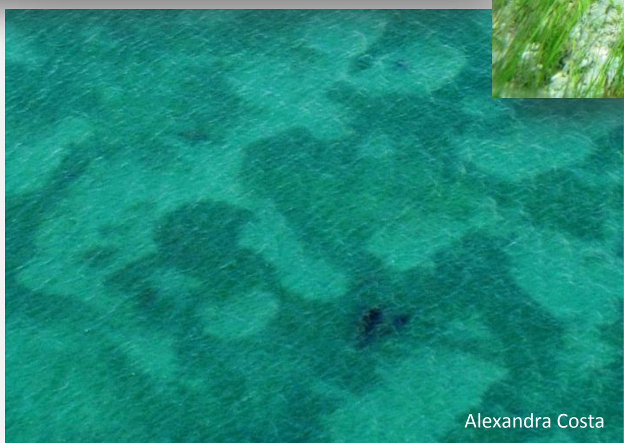
UNIVERSIDADE FEDERAL DE PERNAMBUCO

CENTRO DE TECNOLOGIA E GEOCIÊNCIAS

DEPARTAMENTO DE OCEANOGRAFIA

Habitats da megafauna marinha na costa nordeste do Brasil, com ênfase em peixes-bois.



Maria Danise de Oliveira Alves

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Tese submetida ao curso de Doutorado do Programa de Pós Graduação em Oceanografia da Universidade Federal de Pernambuco, como parte dos requisitos para a obtenção do título de Doutor em Oceanografia.

Orientadora: Prof[a] Drª Maria Elisabeth de Araújo

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Tese submetida em 27 de fevereiro de 2013 ao curso de Doutorado do Programa de Pós-Graduação em Oceanografia da Universidade Federal de Pernambuco, como requisito para obtenção do título de Doutor em Oceanografia e aprovada pela seguinte banca examinadora:

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Dr. Antônio da Silva Souto

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Dr. Cristiano Leite Parente

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Dr. José Souto Rosa Filho

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Dr. Leonardo Liberali Wedekin

“Não tenho a anatomia de uma garça pra receber em mim os perfumes do azul. Mas eu recebo. É uma bênção. / Às vezes se tenho tristeza, as andorinhas me namoram mais de perto. Fico enamorado. É uma bênção. / Logo dou aos caracóis ornamentos de ouro para que se tornem peregrinos do chão. Eles se tornam. É uma bênção. / Até alguém já chegou de me ver passar a mão nos cabelos de Deus! Eu só queria agradecer”.

Manoel de Barros

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Sumário

Resumo

Mamíferos e tartarugas marinhas são considerados organismos-chave para a conservação marinha, sendo fundamental o desenvolvimento de pesquisas que avaliem a distribuição e a abundância de espécies ameaçadas, como o peixe-boi marinho (*Trichechus manatus manatus*). O objetivo deste estudo foi avaliar a distribuição e a abundância da megafauna marinha no nordeste do Brasil, com ênfase em peixes-bois marinhos e seus potencias habitats de forrageio (prados de angiospermas marinhas), por meio de pesquisas aéreas e terrestres. A viabilidade das pesquisas aéreas foi testada satisfatoriamente no norte de Alagoas, devido à ótima transparência da água, com avistagem de 10 peixes-bois, 15 golfinhos (sete *Sotalia guianensis*) e 13 tartarugas marinhas. No entanto, foram necessários ajustes metodológicos para minimizar as limitações características de cada táxon e/ou habitat. Posteriormente, foram sobrevoados 2.590,2 km^2 da costa nordeste do Brasil, entre Piauí e Alagoas, para estimar a abundância do peixe-boi marinho. Foi adotada uma abordagem bayesiana, utilizando-se dados de avistagens aéreas e registros bibliográficos. Este princípio foi idealizado devido à dificuldade de amostragem de uma população dispersa em uma grande área. O número estimado de *T. m. manatus* foi de 1.146 indivíduos, atestando um coeficiente de variação posterior de 29% e intervalo de probabilidade de 95%, com os extremos de 610 e 1.955 animais. No estudo de distribuição da megafauna marinha foram registrados 41 peixes-bois, 78 golfinhos (10 *S. guianensis*) e 286 tartarugas marinhas (família Cheloniidae). Peixes-bois e tartarugas, que compartilham o mesmo hábito alimentar e o habitat costeiro, correlacionaram-se positivamente, ao contrário de golfinhos, que tem distribuição mais longe da costa. A densidade de peixes-bois foi maior nas Áreas Marinhas Protegidas caracterizadas por extensos estuários preservados (“Barra do Rio Mamanguape” e “Delta do Rio Parnaíba”), enquanto que golfinhos e tartarugas por àquelas com formações recifais (“Costa dos Corais” e “Recifes de Corais”, respectivamente). Estes resultados mostram a importância vital de proteção e manejo adequado desses ecossistemas para garantir um futuro sustentável às populações ameaçadas pelo desenvolvimento costeiro urbano. A estimativa de abundância O mapeamento dos potenciais habitats de forrageio do peixe-boi marinho foi realizado entre a costa do Rio Grande do Norte e

Alagoas, utilizando-se registros bibliográficos e estudos *in loco* para o registro de praias com ocorrência de angiospermas marinhas. A distribuição espacial dessas plantas foi correlacionada com os registros bibliográficos de ocorrência de peixes-bois (registros aéreos, de encalhes e informações de pescadores). As espécies *Ruppia maritima*, *Halophila decipiens* e *Halodule wrightii* foram identificadas em 53 praias, porém não apresentaram correlação positiva com os registros de ocorrência de *T. m. manatus*. Este resultado pode estar relacionado à redução desses potenciais habitats de forrageio ao longo da costa nordeste do Brasil e/ou ao hábito generalista de herbivoria dos peixes-bois, sendo caracterizado pelo consumo de diversos tipos de alimento ao longo de sua extensa área de vida, principalmente de macroalgas. A visão global obtida na presente pesquisa envolveu metodologias complementares e eficazes de levantamentos aéreo e terrestre, e forneceu uma caracterização dos ambientes costeiros utilizados pela megafauna marinha. Em especial, reavaliou o *status* populacional do peixe-boi marinho e correlacionou a distribuição desses animais com as angiospermas marinhas. Todas essas informações são inéditas e primordiais para a elaboração de planos de manejo e conservação das espécies e seus habitats.

Palavras-chave: peixes-bois, golfinhos, tartarugas, nordeste do Brasil, levantamentos aéreos, angiospermas marinhas.

Abstract

Marine mammals and sea turtles are considered key organisms for marine conservation. It is therefore important to carry out studies on the distribution and abundance of endangered species, such as the Antillean manatee (*Trichechus manatus manatus*). The aim of the present study was to assess the distribution and abundance of marine megafauna in northeastern Brazil, with an emphasis on Antillean manatees and its potential foraging grounds (seagrass beds), through aerial and terrestrial surveys. The viability of aerial surveys was satisfactorily tested in the northern portion of the state of Alagoas due to the adequate transparency of the water, which allowed the sighting of 10 manatees, 15 dolphins (7 specimens of *Sotalia guianensis*) and 13 sea turtles. However, methodological adjustments were needed to minimize the characteristic limitations of each taxon and/or habitat. Flyovers covering 2590.2 km^2 of coastline along northeastern Brazil (between the states of Piauí and Alagoas) for estimate the abundance of Antillean manatee. The Bayesian approach was adopted, using data from aerial sightings and bibliographic records. This principle was conceived due to the difficulty sampling a dispersed population a large area. The estimated number of *T. m. manatus* was 1146 individuals, demonstrating a coefficient of variation of 29% and a 95% probability interval (range: 610 to 1955 individuals). In the study of distribution of marine megafauna were recorded 41 manatees, 78 dolphins (10 specimens of *S. guianensis*) and 286 sea turtles (family Cheloniidae). Manatees and sea turtles, which share the same feeding habits and coastal habitats, were positively correlated. In contrast, the distribution of dolphins was farther offshore. The density of manatees was higher in Marine Protected Areas characterized by extensive preserved estuaries ("Barra do Rio Mamanguape" and "Delta do Rio Parnaíba"), while dolphins and sea turtles for those with reef formations ("Costa dos Corais" and "Recifes de Corais", respectively). These findings demonstrate the vital importance of the protection and adequate management of these ecosystems to ensure a sustainable future for populations threatened by coastal urban development. The mapping of the spatial distribution of seagrass (between the coast of Rio Grande do Norte and Alagoas) was analyzed in relation to bibliographic records of the occurrence of the Antillean manatee (aerial records, cases of stranding and information from fishermen).

This species *Ruppia maritima*, *Halophila decipiens* and *Halodule wrightii* were identified on 53 beaches, but showed no correlation with the occurrence records of *T. m. manatus*. This result may be related to reducing these potential foraging habitats along the northeast coast of Brazil and/or the generalist habit of herbivory on the part of the Antillean manatee, which feeds on different types of food resources, especially macroalgae, throughout its variable home range. The overview obtained in the present study involved effective, complementary methods of land and aerial surveys and provided a characterization of coastal environments used by endangered marine megafauna. Moreover, this study reevaluated the population status of the Antillean manatee and related the distribution of this species with seagrass beds. This information is has not previously been published and is essential to the drafting of management plans for the conservation of these species and their habitats.

Keywords: manatees, dolphins, sea turtles, northeastern Brazil, aerial surveys, seagrass

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Apresentação

A presente tese aborda duas problemáticas envolvendo a conservação da megafauna marinha no nordeste do Brasil, representada por espécies vulneráveis a criticamente ameaçadas de extinção. São elas: (1) padrões de distribuição espacial do peixe-boi marinho (*Trichechus manatus manatus*), golfinhos e tartarugas, correlacionando-os com fatores ecológicos, como a presença de estuários e angiospermas marinhas, e fatores antropogênicos, como atividades de pesca e crescimento urbano costeiro; (2) Estimativa de abundância do mamífero aquático mais ameaçado de extinção do país, o peixe-boi marinho. Foram empregadas metodologias pioneiras no nordeste do Brasil para o mapeamento dos habitats de ocorrência desses grupos taxonômicos costeiros, definidas pelos levantamentos aéreos, para a detecção e contagem dos indivíduos, e pelo mapeamento terrestre, para identificação dos habitats de forrageio do peixe-boi marinho, caracterizados pelos prados de angiospermas marinhas.

A tese está estruturada em quatro capítulos que incluem seus respectivos objetivos específicos a seguir:

I. Avaliar a aplicabilidade metodológica dos levantamentos aéreos para estudos de distribuição e abundância da megafauna marinha costeira do nordeste do Brasil, utilizando o norte de Alagoas como área para o estudo piloto;

II. Estimar a abundância de peixes-bois marinhos ao longo da costa nordeste do Brasil (entre os estados do Piauí e Alagoas), para subsidiar uma reavaliação do *status* de conservação das populações criticamente ameaçadas de extinção.

III. Quantificar e analisar a distribuição espacial de peixes-bois, golfinhos e tartarugas em larga-escala geográfica no nordeste do Brasil (entre os estados do Piauí e Alagoas), correlacionando-a com o tipo de habitat, atividades humanas e importância das Áreas Marinhas Protegidas;

IV. Mapear as áreas de ocorrência das angiospermas marinhas no nordeste do Brasil (entre os estados do Rio Grande do Norte e Alagoas), visando avaliar a importância desses ecossistemas como potenciais habitats de forrageio do peixe-boi marinho.

Introdução geral

Mamíferos e tartarugas marinhas são considerados organismos-chave para a conservação dos mares em diversas partes do mundo (Chatwin 2007). Muitas populações ocorrem em áreas costeiras que são intensamente exploradas por humanos (Ojeda-Martínez et al. 2011), tornando-as vulneráveis ou ameaçadas de extinção (IUCN 2012), e o estabelecimento de Áreas Marinhas Protegidas (AMPs) são essenciais na proteção desses grupos e seus ecossistemas (Hooker & Gerber 2004).

No litoral nordeste do Brasil, as principais ameaças à biodiversidade costeira são as atividades de pesca e o intenso desenvolvimento urbano, tornando essa região uma das mais vulneráveis da América do Sul (Chatwin 2007). Os mamíferos aquáticos mais comuns dessa região são o peixe-boi marinho, *Trichechus manatus manatus* Linnaeus 1758 (Lima et al. 2011), o mais ameaçado de extinção do Brasil (ICMBio 2011), e o boto-cinza, *Sotalia guianensis* (van Bénéden 1864) (Alvite et al. 2004). Dentre as cinco espécies registradas de tartarugas marinhas, a mais comum é tartaruga-verde, *Chelonia mydas* (Linnaeus 1758) (Marcovaldi & Marcovaldi 1999).

No Brasil, pesquisas de distribuição e abundância da megafauna marinha utilizaram principalmente dados de encalhes e informações de pescadores (Marcovaldi & Marcovaldi 1999, Parente et al. 2004, Luna et al. 2008, Meirelles et al. 2009, Lima et al. 2011). Em particular, estudos com peixes-bois marinhos foram desenvolvidos com base no conhecimento tradicional de pescadores, a partir da década de 80. Os resultados evidenciaram um padrão de distribuição descontínuo ao longo do litoral norte e nordeste do país, com abundância de menos de 500 indivíduos (Albuquerque & Marcovaldi 1982, Luna et al. 2008, Lima et al. 2011).

Estudos mundiais de distribuição e estimativa de abundância da megafauna marinha utilizam comumente os levantamentos aéreos (Preen 2004, Edwards et al. 2007, Jean et al. 2010, Langtimm et al. 2011). No entanto, esta técnica possui fatores limitantes para a sua aplicação, como a turbidez da água aliada ao viés de percepção do observador sobre as avistagens dos animais (Marsh & Sinclair 1989, Pollock et al. 2006, Katsanevakis et al. 2012). No Brasil, essa metodologia foi aplicada principalmente na região sul (Secchi et al. 2001, Danilewicz et al. 2010, Zerbini et al. 2010, 2011), com o golfinho *Pontoporia blainvillei*, destacando-se na região nordeste os trabalhos com a baleia jubarte, *Megaptera novaeangliae* (Andriolo et al. 2006, 2010, Wedekin 2011) e o peixe-boi marinho (Costa 2006).

Os habitats do peixe-boi estão situados nos rios, estuários e águas costeiras rasas do leste do México, América Central, e norte e nordeste da América do Sul (Lefebvre et al. 2001). Sua distribuição é determinada fundamentalmente pela presença de água doce e de vegetação aquática (Hartman 1979, Olivera-Gómez & Mellink 2002, 2005). No Brasil, o padrão de distribuição desses animais é praticamente desconhecido, principalmente em relação às áreas de alimentação, com poucos trabalhos realizados por meio do monitoramento de animais nativos, em áreas restritas (Paludo & Langguth 2002, Alves 2003, 2007, Costa 2006), ou de espécimes reintroduzidas à natureza (Lima 2008). Sugere-se que essa distribuição seja consideravelmente ampla, em virtude da grande diversidade de vegetais identificados na sua dieta (Borges et al. 2008).

Os ecossistemas de angiospermas marinhas, que abrangem diversas espécies consumidas pelos peixes-bois (Hartman 1979, Borges et al. 2008, Lima et al. 2011), são extremamente afetados por atividades antropogênicas, com reduções na sua área de cobertura em áreas costeiras rasas e estuarinas de todo o mundo (Short et al. 2006, Ceccherelli et al. 2007, Pitanga et al. 2012). Na costa do Brasil, o conhecimento sobre a distribuição dessas plantas é reduzido, consistindo em trabalhos desatualizados ou de escalas locais (Laborel-Deguen 1963, den Hartog 1972, Oliveira-Filho et al. 1983, Magalhães & Cazuza 2005, Marques & Creed 2008, Sordo et al. 2011). O conhecimento sobre a distribuição das potenciais áreas de forrageio dos peixes-bois é essencial para o estabelecimento de estratégias conservacionistas a nível local e regional, garantindo a proteção da espécie e seus habitats (Paludo & Langguth 2002, Olivera-Gómez & Mellink 2005, Alves-Stanley et al. 2010).

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Capítulo 1*† - Estudo aéreo piloto da megafauna marinha na costa norte de Alagoas, Brasil.

Chapter 1*† - Pilot aerial study of the marine megafauna in northern coast Alagoas, Brazil.

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PILOT AERIAL STUDY OF THE MARINE MEGAFAUNA IN NORTHERN COAST ALAGOAS, BRAZIL.

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ABSTRACT

This study aimed to investigate the feasibility of strip-transect aerial survey for the study of the marine megafauna in northern coast of Alagoas, chosen as the pilot area due to the better water clarity and the occurrence of the Antillean manatee. It was sighted 15 dolphins, 13 sea turtles and 10 manatees. From five aspects tested on the experimental flight, three adjustments were necessary on the methodology as following: 1) reduction of the transect angle to 40º to increase the sampling area; 2) constant transects of 1.5 nautical miles from shore to standardize the area of coverage; and 3) transects restricted to the mouths of estuaries due to low visibility in turbid waters. This study demonstrated the effectiveness of aerial surveys for the detection of marine megafauna. However, the adjustments proposed are necessary to minimize the characteristic limitations of each species and/or habitat.

Keywords: aerial method, manatees, dolphins, sea turtles, limitations.

RESUMO

O estudo objetivou investigar a viabilidade do censo aéreo no estudo da megafauna marinha no norte de Alagoas, escolhida como área piloto devido à melhor transparência da água e presença de peixes-bois marinhos. Foram avistados 15 golfinhos, 13 tartarugas e 10 peixes-bois. Dentre os cinco parâmetros testados no voo piloto, três sofreram ajustes metodológicos: 1) redução do ângulo de abertura das transecções aéreas para 40°, aumentando a área amostrada; 2) transecções constantes a 1,5 milhas náuticas da costa, padronizando-se a área de cobertura; e 3) transecções restritas às desembocaduras dos estuários, devido à impossibilidade de detecções de animais dentro dos estuários, onde há águas muito turvas. Os resultados mostraram a eficácia metodológica das pesquisas aéreas na detecção da megafauna marinha. No entanto, os ajustes propostos são necessários para minimizar as limitações características de cada táxon e/ou habitat.

Palavras-chave: método aéreo, peixe-boi marinho, golfinhos, tartarugas, limitações.

INTRODUCTION

Aerial surveys have been used throughout the world to estimate the distribution and abundance of aquatic animals, the most studied of which are sea turtles and marine mammals (MCCLELLAN, 1996; PREEN et al., 1997; ROOS et al., 2005; LANGTIMM et al., 2011). However, such surveys are rare in Brazil and mainly restricted to the southern region of the country (SECCHI et al., 2001; DANILEWICZ et al., 2010; ZERBINI et al., 2010; ZERBINI et al., 2011). Indeed, published studies have been carried out in the northeastern region, addressing the humpback whale [*Megaptera novaeangliae* (Borowski, 1781)] (ANDRIOLO et al., 2006; 2010; WEDEKIN, 2011) and Antillean manatee (*Trichechus manatus manatus* LINNAEUS, 1758) (COSTA, 2006). Other studies in the region have relied mainly on data from stranded animals and the reports of fishermen (MARCOVALDI; MARCOVALDI, 1999; PARENTE; VERGARA-PARENTE; LIMA, 2004; LUNA et al., 2008; MEIRELLES et al., 2009; LIMA et al., 2011).

The perception and availability bias regarding the sighting of marine animals are the main limiting factors to aerial surveys (MARSH; SINCLAIR, 1989; KATSANEVAKIS et al., 2012). According to COSTA (2006), the high cost of aircraft rental and the difficulty sighting specimens in turbid coastal waters at particular times of the year limit the use of this method in northeastern Brazil. Sampling difficulties can render the identification of species and the precise count of individuals in a population impossible. However, this method is useful in understanding population tendencies (REYNOLDS, 1999), especially among species vulnerable to extinction, such as the manatee, which is considered the most endangered aquatic mammal in Brazil (ICMBIO, 2011).

The megafauna on the northeastern coast of Brazil is represented by a single species from the order Sirenia, the Antillean manatee (*T. m. manatus*) (LIMA et al., 2011), 19 species of cetaceans (ALVITE et al., 2004), the most frequent of which is the Guiana dolphin [*Sotalia guianensis* (VAN BÉNÉDEN, 1864)], and five of the seven living species of sea turtles: green sea turtle [*Chelonia mydas* (LINNAEUS, 1758)], loggerhead sea turtle [*Caretta caretta* (LINNAEUS, 1758)], hawksbill sea turtle [*Eretmochelys imbricata* (LINNAEUS, 1766)], olive Ridley sea turtle [*Lepidochelys olivacea* (ESCHSCHOLTZ, 1829)] and leatherback sea turtle [*Dermochelys coriacea* (VANDELLI, 1761)] (GOMES; SANTOS; HENRY, 2006). The Antillean manatee has particular characteristics of occurrence in comparison to other species, such as warm, shallow waters (OLIVERA-GÓMEZ; MELLINK, 2005), abundant aquatic vegetation (PALUDO; LANGGUTH, 2002; COSTA, 2006) and human activities (PARENTE; VERGARA-PARENTE; LIMA, 2004; BORGES et al., 2007). Therefore, estuaries are essential habitats as foraging, breeding and resting grounds for the manatee (REYNOLDS; POWELL, 2002; LIMA et al., 2011).

The aim of the present study was to investigate the applicability of aerial surveys using strip-transect for studies of distribution and abundance of marine megafauna in northeastern Brazil, using the northern coast of the state of Alagoas as a pilot area.

STUDY AREA

The geographic limits of the sampling area on the northern coast of the state of Alagoas were Peroba Beach [northernmost portion of the state (08°07'52"S/34°55'33"W)] to Ponta Verde Beach in the capital city Maceió (09°30'39"S/35°47'56"W), totaling approximately 114 km of coastline (Fig. 1). This area was chosen mainly due to its higher water transparency in comparison to other areas of northeastern Brazil as well as the constant occurrence of manatees of either native populations or reintroduced specimens (LIMA, 2008; LIMA et al., 2011). This ideal conditions were decisive for validate the aerial sampling.

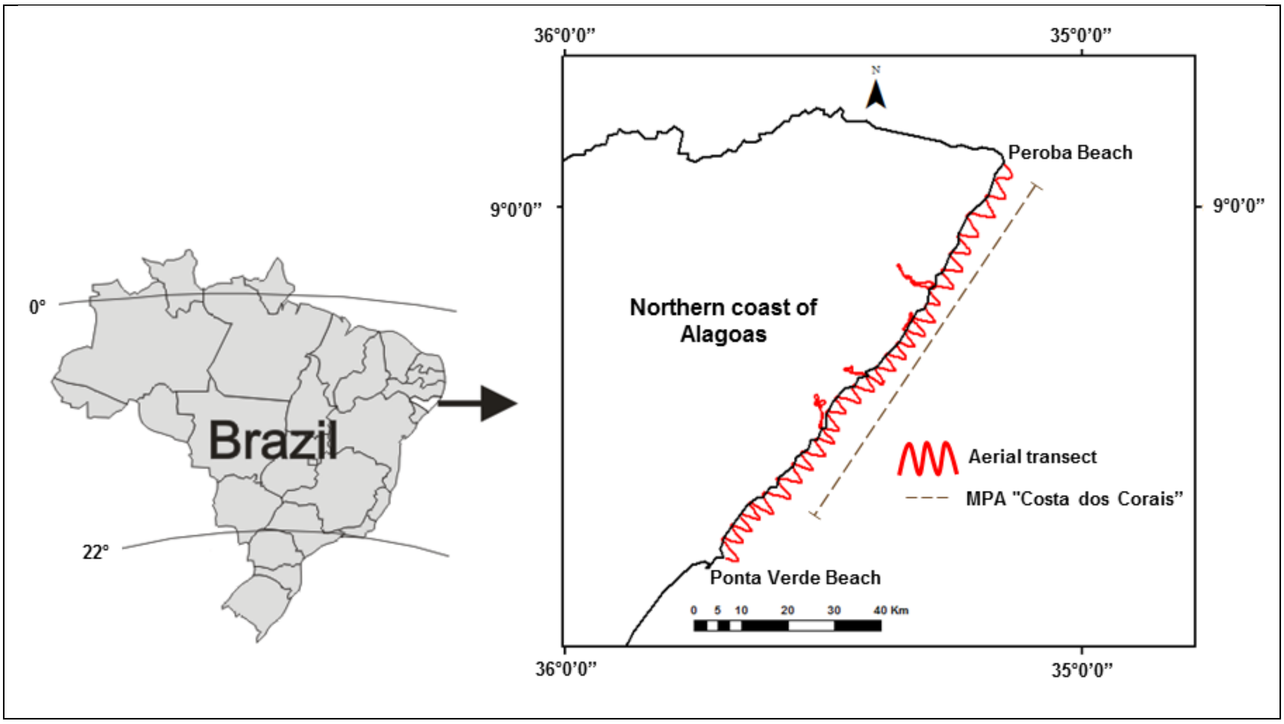

Figure 1 – Northern coast of Alagoas showing the aerial transects (zigzag) between Peroba Beach and Ponta Verde Beach. Highlight for the coverage area of the Marine Protected Area (MPA) "Costa dos Corais" within the study area (dotted line).

This area has different coastal ecosystems, such as estuaries and lagoons with mangroves positioned transversally to the coastline as well as coral and sandstone reefs occurring from the coastline to several meters in depth (CORREIA; SOVIERZOSKI, 2005). A large part of the study area is located within the Marine Protected Area (MPA) "Costa dos Corais" (Fig. 1), considered the largest marine protected area in Brazil. This MPA was established to protect the reef ecosystems, maintain the integrity of the mangroves and preserve the manatee population (FERREIRA; CAVA, 2001; LIMA 2008).

The present study was designed as a pilot plan for a subsequent study from the coast of the state of Piauí to the state of Alagoas, initially focusing on *T. m. manatus*, with the subsequent inclusion of dolphins and sea turtles.

MATERIAL AND METHODS

The main analyzed factors for the detection success of animals were as follows: (1) strip transect methodology, using zigzag transects perpendicular to the coast; (2) the largest angle measure for sighting marine animals and a subsequent calculation of the threshold area scanned; (3) conditions of the flight altitude, speed and visualization of the sea surface (bubbles windows); (4) morphology and behavior of each taxon as influential factors in the detection and identification of species; and (5) environmental conditions of the Beaufort scale and transparency of water (coastal and estuarine) for the ideal aerial survey.

The present study was carried out in January 2010, a month of dry season, with a sampling effort of two hours of flight. The total area covered was 264 km^2, with more than 312 km of distance travelled in a zigzag pattern.

Identification of animals

The identification of the species was based on the diagnostic morphological and behavioral characteristics of each species. In cases of dubious sightings or imprecise counts of individuals, recounts were performed (LANGTIMM et al., 2011) through circular flights over the location of the sight and imprecise records were discarded. A group was defined as two or more animals (MORALES-VELA et al., 2000).

The main morphological characteristics used for the aerial identification of *T. m. manatus* were brownish-gray coloration, robust fusiform body shape, flat oar-shaped caudal fin (HUSAR, 1978) and slow movement (HARTMAN, 1979). A calf was a specimen measuring 1/3 of the adult animal by its side (HARTMAN op. cit.). The distinctive characteristics of dolphins were the fusiform shape, body coloration, morphology of the head and dorsal fin (JEFFERSON; LEATHERWOOD; WEBBER, 1993) and fast swimming with occasional leaps. The references for sea turtles were the greenish-brown (Cheloniidae) or black (Dermochelydae) shell, circular body shape (with fusiform and curvilinear carapace composed of plates) and oar-shaped pectoral fins used simultaneously for swimming (WYNEKEN, 2001).

