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Searching for relations between manatee *Trichechus manatus manatus* calf strandings and environmental degradation in two Northeastern Brazil estuaries

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Abstract

Northeast Brazilian populations of the Antillean manatee are threatened by different causes, where the frequent stranding of calves is possibly an indirect result of anthropic environmental degradation. In this study we surveyed the spatial-temporal stranding patterns of newborn manatee calves at the coast of the state of Rio Grande do Norte and identified potential abiotic and anthropic determinants. To do so, we investigated changes in the mangrove cover and extension of salt evaporation ponds and shrimp farms along two estuaries, Apodi-Mossoró and Piranhas-Açu, during 1998 - 2018. The incidence of strandings increased throughout the study period, especially in Apodi-Mossoró, suggesting that the growing salt and shrimp farming industries are significant contributors to the observed mangrove deforestation. Thus, our findings suggest a correlation between manatee calf stranding patterns and environmental degradation from salt and shrimp production in two Northeast Brazilian estuaries.

Keywords:
anthropogenic threats, Caribbean manatee, habitat loss, marine mammal, newborn calves

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Introduction

The Antillean manatee (*Trichechus manatus manatus* Linnaeus, 1758) is classified as Vulnerable, according to the International Union for Conservation of Nature (Deutsch et al., 2008), and as Endangered on the Brazilian Endangered Species List (MMA, 2022). Historically the species occurred from Amapá to Espírito Santo states (Luna et al., 2008), but it became extinct in many places due to intensive hunting and nowadays it occurs up to Alagoas State (Whitehead, 1978; Luna et al., 2018, 2021a; Attademo et al., 2020). Some manatee specimens released in nature have returned to use areas in Sergipe and Alagoas states. However, these are not formally recognized as populations since, to the best of our knowledge, the individuals found in these regions have only partially used these two areas, with all recorded specimens being males (Souza et al., 2022).

The manatee distribution and population size in Brazil still remains uncertain. During the 1980s, government researchers conducted interviews along the coast and described the extinction of the species in Espírito Santo and Bahia states (Albuquerque & Marcovaldi, 1982). Later, more interviews allowed to estimate a population size of 500 individuals (Luna et al., 2008; Luna & Passavante, 2010) or 1,000 individuals (Luna et al., 2018). During a single aerial survey in 2010 between Ceará and Alagoas states, Alves et al. (2016) estimated a population mean size of 1,104 individuals ranging from 485 to 2,221 individuals. According to the authors, there were still uncertainties in this population size based on analyses performed, and no other estimations about the manatee population size in Brazil were made since then.

Manatees can be considered sentinels of habitat degradation (Bonde et al., 2004), since they are sensitive to the effects of anthropic activities, which may be especially harmful for the species along the Brazilian coast. For instance, degradation and resource exploitation have taken a heavy toll on manatee populations, especially on live newborn calves, as those have been considered the most important factors determining manatee strandings (Lima et al., 1992; Luna et al., 2018). For this reason, calf strandings have been recorded by the Brazilian government since the 1980s, and a Manatee Rescue, Rehabilitation, and Release Program has been implemented to reduce the problem (Luna et al., 2010; ICMBio, 2024).

Other threats like accidental entanglement in fishing gear (Jefferson et al., 2015; Reinert et al., 2017), motorboat strikes (Borges et al., 2018; Rycyk et al., 2018; Galves et al., 2023), and environmental contamination from wastewater, agrochemicals, pesticides, and heavy metals (Anzolin et al., 2012; Attademo et al., 2015; Núñez-Nogueira et al., 2019; Gowans & Siuda, 2023) are also considered relevant to Antillean manatee conservation in Brazil. Reductions in population size can cause serious damage to the species, like the increase of the chances of genetic issues such as inbreeding (Luna, 2013; Luna et al., 2012, 2021a). Another concern related to the genetics of this species is the hybridization with Amazonian manatees in Brazilian waters (Luna, 2013; Luna et al., 2012, 2021a).

The easternmost shores of Ceará and the contiguous northern shores of Rio Grande do Norte have a particularly high incidence of calf stranding associated with the degradation of major estuaries (Meirelles, 2008). These two states display the highest incidence of calf strandings in the country (Balensiefer et al., 2017) although it is not yet clear the role that anthropic activities might play. A study showed an inverse relationship between the mangrove coverage and the number of manatee calf strandings (Medeiros et al., 2021). This data is in line with the density of the species observed during aerial surveys, where it was estimated three manatee individuals for each 50 km of coastline (18 individuals along 310 km of coastline) in marine protected areas (MPAs), versus only one individual for each 50 km of coastline (23 individuals along 1,160 km of coastline) in unprotected areas (Alves et al., 2013). This suggests a positive association between the establishment of MPAs and the abundance of manatees, indicating that preserved habitats in estuaries and bays favor the presence of the species. However, it is important to note that the manatee Brazilian distribution and population size are still not very clear (Choi-Lima et al., 2017; Luna et al., 2018).

Strandings of dependent calves associated with the discontinuous distribution of the species throughout the country can contribute to the genetic isolation in the manatee populations (Attademo et al., 2021). For this reason, the rescue of stranded newborn depended calves followed by rehabilitation and release at Rio Grande do Norte State, can have a crucial role for the conservation of manatee population, especially for Paraíba, Pernambuco, and Alagoas states (Attademo et al., 2020). Anthropic activities such as shrimp farming, expansion of oil and gas extraction, and mangrove deforestation have become relevant threats to the coastal ecosystems in which the species occur (Luna et al., 2008).

In this study, we evaluated the possible correlation between adverse abiotic and anthropic factors with patterns of manatee calf strandings along the northern coast of Rio Grande do Norte, covering the 1998 - 2018 period.

