bee fauna was effectively sampled, however, there was no stabilization of the curves of these estimators, indicating that this percentage may be lower.

Pigozzo and Viana (2010) expect that, mathematically, the richness of species involved in interaction networks and the number of possible interactions themselves would be directly proportional. However, Olesen et al. (2006) point to an inverse trend, where a small part of the possible interactions take place, a trend corroborated by the present study, in which, out of 779 possible interactions, only 115 were established (14.76%).

The connectivity value found for the Grande do Paulino Island interaction network (14.11%) was higher than that calculated for other networks between bees and flowers in open areas, such as restinga environments (Viana & Kleinert, 2006 – 13.9% of 1,044 possible interactions; Pigozzo & Viana, 2010 – 10.6% of 2,800 possible interactions) and Caatinga (Rodarte et al., 2008 – 13.90% of 1,722 possible interactions). The higher the value of the connectivity, the more abundant the actual interactions observed, compared to the possible total value of interactions.

Conclusion

In tropical environments, as well as large plant diversity, it is expected to find a wide diversity of visiting floral and pollinating insects, mostly represented by bees. The present survey conducted on Grande do Paulino Island reflected these expectations for tropical coastal environments, presenting a median diversity index when compared to other surveys in related areas. In addition, the results presented here contribute to the knowledge of the bee fauna of the State of Maranhão.

The species *X. cearensis* was the most abundant species in the study area, being commonly represented in coastal ecosystems. Bees of the Centridini tribe presented a high abundance value, corresponding to the supply of resources and nesting substrate available at the collection site. The occurrence of the species *Ceratina pubescens*, and *Cer. rotundiceps* had not been confirmed for the state of Maranhão, until the present study. The plant *Chamaecrista ramosa* was the most visited by the bee fauna. The visits to botanical species were also well represented by *Byrsonima crassifolia*, which demonstrated an important relationship with bees of the Centridini tribe.

The majority of bee species presented interactions with only one plant species, a proportion not found in relation to plants, where a small number were visited by only one

species. A low number of bee and plant species concentrating most of the interactions was observed, connected with the other species with few interactions.

In addition to providing information about the bee fauna of the state of Maranhão, this study was necessary to establish the various interactions between bees and plants from Grande do Paulino Island. Although it is a pioneer work for this site, it is important to emphasize that the non-stabilization of the collector curve indicates the need for future collections in order to increase the apifaunistic data of the region.

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