Aerial survey

"Strip transect" was the sampling method, which is defined by monitoring a strip of predetermined width in which each observer records all sightings. This method allows acquiring data on distribution and estimating the representative density in the area samples, thereby allowing the estimation of abundance (JOLLY, 1969). To conduct this method is recommended initially a pilot sample, according to the particular characteristics of each environment and species, never assuming their application *a priori* (KATSANEVAKIS et al., 2012). The sampling area (strip) was demarcated from the tip of the wing of the aircraft to the strip directly below the wings (Fig. 5). Clinometers were used to determine the largest angle measure for sighting marine animals and a subsequent calculation of the threshold area scanned.

Sampling was performed in systematic zigzag transects (Fig. 1) with a 60º open angle perpendicular to the coast, accompanying the width of the continental shelf. This transects were designed to better cover the area and to maximize flying effort (ANDRIOLO et al., 2006; 2010). Estuaries were also sampled, as these sites are habitats for manatees (LIMA et al., 2011). Flights over these ecosystems occurred parallel to the margins of river, traveling approximately 1 km inland (Fig. 1 and 2).

The aircraft used was a single-engine high-wing Cessna 172 A, with bubble windows adapted in the posterior portion (ZERBINI et al., 2011), ideal for the observers to view the ocean surface. Flyovers standardized occurred at an altitude of 150 m and a velocity of 140 $km.h^{-1}$ (coast and estuaries), which is within the minimum range recorded in previous studies (MORALES-VELA et al., 2000; WRIGHT et al., 2002; COSTA, 2006) and corresponds to the minimum safety conditions of the crew during the study. The flyover crew was composed of a pilot, positioned on the left of the plane, two independent observers laterally covering each sampling strip (detection bias) in the rear portion of the plane and an annotator alongside the pilot. The observers were equipped with clinometers to measure the width of the strip sampled.

The annotator was equipped with a GPS to register the location of the sightings as well as the GPS of the plane for recording the flight path, two photographic cameras, nautical charts of the study area and standardized charts to record data on the flight conditions (altitude in feet and velocity in $km.h^{-1}$), environmental conditions (visibility, Beaufort Sea state and tide), human activities and sightings of marine megafauna (species, abundance, social structure, time and geographic position). The flight took place in the dry season (summer) during the rising tide, which allowed an increase in the spatial use of the animals, especially those with coastal habits and those that use estuaries. Data collection involved the identification of the specimens, sighting number, size of group, composition of group (presence of offspring), geographic position of sighting within the transect), habitat location/type, time and geographic position of takeoff and landing, time and geographic position of sampling.

The ideal environmental conditions expected for aerial survey were Beaufort Sea state 2 or less, absence of rain or mist (PREEN, 2004; LANYON, 2003), and water transparency "excellent" (animals clearly visible even underwater).

Data analysis

The survey design and locations of the sightings were transferred to the “GPS TrackMaker Pro” program (ANDRIOLO et al., 2010) for subsequent spatialization using the Arcmap program (version 9.3), identified nominally and by two coordinates (lat/long), to determine the spatial pattern of species occurrence.

RESULTS

A total of 16 sightings and 38 specimens of manatees, dolphins and sea turtles were recorded (Tab. 1), with higher occurrence number in the southern portion of the sampling area (Fig. 2).

Table 1 – Summary of sightings of Antillean manatees (*Trichechus manatus manatus*), dolphins and sea turtles during aerial survey on northern coast of Alagoas, northeastern Brazil.

	Manatee	Dolphin	Sea Turtle
Number of sighting	7	4	5
Total animals	10	15	13
Mean animals/sighting	1.4	3.75	2.6
Maximum animals/sighting	3	7	4

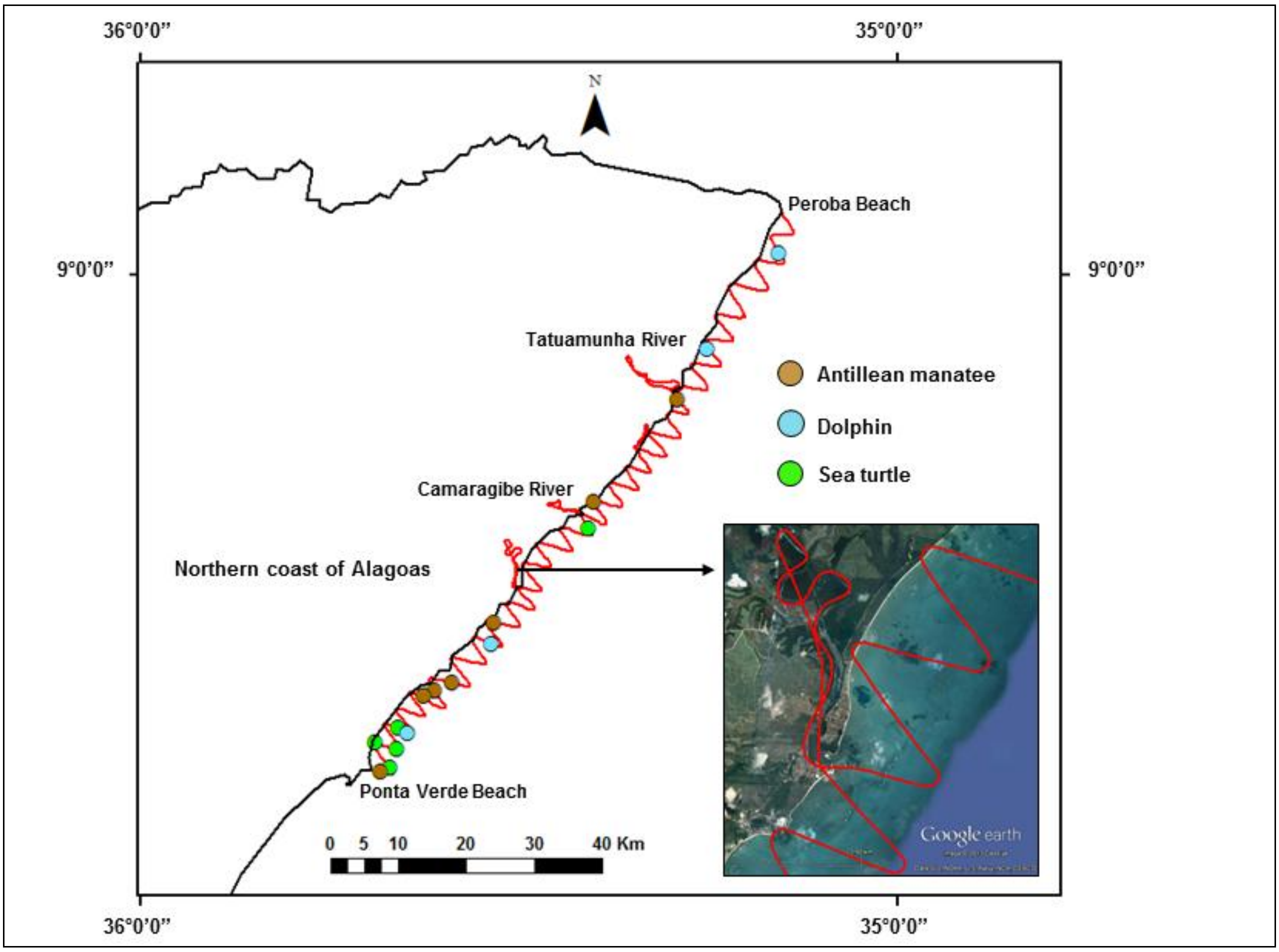

Figure 2 – Spatial distribution of Antillean manatees, dolphins and sea turtles during aerial survey with zigzag trajectory on northern coast of Alagoas, northeastern Brazil. Highlighting the transect sampling irregular-shaped in estuary of "Barra de Santo Antônio", and sightings of manatees near Tatuamunha and Camaragibe Rivers.

The environmental conditions were favorable to the detection of marine megafauna from the air, with optimal water transparency and the absence of clouds and strong winds, which that corresponds Beaufort Sea state 1 (Fig. 3).

Figure 3 – Aerial photo showing favorable conditions (optimal water transparency and calm sea - Beaufort Sea state 1) for sightings of marine mammals and sea turtles during flyover on northern coast of Alagoas.

The behavior of Antillean manatees, with little exposure at the water surface and its predominantly solitary habits (unlike the other taxa studied) did not hamper detection due to the high water transparency, which allowed the visualization of submerged individuals. However, the sightings of some manatees and sea turtles became more confusing when flying over areas located above reefs or in very turbid waters due to the cryptic brownish coloration of these animals. In five of these cases, we performed the recount effort, two of them being discarded.

The detection of manatees within four estuaries was not possible due to the high water turbidity, the difficulty of flying over narrow, twisting channels (e.g. estuary of Barra de

Santo Antônio; Fig. 2) and abundant vegetation on the banks of the rivers. To validate the efficiency of aerial detection under such conditions, a flyover was performed on the estuary of the Tatuamunha River (09°12’83.00”S/35°16’11.29”W), where three manatees are kept in natural captivity (1050 m²) and none were sighted from the airplane (Fig. 4). However, manatees were sighted at the mouths of the Tatuamunha and Camaragibe Rivers (09°18’30.37”S/35°23’42.19”W) (Fig. 2).

Figure 4 – Aerial photo of validation of viability of aerial survey of estuaries performed in natural captivity of three Antillean manatees in estuary of Tatuamunha River, Alagoas; Image reveals non-viability of visual detection due to high water turbidity.

All dolphins sighted belonged to the family Delphinidae, with only one group of seven individuals at Peroba Beach (08◦58'17''S/35◦09'18''W) identified as *S. guianensis*. The social structure of the delphinids was predominantly gregarious, with groups of three to seven animals. Sea turtles, represented by the family Chellonidae, were the second most abundant taxon (Table 1), with groups of up to four specimens detected.

The clinometer readings regarding the some sightings determined the following angles: 30°, 40°, 45°, 50°, 55° and 65°. Considering the constant altitude of the flight (150 m) and the largest angle (65°), the scanning areas per researcher totalized 321.7 m, with 634.4 m of area covered (Fig. 5).

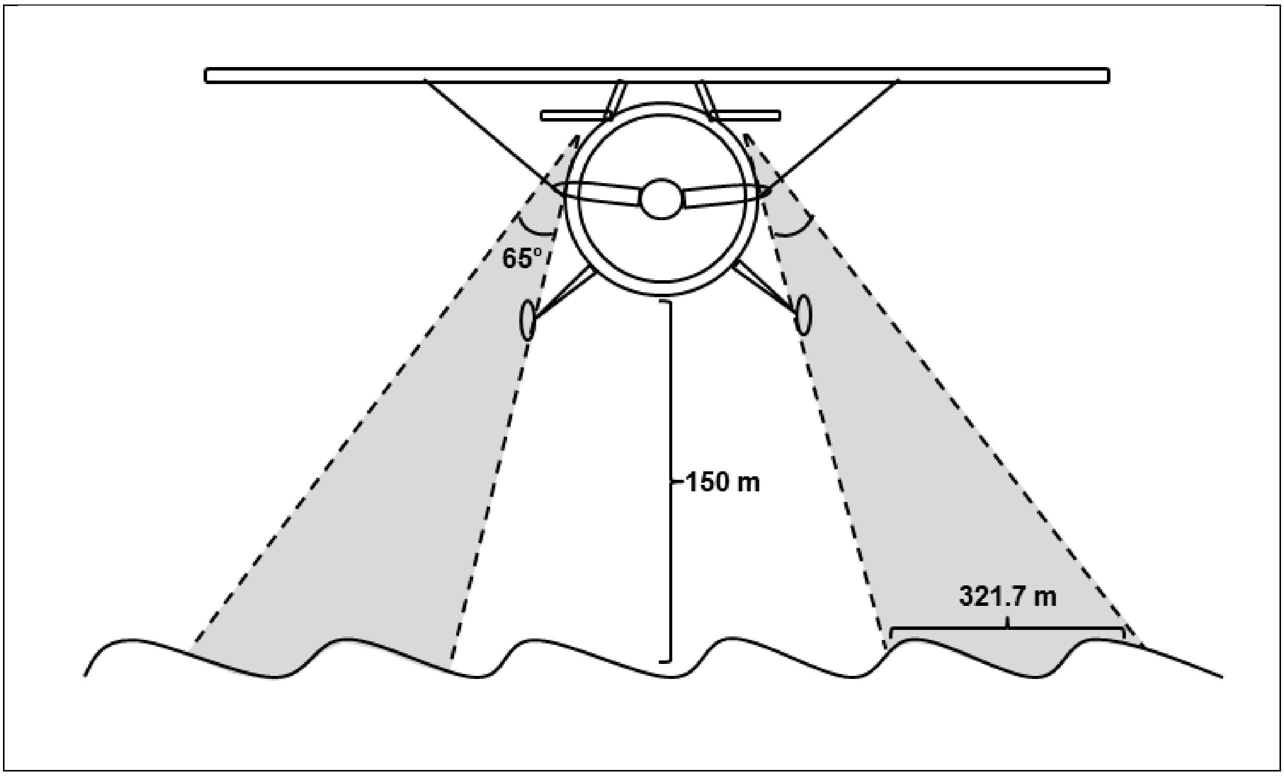

Figure 5 – Schematic of strip transect sampling method from aircraft indicating constant altitude, maximum sighting angle and length of base scanned (tread area) by each observer.

Three small methodological adjustments were necessary: (1) reduction of the open angle of the transects to 40° to increase the sampling area, (2) standardization of the transect lines to 1.5 nautical miles from the coast, corresponding to 2778 km (isobaths of 10 to 20 m), due to the considerable variation in the continental shelf in the area, and (3) replacement of the transects in estuaries with only a scan of the mouths of rivers, due the transparency bad this water in comparison with the sea coast water.

DISCUSSION

This pilot aerial study on the northern coast of the state of Alagoas for detection of marine megafauna attained satisfactory results regarding the flying and environmental conditions, except in water turbid estuaries where the transparency of the water was crucial for the successful detection of manatees. In contrast, COSTA (2006) reported methodological inefficacy regarding the identification and quantification of manatees to the east of the state of Ceará due to the turbidity of the sea water. In the present study, meteorological and environmental variables exerted a positive influence on the sighting of the animals and such favorable variables may be considered a priority to the feasibility of this type of survey in the Brazilian northeast coast.

The methodological inefficacy regarding the identification of species of dolphins (uncertainly of 65% sightings) and sea turtles, even in transparent waters, may be related to the agile movements of the animals, at the water surface and the speed of the aircraft, which did not allow ample time for the diagnosis of the specimens. The little experience of the observers in aerial record type may also have influenced in the diagnosis of the species. The uncertainty in the identification of delfinids is due to the fact that the species are differentiated by slight variations in coloration, morphology and behavioral patterns (JEFFERSON; LEATHERWOOD; WEBBER, 1993). The Guiana dolphin was identified due to the grayish coloration of the dorsum and the triangular shape of the dorsal fin (JEFFERSON et al., 1993).

Difficulties identifying sea turtles are also reported in previous studies, with the small size of the animals the most aggravating factor (EPPERLY; BRAUN; CHESTER, 1995; WYNEKEN, 2001; ROOS et al., 2005). A size threshold of approximately 75 cm in carapace length has been stipulated for optimal aerial detection (SHOOP; KENNEY, 1992). Moreover, fleeing behavior was recorded due to the noise of the aircraft, characterized by ripples caused on the surface of the water due to the rapid diving of the turtles. According to MCCLELLAN (1996), helicopters are more indicated for the identification of species in aerial surveys due to the lesser flight velocity. However, a comparative study found that the noise produced by such aircraft scare marine animals off more than a single-engine high-wing plane (RATHBUN, 1988), as the one used in the present study.

The essentially solitary habits and subtle exposure at the water surface (HARTMAN, 1979) may exert a negative influence on the detection of manatees in turbid waters. Antillean manatees are difficult to sight due to the fact that these animals spent a large amount of time under water (REYNOLDS; POWELL 2002) and are therefore more easily detected when in groups, although the precise count of individuals is more difficult (LANGTIMM et al., 2011). Aerial surveys were used in Florida to estimate the quantity of *Trichechus manatus latirostris* (HARLAN, 1824) in the region. This was done during periods of cold weather, as the manatees gather in areas of warm water, which this facilitated counting the animals (ACKERMAN, 1995; LEFEBVRE et al., 2001). In Brazil, the constant temperature of the coastal waters turns this type of procedure unnecessary (LIMA et al., 2011).

Besides biological traits, degrees of turbidity and tide conditions may lead to detection errors, especially with regard to *T. m. manatus* and sea turtles. At low tide, rocky outcrops and reefs may be confused for these animals due to the similar color (ROOS et al., 2005). Therefore, flyovers during the rising tide, when these formations are submerged, may minimize this type of error. Moreover, the access of manatees to estuaries is facilitated, thereby allowing a greater chance of sighting these animals. Aerial surveys within estuaries are inefficacious due to frequent turns and circuitous flight, path required to sample the irregular-shaped estuarine water bodies, and mainly to the turbidity of the water. This irregular-shaped turns difficult to consistently maintain a formal transect protocol (LANGTIMM et al., 2011). However, there is a considerable need to monitor species that use these ecosystems, such as *T. m. manatus* (LIMA et al., 2011). The use of side-scan sonar in nautical studies is favorable to the detection of manatees in this type of environment (GONZALEZ-SOCOLOSKE; OLIVERA-GÓMEZ; FORD, 2009).

The corrected methodological parameters (reduction of the transect angle, constant zigzag transects of 1.5 nautical miles, and transects restricted to the mouths of estuaries) will minimize the limiting effects regarding the detection of marine mammals and sea turtles related mainly to the morphological and behavioral characteristics of the species in contrast to the conditions of the environment. Aerial surveys can also provide information for the development of management, conservation and recovery programs directed at habitats of ecological importance to the survival of marine mammals and sea turtles.

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Capítulo 2* - Primeira estimativa de abundância de peixe-boi antilhano (*Trichechus manatus manatus*) no Brasil utilizando levantamento aéreo.

Chapter 2* - First abundance estimate of the Antillean manatee (*Trichechus manatus manatus*) in Brazil using aerial survey.

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First abundance estimate of the Antillean manatee (*Trichechus manatus manatus*) in Brazil using aerial survey.

Abundance of the Antillean manatee in Brazil

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ABSTRACT

Aerial surveys were conducted over 2590.2 km^2 of the northeastern Brazilian coast between January and April 2010. The objective was to estimate the abundance of Antillean manatees on a large-scale study and evaluate the efficacy of the method for conservation purposes. Flights were conducted at 150 m altitude and 140 km h^{-1} speed, using two independent observers. Strip transects were flown in a zigzag pattern. A total of 67 individuals (on and off effort) were recorded in 55 sightings. On effort, the highest manatee density was found in Piauí state. These results were used to estimate abundance, using published records of occurrence of the species in the area as correction factors for the perception bias of observers. We estimated the manatee population of northeastern Brazil in 1146 individuals within a Bayesian framework and a weakly informative prior distribution. The wide 95% posterior probability interval associated to this estimate, ranging from 610 to 1955 individuals, indicates high uncertainty. However, the corresponding posterior coefficient of variation of 29% is acceptable for ecological studies of this nature. Large-scale studies in the region are needed to understand the population trends over the years. However, the implementation of studies in small spatial scale, in hotspot areas, is necessary to reduce the coefficient of variation, and may allow improved techniques for monitoring the species, associated to the species-specific characteristics. The study evidenced the efficacy of aerial surveys as a tool applicable to the evaluation of the present conservation status of the species, considered the most endangered aquatic mammal in Brazil.

KEY WORDS: Antillean manatee · population · strip transect · aerial detection

INTRODUCTION

The West Indian manatee (*Trichechus manatus*) is one of the four extant species within the mammalian order Sirenia, being divided into two subspecies: *Trichechus manatus latirostris* (Harlan, 1824) (Florida manatee) and *Trichechus manatus manatus* Linnaeus, 1758 (Antillean manatee) (Hatt 1934). This species inhabits fresh, brackish and marine waters in the Wider Caribbean, from Florida to the northeastern coast of South America, with Antillean manatee's distribution on the east coast of Mexico, Central America, northern and northeastern South America (Lefebvre et al. 2001). The species is listed by the IUCN as "endangered", in continuing decline, with severely fragmented populations (Self-Sullivan & Mignucci-Giannoni 2008).

Publications on *T. m. manatus* population estimates are sparse, and always use *T. m. latirostris*' as a comparative parameter. Scientific papers and personal communication with specialists from half of the Antillean manatee range countries report the present population estimate as less than 2500 mature individuals. These data suggest a decline greater than 20% over the next two generations (estimated as 40 years for an unexploited population) (Self-Sullivan & Mignucci-Giannoni 2008).

The population decline of the Antillean manatee in Brazil initiated with the predatory hunts in the past, and has been intensified by the continuous degradation of coastal and estuarine environments (Domning 1982; Parente et al. 2004, Borges et al. 2007, Luna et al. 2008, Meirelles 2008, Lima et al. 2011). At present the *T. m. manatus* is considered the most endangered aquatic mammal in Brazil (ICMBio 2011). Studies in the 1990's estimated the number of Antillean manatees along the northern and northeastern coasts of Brazil in 485 animals, distributed in a discontinuous pattern between the states of Sergipe and Amapá (Luna et al. 2008). For the northeastern region alone two abundance estimates have been produced: 278 manatees (Lima 1997) and 242 speciments (Lima et al. 2011). The methodology used in those three studies took into account the traditional knowledge by fishermen, based on the maximum number of live manatees sighted by each interviewee. The total sum of these national estimates resulted higher than the estimate published internationally (Self-Sullivan & Mignucci-Giannoni 2008), of only 200 animals. Both results presented innovative information to the understanding of population trends of Antillean manatee in Brazil, albeit questionable in terms of methodological and statistical parameters adopted.

Obtaining a measure of the abundance of sirenians is essential for their conservation, and the method of aerial surveys is the most suitable for monitoring manatee and dugong numbers (Olivera-Gómez & Mellink 2002, 2005, Preen 2004, Edwards et al. 2007, Langtimm et al. 2011). In Brazil, however, only one aerial survey has been conducted, with the aim of evaluating the distribution of Antillean manatees at a small geographic scale in the northeastern state of Ceará (Costa 2006). Furthermore, test flights were conducted by "Fundação Mamíferos Aquáticos" in the 1990's, but with unpublished results (Borges, pers. comm.).

Aerial methods for abundance estimates are susceptible to space variation (availability bias - probability of an animal being available for detection, which may be highly variable in extensive and heterogeneous environments, beyond diving behavior of each species) and to imperfect detectability (perception bias - probability of an animal being detected, assuming it is available for observation) (Pollock et al. 2006, Katsanevakis et al. 2012).

The strip transect method is widely used in aerial studies of manatees and dugongs (Marsh & Sinclair 1989, Lefebvre et al. 2001, Olivera-Gómez & Mellink 2002, Easton et al. 2003, Lanyon 2003, Marsh et al. 2004, Hines et al. 2005, Langtimm et al. 2011). The method is recognized as being easy to apply in the field, when compared to distance sampling, which may record imprecise perpendicular angular distances, as those are simultaneous to detection and counting of animals (Marsh 1995, Miller et al. 1998, Pollock et al. 2006). In addition, smaller species with subtle exposure behavior on the water surface, such as manatees when compared to large whales, make distance sampling even less viable (Lefebvre et al. 1995).

The aim of this study was to apply the strip transect aerial methodology to estimate abundance of Antillean manatees in a large-scale study along the northeastern coast of Brazil, to evaluate the efficacy of aerial survey as a tool in the re-evaluation of the conservation status of the critically endangered populations of *T. m. manatus*.

MATERIALS AND METHODS

Study area

The study ranged over six Brazilian states, covering roughly 44% of the 3400 km of northeastern coast. The limits of the study area were the Canárias island on the Parnaíba river mouth (Piauí state) to the north, and the São Francisco river mouth (Alagoas state) to the south. A stretch of only 22 km of coastline was not surveyed, due to traffic restrictions around the Recife international airport, capital of Pernambuco state (Fig. 1).

The continental shelf of northeastern Brazil ranges in width from 85 km in the north to 40 km in the southern portion. Climate is tropical, with high temperatures (>24°C) (Muehe & Garcez 2005). Diversity in the coastal and estuarine environments includes beaches, dunes, coral reefs, mangrove forests and seagrass beds (Kempf et al. 1970, Oliveira-Filho et al. 1983, Castro & Pires 2001), all of which are vulnerable to anthropogenic actions, especially urban development, tourism and fisheries (Cunha 2005).

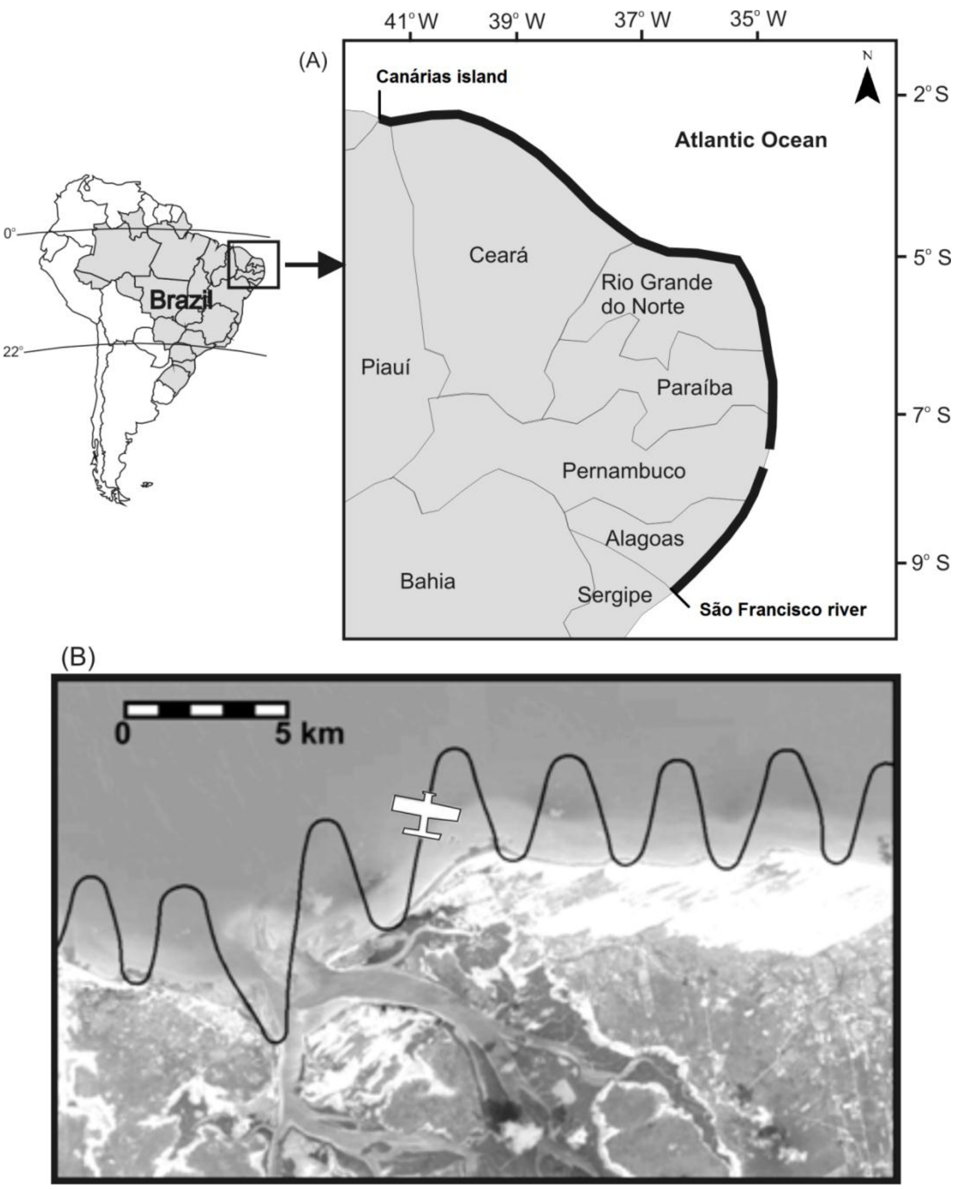

Fig. 1. Study area between the states of Piauí and Alagoas, northeastern Brazil (A). Aerial transects in a zigzag pattern in the estuarine mouth Delta do Rio Parnaíba (B).