Material and Methods

Study area

The study was conducted in the coastal region of Rio Grande do Norte spanning the outer limits of the municipalities of Tibau (04°50'14" S, 37°15'09" W) and Guamaré (05°06'27" S, 36°19'13" W). The area includes the estuaries of the Apodi-Mossoró River, between Grossos (04°58'47" S, 37°09'17" W) and Areia Branca (04°57'22" S, 37°08'13" W), and the Piranhas-Açu River, between Porto do Mangue (05°04'04" S, 36°46'54" W) and Macau (05°06'54" S, 36°38'04" W) (Fig. 1). The two estuaries lie within approximately 50 km of each other and provide ecologically similar habitats for manatees.

The local climate is tropical and predominantly semiarid, with an average temperature of 26 - 28°C (Nimer, 1989). Rainfall is concentrated in the rainy season (usually from February to May), followed by a longer dry season (June - January) (Diniz & Pereira, 2015). The basins of the Apodi-Mossoró River and the Piranhas-Açu River display intense temporal and spatial fluctuations associated with precipitation (annual average: 500 - 800 mm) (Medeiros et al., 2005; Rocha et al., 2009). Most of the year, freshwater input is strongly reduced in both rivers.

Data collection

Manatee calf stranding records for the region were retrieved from the database of Projeto Cetáceos da Costa Branca, Universidade do Estado do Rio Grande do Norte (PCCB/UERN), and Instituto Chico Mendes de Conservação da Biodiversidade,

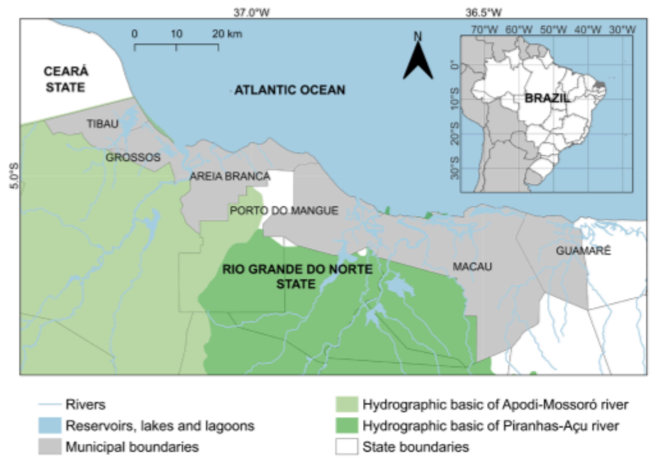

Figure 1. Study area: North coast of Rio Grande do Norte (Northeastern Brazil), involving six municipalities (Tibau, Grossos, Areia Branca, Porto do Mangue, Macau, and Guamaré).

Centro Nacional de Pesquisa e Conservação de Mamíferos Aquáticos (ICMBio/CMA). In the present study, only manatees characterized as calves were considered, with average length of 123 cm and 34 kg of weight for newborn (Borges et al., 2012). In addition, each stranding event was recorded along with the date, geographical location, sex, and physical condition of the individual (alive/dead) at the time of rescue.

Standardized surveys were daily conducted in Apodi-Mossoró River (Tibau, Grossos, and Areia Branca) and Piranhas-Açu River (Porto do Mangue, Macau, and Guamaré) municipalities during 1998 to 2018. Furthermore, through educational campaigns, a network of collaborators was created and manatee strandings were reported by the local communities. Rescue, rehabilitation, or necropsies of stranded manatees followed all the Brazilian protocols available (Vergara-Parente, 2005; Lima et al., 2007; Attademo et al., 2022).

Statistical analysis

A chi-square test was used to detect significant differences in sex between individuals, temporal distribution of strandings per month, year, and season, and in spatial distribution per municipality and estuary. A Kruskal-Wallis test was used to compare the two estuaries with regard to the number of strandings. In both analyses, the level of significance was set at $p < 0.05$.

In order to investigate disparities in stranding patterns between the two examined regions, the phenomenon of strandings was subjected to a modeling approach using a generalized linear model (GLM), with a binomial distribution and the logit link function. The explanatory variable was the estuary (Apodi-Mossoró or Piranhas-Açu) and the occurrence or non-occurrence of a stranding event (stranding = 1; no stranding = 0) in the period 2002 - 2018 (no stranding reports were available for the period 1998 - 2002) was the response variable. The significance of the model in relation to a null model was determined by ANOVA (Zuur et al., 2009). Since a coefficient of determination cannot be calculated for this type of model, we used the explained deviance, or pseudo-R^2 (obtained with the formula below), as a measure of goodness-of-fit for the model (Dobson, 2002; Zuur et al., 2009).

$$100 \cdot \frac{(null\ deviance - residual\ deviance)}{null\ deviance}$$

The predictions of the model were used to estimate the likelihood of stranding in the two estuaries. All analyses were performed using R Statistical Software (v4.0.1; R Core Team, 2020).

Analysis of satellite images

Land cover changes in the sampled ecosystems throughout the study period were assessed by mapping areas with mangrove cover, shrimp farms, and salt ponds along the two estuaries for the years 1998, 2008, and 2018. To do so, we used Landsat 5 (1998 and 2008) and Landsat 8 ETM+ (2018) multispectral digital images retrieved from the website of the US Geological Survey (USGS, 2019).

Shrimp farms and salt ponds were identified based on geometric layout. Each facility was described in terms of regularity, size, shape, and water color, following the examples of Costa et al. (2018) and Meireles et al. (2007) for the Brazilian coast. Salt ponds tended to display a characteristic color gradient, irregular outlines, and large area, when compared to the smaller, mostly regular and even-colored shrimp ponds.

The multispectral images in the visible and near-infrared band with RGB (4, 3, 2) and (5, 4, 3) band combinations allowed to identify areas with mangrove cover along the two rivers (Fitz, 2002). The vegetation was described in terms of changes in color, brightness, and pixel intensity. In images with false-color combinations, areas with mangrove forest displayed intermediate or high density and dark red or brown hues, whereas areas with sparse and/or degraded vegetation displayed intermediate or low density and faint reddish or orange hues (Ceará, 2006).