Aerial surveys

Aerial surveys were conducted using a single-engine high-wing Cessna 172 A aircraft, to facilitate viewing the sea surface, and adapted with bubble windows at the rear (Zerbini et al. 2011), allowing a wider viewing angle. The team was composed by two independent observers (Langtimm et al. 2011), positioned by each of the side windows, wearing polarized sunglasses to minimize perception bias; and a registrar, in the front beside the pilot (Morales-Vela et al. 2000). Two observers were already experienced in manatee observation; however all observers were trained during a test flight (Alves et al. 2013a) to help reduce detection bias of animals. The registrar used a global positioning system (GPS) to indicate all sighting points (latitude and longitude positions), in addition to the GPS of the plane, which recorded the aerial routes. The registrar also used nautical charts (1:300.000), two photographic cameras, and a portable recorder to compile the field records.

Aerial sampling was performed using the strip transect method, a type of line transect sampling which consists of a random sampling of a known fraction of the total study area and assuming that all animals within the searched strip are detected and counted (Jolly 1969). Transects were made in a zigzag pattern, perpendicular to the coast (Morales-Vela et al. 2000, Hines et al. 2005) (Fig. 1), with an angle of turn of 40°, as to better cover the area and to maximize the flying effort. The surveyed areas extended from estuarine inlets (Fig. 1) (Langtimm et al. 2011), to the isobaths of 10 to 20 m. The flight was standardized with 150 m altitude and 140 km h^{-1} speed, minimum values for flight safety, and within the range found in other aerial surveys (Morales-Vela et al. 2000, Easton et al 2003, Olivera-Gómez & Mellink 2005, Costa 2006, Langtimm et al. 2011). The widest sighting angle (approximately 65^{o}) was determined with a clinometer during a test flight, and resulted in an accurate area of 321.7 m per observer (i.e. a total strip width 643.4 m) (Alves et al. 2013a). A variable effort recount method (Lefebvre & Kochman, 1991) was applied in cases of doubtful sightings or imprecise specimen counts, consisting of a circular flight around the sighting point out to confirm identification (Lefebvre et al. 1995, Morales-Vela et al. 2000, Langtimm et al. 2011); unconfirmed sightings were discarded. Calves corresponded to specimens measuring up to 1/3 of the adult size (Hartman 1979). Two or more animals were defined as a group (Morales-Vela et al. 2000).

Aerial surveys were conducted in dry season, period of mild winds and greater water transparency, morning period to avoid glare and to take advantage of generally light winds, and high tide when the animals have a better access to shallow foraging areas (macroalgal banks and seagrass beds) and estuaries (Paludo & Langguth 2002, Lanyon 2003, Hines et al. 2005, Olivera-Gómez & Mellink 2005, Langtimm et al. 2011), and to reduce the potentially confusing effect of reefs and algae sandstone substrates that appear at low tide (Costa 2006). Flights were conducted when weather conditions were excellent, with Beaufort Sea state 2 or less, and absence of rain or mist (Lanyon 2003, Preen 2004).

According to water transparency conditions, manatee sighting classes were defined as: 1 - excellent: manatees clearly visible, even when submerged; 2 - good: manatees visible when close to the water surface; 3 - medium: manatees visible only if exposed a small part of the body on water surface (eg.: rostrum or caudal fin); and 4 - poor: manatees visible only if almost completely exposed on water surface. The classification “terrible” corresponds to high water turbidity found inside estuaries, with impossibility of recording under such conditions (Alves et al. 2013a). Therefore to minimize availability bias, estuaries were excluded from sampling, despite representing an environment widely used by the species (Lima et al. 2011).

Aerial surveys were carried out between January and April 2010. The total coverage area was 2590.2 km^2, calculated by strip transect width (643.4 m) and total linear distance traveled in zigzag. Each flight lasted for less than three hours per day. The effective effort exceeded 27 flight hours in 11 days.

Abundance estimate - structure data and statistical analysis

Antillean manatee distribution data and aerial route maps were produced using ArcMap software (version 10.0), for later production of digital maps and statistical analysis of manatees' abundance estimate.

For estimation of the manatees number a Bayesian approach was used. Description of the statistical model used the following notation: *i* - region identifier index (i = 1, 2... 899), defined by sampling units of *zig* (coast - sea transect) and *zag* (sea - coast transect) coverage in m^2; A_i - total area of region *i*; a_i - area tracked by the observers in region *i* ($a_i < A_i$); y_i – number of manatees sighted on effort in area a_i; z_i – subjectively imputed occurence probability for region *i*, based on *a priori* records of sightings or strandings (Albuquerque & Marcovaldi 1982, Parente et al. 2004, Costa 2006, Alves 2007, Luna et al. 2008, Meirelles 2008, Lima et al. 2011), or observed individuals off effort (Fig. 2, Table 1).

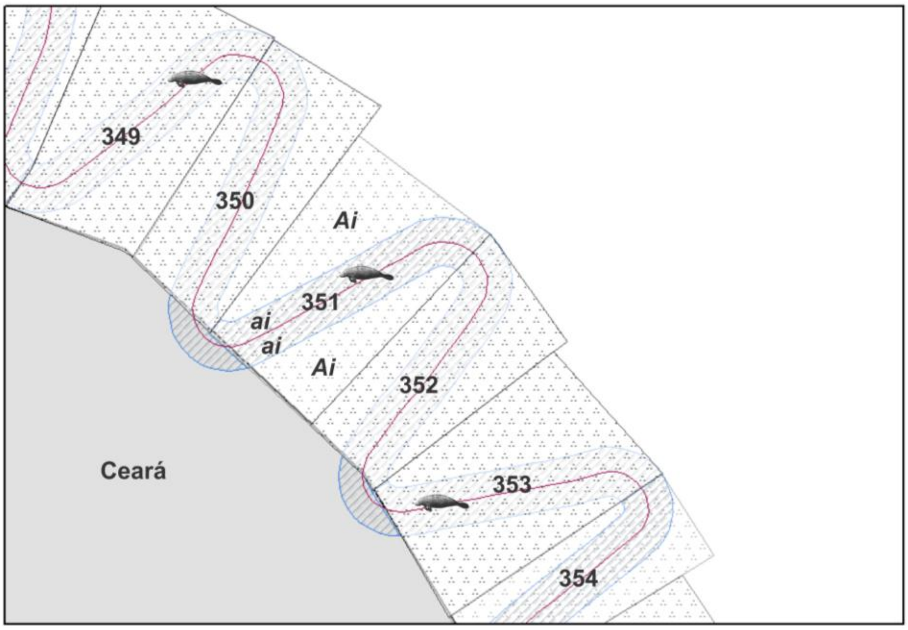

Fig. 2. Figure representing parameters of statistical model used to analyze sightings of manatees (manatee drawing): *i* – identifier index of sampling units (numbers); A_i – total area (rectangular spotted polygon), and a_i – area tracked by observers (wavy band).

Table 1. Criteria to determine occurrence probabilities (z values) relative to occurrence of Antillean manatee in sampling units in northeastern Brazil.

z_i Value	Definition of values according to sampling unit
1	"Aerial detection" of manatee on or off sampling effort.
0.8	"High probability" of manatee occurrence, according to recent historical records and/or appropriate environmental features.
0.5	"Dubious probability" of manatee occurrence, according to past historical records and/or absence of updated information.
0.2	"Low probability" of manatee occurrence, with absence of historical records and/or inappropriate environmental features.

Latent variables and unknown model parameters were as follows: w_i – latent variable indicative of occurrence (w_i = 1) or absence (w_i = 0) of manatee in region i; p – probability to detect a manatee in area a_i at the time of sampling; μ – expected number of manatee per unit of area (i.e. density); N_i – total number of manatee in region i.

$\mathbf{N} = \sum_{\mathbf{i}} \mathbf{N_i}$, manatee abundance in the region covered by the study (i.e. in area $\boldsymbol{A} = \sum_{\boldsymbol{i}} \boldsymbol{A_i}$).

The hierarchical structure of the model starts by the Bernoulli distribution for the occurrence of manatee in a given region i, with imputed probability $\boldsymbol{z_i}$.

$$w_i \sim Bern(z_i)$$

The number of manatees in region i is modeled by a Poisson distribution with mean conditional on manatee density (μ), area (A_i) and occurrence (w_i).

$$\mathrm{N_i} \sim \mathrm{Poi}(\mu \mathrm{A_i} \mathrm{w_i})$$

Given the latent number of manatees (N_i), the model to describe the number of detected individuals is Binomial with detection probability p times the availability probability $a_i A_i^{-1}$.

$$y_i \sim Bin(N_i, p a_i A_i^{-1})$$

Parameters to be estimated from this model are p, μ and total abundance N. The Bayesian estimation procedure (McCarthy 2007, Kinas & Andrade 2010) was chosen, for two reasons: (a) convenience of using this procedure in the case of a hierarchical model with a large number of latent variables and, consequently, a similarity function very complex to obtain estimates of maximum similarity and their approximate standard errors; (b) the possibility to incorporate informative *prioris* that reflect the already available ecological knowledge and may compensate for the insufficient amount of data.

Extra-data information was incorporated in two ways: by means of the z_i variable that describes the probability of occurrence of manatees in the regions, and by means of *prioris* distributions partially informative for p (probability of effective detection of manatee) and μ (mean density of manatee per km^2). These information proved to be particularly useful in the study due to the reduced number of sightings, which rendered the flight data, in isolation, little informative to estimate p and μ simultaneously. The used *prioris* were:

$$\ln\left(\frac{p}{1-p}\right) \sim N(-2.19, 1.0)$$

$$\ln(\mu) \sim \mathrm{N}(-1.20, 0.32)$$

with *N (a, b)* indicating a Gaussian distribution with mean *a* and standard deviation *b*.

The posterior probability distributions were obtained by stochastic simulation using the Monte Carlo method via Markov Chains (MCMC), with three chains in parallel and retaining 3 x 5000 = 15000 final values. The program OpenBUGS (via R libraries BRugs and R2WinBUGS) conducted the simulations (Thomas et al. 2006, R Development Core Team 2008).

RESULTS

Sightings of Antillean manatee

The aerial methodology proved efficient for studies of population estimates of Antillean manatee under conditions found in northeastern Brazil. Efforts to recount manatees were necessary in four occasions only, with success in identification in three of those. Thirty-six sightings and 41 individuals were recorded on effort, with only one calf in Barreta beach (6° 6' S, 35° 4' W), Rio Grande do Norte state; 19 sightings and 26 specimens were recorded off record (i.e. off the transect area), also with only one calf in Coqueirinho beach (7° 26' S, 34° 45' W), Paraíba state (Fig. 3).

Manatees occurred between the Miaí de Baixo beach (10° 14' S, 36° 12' W) in Alagoas state, and the estuarine mouth Delta do Rio Parnaíba in Piauí state (2° 44' S, 41° 47 W). Despite the lack of sightings along large areas in the coasts of Pernambuco, Rio Grande do Norte and Ceará states, aerial survey results expanded the species' known area of distribution, which now includes the Iguape beach, Ceará (3° 54' S, 38° 17' W), and Miaí de Baixo beach, in the southernmost portion of Alagoas (Fig. 3).

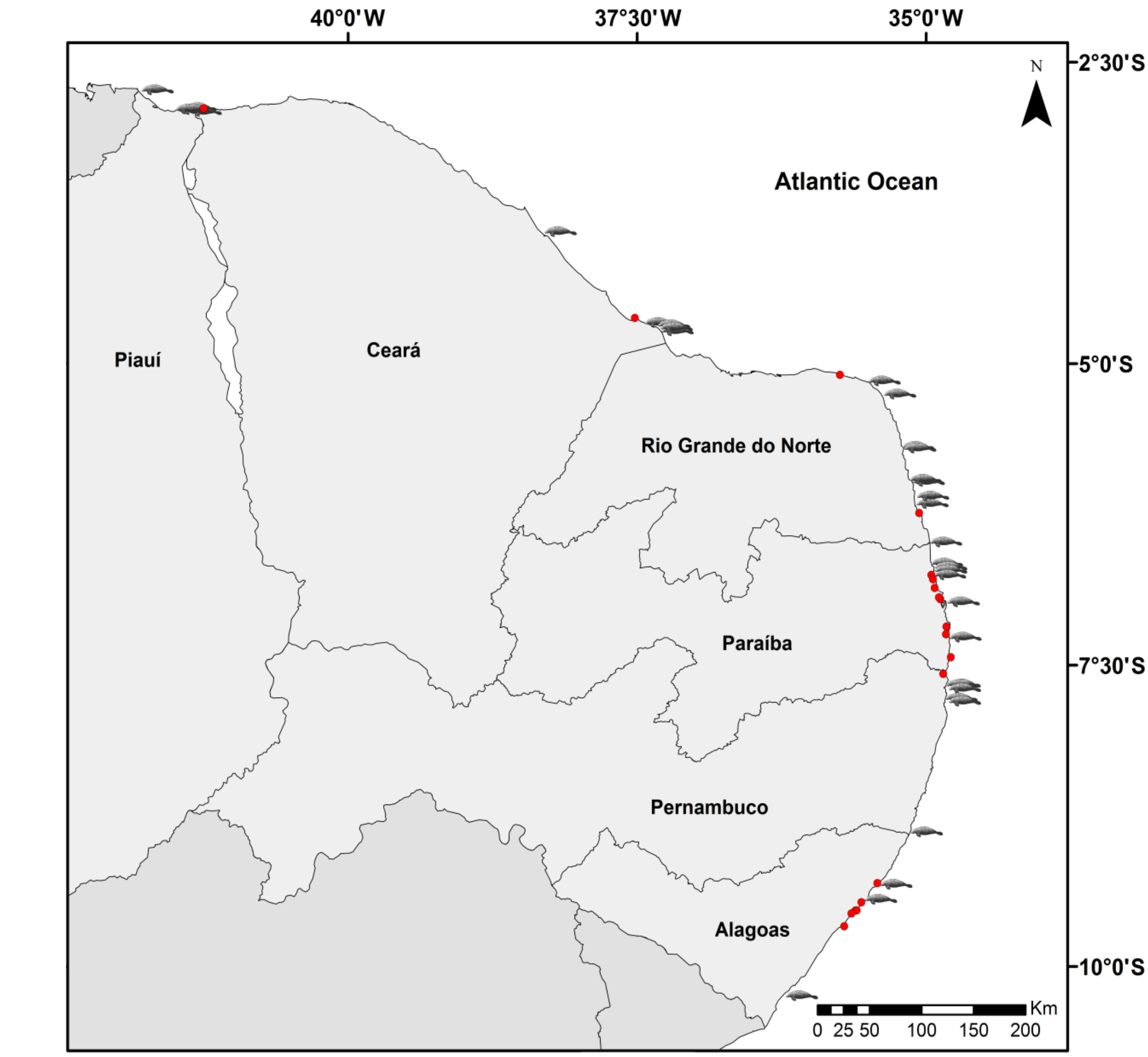

Fig. 3. Manatee sightings between Piauí and Alagoas states, during on effort (manatee drawings) and off effort (red circle) periods.

On effort manatee relative density was 0.24/km of coast, and 0.05/km^2, considering the distance of 10 and 20 m isobaths of approximately 5 km offshore. On effort, the Antillean manatee density was at its highest in Piauí state, with five animals found in the estuarine complex of the rivers Timonha/Ubatuba and Cardoso/Camurupim (between 2° 54' S, 41° 22' W and 2° 53' S, 41° 29' W). The highest sighting numbers and total manatee abundance on and off effort were obtained for Rio Grande do Norte and Paraíba states, respectively (Table 2).

Table 2. Occurrence of manatees on and off effort, and the demographic density by stretch of coast (DC = org/km) and area (DA* = org/km^2) for each state.

States	Area (shoreline)	Manatees on effort		Manatees off effort		Demographic density	
		Sightings	Abundance	Sightings	Abundance	Coast (org/km)	Area* (org/km^2)
Piauí	57.44	5	6	0	0	**0.1**	**0.0209**
Ceará	531.18	5	5	2	2	0.01	0.0019
Rio Grande do Norte	374.01	**9**	**12**	2	2	0.03	0.0064
Paraíba	123	8	8	**8**	**11**	0.06	0.013
Pernambuco	158.15	6	6	1	1	0.03	0.0076
Alagoas	226.88	3	4	6	10	0.01	0.0035
Total	1470.66	36	41	19	26	0.24	0.0533

*Demographic density by area calculated based on distance of 5 km from coast

The error source of availability bias was considerably limiting to animal detection, due to the environmental variation along the extensive coastal area, associated to *T. m. manatus* morphological and behavioral characteristics, such as predominantly solitary habit (64.18% on and off effort), little exposure on the water surface, and cryptic coloration in turbid estuarine waters and sandstone substrate.

Wind conditions during on effort manatee sightings were in accordance with proposed parameters, in levels between 0 and 2, with 52.78% (n = 19) of sightings in level 1. The sampled area was qualitatively characterized as "good" and "medium" transparency, with type "poor" being described for turbid waters close to estuarine mouths and “excellent” predominant between coasts with coral reef formation of the southern Pernambuco and north of Alagoas states. Most of the 67 sighted manatees were detected under "good" conditions (40.3%; n = 27), followed by "medium" (26.86%; n = 18), "excellent" (20.9%; n = 14) and "poor" (11.94%; n = 8) (Fig. 4).

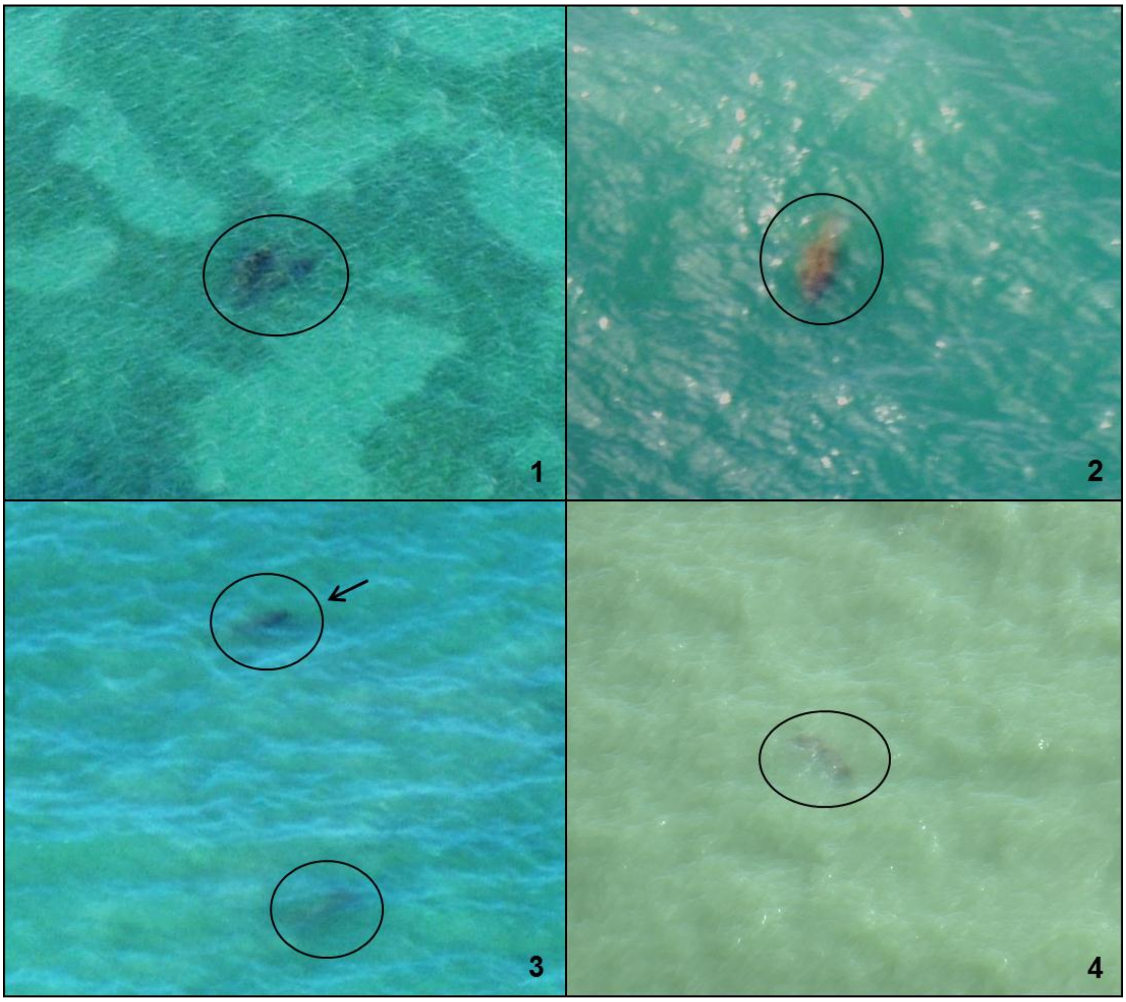

Fig. 4. Manatee sightings (black circles) under different scales of visibility, during aerial surveys in northeastern Brazil: (1) Excellent – two manatees submerged in a seagrass bed, Quitéria's beach (4° 40' S, 37° 18' W) in Ceará state (2); Good – one manatee close to the water surface, Pirangi do Sul beach (5° 58' S, 35° 6' W) in Rio Grande do Norte state; (3) Medium – two manatees, with one identified only because of the rostrum emergence in the water (black arrow), Oiteiro beach (6° 51' S, 34° 53' W) in Paraíba state; and (4) Poor – one manatee visible after almost total body exposure on water surface, estuarine mouth in Guajú River (6° 29' S, 34° 57' W) in Rio Grande do Norte state.

Abundance estimate

The logit distribution for p assumes *a priori* uncertainty for which the 5%, 50% and 95% *quantiles* correspond to p values of 0.020, 0.099 e 0.362, respectively. In addition, the probability that $p > 0.4$ equals 0.0346, i.e. we consider this possibility small, albeit possible. The *a priori* distribution of p follows the figure below (Fig. 5).

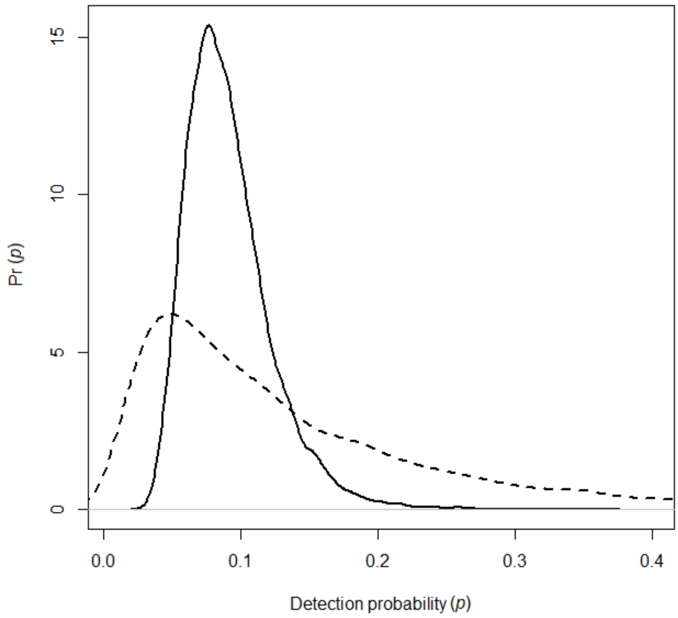

Fig. 5. *A priori* (dotted line) and posterior (continuous line) distribution for the probability of p detection.

In a similar way, the natural logarithm for μ assumes *a priori* uncertainties for which the 5%, 50% and 95% *quantiles* correspond to values of μ 0.018, 0.301 and 0.501, respectively. Furthermore, the probability of $\mu > 0.6$ equals 0.0137. The *a priori* distribution of μ is represented in Figure 6.

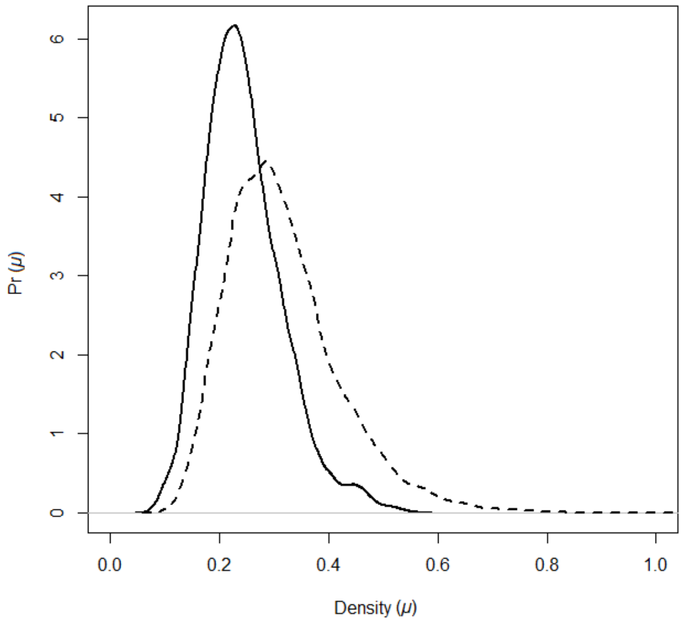

Fig. 6. *A priori* (dotted line) and posterior (continuous line) distribution for the density of individuals μ.

This *a priori* distribution, relatively informative for μ, corresponds to the statement that the total manatee abundance in the study region is lower than 3400 individuals with 95% probability. Nevertheless, it leaves open (5%) the possibility of values above 3400 if the adjustment of the model to the data suggested so.

Manatee sightings occurred in only 52 sampling units of the 899 defined regions. In 18 of them, sightings occurred off effort (*a*) and therefore have values y = zero (but with value z = 1) and summed 26 individuals, in 19 sightings. In the 34 regions where sightings occurred "on effort", these summed 41 individuals, in 36 sighting events. The remainder regions only had the value $y = 0$ (no sightings) (Table 3), qualified by the occurrence probability (z) (Table 1).

Table 3. Distribution of 899 regions according to probability of manatee occurrence (*z*) and number of sighted individuals "on effort" (*Y*).

		Y	
z	0	1	2
0.2	146	0	0
0.5	85	0	0
0.8	617	0	0
1.0	18	27	7

The posterior distribution for abundance *N* is represented by the histogram below (Fig. 7).

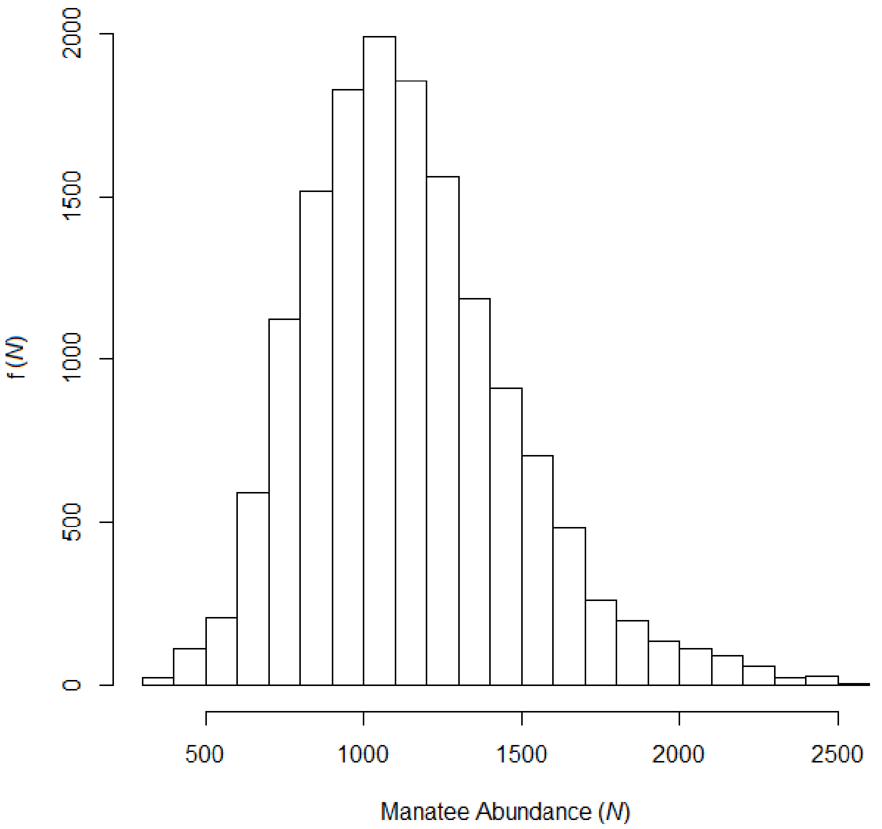

Fig. 7. Posterior distribution of manatee abundance (*N*) in the study area.

In comparison with the *a priori* probability attributed to abundance, the *a posteriori* probability that *N* be larger than 3400 is practically null. In other words, the 95% *quantile* that inicially was 3400 is reduced *a posteriori*, to approximately half, or 1752. The statistical summary of the marginal posterior distributions of the three parameters of interest is shown below (Table 4).

Table 4. Statistical summaries of posterior distributions of main parameters (2.5% and 97.5% *quantile* delimit the 95% creditability intervals; "Mean" corresponds to the specific estimate in the study).

Parameter	2.5%	Median	97.5%	Mean	SD
p	0.050	0.092	0.177	0.098	0.033
μ	0.165	0.298	0.528	0.309	0.090
N	610	1106	1955	1146	334.2

The estimated number of manatees inhabiting the study area is 1146 individuals. Nevertheless, and despite the use of *a prioris* distribution, which are partially informative, the results presented a considerable level of uncertainty, represented by the posterior coefficient of variation of 29% and the 95% probability interval ranging from 610 to 1955 individuals.

DISCUSSION

Antillean manatee distribution

The data generated on Antillean manatee distribution in northeastern Brazil were similar to historical records of the species' occurrence (Albuquerque & Marcovaldi 1982, Parente et al. 2004, Costa 2006, Alves 2007, Luna et al. 2008, Meirelles 2008, Lima et al. 2011). However, the expansion of the area of use of the species could be related, the implementation of conservation measures in the 1980s (Luna et al. op. cit.) and the current translocation of captive specimens in the northern portion of the state of Alagoas (Lima 2008).

High densities of dugongs, up to 7.25/km^2 in Australia, have been recorded in specific foraging areas, with several individuals sharing a limited space (Lanyon 2003). The apparent discontinuity of sightings and the low relative density of manatees, of only 0.05/km^2, may indicate the existence of reduced and fragmented populations along the Brazilian northeastern coast (Albuquerque & Marcovaldi 1982, Lima et al. 2011, Alves et al. 2013b), with an index lower than those found in other studies with sirenians, which vary between 0.075 and 0.240/km^2 (Preen et al. 1997, Morales-Vela & Olivera-Gómez 1994, Olivera-Gómez & Mellink 2002, Preen 2004). The sightings discontinuity in the states of Pernambuco, Rio Grande do Norte and Ceará may be related to the natural lack of natural resources essential to the species such as abundant aquatic vegetation but, mainly, to the degradation of coastal and estuarine habitats due to human development (Lima et al. 2011, Alves et al. 2013b), causing the animals to search for less impacted areas.

The greatest demographic density of this species found on the Piauí coast can be directly linked to the presence of a collection of islands interspersed with estuaries and preserved bays, within the Environmental Protection Area of the Parnaíba Delta (IBAMA 1998). The estuarine complex of the rivers Timonha/Ubatuba and Cardoso/Camurupim, where were sighted five animals, as well as the adjacent coastal zone is considered to be an important niche for the species, with seagrass beds, freshwater sources and excellent parenting locations (Choi et al. 2009). Recorded sighting of only one animal, at approximately 40 km distance of the other five sightings, was localized in Canárias Island estuarine mouth. This discontinuity of sightings could be directly linked to the presence of the Luís Correia seaport (2° 51' S, 41° 38' W) in the estuary of the Parnaíba River, with intense vessel traffic, rendering this area inaccessible for animals. These human activities, associated to manatees' costal habit, potentiate risks of collision and accidental captures, (Borges et al. 2007, Meirelles 2008, Alves et al. 2013b), probably forcing animals to find new habitats (Reynolds & Szelistowski 1995, Alves 2007).

The susceptibility to errors in abundance estimates, common in aerial surveys, may have influenced the few sighting records of this study. The great extension of coastal area surveyed, with a wide variety of environments and sea states (e.g. coastal morphology and water turbidity), associated to characteristics of the species (shy behavior during exposure on water surface, cryptic morphology and solitary habit) may have affected the detection probability by the observers, generating imperfect or heterogeneous detection of individuals, defined by the variable proportion of animals present in a given area, and yet not sighted (Katsanevakis et al. 2012).

The excellent transparency level of waters on the northern coast of Alagoas was similar to that found by, Alves et al (2013a), highlighting the favorable conditions for aerial detection of manatees in this area. However, the low manatee abundance under "excellent" and "poor" conditions may suggest an underestimation in more turbid waters: these situations do not provide the ideal conditions for detection of individuals, and yet are associated to proximity with estuaries, habitats with high water turbidity it impossible this detection (Alves et al. 2013a). The estuaries are highly favorable environments to the occurrence of the species, for both feeding, reproduction and resting (Olivera-Gómez & Mellink 2005, Lima et al. 2011), although many estuaries find themselves silted (Alves et al. 2013b), making them inaccessible and causing strandings, especially of calves (Parente et al. 2004, Meirelles 2008).

The water transparency is a key factor in abundance estimates (Marsh & Sinclair 1989, Ackerman 1995), and may negatively influence the availability bias when it is very variable (Hines et al. 2005, Pollock et al. 2006). During periods of cold weather in Florida, aerial surveys uncovered large groups of manatees in areas of warm and transparent water, which facilitated the counting (Edwards et al. 2007). The detection of aquatic fauna (especially those cryptic, shy species with essentially solitary habit) is particularly hampered in turbid waters of estuaries, lakes and rivers (Reynolds & Powell 2002). In eastern Ceará, where water transparency categories ranged from "excellent" to "regular", nautical monitoring of manatees was more effective than aerial surveys, (Costa 2006). An alternative for sampling in turbid waters would be the use of nautical surveys using side-scan sonar, allegedly efficient in acoustic detection of manatees in limited and turbid waters of Mexico and Florida (Gonzalez-Socoloske et al. 2009, Gonzalez-Sololoske & Olivera-Gómez 2012).

Antillean manatee abundance estimate

The abundance estimate of 1146 manatees along approximately 1500 km of coastline suggests a reduced population index for an important large area of occurrence of *T. m. manatus* in Brazil. Although this number is higher than the estimated abundance of manatees between the states of Piauí and Sergipe, with only 242 (Lima et al. 2011) or 278 animals (Lima 1997), one cannot say that there was an increase in manatee population, in the region from the 1990s until the present time, due to different methodologies employed.

This result does not correspond to a precise estimate of the number of animals, but to an estimate of a minimum abundance, which highlights the conservationist character of the information. These data will represent a baseline for future studies of evaluation of distribution and population trends of the species (Ackerman 1995, Lefebvre et al. 1995, Miller et al. 1998, Olivera-Gómez & Mellink 2002, Katsanevakis et al. 2012), suggesting the need of directing new efforts in the same area sampled and/or smaller scale for improvement of the methodology.

The only aerial study conducted in the Brazilian northeast so far, in a restricted area of only 50 km of coast in Ceará state, generated errors associated to the water turbidity and difficulty of identification and counting of manatees (Costa 2006). These errors were possibly increased, respectively, by the inappropriate sampling period (winter) and the flight design (e.g. reduced sampling effort due to transect parallel to the coast, and absence of bubble windows). Among the recommendations for improvement, Costa (op. cit.) proposed the need of application of aerial methodologies in other areas, with the aim of future systematic monitoring of the species, objective attained in the present study.

Based on the ideal figure for the coefficient of variation less than 20% (Hines et al 2005, Marsh et al. 2005), the value of 29% suggest a considerable level of uncertainty in the abundance estimate of manatees in this study. Nevertheless, values above the ideal are commonly recorded in aerial surveys for sirenian estimates, related mainly to monitoring habitats with turbid waters, such as Chetumal Bay, in Mexico, with percentages 21-70.3% (Morales-Vela et al. 2000) and 34.4-65.5% (Olivera-Gómez & Mellink 2002), in the Andaman coast, in Thailand, with 33.4% (Hines et al. 2005), and in Porto Rico, with 55.8% (Powell et al. 1981). Large-scale studies in the region are needed to understand the population trends over the years. However refinements of the aerial methodology in small spatial scales are necessary to reduce the coefficient of variation, in order to avoid sources of error of perception and availability biases (Marsh & Sinclair 1989, Marsh 1995). Other methodologies must also be adapted for population manatees estimates, such as nautical surveys using side-scan sonar (Gonzalez-Socoloske et al. 2009, Gonzalez-Sololoske & Olivera-Gómez 2012). This method is presently being used in Brazil in Amazonian (*Trichechus inunguis*) (Marmontel pers. comm.) and Antillean (Choi pers. comm.) manatee research.

The implementation of distribution and abundance studies of Antillean manatee at appropriate scales, in northeastern Brazil, is hereby recommended to allow the implantation of efficient management strategies for the protection of the species, notwithstanding logistic difficulties and high financial cost. The identification, at a local scale, of manatee and dugong abundance hotspots areas is favorably used in population surveys and analyses of conservation status, mainly through aerial surveys (Rajamani & Marsh 2010, Lanyon 2003, Castelblanco-Martínez 2012). Based on the results of the present study, we suggest as some of the main hotspots for future aerial surveys along the Brazilian northeastern region: the coast of Piauí, the state which presents the largest density of individuals; the easternmost portion of Ceará, an important area in terms of manatee calf strandings (Parente et al. 2004, Meirelles 2008); areas along the southwestern coast of Rio Grande do Norte state; the whole state of Paraíba, particularly the Barra de Mamanguape Area of Environmental Protection, with a past record of up to 15 individuals (Albuquerque & Marcovaldi 1982), and traditional area of release area of captive animals (Lima 2008); northernmost portion of Pernambuco, which contains extensive seagrass beds (Magalhães & Cazuza 2005); and northern Alagoas, present area of reintroduction of captive animals (Lima op. cit).

CONCLUSION AND IMPLICATIONS FOR CONSERVATION

The results of this survey highlight its importance for the conservation of this endangered species, being an essential tool for future studies on large-scale in the country, to the understanding of the population trends over the years. The implementation of studies in small spatial scale may allow improved techniques for monitoring the species, with better knowledge of their occurrence.

The statistical arrangement applied, using bibliographic data and sightings from aerial surveys, was applied due to the difficulty of sampling a dispersed population over a large area, rendering the analysis of abundance estimate susceptible to errors. In this case, future efforts are needed, where individuals may be detected and counted. The application of statistical and methodological models specific at the local level also will allow, in the future, the compilation of data for the whole study region, according to existing environmental particularities, refining the abundance estimates. This will generate consistent population trends, with the identification of a probable population decline or increase, according to conservation actions developed for the protection of the species.

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Capítulo 3*† - Pesquisa aérea de peixes-bois, golfinhos e tartarugas marinhas no nordeste do Brasil: correlação com as feições costeiras e as atividades humanas.

Chapter 3*† - Aerial survey of manatees, dolphins and sea turtles off northeastern Brazil: correlations with coastal features and human activities.

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Aerial survey of manatees, dolphins and sea turtles off northeastern Brazil: Correlations with coastal features and human activities.

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Abstract

The objective of the present study was to analyze the distribution of manatees, dolphins and sea turtles off northeastern Brazil through aerial surveys, relating them to specific habitats and human activities, with emphasis on marine protected areas (MPAs). Surveys were conducted between January and April 2010 at 150 m altitude and 140 km h^{-1}, using two independent observers. Strip transects were flown in a zigzag pattern. Transects covered 4026 km in more than 27 flight hours. A total of 36 sightings of manatees (*Trichechus manatus manatus*, 41 individuals), 28 of dolphins (Delphinidae, 78 individuals, including 10 *Sotalia guianensis*) and 256 of sea turtles (Cheloniidae, 286 individuals) were recorded. Manatees and sea turtles displayed solitary habits, while dolphins were commonly seen in groups. Manatees were positively correlated with sea turtles, probably due to their preference for sheltered shallow habitats with favorable conditions for foraging and resting. Furthermore, manatees showed a positive relationship with mangrove estuaries, and medium-sized coastal cities probably due to the intense urban development in many estuarine areas. Manatees and sea turtles were also positively correlated with boats, showing a severe threat for these species. Density of manatees was significantly higher within MPAs with preserved mangrove estuaries than in non-protected areas, while dolphins and sea turtles were observed in high densities MPAs with coral reefs. The elevated density of these organisms shows the vital importance of protecting and adequately managing unique ecosystems to ensure a sustainable future for the populations of severely threatened species.

Keywords: Manatees, Dolphins, Sea turtles, Aerial surveys, Northeastern Brazil.

1. Introduction

Marine mammals and sea turtles are considered key organisms for marine conservation in several parts of the world (Chatwin, 2007). Many populations of these animals occur in coastal areas that are intensively used by local people (Ojeda-Martínez et al., 2011), which make them vulnerable or threatened by extinction (IUCN, 2012). Marine protected areas (MPAs) are thus essential tools to ensure the conservation of these organisms and their ecosystems (Hooker and Gerber, 2004). However, the efficiency of MPAs should be based on thorough surveys (Ojeda-Martínez et al., 2011), which in effect, are often incipient or too small-scaled spatial (Witt et al., 2009; Panigada et al., 2011; Knip et al., 2012). Large-scale studies that quantitatively determine the correlations between endangered species, such as manatees, dolphins and sea turtles, coastal features and human activities are rare.

In northeast Brazilian waters, the most important threats to coastal biodiversity are fisheries and intensive urban development, thus turning this region one of the most vulnerable within South America (Chatwin, 2007). The most common marine mammals in the coastal zone off northeastern Brazil are the Antillean manatee (*Trichechus manatus manatus*) (Lima et al., 2011) and 19 species of cetaceans, among which the Guiana dolphin (*Sotalia guianensis*) is the most frequent species (Alvite et al., 2004). Also, this region occur five of the seven living species of sea turtles, the loggerhead (*Caretta caretta*), hawksbill (*Eretmochelys imbricata*), olive ridley (*Lepidochelys olivacea*), leatherback (*Dermochelys coriacea*), and the green turtle (*Chelonia mydas*), the most common species in Brazil (Marcovaldi and Marcovaldi, 1999). Antillean manatee is the most endangered aquatic mammal in Brazil (ICMBio, 2011), being classified internationally as "endangered" as *S. guianensis* is listed as "data deficient" (IUCN, 2012). All sea turtles mentioned are under threat, *D. coriacea* and *E. imbricata* being classified as “critically endangered”, *C. caretta* and *C. mydas* as “endangered” and *L. olivacea* as “vulnerable” (IUCN, 2012).

Aerial surveys are considered a standard technique to assess distribution, abundance and habitat characteristics of marine mammals and sea turtles worldwide (e.g. Preen, 2004; Edwards et al., 2007; Certain et al., 2008; Witt et al., 2009; Jean et al., 2010; Langtimm et al., 2011). In Brazil, however, few studies have been based on aerial surveys (Secchi et al., 2001; Andriolo et al., 2006, 2010; Danilewicz et al., 2010; Zerbini et al., 2010, 2011; Wedekin, 2011). In the northeastern coast, only one single aerial survey of manatees was performed on a local scale off Ceará state (Costa, 2006).

The objective of the present study was to quantify and analyze the large-scale spatial distribution of manatees, dolphins and sea turtles off northeastern Brazil, in relation to habitat characteristics, current human activities, and the importance of MPAs for the conservation of these animals.

2. Material and Methods

2.1. Study area

The northern limit of the study area was the mouth of the Parnaíba River Delta, around Canárias Island (02°44'S, 41°47'W), Piauí State. The southern limit was the mouth of the São Francisco River (10°30'S, 36°24'W), located in Alagoas State (Fig. 1).

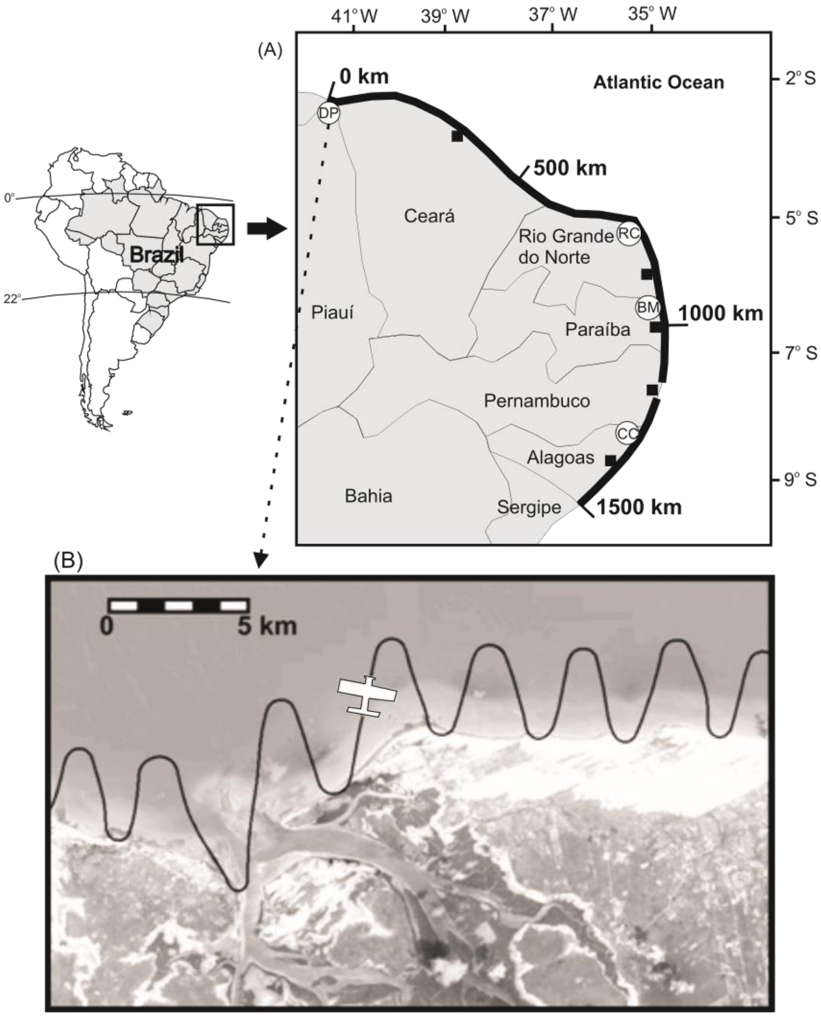

Fig. 1. Map of the study area between the states of Piauí and Alagoas, northeastern Brazil (A) showing the main Marine Protected Areas (DP - Delta do Rio Parnaíba, RC - Recifes de Corais, BM - Barra do Rio Mamanguape, CC - Costa dos Corais) and coastal cities (black squares). Inlet: Aerial transects in a zigzag pattern in the marine protected area Delta do Rio Parnaíba (B).

The northeastern coast of Brazil extends for approximately 3400 km and displays variety of environments such as beaches, dunes, cliffs, coral reefs, mangrove estuaries, and seagrass beds, each being governed by specific dynamics and anthropogenic vulnerabilities (Cunha, 2005; Muehe and Garcez, 2005). The continental shelf is 85 km wide in the north and narrows to 40 km in the southern part. Climate is tropical, with high temperatures and salinities, and low concentrations of nutrients, except for estuarine areas, where primary productivity and biomass are high (Muehe and Garcez, 2005).

There are four relevant Marine Protected Areas (MPAs) in this region, each with its specific conservation targets: "Delta do Rio Parnaíba" (manatees, mangroves, beaches, sand banks, estuaries, coastal grasslands, marshes, dunes, lakes and lagoons), "Recifes de Corais" (defined around the “Parrachos de Maracajaú” offshore coral reefs), "Barra do Rio Mamanguape" (manatees, mangroves, lagoons, sand banks) and "Costa dos Corais", Brazil's largest MPA (manatees, coral and sandstone reefs, estuarine mangroves) (Figs. 1 and 2). Their function is to protect and preserve natural resources and to promote sustainable development (FAO, 2011).

2.2. Aerial surveys

Aerial surveys were accomplished after a pilot study (Alves et al. 2013), using a single-engine Cessna 172 A aircraft with a high-wing design to facilitate viewing the sea surface. It was adapted with bubble windows at the rear (Zerbini et al., 2010, 2011), allowing for a wider viewing angle. Sampling was performed using the strip transect method, assuming that all animals within the strip (a band of fixed width on each side of the transect line) were detected and counted (Jolly, 1969). This method has been widely applied for marine mammals and sea turtles (Cardona et al., 2005; Certain et al., 2008; Witt et al., 2009; Langtimm et al., 2011; Katsanevakis et al., 2012).

A total 899 lines transects were made in a zigzag pattern, with an angle of turn of 40°, as to better cover the area and to maximize the flying effort (Secchi et al., 2001; Cardona et al., 2005; Andriolo et al., 2006, 2010). The surveyed areas extended from estuarine inlets, especially aiming at sightings of manatees, to the isobaths of 10–20 m (Fig. 1). The flight was standardized with 150 m altitude and 140 km h^{-1} speed, which is within the range found in other aerial surveys (Morales-Vela et al., 2000; Olivera-Gómez and Mellink, 2005; Roos et al., 2005; Costa, 2006; Langtimm et al., 2011). The widest sighting angle (approximately 65º) was determined with a clinometer during a test flight, and resulted in a sampled width of 321.7 m per observer (i.e., the total strip width equals 643.4 m) (Alves et al., 2013). Sea conditions were Beaufort Sea state 2 or less (Certain et al., 2008), characterized by flat or calm sea, and conditions of visibility and water transparency between "excellent" and "average". Aerial surveys were conducted during the dry season, between January and April 2010, in the morning period and at high tide, when the animals have a better access to shallow foraging areas such as macroalgal banks and seagrass beds (Paludo and Langguth, 2002; Olivera-Gómez and Mellink, 2005), and to reduce the potentially confusing effect of reefs and algae sandstone substrates that appear at low tide (Costa, 2006; Alves et al., 2013). Observations were performed by two independent observers, located at each of the side windows to minimize perception bias (Langtimm et al., 2011), and who were wearing polarized sunglasses to minimize the effect of glare on the water surface and accentuate the color gradient. A registrar, in the front beside the pilot, used a GPS to indicate sighting points, in addition to the GPS of the plane, which recorded the route. The registrar also used two photographic cameras, a portable recorder, and nautical charts to compile the field records. Each flight lasted for less than 3 h per day.

All identifications were based on morphological and characteristic behavioral diagnostics. Calves corresponded to specimens measuring up to 1/3 of the adult size (Hartman, 1979). Two or more animals were defined as a group (Morales-Vela et al., 2000). In cases of doubtful sightings or imprecise counts, a circular flight around the sighting point was carried out to confirm identification (Morales-Vela et al., 2000; Langtimm et al., 2011).

Approximately 1500 km of coastline were flown over in six Brazilian states, totaling 4026 km along the zigzag path (Fig. 1). The total coverage area was 2590.2 km^2, calculated as the zigzag path multiplied by the strip width (643.4 m). The effective effort exceeded 27 flight hours in 11 days. A stretch of only 22 km coastline was not surveyed, due to traffic restrictions around the Recife international airport (Fig. 1).

2.3. Data analysis

Sighting data were transferred to GIS using the Arcmap software (version 9.2) and received identification numbers and coordinates. The data were plotted on nautical charts (1:300.000) to obtain isobaths and maximal depths for each sighting (with tide at 0.0 m).

A descriptive analysis of the large-scale distribution patterns of marine mammals and sea turtles was carried out in the different areas. The results were also used to perform statistical analyses of potential relationships between the sightings of these animals, human activities, and coastline features. For this purpose, the coastline under investigation was divided into 294 segments of 5 km length. For each segment, seven ecological and human parameters were examined. During flights, the following information of occurrence records was obtained for each segment: (1) animal abundance, (2) coastal zone occupation patterns (shrimp farms, salt works and ports), and (3) fishing and tourism activities (trawling boats, motor boats, sail boats and rowing boats). Based on cartographic and bibliographic analysis, the following were diagnosed:

(4) MPAs ("Delta do Rio Parnaíba", "Recifes de Corais", "Barra do Rio Mamanguape" and “Costa dos Corais"), (5) Reefs (Northern Beach Rocks, Offshore Reef Patches, Coastal Reef Lines) (Castro and Pires, 2001), (6) Estuarine mouths (complex, mangrove, partially obstructed sandy barrier/small: 0.01–0.05 km, intermediate: 0.06–0.1 km, large: above 0.1 km), and (7) coastal urban centers (small < 180 km^2, medium-sized: 180–840 km^2, large > 840 km^2 (IBGE, 2007).

Spearman rank correlation analysis (Zar, 1996) was used to test for significant correlations between human activities, coastline features, MPAs, and animal abundance per segment. This method of correlation analysis was chosen due to the non-linearity of relationships and non-normality and heteroscedascity of most distributions. All analyses were performed using the “R” language and environment at $\alpha = 0.05$ (R Development Core Team, 2009, version 2.9).

3. Results

3.1. Distribution of sightings

A total of 320 sightings of marine mammals and sea turtles were recorded during the surveys. Of these, 36 were sightings of Antillean manatees (41 individuals), 28 were sightings of dolphins (Delphinidae, 78 individuals), with 10 individuals identified as *S. guianensis*, and 256 were sightings of sea turtles (Cheloniidae, 286 individuals) (Fig. 2 and Table 1). Although it was generally possible to see head, carapace and fins of turtles on the surface, this was not sufficient for identification at species level. Fish were also spotted occasionally, including 22 sightings of individual flying fish, seven unidentified large schools, seven rays and two sharks.