The percentage of each activity developed in the estuary (*e.g.,* shrimp farming and salt extraction) and environmental factors (*e.g.,* mangrove forests and rivers) was estimated in relation to the total area in hectares (ha) of each estuary for the years 1998, 2008, and 2018.

Results

Twenty-five stranded manatee calves (14 males, 11 females) were recovered during the study period, of which only one was found dead. Stranding events were not regularly reported by standardized surveys or reports by the community prior to 2002.

Spatial and temporal factors

The greatest number of strandings occurred in the municipality of Areia Branca (n = 14; x^2 = 23.6; $p < 0.05$), followed by Porto do Mangue (n = 6), Grossos (n = 3), Tibau (n = 1), and Macau

Table 1. Number of manatee (*Trichechus manatus manatus*) calf strandings in each estuary, according to the year between 1992 and 2018.

Years	Number of strandings	
	Apodi-Mossoró Estuary	Piranhas-Açu Estuary
1992-2001	0	0
2002	2	0
2003	1	0
2004	1	1
2005	0	1
2006	1	0
2007	1	1
2008	1	0
2009	1	0
2010	1	0
2011	1	1
2012	2	1
2013	2	0
2014	0	0
2015	2	1
2016	0	0
2017	0	2
2018	1	0
Total of strandings	17	8

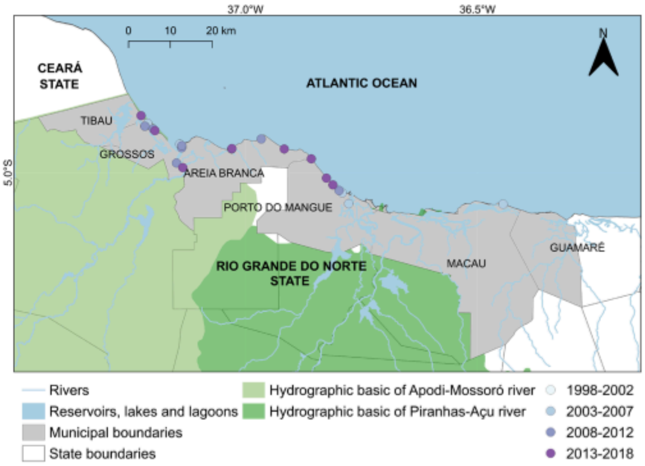

Figure 2. Calf manatee (*Trichechus manatus manatus*) strandings in the North Coast of Rio Grande do Norte (Northeastern Brazil) between 1998 and 2018.

(n = 1). No strandings occurred in Guamaré (Fig. 2). When the two estuaries were compared, Apodi-Mossoró (Tibau, Grossos, Areia Branca) accounted for significantly more strandings than Piranhas-Açu (Porto do Mangue, Macau, Guamaré) (Kruskal-Wallis test, x^2 = 6.03, $p < 0.05$) (Table 1).

The logistic model differed significantly from the null model. Almost half the variation in the occurrence of strandings was explained by the variable 'estuary' (pseudo R^2 = 45.79%). Both parameters estimated by the model were significant (Table 2). The following equation was used to correlate a stranding event with the estuary in which it occurred:

$$logit(Y) = 1.1787 - 1.7848 \cdot Estuary (eqn1)$$

where Y is the odds ratio of a stranding event, and Estuary is a nominal variable that assumes the value of 0 when Estuary = Apodi-Mossoró and 1 when Estuary = Piranhas-Açu.

The municipalities did not differ significantly regarding the annual distribution of strandings (x^2 = 14.5, $p > 0.05$). Areia Branca and Porto do Mangue were the only municipalities with more than one stranding in the same year (2002 and 2012 for Areia Branca; 2017 for Porto do Mangue). The years 2012 and 2015 saw the greatest number of strandings (n = 3), regardless of location (Fig. 3).

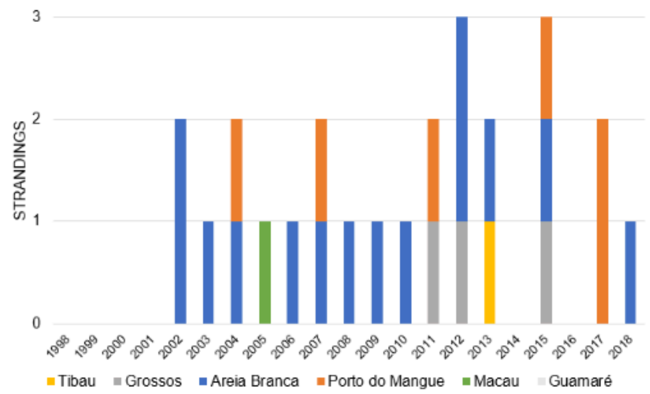

Figure 3. Annual distribution of strandings of manatee (*Trichechus manatus manatus*) calves between 1998 and 2018, according to the municipality.

Table 2. Estimated regression parameters, standard error, Z value, and *p* values for the Binomial GLM in Equation 1.

	Estimate	Std. error	Z value	*p* value
Constant	1.1787	0.5718	2.061	0.0393*
Estuary	-1.7848	0.7645	-2.335	0.0196*

*$p < 0.05$

Although no significant difference was found in monthly distribution (x^2 = 1.56, $p > 0.05$), strandings tended to occur in the dry season (December, January, and March recorded four events each) (n = 18; X^2 = 4.84, $p < 0.05$), while no strandings were recorded in February, May, June, or July.

Anthropic factors

Generally speaking, the areas occupied by mangrove forest, salt ponds, and shrimp farms increased over time in both estuaries (Fig. 4; Table 3). The mangrove forest along the Apodi-Mossoró River increased from 339 to 399 ha (+12.42%) between 1998 and 2018. The corresponding figures for salt ponds and shrimp farms were 12,765 ha to 14,352 ha (+11.76%) and 10.55 ha to 1,044 ha (+9,801.75%), respectively (Fig. 5).

The mangrove cover along the Piranhas-Açu decreased slightly from 3,161 to 2,998 ha (-5.15%) between 1998 and 2018, while the area occupied by salt ponds increased from 9,856 to 12,015 ha (+21.90%). No shrimp farms existed in this location in 1998, but between 2008 and 2018 the area increased from 1,979 ha to 3,257.5 ha (+64.63%) (Fig. 6).

Discussion

Context

The Antillean manatee is classified as Endangered on the Brazilian Endangered Species List (MMA, 2022). In the past, this species could be largely found along the Brazilian coastline, from Cape Orange, Amapá State to Espírito Santo State (Whitehead, 1978). However, overhunting activities in the past took a heavy toll on the manatee population (Whitehead, 1978), and now this species is considered Extinct in Sergipe, Bahia and Espírito Santo states (Albuquerque & Marcovaldi, 1982; Lima et al., 1992). The current size of the Antillean manatee population in Brazil is uncertain. Based on interviews, Luna and Passavante (2010) estimated the population in the country during the 1980s was around 500 individuals. Later, in an aerial survey covering 2,590.2 km² of the Brazilian coastline, it was estimated that the population size in 2010 ranged from 485 to 2,221, with a distribution mean of 1,104 individuals (Alves et al., 2016). No other surveys have been conducted in the country since then.

Overhunting almost extinguished the Brazilian manatee population (Whitehead, 1978), but after the 1967 Wildlife Protection Law (Brasil, 1967) commercial hunting was banned in the country. Subsistence capture still continues in the northern region until today (Luna et al., 2008), but other relevant anthropic activities act simultaneously and synergistically on manatees in Brazil throughout the coastlines. Incidental capture in fishing gears (Jefferson et al., 2015; Reinert et al., 2017), boat traffic and collision (Borges et al., 2018; Rycyk et al., 2018; Galves et al., 2023), pollution (Anzolin et al., 2012; Attademo et al.,

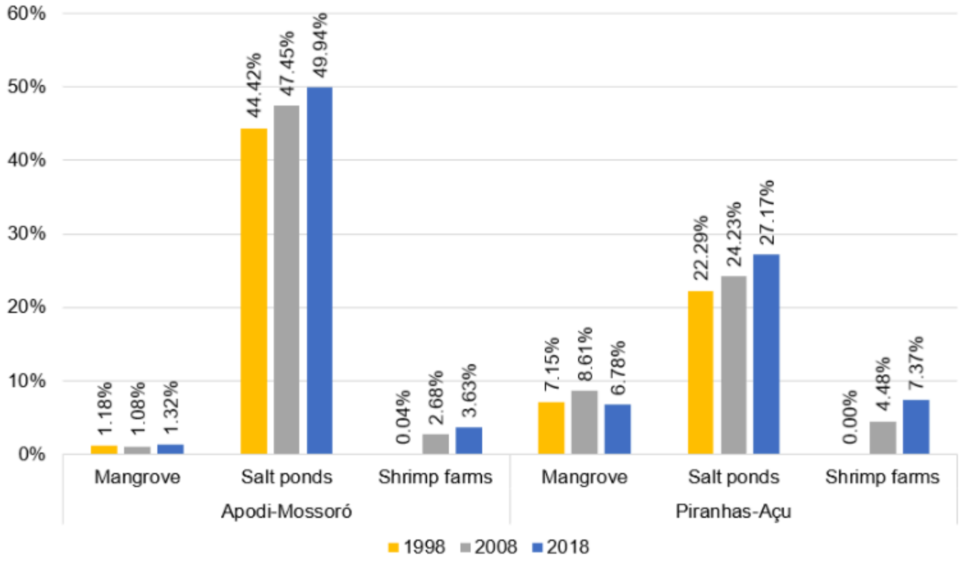

Figure 4. Percentage area covered by mangrove forest, salt ponds, and shrimp farms along the estuaries of the Apodi-Mossoró River and the Piranhas-Açu River in the years 1998, 2008, and 2018.

2015; Núñez-Nogueira et al., 2019; Gowans & Siuda, 2023), and genetic diversity loss caused by inbreeding and hybridization with Amazonian manatees (Luna et al., 2012, 2021a; Luna, 2013) are considered important to the Antillean manatee conservation in Brazil. However, habitat loss (Lima et al., 1992; Luna et al., 2018) and calf strandings (Parente et al., 2004; Meirelles, 2008; Balensiefer et al., 2017; Medeiros et al., 2021) are seen as the most impactful for the species in the country.

Since the 1980s calf strandings have been recorded by the Brazilian government, and in 1989 a Manatee Rescue, Rehabilitation, and Release Program was implemented to reduce the problem. According to Parente et al. (2004), cases of live calf stranding have become more common since 1990, and a Northeastern Aquatic Mammals Stranding Network was formed in 2000. During rescue and rehabilitation activities, it was observed that most of stranded calves were alive and with no diagnosed diseases by clinical and laboratory tests, as well as with no signs of congenital diseases (Balensiefer et al., 2017). Also, calves commonly showed neonate characteristics, like remnants of the umbilical cord and folded tail (Aquasis, 2016; Balensiefer et al., 2017). In Brazil, the rescued calves are transferred to a rehabilitation facility where, after a clinical and physical examination, they stay in rehabilitation for the next few years. After this period, individuals can be transferred to an acclimatization enclosure where they stay in the natural environment until release and the beginning of monitoring activities (Aquasis, 2016). To accomplish that, the rehabilitated manatees must have the following characteristics: have stayed in captivity for two to five years in maximum; be completely adapted to natural diet; measure more than two meters and weigh more than 175 kg; have no diseases; have low domestication degree; and have to be originated from the same population of the release site (Luna et al., 2021b).