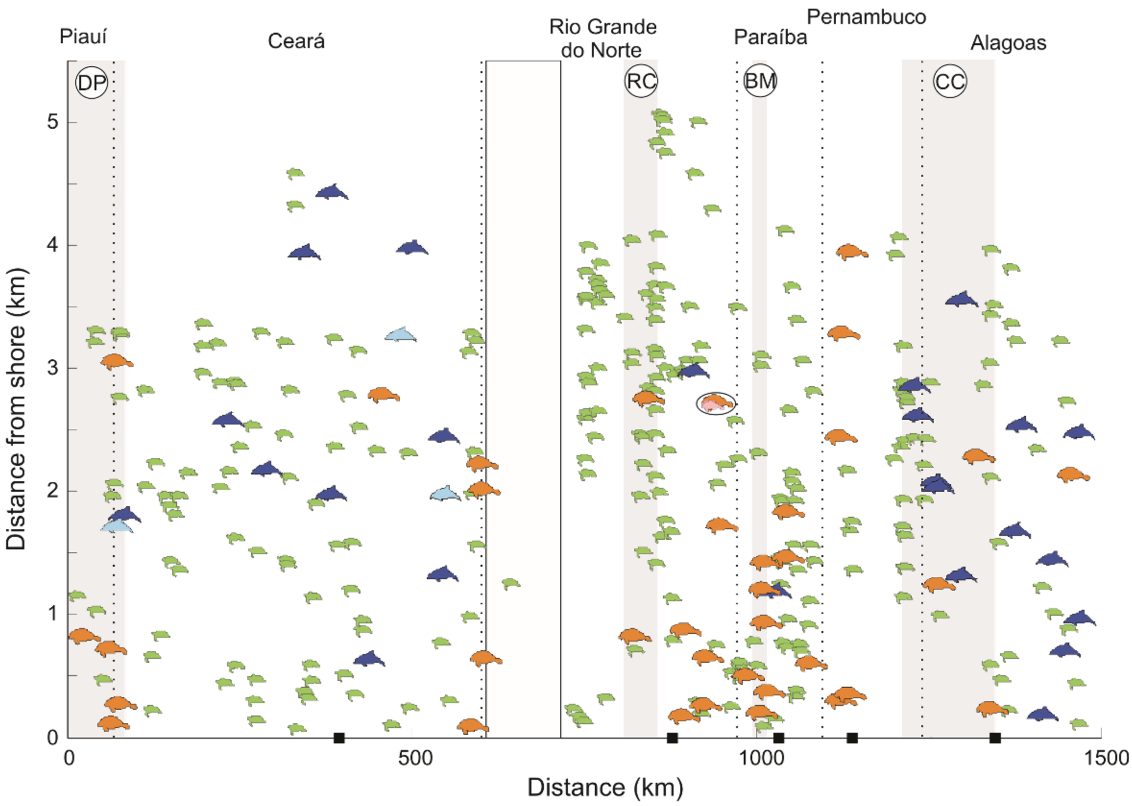

Fig. 2. Spatial distribution of manatees, dolphins and sea turtles between the states of Piauí and Alagoas, northeastern Brazil. Marine protected areas are indicated as gray rectangles (DP: Delta do Rio Parnaíba, RC: Recifes de Corais, BM: Barra do Rio Mamanguape, CC: Costa dos Corais). White rectangle: area with scarce sightings. A single sighting of manatee mother and calf is highlighted in a circle, and specimens of *Sotalia guianensis* in light blue color. Dotted lines: state borders.

Table 1. Summary of the sightings of manatees, dolphins and sea turtles during aerial surveys in northeastern Brazil. N = number.

	Manatees	**Dolphins**	**Sea Turtles**
Individuals	41	78	286
Sightings	36	28	256
Mean N / sighting	1.1	2.8	1.1
Maximum N / sighting	2	8	2
Positive segments*	29	24	127
Positive segments (%)*	10	8	43
Maximum N / segment*	3	10	10

*The coastline was divided into 294 segments of 5 km in length. Positive segments are those where sightings occurred.

Marine mammals and sea turtles were recorded throughout the study area, except along approximately 130 km of coastline around the western portion of the state of Rio Grande do Norte (Potiguar Basin), where only a single sea turtle sighting occurred (Fig. 2).

Manatees and sea turtles were most frequently observed as solitary animals (86.1% and 88.3%, respectively), or as groups of two adults. A pair of manatee mother and calf was sighted only once, at Barreta beach (06°06'S, 35°04'W, Rio Grande do Norte). Dolphins were generally found in groups (64.3%) composed of two to eight individuals (mean: 4.4 individuals per group) (Fig. 2, Table 1).

Sightings of all three taxa were concentrated within 2–10 m depth (Fig. 3). Manatees were clearly concentrated in shallower areas, being most frequently sighted within 6–8 m depth, reaching a maximum local depth of 14.8 m. Regarding the distance from the coast, manatees were also clearly concentrated in areas closest to shore, being most frequently sighted at distances that ranged from only 0.01 to 3.9 km from the coast, with a continuous decrease in frequency toward offshore areas. Accordingly, this species showed the lowest mean distance from the coast, with only 1.2 km, as compared to 2.1 km for dolphins and for sea turtles. Dolphins showed maximum frequency at the 8–10 m isobath, and three sightings occurred within the 16–18 m isobaths. Dolphins showed a more offshore distribution (0.1–4.4 km from the coast), with higher frequencies in the central part of the surveyed area, at 1.5–2.0 km from the coast.

Guiana dolphins were recorded between 2.1 and 9.2 m depth and between 1.6 and 3.2 km from the coast. The highest maximum values of depth and distance from the coast were recorded for sea turtles, with 18.5 m and 5 km, respectively, with high frequencies throughout the surveyed area (Figs. 2 and 3).

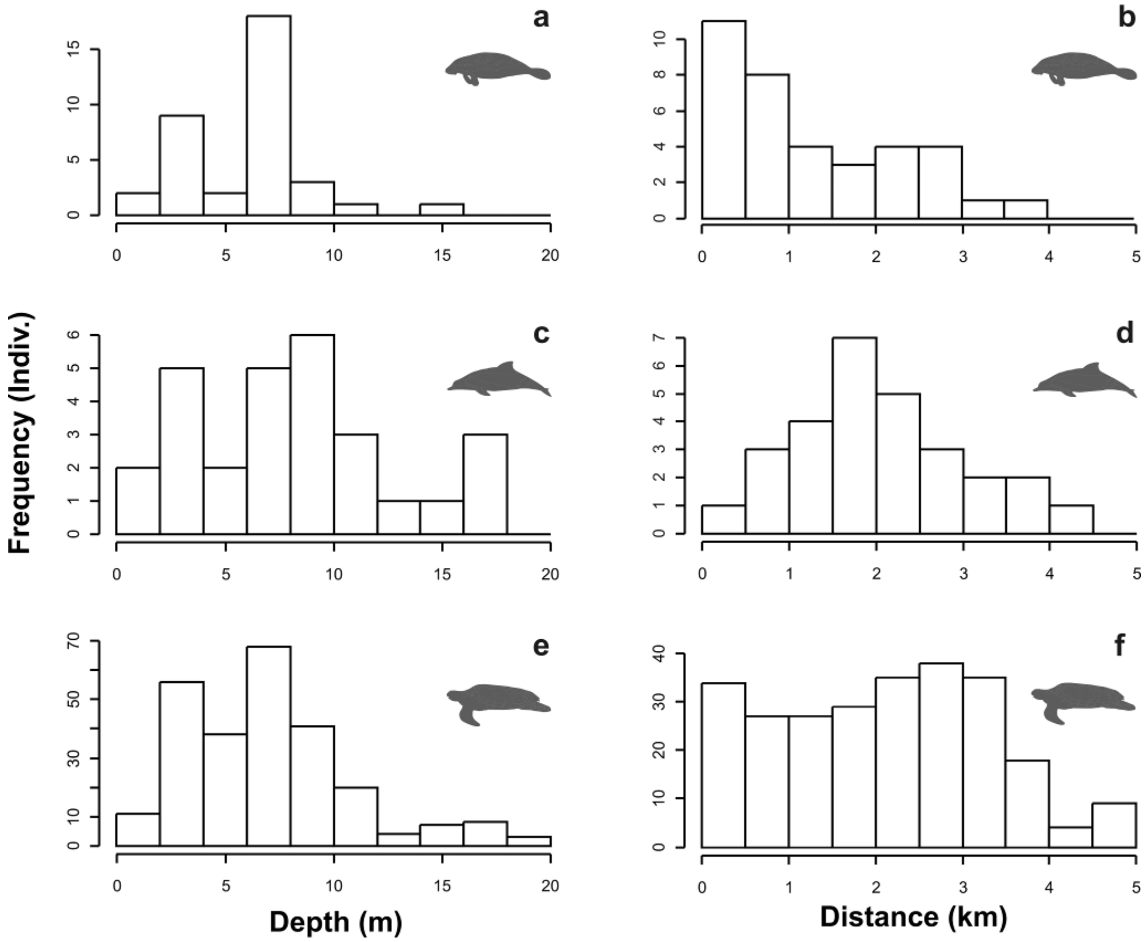

Fig. 3. Frequency histograms of depth (m) and distance from shore (km) at the sighting locations for manatees (a, b), dolphins (c, d), and sea turtles (e, f) in northeastern Brazil. Data are based on 27 hours of aerial surveys carried out along the northeastern Brazilian coast from the states of Piauí to Alagoas.

Spearman rank correlation analysis showed that manatees were positively correlated with sea turtles ($p = 0.032$, Table 2), while dolphins were not correlated with any of these groups.

Table 2. Results of Spearman correlation analysis of sightings of manatees, dolphins, sea turtles, selected coastal features and human activities, based on 27 hours of aerial surveys in northeastern Brazil. Values given in the table are “p” values of the analyses based on N = 294 coastal segments of 5 km in length.

	Spearman correlation		
	Manatees	**Dolphins**	**Sea Turtles**
Manatees	-	n.s.	n.s.
Dolphins	n.s.	-	n.s.
Sea Turtles	0.032	n.s.	-
Reefs			
Northern Beach Rocks	0.0089	n.s.	0.0041
Offshore Reef Patches	n.s.	n.s.	0.0012
Coastal Reef Lines	n.s.	n.s.	n.s.
Estuarine mouths			
Estuaries (all)	n.s.	n.s.	n.s.
Small	n.s.	n.s.	n.s.
Medium	n.s.	n.s.	n.s.
Large	n.s.	0.027	n.s.
Complex	n.s.	n.s.	n.s.
Mangrove	0.027	0.023	n.s.
Sandy barrier	n.s.	n.s.	n.s.
Land Use			
Shrimp farms	n.s.	n.s.	n.s.
Salt works	n.s.	n.s.	n.s.
Ports	n.s.	n.s.	n.s.
Cities (all)	n.s.	n.s.	n.s.
Small	n.s.	n.s.	n.s.
Medium	0.034	n.s.	n.s.
Large	n.s.	n.s.	n.s.
Fishing and tourism boats			
Boats (all)	n.s.	n.s.	0.030
Trawling	n.s.	n.s.	n.s.
Motor	0.011	n.s.	0.0017
Sail	n.s.	n.s.	n.s.
Rowing	n.s.	n.s.	n.s.

“n.s.”: not significant at $\alpha = 0.05$.

3.2. Correlations of coastal features and human activities

Spearman rank correlation analysis detected several significant correlations of coastline features and human activities with the density of manatees, dolphins and sea turtles (Table 2). A significant positive correlation of manatee sightings with reef habitats was detected for “Northern Beach Rocks” (p = 0.0089). For sea turtles, sightings were also positively correlated with “Northern Beach Rocks” (p = 0.0041) and “Offshore Reef Patches” (p = 0.0012). A significant positive correlation (p = 0.027) was detected between the density of open, mangrove-lined estuaries and manatee sightings. Other estuarine types such as partially obstructed sand bar (barrier) estuaries or seasonally obstructed sand bar estuaries, which are both typical of coasts with sandy beaches, sand bars, sand banks, dunes, strong wave action and wind-driven currents, showed no correlation with the density of manatees. Dolphin sightings were positively correlated with large estuaries (p = 0.027) and mangroves (p = 0.023) (Table 2).

Manatee sightings were positively correlated with the presence of medium-sized cities (p = 0.034) and motor boats (p = 0.011). Sea turtles were positively correlated with the total number of fishing boats (p = 0.030) and with motorized boats (p = 0.0017). Shrimp farms, salt works and ports did not show any positive or negative correlations with any animals (Table 2).

3.3. Marine protected areas (MPAs)

Significant positive correlations with MPAs were detected for manatees, dolphins and sea turtles, and varied considerably between taxonomic groups and areas (Fig. 4 and Table 3). When considering all four MPAs and comparing sightings in these areas to areas outside MPAs, manatees were the only group to show significantly higher density within MPAs (Table 3). The average density of manatees within MPAs was 0.3 individuals per 5 km-segment (18 individuals along 310 km coastline), three times larger than in areas outside MPAs (0.1 individuals per 5 km-segment, 23 individuals along 1160 km coastline). This positive relationship was confirmed by Spearman correlation analysis (p = 0.001).

When considering individual MPAs, manatees showed significantly higher density in two estuarine MPAs (“Delta do Rio Parnaíba” and “Barra do Rio Mamanguape”) than outside, with six and five manatees, respectively. Dolphins showed significantly higher density within the “Costa dos Corais” MPA (24 dolphins), while sea turtles showed significantly higher density within the “Recifes de Corais” MPA (41 sea turtles) (Fig. 4 and Table 3).

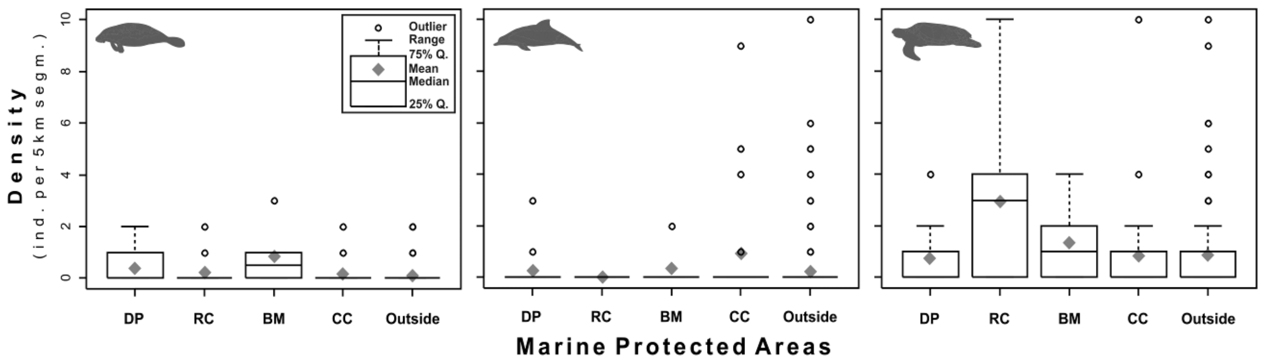

Fig. 4. Density of manatees (left), dolphins (center) and sea turtles (right) in marine protected areas in northeastern Brazil (DP: Delta do Rio Parnaíba, RC: Recifes de Corais, BM: Barra do Rio Mamanguape, CC: Costa dos Corais, Outside: areas outside marine protected areas). Data are based on 27 hours of aerial surveys from the states of Piauí to Alagoas. N = 294 coastal segments of 5 km length.

Table 3. Marine Protected Areas (MPAs) in northeastern Brazil and total sightings of manatees, dolphins and sea turtles. Data are based on 27 hours of aerial surveys. N = 294 coastal segments of 5 km length. Values given in the table are total number of organisms (N) and density (N per km coastline).

MPAs	**Area** (km^2 / segment)	**Main Habitat**	**N / Density per segment**			**Spearman correlation**		
			Manatees	**Dolphins**	**Sea Turtles**	**Manatees**	**Dolphins**	**Sea Turtles**
Delta do Rio Parnaíba	3.14 / 16	Extensive Mangroves	6 / 0.4	4 / 0.3	12 / 0.8	0.004	n.s.	n.s.
Recifes de Corais	1.8 / 14	Offshore Reef Patches	3 / 0.2	0 / 0.0	41/ 2.9	n.s.	n.s.	0.0008
Barra do Rio Mamanguape	0.15 / 6	Coastal Reef Lines	5 / 0.8	2 / 0.3	8 / 1.3	0.0007	n.s.	n.s.
Costa dos Corais	4.14 / 26	Coastal Reef Lines	4 / 0.2	24 / 0.9	22 / 0.8	n.s.	0.024	n.s.
All MPAs	Total: 9.23 / 62		18 / 0.3	30 / 0.5	83 / 1.3	0.001	n.s.	n.s.
Outside MPAs	Total: - / 232		23 / 0.1	48 / 0.2	203 / 0.9			

“n.s.“: not significant at α= 0.05.

4. Discussion

The data generated by the hitherto largest effort to quantify and correlate the distribution of manatees, dolphins and sea turtles in Brazil yielded important new insights into the situation of conservation these groups.

This study revealed a wide distribution of manatees, dolphins and sea turtles, except for a single area (the Potiguar Basin), probably due to specific hydrographic features and anthropogenic factors in this area. The present data showed that some species were associated with each other and with coastal features, such as estuaries and reefs. The important role of MPAs was corroborated by the high densities of these animals. One alarming finding was the association of manatees and sea turtles with motorized fishing boats and coastal cities, which is a relevant conservation issue.

4.1. Spatial distribution

Manatees, dolphins and sea turtles occurred more or less continuously along the study area. The only extensive area with virtually no sightings of animals was inserted in Potiguar Basin area, located at the northwestern coast of Rio Grande do Norte state. This region presents extremely harsh conditions due to the high energy of winds, waves and tides, with strong alongshore currents in westerly direction (Silva and Amaro, 2008). It is also considered one of the most oligotrophic regions of Brazil and has the lowest estuarine influence of the entire coastline, with virtually no freshwater input (Júnior et al., 2010). Furthermore, intensive resource exploration and coastal degradation have persisted for many decades due to the activities of the offshore oil industry, salt works and shrimp farming (Silva and Amaro, 2008), as observed during the survey. Seismic surveys associated with the offshore industry may cause severe physiological and behavioral changes in several organisms, especially in marine mammals (McCauley et al., 2000; Early, 2001). However, the present study and earlier assessments (Parente et al., 2006; Parente and Araújo, 2011) are still insufficient to evaluate the influence of offshore activities on the distribution and behavior of marine mammals and sea turtles in northeastern Brazil. The distribution of manatees, that forage on macrophytes and seagrass beds and are known to actively seek freshwater to drink, seems to be fundamentally determined by the availability of freshwater and food sources, and shelter in estuaries for reproduction (Hartman, 1979; Reynolds et al., 2009). However, the extreme harshness of the dynamic coastline, the scarcity or absence of freshwater sources and foods, the scarce and inaccessible sand bar estuaries, the absence of any shelter provided by barrier reefs and the intense human exploration may together explain the absence of manatees in the Potiguar Basin. This area and the eastern portion of the state of Ceará show the largest numbers of cases of manatee strandings, especially neonates, probably related to these factors (Parente et al., 2004; Meirelles, 2008; Lima et al., 2011).

The coexistence of manatees and sea turtles found in this study has been recorded in various other locations worldwide (Fertl and Fulling, 2007). This positive relationship is a function of the ecological requirements of both taxa, which may share common shelter and coastal foraging areas. Herbivory is a common trait among sirenians and *C. mydas*, feeding on seagrass beds and macroalgae (Hartman, 1979; Borges et al., 2008; López-Mendilaharsu et al., 2008; Guebert-Bartholo et al., 2011). There is a correlation of both taxa and fishing boats, both being concentrated close to shore, in the same, productive areas. This proximity implies a high risk of collision, accidental capture and habitat destruction, mainly by shrimp trawlers (Borges et al., 2007; Meirelles, 2008; Eguchi et al., 2010; Guebert-Bartholo et al., 2011). In Florida, most of the reported mortalities and serious mutilations of manatees (*T. m. latirostris*) are due to collisions with motor boats (Nowacek et al., 2004; Rommel et al., 2007). In northeastern Brazil, previous reports indicate that the interaction of *T. m. manatus* with motor boat traffic represents a direct threat for this species, causing lesions and deaths (Borges et al., 2007; Meirelles, 2008). In San Diego Bay, an intensively urbanized coastal area, frequent strandings of green turtles have been reported, probably related to collisions with motor boats (Eguchi et al., 2010).

4.1.1. Antillean manatee

Studies on the distribution of manatees in Brazil have been conducted since the 80s, based on information from fishermen and stranding data (Parente et al., 2004; Luna et al., 2008; Lima et al., 2011). Only one single study in the eastern part of Ceará state used an aerial survey, however with difficulties associated to the observation of these animals in turbid waters during the rainy season and flight logistics (Costa, 2006). Conversely, the aerial methodology used in this study was very favorable for the detection of manatees, highlighting its importance for the conservation of this endangered species.

The detection of some manatees has been hampered due to the following factors: (1) solitary habit, (2) barely visible exposure on the surface, and (3) cryptic brownish color surrounded by turbid waters near estuaries. These limitations may make counting and identification inaccurate (Edwards et al., 2007), one alternative being the use of a side-scan sonar (Gonzalez-Socoloske et al., 2009). During periods of cold weather, aerial surveys conducted in Florida uncovered large groups of manatees in areas of warm and transparent water, which facilitated the counting (Edwards et al., 2007). In the study area, the almost constant temperature of coastal waters prevents this type of phenomenon (Lima et al., 2011).

The social structure of manatees, predominantly solitary or in couples, was also found in other studies in this region (Borobia and Lodi, 1992; Paludo and Langguth, 2002; Costa, 2006). The presence of calves on Barreta beach, Rio Grande do Norte state, was also recorded by other researchers (Oliveira et al., 1990; Paludo, 1998), suggesting the existence of a nursery area. The mating period of manatees in northeastern Brazil is the dry season, from October to May (Paludo, 1998; Parente et al., 2004; Meirelles, 2008; Lima et al., 2011). The observation of a single calf only within the reproductive season (March) during the aerial survey may be considered worrisome for the conservation of this species, which is threatened by the destruction and degradation of its estuaries (Parente et al., 2004; Meirelles, 2008). Furthermore, these few records may be due to lack of sampling within the estuaries, which are ecosystems using for reproduction and parental care of manatees (Hartman, 1979; Lima et al., 2011), or detection difficulty related smaller size.

The presence of manatees in shallow coastal waters, generally with less than 12 m depth, seems to be related to the availability of food sources (Hartman, 1979; Olivera-Gómez and Mellink, 2005; Rodas-Trejo et al., 2008; Langtimm et al., 2011). Furthermore, these are often shallow sheltered sites that allow animals to spend less energy in respiratory intervals (Smethurst and Nietschmann, 1999; Bacchus et al., 2009). The access to shallow foraging areas at high tide only introduces additional variability to the depth range of manatees. In previous studies conducted in northeastern Brazil with observations from shore or on boats, water depth of manatee sightings varied between only 0.4 and 5.6 m (Borobia and Lodi, 1992; Paludo and Langguth, 2002; Costa, 2006), which is much shallower than the range observed in our study (most frequently within 6–8 m, reaching 14.8 m). This difference is probably due to the more efficient coverage of deeper waters in this aerial survey as compared to earlier studies. The most common seagrass in this region, *Halodule wrightii*, which is considered one of the main food sources for this species (Borges et al., 2008; Lima et al., 2011), is found from the intertidal zone down to 10 m depth (Laborel-Deguen, 1963).

Furthermore, the occurrence of manatees near well-preserved mangrove estuaries located in the northern part of the study area reflects the use of these types of habitats for breeding and foraging (Olivera-Gómez and Mellink, 2005; Rodas-Trejo et al., 2008; Lima et al., 2011). In many other estuaries surveyed in this study, the visible deforestation of mangrove vegetation due to the expansion of shrimp farms, salt works, and urbanization has caused the closing of estuaries with sand bars, hampering the access by manatees (Lima et al., 2011).

The positive correlation between manatees and medium-sized cities highlights the intense human occupation of the coastal zone around estuarine and sheltered areas that are important for this species. The attractiveness of bays and estuaries for human populations in Brazil resulted in a long process of intense urban development, fisheries, ports, industries and recreational activities in these areas, which are major threats for coastal ecosystems (Cunha, 2005) and many endangered species.

4.1.2. Dolphins

Even under ideal conditions of water transparency and swimming in groups, the identification of dolphins was difficult due to their quick movements in opposition to the speed of the aircraft. The small morphological variations between some cetaceans make aerial identification difficult (Preen, 2004). *S. guianensis* was diagnosed by the morphology of the rostrum and melon, pink-gray coloration and its triangular dorsal fin (Flores, 2002).

Groups of two to eight Guiana dolphins found in this study are commonly observed in northeastern Brazil (Araújo et al., 2001, 2008), while groups of this species may reach 150 specimens in the southern region (Flores, 2002), where waters are more productive due to seasonal upwelling (Muehe and Garcez, 2005). This explains the tendency of large groups to inhabit the southern and southeastern region, and small groups to occur in the northeastern region (Araújo et al., 2008).

The higher frequency of dolphins in deep waters, reaching a depth of 17.1 m and at a distance of up to 4.4 km from the coast in the present study, is similar to findings of previous studies on Guiana dolphins in Brazil, with up to 16 m depth and four km from the coast (Bazzalo et al., 2008; Wedekin et al., 2010). Previous studies showed that the bathymetry is important for the distributions of dolphins, mainly due to the depth-related distribution of prey (Baumgartner et al., 2001; Certain et al., 2008). This may reflect their search for food, corroborated by the migration of fish to deeper areas and away from the coast due to environmental perturbations in nearshore reef ecosystems in northeastern Brazil (Frédou and Ferreira, 2005). The search of these animals for more offshore areas may suggest a strategy to find favorable foraging areas, and possibly to avoid the intense coastal artisanal fishing activity recorded in this study. Accidental capture in fishing nets is a main threat for Guiana dolphins in Ceará state, cetacean species with highest (62%) incidence of strandings (Meirelles et al., 2009). This species and bottlenose dolphins (*Tursiops truncatus*) have foraging as a determinant factor for habitat choice (Hastie et al., 2004; Wedekin et al., 2010).

The occurrence of dolphins close to estuaries may indicate the search for food sources that are associated to these important nurseries for crustaceans and fish, both for resident species and for marine migratory species (Blaber, 2000). In Brazil, *S. guianensis* frequently occurs in estuarine areas and their surroundings (Flores, 2002; Araújo et al., 2008), suggesting that many unidentified specimens are probably of this species.

4.1.3. Sea turtles

Sea turtles were the most abundant taxon in this study. This is the first aerial survey of sea turtles carried out in Brazil. This methodology has been shown to provide important abundance estimates of sea turtle populations, especially in foraging or nesting grounds (Epperly et al., 1995; Cardona et al., 2005; Roos et al., 2005; Witt et al., 2009).

Individuals from the family Cheloniidae have been identified by the greenish-brown shell coloration, that is distinct from Dermochelyidae, which have a black color and very prominent ridges. The detection of the specimens, even in moderate visibility conditions, occurred through the total body exposure and turbulence at the water surface caused by the fins during the dive, which could reveal the number of animals (McClellan, 1996). However, flight altitude and speed, and escape behavior caused by the noise of the aircraft, made the identification at species level difficult, as observed in other studies (Shoop and Kenney, 1992; Epperly et al., 1995, McClellan, 1996). The smaller size of sea turtles in relation to other taxa studied also contributed as a limiting factor for identification to species level. Previous studies based on aerial surveys suggested a minimum size of 30 (Epperly et al., 1995) to 75 cm (Shoop and Kenney, 1992) carapace width for a specific diagnosis of sea turtles. Conversely, in the present study, identification to species level was not possible even for large-sized specimens.