In 1994 the first rehabilitated manatees in Brazil were released back to nature at the Alagoas State, “Astro” and “Lua” (Luna et al., 2021b). Since then, 48 individuals were released in the country until 2020 (Luna et al., 2021b). Manatee releases on the Northeastern coast of Brazil have a high success rate of 76.7% (Normande et al., 2014, 2016), and it was observed that their home range varied between 2.56 and 42.07 km² (Normande et al., 2014; Santos et al., 2022). In addition, some reintroduced individuals move over long distances in the coastline and contact with historically isolated sub-populations, specifically between Alagoas, Pernambuco, and Paraíba states (Normande et al., 2016; Luna et al., 2021b), where confirmed mating behavior between released and wild manatees had occurred (Normande et al., 2016). As result, rehabilitated and released individuals were tracked in areas of historical occurrence of the species, like Sergipe and Bahia states (Luna et al., 2018, 2021b; Santos et al., 2022), and were also able to produce calves in nature (Normande et al., 2014).

Sex and body condition of the specimens

No significant difference was observed in the male/female ratio, matching the findings of other studies along the Northeastern coast of Brazil (Meirelles, 2008; Balensiefer et al., 2017). Ceará and Rio Grande do Norte states display the highest incidence of calf strandings in the country (Lima et al., 1992; Parente et al., 2004; Attademo et al., 2020); 88% (Meirelles, 2008) and 65% (Balensiefer et al., 2017) of all strandings that occurred at those states corresponded only to calves, respectively. For this reason, Ceará and Rio Grande do Norte states can be considered relevant areas for manatee conservation. Despite the high incidence of strandings, calves are usually found alive in Ceará and Rio Grande do Norte states, and with no signs of disease (Balensiefer et al., 2017). On the other hand, in this area calves are commonly found with umbilical cord remnants and folded tail, indicating to be newborn manatees (Balensiefer et al., 2017; Medeiros et al., 2021). In this study those characteristics were observed in all stranded calves by the rescue and rehabilitation teams.

Spatial and temporal distribution

The spatial distribution of manatee calf strandings was not homogeneous throughout the study area, but a cluster was observed in the Apodi-Mossoró Estuary, especially within the area covered by the municipality of Areia Branca. No strandings

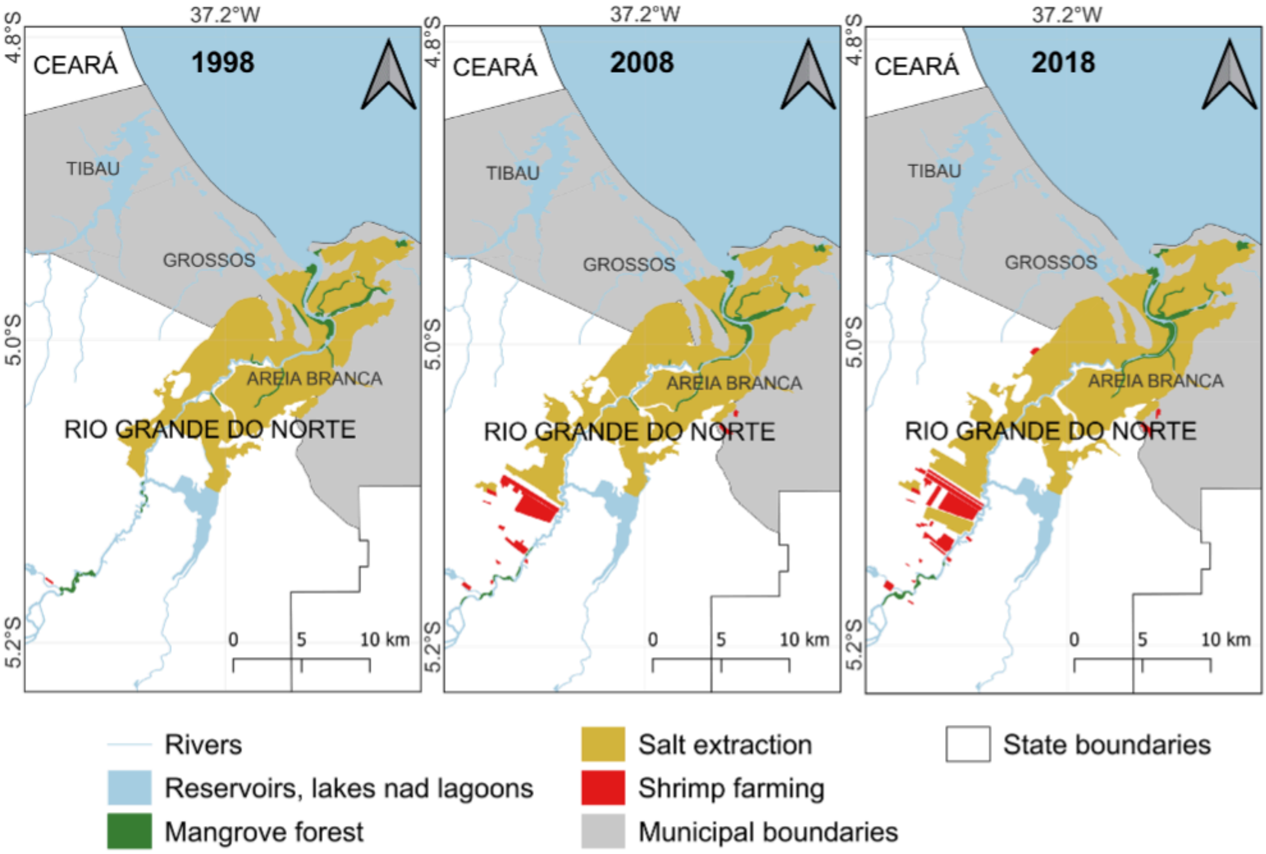

Figure 5. Area covered by mangrove forest, salt ponds, and shrimp farms along the estuaries of the Apodi-Mossoró River in the years 1998, 2008, and 2018.

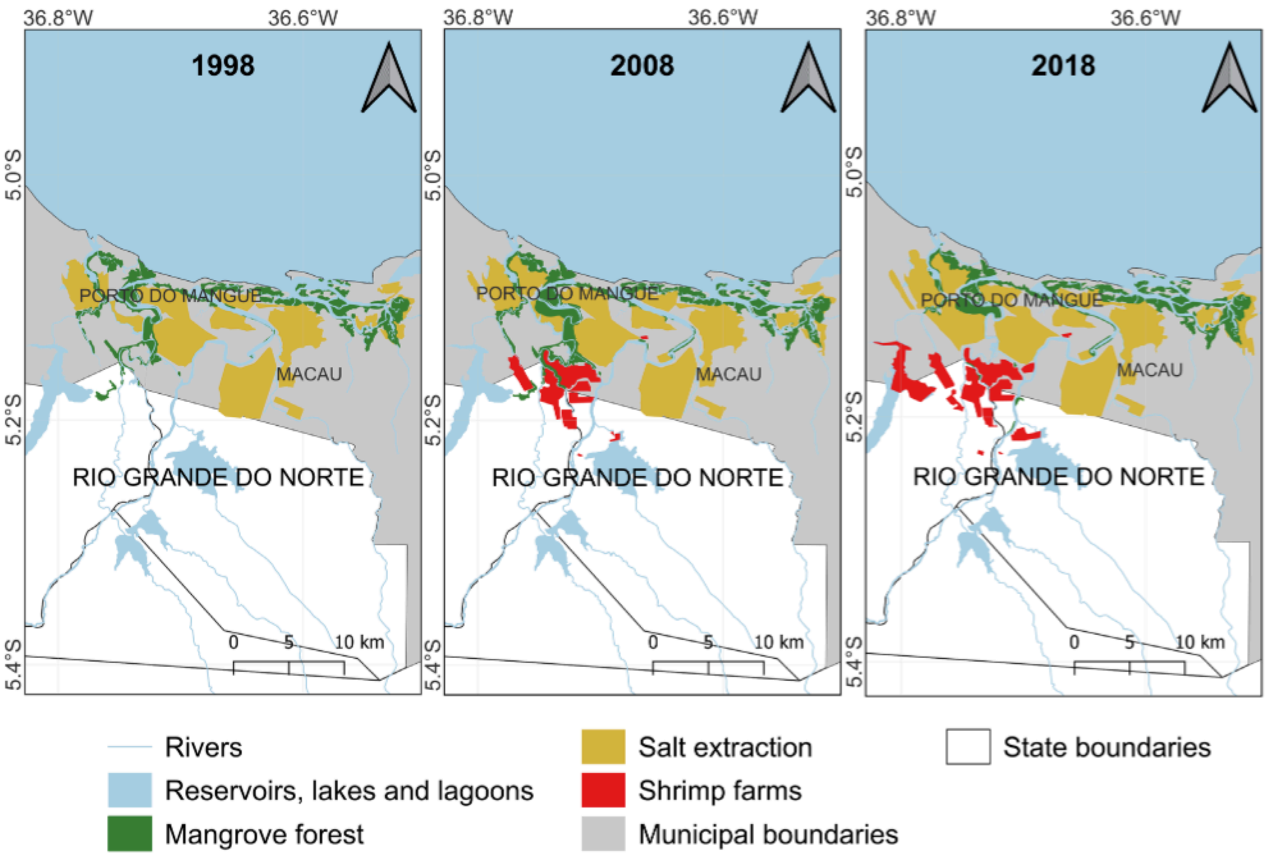

Figure 6. Area covered by mangrove forest, salt ponds, and shrimp farms along the estuaries of the Piranhas-Açu River in the years 1998, 2008, and 2018.

Table 3. Differences between Apodi-Mossoró and Piranhas-Açu regarding the number of calf strandings and the anthropic factors analyzed in this study.

Model ID	Estuaries	
	Apodi-Mossoró	Piranhas-Açu
Number of calf strandings	Most strandings occurred at this estuary, where municipality of Areia Branca corresponded to 72% of calf strandings for the whole study period. We also observed that there is 2.17 times more likely to occur a stranding event at Apodi-Mossoró than in Piranhas-Açu.	There were less records at this estuary than Apodi-Mossoró, where Piranhas-Açu was responsible for 28% of total calf stranding records. No strandings occurred in Guamaré municipality.
Mangrove vegetation	There was an increase in mangrove vegetation at this estuary in twenty years (+12.42%). However, when comparing both estuaries, Apodi-Mossoró is still considered historically more degraded.	Although Piranhas-Açu has less calf strandings and is also considered the most preserved estuary, we observed a decrease in mangrove cover in twenty years.
Salt extraction	Despite Apodi-Mossoró was historically occupied with salt extraction through years, we still observed an expansion of this activity (+11.76%).	We observed an increase in salt extraction in Piranhas-Açu (+21.90%) through the study timeline higher than in Apodi-Mossoró.
Shrimp Farming	Apodi-Mossoró presented a high increase in shrimp farming, with an expansion of 9,801.75%	In the last ten analyzed years (2008-2018), shrimp farming increased 64.63%. No shrimp farming was observed at this estuary in 1998.

were reported in Guamaré, and in a recent field study based on traditional ecological knowledge Choi-Lima et al. (2017) reported that manatees are rarely observed in this location. This may be explained by the environmental characteristics of the shore in this municipality, which restricts human access, reducing the likelihood of registering strandings. Also, the protected area Reserva de Desenvolvimento Sustentável Estadual Ponta do Tubarão located in Macau and Guamaré municipalities, is responsible for protection of almost 13,000 hectares of estuary, mangrove, and dune ecosystems. In this protected area, the construction of new shrimp farms and salt ponds is prohibited, as well as mangrove deforestation. Thus, if an exception is made for Guamaré, the difference between the two estuaries regarding the number of reported strandings may be explained by differences in the level of anthropic activity.