The high number of solitary sea turtles sighted could indicate that the areas studied did not include major breeding grounds, since mating occurs in large groups in shallow waters (Hirth, 1980). In Brazil, green turtles, for example, may be sighted in groups during the reproductive period from September to March, which includes the study period. This species uses oceanic islands for mating, being rarely sighted in large groups along the continental northeastern coast of Brazil. The northeastern coast harbors 12 of the 19 main breeding areas for sea turtles in country (Marcovaldi and Marcovaldi, 1999). However, none is included in the study area, although nesting areas along the coast have been recorded. Aerial and snorkel census techniques for estimating green turtle abundance in foraging areas identified small groups of 4–5 individuals, that apparently were randomly distributed (Roos et al., 2005). It is therefore likely that the study area is mainly used for feeding and resting.

In this study, varying depths (0.9–18.5 m) and distances from the coast (from the coastline up to 5 km) occupied by sea turtles showed the diversity of existing habitats. Their spatial distribution can be influenced by physical and biological parameters, and depth distribution is closely related to their feeding, breeding and resting behavior (Griffin and Griffin, 2003; Roos et al., 2005; Witt et al., 2010). In a previous study in Brazil, green turtles were sighted during scuba dives feeding at 6 m depth (Guebert-Bartholo et al., 2011), and swimming in areas with vegetation at 10 m depth and up to

10 km distant from the coast (Parente et al., 2006). These numbers are within the range recorded in this study, suggesting the occurrence of important foraging areas in northeastern Brazil.

The positive correlation of sea turtles with reef formations such as Northern Beach Rocks and Offshore Reef Patches, as observed by the high density of individuals in the MPA “Recifes de Coral" may be intimately related to the search for shallow sheltered areas and for areas with abundant macroalgae that grow on sandstone substrates. Likewise, an aerial survey carried out in Western Australia revealed a higher density of sea turtles in reef areas (Preen et al., 1997). In a study conducted in the South-West Indian Ocean, the distribution of these animals close to coral reefs and on the outer reef slopes was explained by the availability of shelter and food (Jean et al., 2010), similarly to the findings of the present study.

4.2. Marine protected areas (MPAs)

The high density of manatees in the MPAs "Delta do Rio Parnaíba” and "Barra do Rio Mamanguape" highlights the importance of these areas for the protection of this species and its habitats. These areas are mainly composed of a complex deltaic environment with well-preserved mangroves ("Delta do Rio Parnaíba”) or estuarine mangroves with adjacent coastal reef lines ("Barra do Rio Mamanguape"), allowing for the occurrence of groups of manatees in sheltered, well-preserved areas and an open access to upstream environments for reproduction and resting (Borobia and Lodi, 1992; Lima et al., 2011). In the Persian Gulf, areas with high densities of dugongs and sea turtles were related to habitats that are rich in seagrass beds and coral reefs, and were chosen for the establishment of MPAs (Preen, 2004).

The occurrence of dolphins and sea turtles in MPAs characterized by linear coastal reef formations can ensure sheltered areas for foraging and resting. The MPA “Recifes de Coral”, with high numbers of sea turtle sightings, has coastal and offshore reefs, as well as seagrass beds and banks of macroalgae, which likely represent food sources for these animals (Guebert-Bartholo et al., 2011). In the MPA "Costa dos Corais", the configuration of a large-scale barrier reef may allow for higher food availability and facilitate fish capture strategies by dolphins. The use of specific foraging techniques is commonplace for some species of delphinids, such as the bottlenose dolphin, that adapt its distribution patterns towards habitats that are favorable for prey capture (Hastie et al., 2004; Torres and Read, 2009). In Brazil, Guiana dolphins feed preferentially in bays, barrier reefs and estuaries, where they can direct fish schools to shallower waters (Araújo et al., 2001; Rossi-Santos and Flores, 2009). Such areas are widely found in the MPA "Costa dos Corais" (FAO, 2011).

It is noteworthy that there is a captive manatee reintroduction program within the MPA "Costa dos Corais", located in the northern part of the state of Alagoas. This very successful program has possibly provided an increase of the manatee population in this area (ICMBio, 2011). However, proximity and easy access of human populations to reef areas found in the study can directly affect the biological communities (Castro and Pires, 2001). Habitat loss and the degradation of feeding areas for sea turtles are a potential cause of population decline (López-Mendilaharsu et al., 2008; Guebert-Bartholo et al., 2011) and the presence of motor boat traffic and trawling can cause behavioral changes in dolphins (Constantine et al., 2004; Wedekin et al., 2010; Carrera et al., 2008).

The results of the present study cannot be used to test whether the existence of MPAs increases the density of endangered species in these areas, as in other studies (Witt et al., 2009; Panigada et al., 2011; Knip et al., 2012). All MPAs were delineated around special coastal features, such as outstandingly large or exceptionally well-preserved estuaries and barrier reefs, which create favorable and essential habitats for these and many other species. Rather than proving the effect of MPAs, the elevated density of these organisms shows the vital importance of protecting and adequately managing such unique ecosystems to ensure a sustainable future for the populations of severely threatened species.

5. Conclusions

The spatial distributions of manatees, dolphins and sea turtles show the different types of behavior of these species and the variety of ecosystems along the coast, with a preference for well-preserved foraging and resting habitats.

In northeastern Brazil, aerial monitoring in areas of occurrence of marine mammals and sea turtles, that are susceptible to habitat loss, can encourage the development of management, environmental conservation and recovery programs. The diagnosis and monitoring of ecosystems are essential for the survival of marine biodiversity, highlighting the role of MPAs for the protection of ecosystems and species.

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Capítulo 4* - Distribuição do peixe-boi marinho em relação às angiospermas marinhas no nordeste do Brasil.

Chapter 4* - Distribution of Antillean manatee in relation to seagrass in northeastern Brazil.

* Capítulo em formato de artigo e padronizado de acordo com as normas da revista *Aquatic Conservation: Marine and Freshwater Ecosystems.*

Distribution of Antillean manatee in relation to seagrass in northeastern Brazil

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ABSTRACT

1. Seagrass is one of the main food items in the diet of the Antillean manatee.

2. The aim of the present study was to relate the spatial distribution pattern of seagrass with the occurrence of the Antillean manatee in northeastern Brazil and characterize potential foraging grounds for the species.

3. The identification of areas with seagrass was based on *in situ* observations, data from the literature and personal information from the researchers and the local fishermen. Data on the occurrence of Antillean manatees consisted of aerial sightings, cases of stranding and information from fishermen.

4. Seagrass was recorded at 41 beaches, wich is 69% greater than the number of records described in the literature. The species identified were *Halodule wrightii*, which was the most frequent, *Halophila decipiens* and *Ruppia maritima*. The distance from shore and depth of the coastal habitats and estuarine with seagrass were similar to the spatial distribution described by literature for the Antillean manatee

5. Despite the 27 records of occurrence of both seagrass and manatees at the same sites, the correlation analysis of the two factors was not significative. This lack of significant correlation may be related to the reduction in the foraging grounds and/or the generalist habit of manatees, which feeds on different types of vegetation, especially macroalgae, throughout its variable home range.

6. The present findings emphasize the importance of directing efforts toward reducing additional losses of seagrass beds and serve as a useful tool for the drafting of regional management plans to prevent the further decline of these ecosystems, which are potential foraging grounds for the Antillean manatee.

KEY WORDS: seagrass; manatees; occurrences; food resources; habitats; Brazil

INTRODUCTION

The Antillean manatee, *Trichechus manatus manatus* Linneaus 1758, is a herbivorous aquatic mammal (Hartman, 1979) that inhabits, rivers, estuaries and shallow coastal waters from the eastern coast of Mexico to the northeastern portion of South America (Lefebvre *et al*., 2001). The presence of fresh water and an abundance of aquatic vegetation, especially seagrass, are important environmental characteristics influencing of occurrence of these animals (Morales-Vela *et al*., 2000; Paludo and Langguth, 2002; Olivera-Gómez and Mellink, 2005; Costa, 2006; LaCommare *et al.*, 2008).

In Brazil, *T. m. manatus* exhibits heterogeneous distribution along the northern and northeastern regions of the country (Luna *et al.*, 2008; Lima *et al.*, 2011; Alves *et al.*, 2013). The history of hunting practiced in the past (Oliveira *et al*., 1990) and the significant reduction current in coastal habitats and estuaries, which have traditionally been used by the species for feeding, breeding and resting grounds (Parente *et al*., 2004; Meirelles, 2008; Alves *et al*., 2013), has led to a population decline, making the Antillean manatee the most endangered aquatic mammal in Brazil (ICMBio, 2011).

In terms of diet, the Antillean manatee is an opportunistic, generalist herbivore that feeds on a variety of algae, seagrass and freshwater macrophytes (Hartman, 1979; Smith, 1993). The main seagrasses consumed by this manatee are turtle seagrass (*Thalassia testudinum* Banks ex König 1805), manatee seagrass (*Syringodium filiforme* Kützing in Hohenacker 1860), widgeon grass (*Ruppia maritima* Linneaus 1753), three species of the genus *Halophila* (*H. engelmannii* Ascherson in Neumayer 1875, *H. johnsonii* Eiseman 1980 and *H. decipiens* Ostenfeld 1902) and shoal grass (*Halodule wrightii* Ascherson 1868) (Provancha and Hall, 1991; Lefebvre *et al.*, 2000; Reich and Worthy, 2006; Castelblanco-Martínez *et al.*, 2009; Alves-Stanley *et al.*, 2010), the latter of which is considered the most consumed by populations of the Antillean manatee in Brazil (Banks and Albuquerque-Neto, 1985; Costa, 2006; Borges *et al.*, 2008; Lima *et al.*, 2011).

Seagrass is represented by approximately 60 species worldwide, distributed among 13 genera (Short *et al.*, 2001). Despite the low degree of taxonomic diversity, seagrass plays an important ecological role in coastal environments (Heck and Valentine, 2006; Marques & Creed, 2008; Pereira et al. 2010). In the Brazilian coast are recorded *R. maritima*, *H. decipiens*, *Halophila baillonis* Ascherson ex Dickie in JD Hooker 1874, *Halodule emarginata* Hartog, 1970 and *H. wrightii*, the latter of which is the most widely distributed and best studied (Short *et al.*, 2007).

The general distribution and composition of seagrass beds in Brazil have been documented in only two studies (Den Hartog, 1972; Oliveira-Filho *et al.*, 1983), with a more recent bibliographic review (Marques and Creed, 2008). In the northeastern region, studies have been restricted to small areas (Vieira, 2006; Silva, 2010; Silva *et al.*, 2012), and most of them were carried out in the state of Pernambuco (Laborel-Deguen, 1963; Magalhães and Alves, 2002; Magalhães and Cazuza, 2005; Reis, 2007).

Seagrass are restricted to shallow coastal waters and estuaries, and so has historically been endangered by intensive activities of urbanization and fishing worldwide, making them vulnerable to extinction (Duarte, 2002; Ceccherelli *et al.*, 2007; Freeman *et al.*, 2008; Short *et al.*, 2011; Pitanga *et al.*, 2012).

Knowledge on the spatial distribution of manatees based on the presence of food resources is essential to the establishment of local and regional conservation strategies aimed to insure the protection of the species and of its habitats (Olivera-Gómez and Mellink, 2005; Alves-Stanley *et al.*, 2010; Semeyn *et al.*, 2011). Studies on the presence of *T. m. manatus* and its foraging grounds are rare in Brazil and have been limited to the monitoring of native animals in restricted areas (Paludo and Langguth, 2002; Costa, 2006) or specimens reintroduced into the natural environment (Lima, 2008).

Due to the lack of data on the distribution of seagrass and the large-scale association between this ecosystem and the spatial distribution of manatees, the aim of the present study was to relate the spatial distribution pattern of seagrass to the presence of the Antillean manatee in northeastern Brazil. The results will allow mapping the current areas of occurrence of seagrass in part of this region of the country and allow the establishment of priority areas for the protection of such ecosystems. This is the first survey on the spatial distribution of possible foraging grounds of the Antillean manatee in Brazil.

METHODS

Study region

The study area was located between the states of Rio Grande do Norte and Alagoas, covering approximately 932 km of the 3400 km of coastline throughout northeastern Brazil (Figure 1). This region is characterized by a variety of ecosystems, including beaches, dunes, coral reefs, mangroves and estuaries. The area is defined by two seasons (dry and rainy), high temperatures (>26°C), high salinity and a low concentration of nutrients, except in estuarine areas, in which high primary productivity and biomass are found (Andrade and Lins, 2005; Muehe and Garcez, 2005).

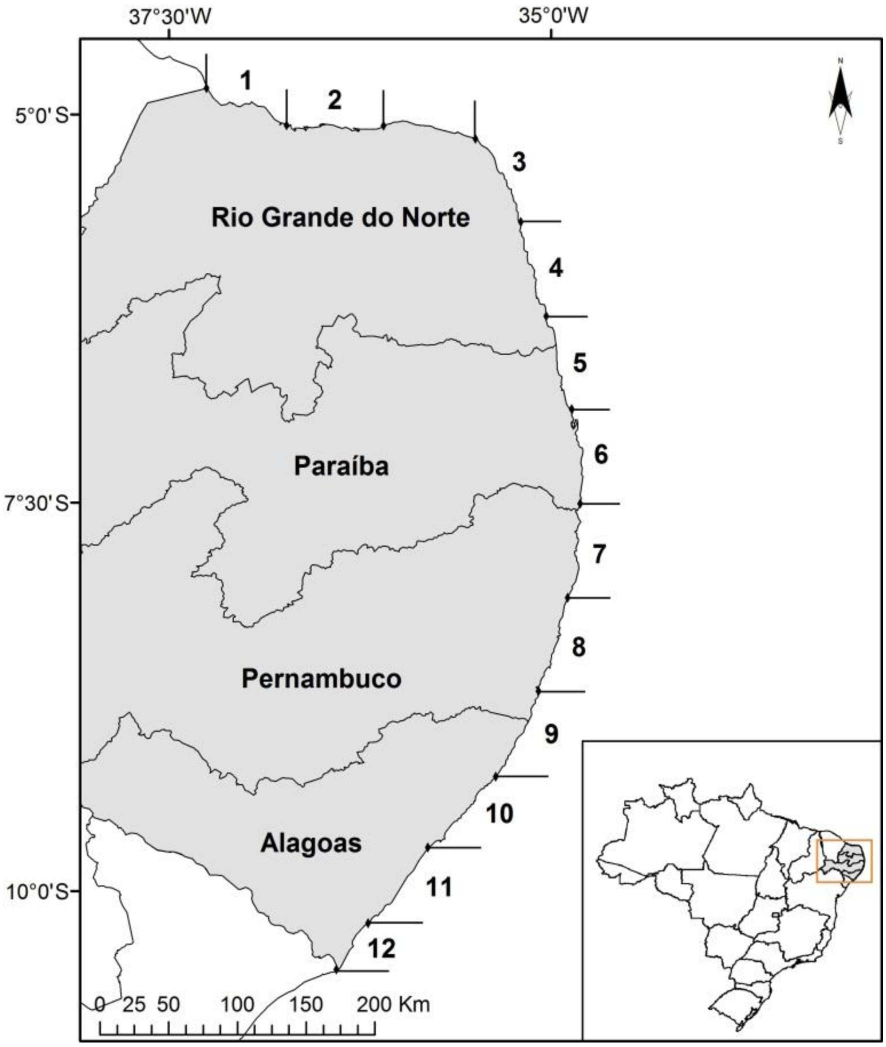

Figure 1. Study area with demarcation of sampling units (70 km) for analysis of the spatial distribution of seagrass between the states of Rio Grande do Norte and Alagoas along the northeastern coast of Brazil.

Seagrass in northeastern Brazil is represented by five species (Oliveira-Filho *et al.*, 1983; Marques and Creed, 2008) and corresponds to more than 70% of the national coverage, which is estimated at 200 km^2 (Freire *et al.*, 2008). In the region, the Antillean manatee was estimated at less than 300 animals, basing fisherman information (Lima *et al.*, 2011), and 1146 specimens in recent study of the aerial survey (Alves et al., unpublished).

Seagrass sampling

The identification of potential foraging areas of the Antillean manatee in northeastern Brazil (characterized by the presence/absence of seagrass) was based on 33 records available in the literature (Laborel-Deguen, 1963; Den Hartog, 1972; Oliveira-Filho et al., 1983; Magalhães and Cazuza, 2005; Vieira, 2006; Reis, 2007; Silva, 2010; Silva et al., 2012) (Figure 2B), personal information from specialists in each state as well as 92 interviews with local fishermen. In exceptional cases of an absence of such information, beaches with records of the occurrence of Antillean manatees were selected for field investigations. Bibliographic data on the occurrence of seagrass in non-visited areas were used to detail information on the distribution of this aquatic vegetation. The in situ mapping for the confirmation of areas of occurrence of seagrass beds was performed between April 2011 and December 2012, with intensive search for samples stranded in the mid littoral zone at low tide ($\leq$ 0.4 m).

For the identification of the species, samples were preferably taken from the central region of the seagrass bed. The depth of the areas of seagrass beds was measured using a portable digital echo sounder to determine free diving (depths $\leq$ 60 cm) or scuba diving (depths > 70 cm) for the collection of samples. Stranded plants were sampled only when no seagrass beds were found. The species were identified based on descriptions by Oliveira-Filho *et al.* (1983).

Records of the occurrence of *T. m. manatus* were defined by 30 aerial sightings (Alves *et al.*, unpublished data), 32 stranded specimens (Parente *et al.*, 2004; Oliveira *et al.*, 1990) and 62 interviews with fishermen (Lima *et al.*, 2011), totaling 124 records.

Data analysis

The records of the occurrence of seagrass were georeferenced and the data transferred to the GPS TrackMaker PRO (version 4.8) Geographic Information System, and each geographic coordinate received an identification code by species. Manatee records were georeferenced using Google Earth 2013 and the data then entered in the ArcMap program (version 10.0) for the construction of a map of Antillean manatee distribution *versus* vegetal distribution.

For the analysis of the spatial distribution patterns of seagrass and the Antillean manatee, the study area was divided into 12 sectors (sampling units), each one with approximately 70 km of coastline (Figure 1). This distance was based on the mean distances recorded between sites of fidelity (home range) of the Antillean manatees and areas of reintroduction in Brazil (Lima, 2008). Only one site (located between sectors 2 and 3, to the northeast of the state of Rio Grande do Norte) was not sampled due to the absence of records of seagrass. Furthermore, were also analyzed sectors of smaller size corresponding to 5, 10, 20 and 40 km. At each one these sectors bibliographic and current records of seagrass and manatee were counted.

Two cluster analyses were performed to investigate the similarity among sectors. The first was based on bibliographic and current records of seagrass. The second was based on manatee occurrence determined by aerial sightings, stranding data and information from fisherman. The Bray-Curtis index was used as the similarity measure and the group average was used for the cluster mode. The analyses were performed using Primer 6.0 (Clarke and Gorlye, 2006).

Spearman rank correlation analysis (Zar, 1996) was used to relate records of seagrass and manatees at each sector (5, 10, 20, 40 and 70 km), as data presence/absence. This method of correlation analysis was chosen due to the non-linearity of relationships and non-normality and heteroscedascity of most records. All analyses were performed using the "R" language and environment, considering $\alpha = 0.05$ (R Development Core Team 2009, version 2.9).

RESULTS

Spatial distribution of seagrass

Seagrass was recorded in 41 of the 53 beaches mapped. Among these, 32 were seagrass beds and nine were fragments plants. The following species were found: *H. wrightii* (n = 35), *H. decipiens* (n = 1) and *R. maritima* (n = 1). Moreover, *Halodule wrightii* and *Halophila decipiens* were found coexisting in the same seagrass bed (n = 4) (Figure 2). *H. wrightii* was found predominantly in marine habitats (48.57%), whereas *H. decipiens* and *R. maritima* were found exclusively in estuaries and coastal lagoon, respectively. The most cases of *Halodule wrightii* and *Halophila decipiens* coexistence was in marine environments (75%). The distance of the seagrass beds from the coastline ranged from 0 to 7.6 km (mean: 1.28 km). Depths at low tide ranged from 0 to 10.2 m (mean: 1.28 m). The localization of more distant and deeper seagrass beds was only possible due to information acquired from local fishermen.

The spatial distribution of seagrass in the present study broadens information found in the literature on the occurrence of the species, with *H. wrightii* the most common and most widely distributed. The major "hot spots" for the occurrence of seagrass were sectors 5, 6 and 7 using current information and sectors 7 and 8 using bibliographic information (Figure 2).

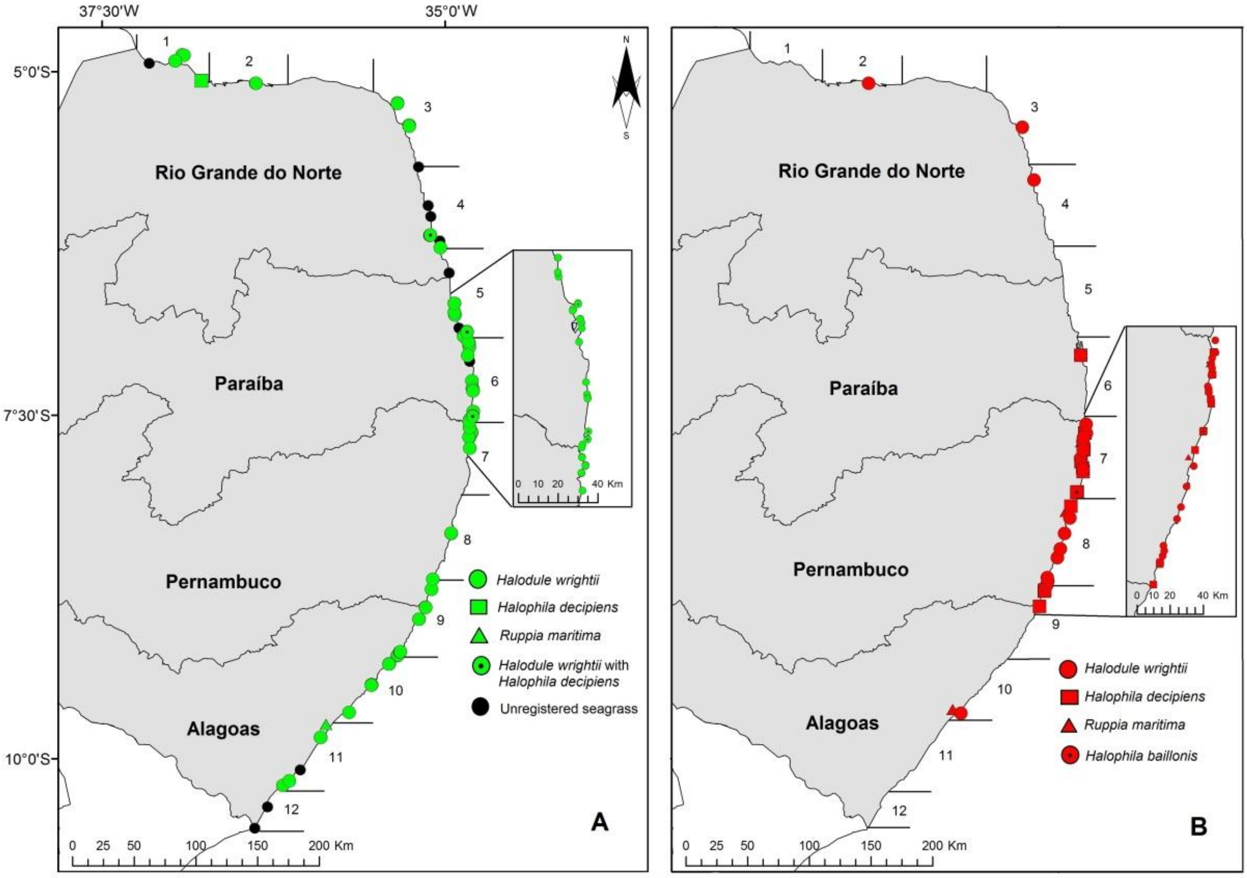

Figure 2. Distribution of seagrass in present study (A) and based on data from the literature (B) (Laborel-Deguen, 1963; Den Hartog, 1972; Oliveira-Filho *et al.*, 1983; Magalhães and Cazuza, 2005; Vieira, 2006; Reis, 2007; Silva, 2010; Silva *et al.*, 2012). The details show the areas with the greatest numbers of these plants.

Based on the occurrence of seagrass was possible to identify two groups of sites (similarity of 40%). Sector 12 was not grouped. The isolation of this sector was due to the absence of seagrass (confirmed in both the literature and present study). Sectors 7 and 8 were united by a greater number of bibliographic records of seagrass, with similarity greater than 60%. The remaining sectors were grouped (similarity around 50%) due to the small amount or absence of bibliographic records of seagrass records. One hundred percent similarity was found between sectors 3 and 4 as well as between sectors 1 and 11 (Figure 3).

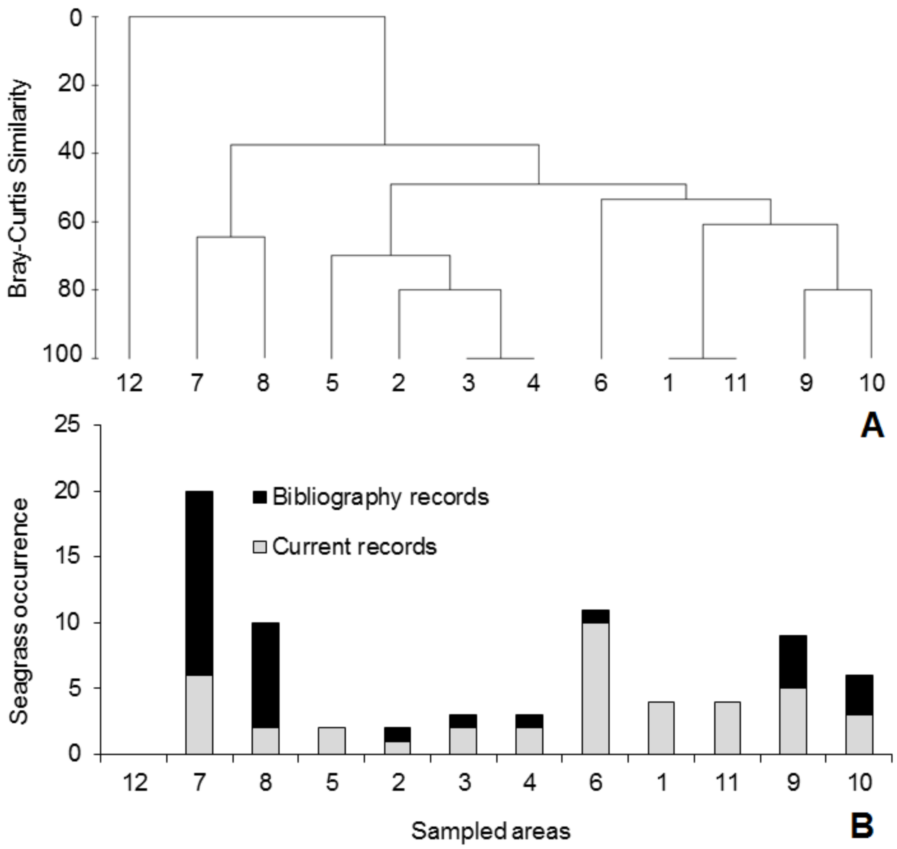

Figure 3. Bray-Curtis dendogram (A) and graph (B) of occurrence of seagrass in sampling sectors based on data from the literature and the present study.