Manatee calf strandings have become more frequent since the 1990s. In a study covering the period 1981 - 2002, Parente et al. (2004) observed an increase in the number of live manatee strandings (especially calves) from 1991 on. Likewise, in the long period (1957 - 2002) surveyed by Meirelles (2008), 52% of strandings were clustered in the four-year period from 1999 to 2002. However, the increase in reports of calf strandings in this decade does not necessarily imply increased mortality, but may be the result of more efficient surveillance and greater investments in awareness campaigns targeting coastal communities.

Strandings tended to occur in the dry season, especially between August and January. A similar temporal pattern (September to December) was observed for marine mammals on the shores of Rio Grande do Norte (Lima et al., 2021) and Pernambuco (Attademo et al., 2020) states. The availability of freshwater has a direct influence on the presence of manatees (Landero et al., 2014; Favero et al., 2020; Medeiros et al., 2021) which prefer coastal environments with an abundance of flowing freshwater and food (Aquasis, 2016). However, the semiarid climate of Northeastern Brazil is characterized by irregular rainfalls, extended drought periods, and intermittent rivers (Soares et al., 2021). Thus, freshwater can be scarce in this region and rivers often display extensive silting (Godoy et al., 2018; Soares et al., 2021), making it difficult for pregnant females to access and increasing the risk of stranding of newborn calves (Lima et al., 1992).

Anthropic factors

Up until the early 20th century, Brazilian mangrove forests had been little exploited by fishing, aquaculture, and real estate developments. Their economic potential was eventually discovered by entrepreneurs and real estate developers in the 1950s. On the north coast of Rio Grande do Norte State, mangrove vegetation was first impacted by human activity in the 16th century (Costa et al., 2013) with the establishment of salt ponds. This was followed in the 1970s by a shrimp farming boom in both Ceará and Rio Grande do Norte states (Ceará, 2006). The negative impacts of these activities include damage to riverside vegetation, estuarine ecosystems, landscape, nursing grounds, and aquatic shelters, in addition to disruption of biological filtering functions, pollution of the soil and groundwater, and increase of the salt wedge (Lacerda et al., 2019).

In this study, a relatively large mangrove cover was observed in Piranhas-Açu, but over the 20-year study period a 5.15% reduction occurred. While the salt extraction and shrimp farming sectors grew and the frequency of manatee calf stranding increased in the period, the mangrove forest cover in the Piranhas-Açu Estuary was reduced by these activities. Habitat loss and fragmentation favor the extinction of species (Jacobson et al., 2019; Chase et al., 2020) and difficulties of access of pregnant manatees to silted estuaries can force mothers to provide parental care in less protected areas along the coast (Medeiros et al., 2021). Lima et al. (1992) suggested that females that do not find a safe refuge for birth and parental care also cannot maintain their calves under ideal conditions (like exposed areas to wind, currents, and waves actions), often leading to separation from the calf.

In contrast, the mangrove cover in Apodi-Mossoró increased by 12.42% (advancing inland), probably as a result of the decreasing freshwater input, the heightened influence of the tides, and the intrusion of salt into the soil and groundwater (Godoy et al., 2018). Similar patterns were previously reported from other estuaries at Northeastern Brazil (Godoy et al., 2018; Pelage et al., 2019). In some cases, abandoned salt ponds may be colonized by mangrove due to the high salt concentration in the soil (Lacerda et al., 2007; Godoy et al., 2018; Reis-Neto et al., 2019).

For decades, salt production has contributed to environmental degradation in the estuaries of Apodi-Mossoró and Piranhas-Açu (Costa et al., 2013). The state of Rio Grande do Norte currently accounts for over 90% of the Brazilian salt production (Diniz & Vasconcelos, 2017) and our data show the sector expanded during the 20-year study period, more so in Piranhas-Açu (+21.90%) than in Apodi-Mossoró (+11.76%). Salt extraction has been practiced for centuries in the Apodi-Mossoró Estuary, contributing to deforestation and habitat degradation. Although Piranhas-Açu is currently better preserved than Apodi-Mossoró, the promising economic prospects of salt production are leading businesses to search for new productive areas, increasing the risk of deforestation, as observed in this study.

The satellite image analysis suggests that Apodi-Mossoró was more severely affected by anthropic activity than Piranhas-Açu. Also, according to the results of the logistic model, a stranding event is 2.17 times more likely to occur in Apodi-Mossoró than in Piranhas-Açu. Since there are no studies estimating the manatee population of Rio Grande do Norte State, neither specifically in the Apodi-Mossoró and Piranhas-Açu estuaries, we cannot affirm that the manatee distribution in the present study area is homogeneous. However, both estuaries have similar natural environments, and the main difference appears to be in the level of anthropic impact. It is therefore reasonable to posit that the higher probability of stranding in Apodi-Mossoró shown by the model is due to the higher level of human activity in this estuary.

Anthropic activities are the main cause of habitat loss for coastal species (Alongi, 2002), especially shrimp farming (Guimarães et al., 2010; Silva, 2012; Santos et al., 2014; Godoy et al., 2018; Lacerda et al., 2019). The latter was the main contributor to the reduction of the mangrove cover in Apodi-Mossoró. Our data show that shrimp farming increased in both estuaries during the study period, especially in the period 2008 - 2018, because of heavy investments in enterprises on the north coast of Rio Grande do Norte in the late 1990s, particularly in 1996 and 1997 (Meireles et al., 2007). For example, shrimp production in the Apodi-Mossoró Estuary grew markedly over the 20-year period from 1989 (0 ha) to 2009 (1,006.75 ha) (Rocha et al., 2011). Similar patterns were observed for the Piranhas-Açu Estuary located within the municipality of Macau (from 40 ha in 1998 to 583 ha in 2008) (Santos & Lima, 2013). However, due to floods from heavy rainfalls in Rio Grande do Norte in the years 2004, 2008, and 2009 (Santos et al., 2015), and outbreaks of white spot syndrome on Brazilian shrimp farms in 2005 (Seiffert et al., 2005), the growth rate decreased in the second decade of the study period (2008 - 2018). Despite the decrease in production and implementation of shrimp farms due to economic factors, the environmental impacts caused by these enterprises remain even after the deactivation of production. Linked to this, the natural low reproductive rate of manatees (Luna et al., 2018), associated with an interval between pregnancies of two to three years (Hartman, 1979), and a generational time of approximately 20 years (Deutsch et al., 2008), suggest that the impact that shrimp farming caused on manatee populations in this region remains to the present day.

Environmental factors such as adverse oceanographic and meteorological conditions may also contribute to manatee calf stranding (Silva & Sequeira, 2003; Coombs et al., 2019). Other factors related to the stranding of marine mammals include the direction of the wind and the season (Battaglia et al., 2020; Lima et al., 2021), the phases of the moon (Wright, 2005), and coastal topography (Silva et al., 2003).

River silting probably influences the incidence of manatee calf strandings in the region. With the concomitant reduction in freshwater flow in intermittent rivers, especially during the dry season, the degradation of estuaries leads to excess silting of the river mouth (Godoy et al., 2018; Soares et al., 2021), in some cases preventing pregnant manatees from entering the river (Lima et al., 1992; Aquasis, 2016) and forcing them to provide parental care in unsheltered areas along the coast (Medeiros et al., 2021). Calves born in areas with strong winds and currents are more likely to drift away from their mother and strand (Parente et al., 2004; Meirelles, 2008; Balensiefer et al., 2017; Choi-Lima et al., 2017).

In addition, another anthropic factor that might contribute to manatee calf stranding is the increase in boat traffic. This activity might change feeding and resting behaviors, or even can contribute to the separation of females and calves (Meirelles et al., 2014). In the Northeastern coast of Brazil, Borges et al. (2007) observed that watercraft collisions occurred mostly in dry season, and stranded calves for this reason were found in areas of reproduction of manatees. There are indications that unregulated boating tourism in areas of high manatee density can influence the number of boat collisions and the number of strandings (Galves et al., 2023), and that faster boats likely pose a greater risk of collision with manatees than the slower ones (Rycyk et al., 2018). However, more studies must be conducted to estimate the mortality rate of the species and identify the main areas of risk of watercraft collisions in Brazil.

Another local threat to the manatee population has recently been added to the list: oil and gas drilling on the north coast of Rio Grande do Norte (Rocha et al., 2011; Santos & Lima, 2013). This activity is likely to increase boat traffic and seismic noise (Borges et al., 2007), in addition to the possibility of oil spills. Oil is not only toxic upon direct contact but can impact the dynamics of the seagrass beds where manatees graze (Campagna et al., 2011; Magalhães et al., 2021). Thus, to minimize risks to the local manatee population, oil and gas drilling in this region should be carefully monitored.

General considerations

Calm, shallow and protected waters like estuaries and mangroves are commonly used by manatees to rest, feed, and breed, especially pregnant females (Hartman, 1979). However, degradation from direct or indirect human activities compromises living conditions for females. The action of waves, winds, and tides in unprotected areas can separate the mother and the calf, and in some cases the newborn strands alive on the beach (Lima et al., 1992). Thus, habitat degradation, especially in estuaries and mangroves, is critical for manatee conservation in Brazil (Lima et al., 1992). The effect of calf strandings on the manatee population is still not well documented (Luna et al., 2021b).

Manatee calf strandings are rare in estuaries with little or no damage to the mangrove cover. Such favorable conditions are present in preserved estuaries, like the Timonha River and the Ubatuba River Estuary complex, at the boundary between Ceará and Piauí (Aquasis, 2016). During an aerial survey, it was observed that the manatee population density in MPAs was higher than in unprotected areas (Alves et al., 2013). However, the Brazilian distribution and population size are still not very clear (Choi-Lima et al., 2017; Luna et al., 2018). During the 1980s, government researchers conducted interviews along the coast and described the extinction of the species in Espírito Santo and Bahia states (Albuquerque & Marcovaldi, 1982). Later, more interviews allowed to estimate a population size of 500 individuals (Luna et al., 2008; Luna & Passavante, 2010) or 1,000 individuals (Luna et al., 2018). During a single aerial survey in 2010 between Ceará and Alagoas states, Alves et al. (2016) observed a total of 67 manatees, estimating a mean population size of 1,104 individuals ranging from 485 to 2,221 individuals. According to the authors, there were still uncertainties in this population size based on analyses performed.

Environmental degradation associated with human exploitation of estuaries is compromising the preservation of manatee populations in Brazil. Extensive mangrove deforestation, silting, and the loss of freshwater sources are the main factors destroying the habitats used by manatees for feeding, resting, reproduction, and parental care. Records of the Antillean manatee predation are unusual (Falcón-Matos et al., 2003; Aquasis, 2016). Our study revealed a clear temporal increase in manatee calf strandings in two Northeast Brazilian ecosystems over a 20-year period. Strandings were more likely to occur in the dry season, coinciding with the nursing period. As for the spatial pattern, strandings were significantly more frequent in the Apodi-Mossoró Estuary (especially within the municipality of Areia Branca) than in the Piranhas-Açu Estuary, possibly due to the higher level of environmental degradation associated with salt extraction and shrimp farming. Apodi-Mossoró was more heavily impacted environmentally and therefore potentially less safe for reproduction and calving. However, despite being slightly better preserved, Piranhas-Açu is increasingly targeted by investors, especially in the shrimp farming industry.

Notwithstanding, the reduction or absence of strandings in any of the surveyed regions cannot be interpreted as an improvement in the conservation status of manatees. The absence or reduction of strandings may also be associated with a reduction in population in the region or the impediment of animals entering the estuaries due to silting up or transit of vessels. In view of their ecological importance, the evaluated estuaries are in need of more effective environmental measures. The establishment of conservation units and greater investments in local awareness campaigns may help preserve manatee populations along the Brazilian coast. Our results provide support for coastal management efforts in the region and allow for a better understanding of the population dynamics and conservation of the Antillean manatee.

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