Spatial distribution of Antillean manatee *versus* seagrass

In the analysis of the spatial distribution of manatees and seagrass, no significant correlations were found in any of the combinations tested, all sizes of sectors proposed, including the individual analysis between the Antillean manatees and "hot spot" sectors regarding the occurrence of seagrass. However, a total of 27 beaches had joint records of occurrence of manatees and seagrass. Aerial sightings, which were considered the most current data on the presence of *T. m. manatus* in the study area, occurred in 40.74% of the beaches with records of seagrass. Likewise, information from fishermen, which constituted the oldest records of the occurrence of Antillean manatees, occurred in 66.66% of the beaches with seagrass. The occurrence of both seagrass and stranded manatees was recorded on 29.63% of the beaches (Figure 4).

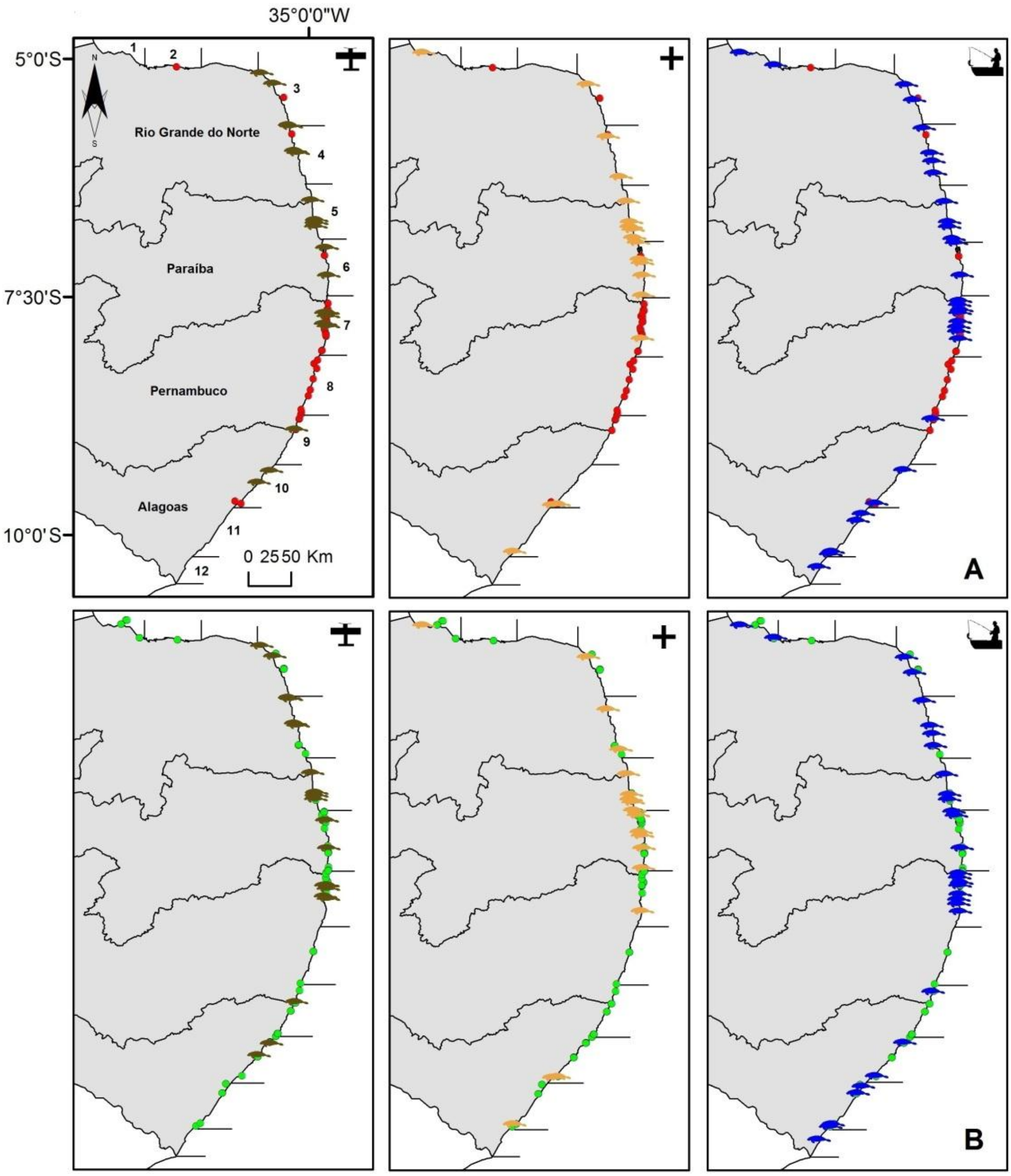

Figure 4. Spatial distribution of records of occurrence of seagrass in the study area based on data from the literature (A) and the present study (B) as well as the occurrence of manatees based on aerial sightings (A, B – airplane), stranding (A, B – cross) and information from fishermen (A, B – fisherman).

The clusters of sectors 2 and 12 had approximately 65% similarity regarding the occurrence of Antillean manatees due to the few records of this species and seagrass (Figure 5). Sector 8 was isolated due to the absence of manatees, which is contrary to the result for seagrass (Figure 4). The largest cluster, with similarity indices greater than 60%, encompasses areas with the greatest records of occurrence manatees. The cluster formed by sectors 1 and 11 is distinguished by the absence of aerial sightings. Stranded manatees occurred with greater frequency in sectors 5 and 6 (Figure 5), which also exhibited current occurrences of seagrass (Figure 3).

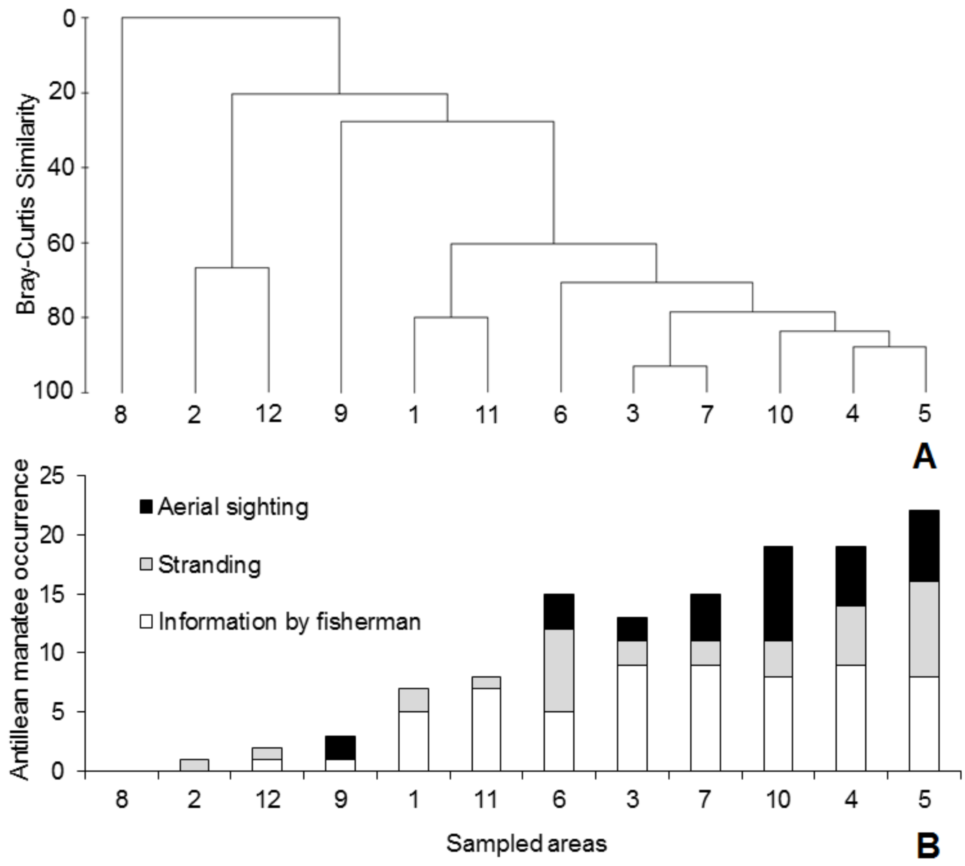

Figure 5. Bray-Curtis dendogram (A) and graph (B) of occurrence of manatees in sampling sectors based on aerial sightings, stranding and information from fisherman.

DISCUSSION

The present study updates information on the distribution seagrass beds in northeastern Brazil and is the first study to relate the occurrence of these plants to the Antillean manatee in the country. The mapping of seagrass increases the number of beaches with records of these plants by 69% in comparison to data found during previous surveys carried out in the region (Laborel-Deguen, 1963; Den Hartog, 1972; Oliveira-Filho *et al.*, 1983; Magalhães and Cazuza, 2005; Vieira, 2006; Reis, 2007; Silva, 2010; Silva *et al.*, 2012), demonstrating a greater knowledge of the distribution of seagrasses in this part of northeastern Brazil.

Despite the increase in the number of records seagrass, was not observed a statistic correlation between occurrence these plants and the manatees. This lack of correlation may be associated with the reduction in these foraging grounds due to countless human activities impactful in their habitats and/or the manatees' generalist habit of herbivory due to their possibly broad home range.

Most studies addressing the dependence of the manatees on seagrass beds in Brazil are restricted to information from specific sites and therefore classify the feeding preferences of this species in a qualitatively suggestive manner (Banks and Albuquerque-Neto, 1985; Lima, 2008; Costa, 2006). However, two studies stand out for direct indication of the diet of *T. m. manatus* in northeastern Brazil. In the first study, according to fishermen who hunted the species, the main food found in the intestinal tract of manatees killed were species *Halodule* sp. and *Halophila* sp. (Lima, 1997). In the other study, the diet of the Antillean manatee based on fecal and stomach samples collected in northeastern Brazil demonstrates that these mammals consume a diversity of food items, with a preference for macroalgae (Borges et al., 2008). This last may explain the lack of a direct correlation between T. m. manatus and seagrass beds in the present study. Moreover, large home ranges are suggested for reintroduced manatees specimens in northeastern Brazil (Lima, 2008), which could explain both the variety of food resources used by native animals as well as the low degree of dependence on local seagrass beds.

Characterization of seagrass habitats

The lack of previous information on the occurrence of seagrass, the extensive coastline and turbid coastal waters limited the localization and detailed characterization of seagrass habitats in the present study. Seagrass beds can be mapped using a range of approaches from *in situ* observations to remote sensing (McKenzie, 2003). Sampling can vary on a scale ranging from meters to kilometers and may include aerial photographs and satellite images (McKenzie *et al.*, 2001). In small areas with turbid waters, methods involving underwater monitoring with video cameras may overcome the difficulty in spotting seagrass beds (Adulyanukosol and Poovachiranon, 2006) However, for large areas, as in the present study large scale, seagrass bed identification studies are first needed, followed by more detailed studies on a smaller geographic scale adjusted to each type of environment.

The species of seagrass identified in the present study (*Halodule wrightii*, *Halophila decipiens* and *R. maritima*) represent the three genera of the five species of seagrass found along the coast of Brazil (Oliveira-Filho *et al.*, 1983). The present findings are in agreement with those reported in previous studies, which describe *H. wrightii* as the species with the widest distribution in the northeastern region, followed by *H. decipiens* (Laborel-Deguen, 1963; Olivieira-Filho *et al.*, 1983; Magalhães and Alves, 2002). The coexistence of two or more species in the same seagrass bed, as occurred with *Halodule wrightii* and *Halophila decipiens* in the present study, seems to be a common pattern in seagrass occurrence (Hemminga and Duarte, 2000). However this definition was contrary the past studies in the Paraíba e Pernambuco states, where *Halophila decipiens* completely eliminates *Halodule wrightii* when both grow in one place (Laborel-Deguen, 1963). This proves the importance of this study re-evaluating the occurrence patterns of seagrasses in northeastern Brazil.

In Brazil, the distribution of seagrass of these genera was previously described exclusively for the marine environment (Oliveira-Filho *et al.*, 1983). Recently, however, shoal grass has been described in estuarine environments in the state of Pernambuco (northeastern region of the country) (Reis, 2007). The presence of *Halodule wrightii* and *Halophila decipiens* within or near the estuaries mapped in the present study offers further evidence of the diversity of environments occupied by these species (Short *et al.*, 2007), which may also be exploited by the Antillean manatee. The type of habitat in which *R. maritima* was found (coastal lagoon complex) is common to species of this genus, which develop in calm waters with low salinity, as found in mangroves, estuaries and coastal lagoons (Creed, 2000; Short *et al.*, 2007).

Distribution of manatees *versus* seagrass

The use of coastal habitats and estuaries is also characteristic of the spatial distribution of the manatees for feeding throughout the world (Olivera-Gómez and Mellink, 2005; Lima, 2008; Rodas-Trejo *et al.*, 2008; Lima *et al.*, 2011). The greater number of occurrences of these mammals in estuaries with preserved mangroves in northeastern Brazil (Alves *et al.*, unpublished data) suggests greater use of these habitats for foraging activities. In such ecosystems, the availability of food items is considerably broader due to the additional provision of freshwater macrophytes, which make up part of the diet of the Antillean manatee in the region (Borges *et al.*, 2008). The opportunistic, generalist habits of herbivory of *T. m. manatus* (Hartman, 1979) lead to an increase in the spatial area of use and reduces the dependence of the species on seagrass beds. Sheltered areas in the interior of estuaries ensure the protection of these mammals and their food resources. Therefore, the diversified use of food items seems to be mainly associated with the type of resources available. For example, manatees in the northern portion of the Gulf of Mexico feed mainly on submerged and floating vegetation (Hartman, 1979; Smith, 1993), whereas manatees in South America and on the northern coast of the state of Florida (USA) commonly consume mangrove vegetation (Smethurst and Nietschmann, 1999; Borges *et al.*, 2008).

The greater number of records of seagrass in shallows coastal waters along the northeastern coast of Brazil (mean depth: 1.28 m) may be related to the shape and distance of the reefs in relation to the coastline. Reefs offer shelter from strong winds and currents and lower depths assist in the protection of seagrass from hydrodynamics, as reported for other locations (Laborel-Deguen, 1963; Kempf, 1970; Koch, 2001). In the state of Rio Grande do Norte, which has the widest continental shelf among the states mapped herein, the semi-arid climate and low degree of influence from estuaries with regard to nutrient content (Muehe and Garcez, 2005) make the coastal environment in this state less productive. Thus, the presence of offshore reef patches (Castro and Pires, 2001) likely allows the occurrence of seagrasss beds at greater distances from the shore (5.5 km to 7.6 km) and at greater depths (3 to 10.20 m), as reported by Silva (2010), by offering shelter and adequate water transparency, which are necessary to the survival of these plants. The maximum depths of occurrence of *H. wrightii*, *H. decipiens* and species of the genus *Ruppia* can reach 10 m (Laborel-Deguen, 1963), 85 m (Den Hartog, 1970) and 3 m (Creed, 2000), respectively.

The presence of the Antillean manatees at depths of 14.8 m and between 0.4 and 3.9 km from shore in northeastern Brazil (Borobia and Lodi, 1992; Paludo and Langguth, 2002; Costa, 2006; Alves, unpublished data) is similar to the patterns of occurrence of seagrass in the present study. In the state of Florida (USA), all species of seagrass are found at depths used by manatees during foraging activities (Smith, 1993). The localization of food resources is essential to the determination of the distribution of manatees (Hartman, 1979; Lefebvre *et al.*, 2000; Olivera-Gómez and Mellink, 2005; Rodas-Trejo *et al.*, 2008; Langtimm *et al.*, 2011).

The simultaneous records of occurrence of manatees and seagrass at 27 of the beaches studies herein (66% of beaches with seagrass) suggest the spatial use of these ecosystems, despite the lack of a significant correlation between them. It is possible that the occurrence of the Antillean manatee is more influenced by other characteristics of seagrass beds, such as extension and area of coverage as well as the density and biomass of the plants. However, this type of assessment requires an intensive effort on the local scale, which is unviable when working on a spatial scale as large as that used in the present study.

Another explanation for the lack of a correlation between the records of occurrence of seagrass and the Antillean manatee may be the potentially broad home range of these mammals. Although only conducted with captive animals that were reintroduced into the wild, studies on the home range of the Antillean manatee on the coast of northeastern Brazil report considerable diversity in the size of the area exploited by the different specimens observed (Lima, 2008). Some animals remain restricted to small home ranges, whereas others can travel as many as hundreds of kilometers in a few days, using resources in a broad geographic area (Lima op. cit.). This variable behavior in terms of the area use has been described for manatees in the state of Florida (USA), suggesting that long-distance migration allows the use of habitats that are favorable to foraging (Deutsch *et al.,* 2003). Considering observations of specimens that have been reintroduced into the wild, native animals are also thought to exhibit this variable behavior in terms of the extension of area use and it would therefore be natural not to observe records of the simultaneous occurrence of seagrass and the Antillean manatee.

The bibliographic data on the occurrence of seagrass serve as a comparative parameter in the assessment of the current state of conservation of seagrass beds. Itamaracá Island beach on the northern coast of the state of Pernambuco (sector 7) exemplifies this. The area in question has been described as one of the beaches with the greatest indices of *H. wrightii* biomass and density on the coast of Brazil (Kempf, 1970; Magalhães and Eskinazi-Leça, 2000; Magalhães and Alves, 2002). In the present study, however, this site was characterized by only small patches of seagrass beds. The impact of urban development, boat traffic, shellfish extraction and beach seine fishing activities may have contributed to this reduction (Pitanga *et al.*, 2012). However, it is likely that local extraction of approximately 20 tons per year of shoal grass for the feeding of Antillean manatees maintained in captivity at the Aquatic Mammal Center [Centro Mamíferos Aquáticos] beginning in the 1960s (Banks and Albuquerque-Neto, 1985; Magalhães and Alves, 2002) is a relevant factor and should be studied in details. In order to minimize the damage to these ecosystems, a seagrass collection protocol was created in northeastern Brazil (Pitanga *et al.*, in press), which has led to the interruption of plant collection when seagrass abundance is low. As this area is considered an important habitat for the Antillean manatee, with records of occurrence based on information from fishermen (Lima *et al.*, 2011) as well aerial sightings (Alves *et al.*, unpublished data), the reduction in seagrass coverage may compromise directly the foraging activities of this species. To support the conservation and further research in the area, worldwide studies on feeding ecology of manatees and dugongs, based on both aerial and nautical surveys, demonstrates that these animals are most frequent registered in areas with a greater abundance of seagrass (Provancha and Hall, 1991; Lefebvre *et al*., 2000; LaCommare *et al.*, 2008; Semeyn *et al*., 2011).

Among the species of seagrass identified in the present study, only *R. maritima* is not included in the diet of *T. m. manatus* in northeastern Brazil. However, according to fishermen and researchers of the Aquatic Mammal Center, this species is currently collected and offered to manatees in captivity in the northern portion of the state of Alagoas (sector 9) and serves as a potential food resource for manatees that have been reintroduced into the wild in the area. The consumption of this species is described for manatees in Chetumal Bay (Gulf of Mexico) (Castelblanco-Martínez *et al.*, 2009) and the state of Florida (USA) (Hartman, 1979; Reich and Worthy, 2006).

In the literature, the largest numbers of records of seagrass occurred in sectors 7 and 8, where studies have been carried out since the 1960s (Laborel-Deguen, 1963). Regarding the records in the current mapping, seagrass was identified in all sectors (except sector 12), with sector 6 standing out due to the greater number of records. These results indicate that sectors 6, 7 and 8 are the most important regarding the abundance of seagrass in the study area. Moreover, the findings underscore the importance of the state of Pernambuco to the execution of studies on seagrass over the years (Kempf, 1970; Reis, 2007; Freire *et al.*, 2008) as well as the need to increase efforts in previously unexplored areas, such as sites in the states of Alagoas and Paraíba, which had a high number of current records of seagrass.

On the coast of the states of Paraíba and Pernambuco (sectors 5 to 8), the high number of records of occurrence of both seagrass and the Antillean manatee indicate that this region is favorable to the survival of the species studied. These areas are characterized by a narrow continental shelf (Muehe and Garcez, 2005), reefs parallel to the shoreline (Castro and Pires, 2001) and a high degree of connectivity among coastal ecosystems (Pereira *et al.*, 2010; Silva-Falcão *et al.*, 2012), which makes this region rich in species diversity and protected from extreme oceanographic action.

CONCLUSION

The lack of a correlation between the records of occurrence of seagrass and the Antillean manatee may be associated to the reduction in these potential foraging grounds and/or the generalist habit of herbivory on the part of the Antillean manatee, with allows it to consume different types of food resources throughout its variable home range. Despite the lack of a significant correlation, the present findings emphasizes the importance of directing efforts toward reducing additional losses of seagrass beds in northeastern Brazil, especially in areas with the simultaneous occurrence of the Antillean manatee. Therefore, seagrass beds should be considered potential foraging grounds for this species, which justifies the efforts of future studies on these plants and as habitats for the release of captive manatees in northeastern Brazil. The mapping of areas of occurrence of seagrass beds is useful to the drafting of regional management plans and specific legislation to prevent the further decline of these ecosystems, which are important ecosystems for manatees throughout the world.

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Considerações finais

O conhecimento sobre o padrão de distribuição espacial da megafauna marinha costeira e a abundância de espécies criticamente ameaçadas de extinção, como o peixe-boi marinho, é fundamental para o estabelecimento de diretrizes de gestão e manejo dos principais ecossistemas funcionais aos animais. Essas pesquisas são consideradas prioritárias e urgentes pelos planos de ação de mamíferos aquáticos e tartarugas marinhas do Brasil.

As considerações aqui apresentadas sobre a distribuição espacial, a abundância e a caracterização dos habitats de ocorrência da megafauna marinha, na costa nordeste do Brasil, representam o primeiro passo para se compreender o padrão de distribuição e uso de habitats das espécies por meio de metodologia aérea, além de quantificar as ações antropogênicas negativas à manutenção do equilíbrio ecológico.

O emprego de levantamento aéreo piloto no norte de Alagoas, para avaliar a viabilidade dessa ferramenta em estudos de distribuição e estimativa populacional da megafauna no nordeste do Brasil, foi considerado satisfatório pelo número de peixes-bois, golfinhos e tartarugas observados e pelas condições ambientais favoráveis ao monitoramento, como elevada transparência da água e ventos amenos. No entanto, a elevada turbidez da água no interior dos estuários limitou a detecção dos animais, sendo esses ecossistemas retirados das futuras amostragens.

A quantificação e a análise em larga escala geográfica da distribuição espacial de peixes-bois, golfinhos e tartarugas, entre os estados do Piauí e Alagoas, evidenciaram a importância dos habitats costeiros e estuarinos e das atividades humanas para a ocorrência das espécies. Os estuários preservados e os recifes costeiros, analisados neste estudo, foram considerados ecossistemas de extrema importância na distribuição da megafauna, por serem propícios à reprodução, alimentação e descanso de diversos táxons, principalmente dos peixes-bois marinhos. No entanto, destacou-se a exploração desses habitats para atividades humanas diversas, como o desenvolvimento urbano e as atividades de pesca, que podem levar a redução de suas funcionalidades ecológicas de modo drástico, com a subsequente fragmentação dos habitats de ocorrência das espécies. A intensidade dos impactos antropogênicos costeiros vem, ao longo dos anos, acarretando a degradação ambiental de habitats essenciais à sobrevivência de diversas espécies da megafauna, consideradas organismos-chave para a conservação marinha. Ressaltou-se a importância das Áreas Marinhas Protegidas na conservação da megafauna, evidenciando a importância da criação de novos habitats protegidos para as espécies vulneráveis às ações humanas.

A abundância de peixes-bois ao longo da costa nordeste do Brasil, com pouco mais de 1000 indivíduos, representou os primeiros dados de tamanho populacional de *T. m. manatus* em distribuição mais ao sul da América, utilizando a ferramenta padrão de monitoramento aéreo. O arranjo estatístico adotado, com a incorporação de dados bibliográficos e avistagens aéreas dentro e fora do esforço amostral, foi necessário devido à provável dispersão das populações em uma grande extensão costeira, podendo induzir a erros de subestimativa de abundância. Por isso, é fundamental que novos estudos sejam realizados em áreas consideradas *hot spots* de abundância dos peixes-bois, para que haja um refinamento nas estimativas futuras.

Em particular, a não correlação dos registros de ocorrência das angiospermas marinhas com os peixes-bois sugere que as prováveis reduções desses habitats de forrageio possam interferir no padrão de distribuição da espécie. Além disso, o hábito herbívoro generalista dos animais, com a utilização de uma extensa e variável área de vida, propicia o acesso a diferentes fontes alimentares, não havendo, portanto, uma dependência direta dos animais com as plantas. O mapeamento das áreas de ocorrência das angiospermas marinhas é uma ferramenta útil para auxiliar na elaboração de planos regionais de gestão e legislação específica, visando o manejo e à prevenção do declínio desses ecossistemas, considerados fundamentais aos peixes-bois em todo o mundo.

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Aerial survey of manatees, dolphins and sea turtles off northeastern Brazil: Correlations with coastal features and human activities

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A B S T R A C T

The objective of the present study was to analyze the distribution of manatees, dolphins and sea turtles off northeastern Brazil through aerial surveys, relating them to specific habitats and human activities, with emphasis on marine protected areas (MPAs). Surveys were conducted between January and April 2010 at 150 m altitude and 140 km h^{-1}, using two independent observers. Strip transects were flown in a zigzag pattern. Transects covered 4026 km in more than 27 flight hours. A total of 36 sightings of manatees (*Trichechus manatus manatus*, 41 individuals), 28 of dolphins (Delphinidae, 78 individuals, including 10 *Sotalia guianensis*) and 256 of sea turtles (Cheloniidae, 286 individuals) were recorded. Manatees and sea turtles displayed solitary habits, while dolphins were commonly seen in groups. Manatees were positively correlated with sea turtles, probably due to their preference for sheltered shallow habitats with favorable conditions for foraging and resting. Furthermore, manatees showed a positive relationship with mangrove estuaries, and medium-sized coastal cities probably due to the intense urban development in many estuarine areas. Manatees and sea turtles were also positively correlated with boats, showing a severe threat for these species. Density of manatees was significantly higher within MPAs with preserved mangrove estuaries than in non-protected areas, while dolphins and sea turtles were observed in high densities MPAs with coral reefs. The elevated density of these organisms shows the vital importance of protecting and adequately managing unique ecosystems to ensure a sustainable future for the populations of severely threatened species.

1. Introduction

Marine mammals and sea turtles are considered key organisms for marine conservation in several parts of the world (Chatwin, 2007). Many populations of these animals occur in coastal areas that are intensively used by local people (Ojeda-Martínez et al., 2011), which make them vulnerable or threatened by extinction (IUCN, 2012). Marine protected areas (MPAs) are thus essential tools to ensure the conservation of these organisms and their ecosystems (Hooker and Gerber, 2004). However, the efficiency of MPAs should be based on thorough surveys (Ojeda-Martínez et al., 2011), which in effect, are often incipient or too small-scaled spatial (Witt et al., 2009; Panigada et al., 2011; Knip et al., 2012). Large-scale studies that quantitatively determine the correlations between endangered species, such as manatees, dolphins and sea turtles, coastal features and human activities are rare.

In northeast Brazilian waters, the most important threats to coastal biodiversity are fisheries and intensive urban development, thus turning this region one of the most vulnerable within South America (Chatwin, 2007). The most common marine mammals in the coastal zone off northeastern Brazil are the Antillean manatee (*Trichechus manatus manatus*) (Lima et al., 2011) and 19 species of cetaceans, among which the Guiana dolphin (*Sotalia guianensis*) is the most frequent species (Alvite et al., 2004). Also, this region occur five of the seven living species of sea turtles, the loggerhead (*Caretta caretta*), hawksbill (*Eretmochelys imbricata*), olive ridley

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(*Lepidochelys olivacea*), leatherback (*Dermochelys coriacea*), and the green turtle (*Chelonia mydas*), the most common species in Brazil (Marcovaldi and Marcovaldi, 1999). Antillean manatee is the most endangered aquatic mammal in Brazil (ICMBio, 2011), being classified internationally as ''endangered'' as *S. guianensis* is listed as ''data deficient'' (IUCN, 2012). All sea turtles mentioned are under threat, *D. coriacea* and *E. imbricata* being classified as ''critically endangered'', *C. caretta* and *C. mydas* as ''endangered'' and *L. olivacea* as ''vulnerable'' (IUCN, 2012).

Aerial surveys are considered a standard technique to assess distribution, abundance and habitat characteristics of marine mammals and sea turtles worldwide (e.g. Preen, 2004; Edwards et al., 2007; Certain et al., 2008; Witt et al., 2009; Jean et al., 2010; Langtimm et al., 2011). In Brazil, however, few studies have been based on aerial surveys (Secchi et al., 2001; Andriolo et al., 2006, 2010; Danilewicz et al., 2010; Zerbini et al., 2010, 2011; Wedekin, 2011). In the northeastern coast, only one single aerial survey of manatees was performed on a local scale off Ceará state (Costa, 2006).

The objective of the present study was to quantify and analyze the large-scale spatial distribution of manatees, dolphins and sea turtles off northeastern Brazil, in relation to habitat characteristics, current human activities, and the importance of MPAs for the conservation of these animals.

2. Materials and methods

2.1. Study area

The northern limit of the study area was the mouth of the Parnaíba River Delta, around Canárias Island (02°44′S, 41°47′W), Piauí State. The southern limit was the mouth of the São Francisco River (10°30′S, 36°24′W), located in Alagoas State (Fig. 1).

The northeastern coast of Brazil extends for approximately 3400 km and displays variety of environments such as beaches, dunes, cliffs, coral reefs, mangrove estuaries, and seagrass beds, each being governed by specific dynamics and anthropogenic vulnerabilities (Cunha, 2005; Muehe and Garcez, 2005). The continental shelf is 85 km wide in the north and narrows to 40 km in the southern part. Climate is tropical, with high temperatures and salinities, and low concentrations of nutrients, except for estuarine areas, where primary productivity and biomass are high (Muehe and Garcez, 2005).

There are four relevant Marine Protected Areas (MPAs) in this region, each with its specific conservation targets: ''Delta do Rio Parnaíba'' (manatees, mangroves, beaches, sand banks, estuaries, coastal grasslands, marshes, dunes, lakes and lagoons), ''Recifes de Corais'' (defined around the ''Parrachos de Maracajaú'' offshore coral reefs), ''Barra do Rio Mamanguape'' (manatees, mangroves,

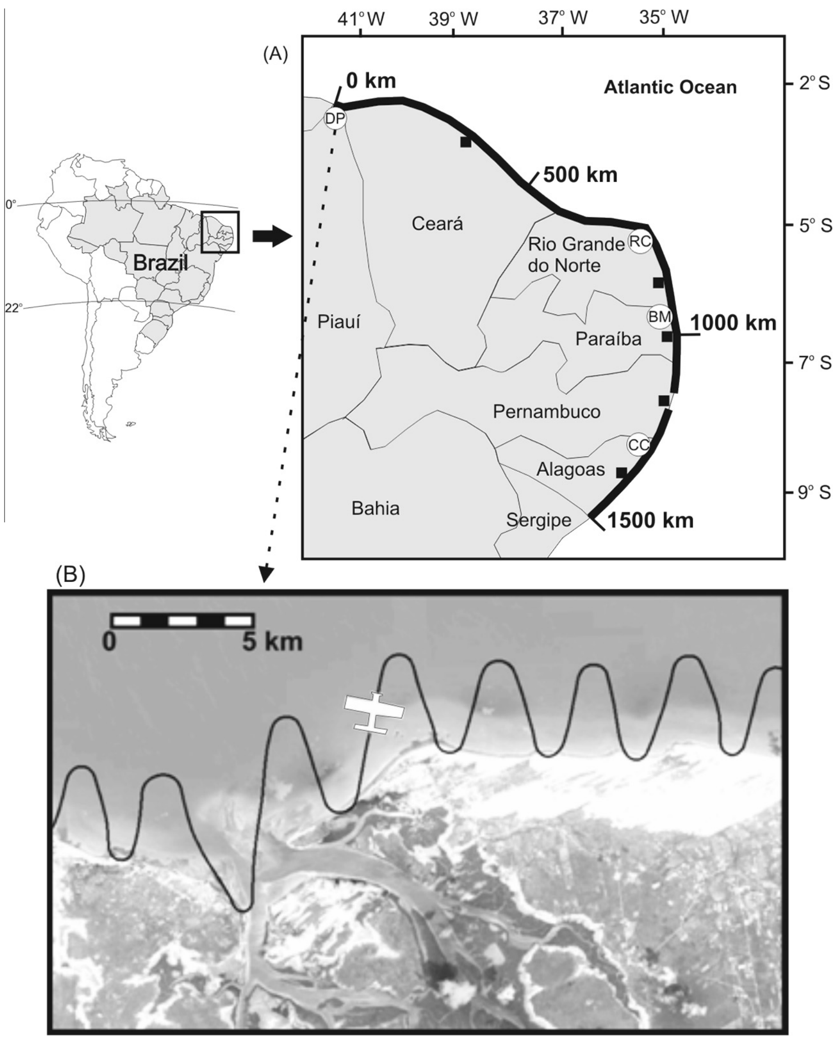

Fig. 1. Map of the study area between the states of Piauí and Alagoas, northeastern Brazil (a) showing the main Marine protected areas (DP – Delta do Rio Parnaíba, RC – Recifes de Corais, BM – Barra do Rio Mamanguape, CC – Costa dos Corais) and coastal cities (black squares). Inlet: Aerial transects in a zigzag pattern in the marine protected area Delta do Rio Parnaíba (b).

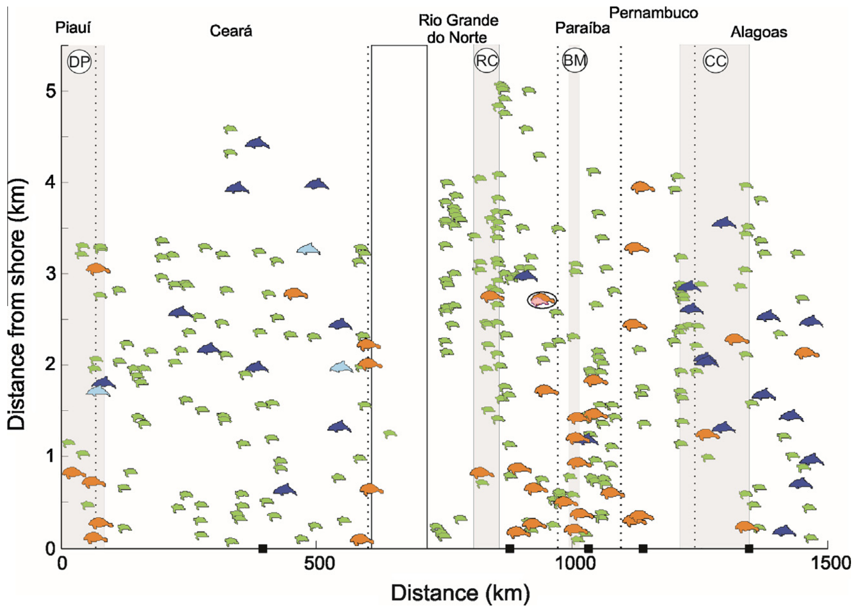

Fig. 2. Spatial distribution of manatees, dolphins and sea turtles between the states of Piauí and Alagoas, northeastern Brazil. Marine protected areas are indicated as gray rectangles (DP: Delta do Rio Parnaíba, RC: Recifes de Corais, BM: Barra do Rio Mamanguape, CC: Costa dos Corais). White rectangle: area with scarce sightings. A single sighting of manatee mother and calf is highlighted in a circle, and specimens of Sotalia guianensis in light blue color. Dotted lines: state borders. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

lagoons, sand banks) and "Costa dos Corais", Brazil's largest MPA (manatees, coral and sandstone reefs, estuarine mangroves) (Figs. 1 and 2). Their function is to protect and preserve natural resources and to promote sustainable development (FAO, 2011).

2.2. Aerial surveys

Aerial surveys were accomplished after a pilot study (Alves et al., 2013), using a single-engine Cessna 172 A aircraft with a high-wing design to facilitate viewing the sea surface. It was adapted with bubble windows at the rear (Zerbini et al., 2010, 2011), allowing for a wider viewing angle. Sampling was performed using the strip transect method, assuming that all animals within the strip (a band of fixed width on each side of the transect line) were detected and counted (Jolly, 1969). This method has been widely applied for marine mammals and sea turtles (Cardona et al., 2005; Certain et al., 2008; Witt et al., 2009; Langtimm et al., 2011; Katsanevakis et al., 2012).

A total 899 lines transects were made in a zigzag pattern, with an angle of turn of 40°, as to better cover the area and to maximize the flying effort (Secchi et al., 2001; Cardona et al., 2005; Andriolo et al., 2006, 2010). The surveyed areas extended from estuarine inlets, especially aiming at sightings of manatees, to the isobaths of 10–20 m (Fig. 1). The flight was standardized with 150 m altitude and 140 km h^{-1} speed, which is within the range found in other aerial surveys (Morales-Vela et al., 2000; Olivera-Gómez and Mellink, 2005; Roos et al., 2005; Costa, 2006; Langtimm et al., 2011). The widest sighting angle (approximately 65°) was determined with a clinometer during a test flight, and resulted in a sampled width of 321.7 m per observer (i.e., the total strip width equals 643.4 m) (Alves et al., 2013). Sea conditions were Beaufort Sea state 2 or less (Certain et al., 2008), characterized by flat or calm sea, and conditions of visibility and water transparency between "excellent" and "average". Aerial surveys were conducted during the dry season, between January and April 2010, in the morning period and at high tide, when the animals have a better access to shallow foraging areas such as macroalgal banks and seagrass beds (Paludo and Langguth, 2002; Olivera-Gómez and Mellink, 2005), and to reduce the potentially confusing effect of reefs and algae sandstone substrates that appear at low tide (Costa, 2006; Alves et al., 2013).

Observations were performed by two independent observers, located at each of the side windows to minimize perception bias (Langtimm et al., 2011), and who were wearing polarized sunglasses to minimize the effect of glare on the water surface and accentuate the color gradient. A registrar, in the front beside the pilot, used a GPS to indicate sighting points, in addition to the GPS of the plane, which recorded the route. The registrar also used two photographic cameras, a portable recorder, and nautical charts to compile the field records. Each flight lasted for less than 3 h per day.

All identifications were based on morphological and characteristic behavioral diagnostics. Calves corresponded to specimens measuring up to 1/3 of the adult size (Hartman, 1979). Two or more animals were defined as a group (Morales-Vela et al., 2000). In cases of doubtful sightings or imprecise counts, a circular flight around the sighting point was carried out to confirm identification (Morales-Vela et al., 2000; Langtimm et al., 2011).

Approximately 1500 km of coastline were flown over in six Brazilian states, totaling 4026 km along the zigzag path (Fig. 1). The total coverage area was 2590.2 km^2, calculated as the zigzag path multiplied by the strip width (643.4 m). The effective effort exceeded 27 flight hours in 11 days. A stretch of only 22 km coastline was not surveyed, due to traffic restrictions around the Recife international airport (Fig. 1).

2.3. Data analysis

Sighting data were transferred to GIS using the Arcmap software (version 9.2) and received identification numbers and coordinates. The data were plotted on nautical charts (1:300.000) to obtain isobaths and maximal depths for each sighting (with tide at 0.0 m).

A descriptive analysis of the large-scale distribution patterns of marine mammals and sea turtles was carried out in the different areas. The results were also used to perform statistical analyses of potential relationships between the sightings of these animals,

Table 1
Summary of the sightings of manatees, dolphins and sea turtles during aerial surveys in northeastern Brazil.

	Manatees	Dolphins	Sea turtles
Individuals	41	78	286
Sightings	36	28	256
Mean N/sighting	1.1	2.8	1.1
Maximum N/sighting	2	8	2
Positive segments[a]	29	24	127
Positive segments (%)[a]	10	8	43
Maximum N/segment[a]	3	10	10

[a] The coastline was divided into 294 segments of 5 km in length. Positive segments are those where sightings occurred.

human activities, and coastline features. For this purpose, the coastline under investigation was divided into 294 segments of 5 km length. For each segment, seven ecological and human parameters were examined. During flights, the following information of occurrence records was obtained for each segment: (1) animal abundance, (2) coastal zone occupation patterns (shrimp farms, salt works and ports), and (3) fishing and tourism activities (trawling boats, motor boats, sail boats, and rowing boats). Based on cartographic and bibliographic analysis, the following were diagnosed: (4) MPAs (“Delta do Rio Parnaíba”, “Recifes de Corais”, “Barra do Rio Mamanguape” and “Costa dos Corais”), (5) Reefs (Northern Beach Rocks, Offshore Reef Patches, Coastal Reef Lines) (Castro and Pires, 2001), (6) Estuarine mouths (complex, mangrove, partially obstructed sandy barrier/small: 0.01–0.05 km, intermediate: 0.06–0.1 km, large: above 0.1 km), and (7) coastal urban centers (small < 180 km^2, medium-sized: 180–840 km^2, large > 840 km^2) (IBGE, 2007).

Spearman rank correlation analysis (Zar, 1996) was used to test for significant correlations between human activities, coastline features, MPAs, and animal abundance per segment. This method of correlation analysis was chosen due to the non-linearity of relationships and non-normality and heteroscedascity of most distributions. All analyses were performed using the “R” language and environment at $\alpha = 0.05$ (R Development Core Team, 2009, version 2.9).

3. Results

3.1. Distribution of sightings

A total of 320 sightings of marine mammals and sea turtles were recorded during the surveys. Of these, 36 were sightings of Antillean manatees (41 individuals), 28 were sightings of dolphins (Delphinidae, 78 individuals), with 10 individuals identified as *S. guianensis*, and 256 were sightings of sea turtles (Cheloniidae, 286 individuals) (Fig. 2 and Table 1). Although it was generally possible to see head, carapace and fins of turtles on the surface, this was not sufficient for identification at species level. Fish were also spotted occasionally, including 22 sightings of individual flying fish, seven unidentified large schools, seven rays and two sharks.

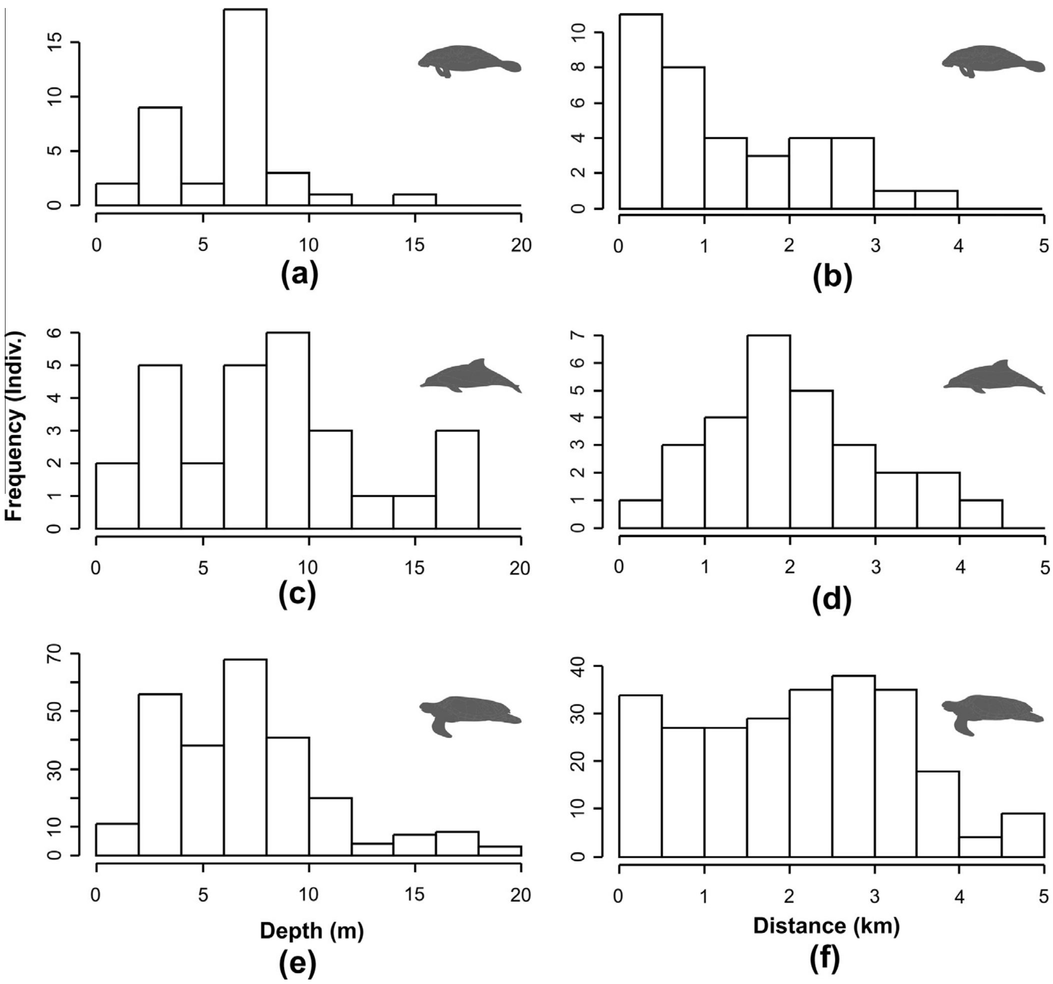

Fig. 3. Frequency histograms of depth (m) and distance from shore (km) at the sighting locations for manatees (a and b), dolphins (c and d), and sea turtles (e and f) in northeastern Brazil. Data are based on 27 h of aerial surveys carried out along the northeastern Brazilian coast from the states of Piauí to Alagoas.

Marine mammals and sea turtles were recorded throughout the study area, except along approximately 130 km of coastline around the western portion of the state of Rio Grande do Norte (Potiguar Basin), where only a single sea turtle sighting occurred (Fig. 2).

Manatees and sea turtles were most frequently observed as solitary animals (86.1% and 88.3%, respectively), or as groups of two adults. A pair of manatee mother and calf was sighted only once, at Barreta beach (06°06′S, 35°04′W, Rio Grande do Norte). Dolphins were generally found in groups (64.3%) composed of two to eight individuals (mean: 4.4 individuals per group) (Fig. 2 and Table 1).

Sightings of all three taxa were concentrated within 2–10 m depth (Fig. 3). Manatees were clearly concentrated in shallower areas, being most frequently sighted within 6–8 m depth, reaching a maximum local depth of 14.8 m. Regarding the distance from the coast, manatees were also clearly concentrated in areas closest to shore, being most frequently sighted at distances that ranged from only 0.01 to 3.9 km from the coast, with a continuous decrease in frequency toward offshore areas. Accordingly, this species showed the lowest mean distance from the coast, with only 1.2 km, as compared to 2.1 km for dolphins and for sea turtles. Dolphins showed maximum frequency at the 8–10 m isobath, and three sightings occurred within the 16–18 m isobaths. Dolphins showed a more offshore distribution (0.1–4.4 km from the coast), with higher frequencies in the central part of the surveyed area, at 1.5–2.0 km from the coast. Guiana dolphins were recorded between 2.1 and 9.2 m depth and between 1.6 and 3.2 km from the coast. The highest maximum values of depth and distance from the coast were recorded for sea turtles, with 18.5 m and 5 km, respectively, with high frequencies throughout the surveyed area (Figs. 2 and 3).

Spearman rank correlation analysis showed that manatees were positively correlated with sea turtles ($p = 0.032$, Table 2), while dolphins were not correlated with any of these groups.

3.2. Correlations of coastal features and human activities

Spearman rank correlation analysis detected several significant correlations of coastline features and human activities with the density of manatees, dolphins and sea turtles (Table 2). A significant positive correlation of manatee sightings with reef habitats was detected for "Northern Beach Rocks" ($p = 0.0089$). For sea turtles, sightings were also positively correlated with "Northern Beach Rocks" ($p = 0.0041$) and "Offshore Reef Patches" ($p = 0.0012$). A significant positive correlation ($p = 0.027$) was detected between the density of open, mangrove-lined estuaries and manatee sightings. Other estuarine types such as partially obstructed sand bar (barrier) estuaries or seasonally obstructed sand bar estuaries, which are both typical of coasts with sandy beaches, sand bars, sand banks, dunes, strong wave action and wind-driven currents, showed no correlation with the density of manatees. Dolphin sightings were positively correlated with large estuaries ($p = 0.027$) and mangroves ($p = 0.023$) (Table 2).

Manatee sightings were positively correlated with the presence of medium-sized cities ($p = 0.034$) and motor boats ($p = 0.011$). Sea turtles were positively correlated with the total number of fishing boats ($p = 0.030$) and with motorized boats ($p = 0.0017$). Shrimp farms, salt works and ports did not show any positive or negative correlations with any animals (Table 2).

3.3. Marine protected areas (MPAs)

Significant positive correlations with MPAs were detected for manatees, dolphins and sea turtles, and varied considerably between taxonomic groups and areas (Fig. 4 and Table 3). When considering all four MPAs and comparing sightings in these areas to areas outside MPAs, manatees were the only group to show significantly higher density within MPAs (Table 3). The average density of manatees within MPAs was 0.3 individuals per 5 km-segment (18 individuals along 310 km coastline), three times larger than in areas outside MPAs (0.1 individuals per 5 km-segment, 23 individuals along 1160 km coastline). This positive relationship was confirmed by Spearman correlation analysis ($p = 0.001$).

When considering individual MPAs, manatees showed significantly higher density in two estuarine MPAs ("Delta do Rio Parnaíba" and "Barra do Rio Mamanguape") than outside, with six and five manatees, respectively. Dolphins showed significantly higher density within the "Costa dos Corais" MPA (24 dolphins), while sea turtles showed significantly higher density within the "Recifes de Corais" MPA (41 sea turtles) (Fig. 4 and Table 3).

Table 2
Results of Spearman correlation analysis of sightings of manatees, dolphins, sea turtles, selected coastal features and human activities, based on 27 h of aerial surveys in northeastern Brazil. Values given in the table are "p" values of the analyses based on $N = 294$ coastal segments of 5 km in length.

	Spearman correlation		
	Manatees	Dolphins	Sea turtles
Manatees	–	n.s.	n.s.
Dolphins	n.s.	–	n.s.
Sea turtles	0.032	n.s.	–
Reefs			
Northern Beach Rocks	0.0089	n.s.	0.0041
Offshore Reef Patches	n.s.	n.s.	0.0012
Coastal Reef Lines	n.s.	n.s.	n.s.
Estuarine mouths			
Estuaries (all)	n.s.	n.s.	n.s.
Small	n.s.	n.s.	n.s.
Medium	n.s.	n.s.	n.s.
Large	n.s.	0.027	n.s.
Complex	n.s.	n.s.	n.s.
Mangrove	0.027	0.023	n.s.
Sandy barrier	n.s.	n.s.	n.s.
Land use			
Shrimp farms	n.s.	n.s.	n.s.
Salt works	n.s.	n.s.	n.s.
Ports	n.s.	n.s.	n.s.
Cities (all)	n.s.	n.s.	n.s.
Small	n.s.	n.s.	n.s.
Medium	0.034	n.s.	n.s.
Large	n.s.	n.s.	n.s.
Fishing and tourism boats			
Boats (all)	n.s.	n.s.	0.030
Trawling	n.s.	n.s.	n.s.
Motor	0.011	n.s.	0.0017
Sail	n.s.	n.s.	n.s.
Rowing	n.s.	n.s.	n.s.

n.s.: not significant at $\alpha = 0.05$.

4. Discussion

The data generated by the hitherto largest effort to quantify and correlate the distribution of manatees, dolphins and sea turtles in northeast Brazil yielded important new insights into the situation of these taxon's.

This study revealed a wide distribution of manatees, dolphins and sea turtles, except for a single area (the Potiguar Basin), probably due to specific hydrographic features and anthropogenic factors in this area. The present data showed that some species were associated with each other and with coastal features, such as estuaries and reefs. The important role of MPAs was corroborated by the high densities of these animals. One alarming finding was the association of manatees and sea turtles with motorized fishing boats and coastal cities, which is a relevant conservation issue.

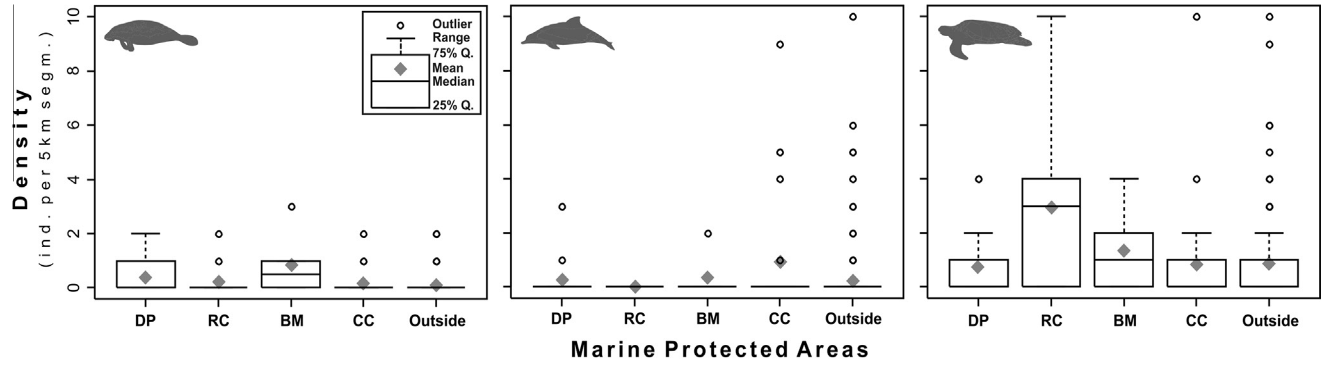

Fig. 4. Density of manatees (left), dolphins (center) and sea turtles (right) in marine protected areas in northeastern Brazil (DP: Delta do Rio Parnaíba, RC: Recifes de Corais, BM: Barra do Rio Mamanguape, CC: Costa dos Corais, Outside: areas outside marine protected areas). Data are based on 27 h of aerial surveys from the states of Piauí to Alagoas. *N* = 294 coastal segments of 5 km length.

Table 3
Marine protected areas (MPAs) in northeastern Brazil and total sightings of manatees, dolphins and sea turtles. Data are based on 27 h of aerial surveys. *N* = 294 coastal segments of 5 km length. Values given in the table are total number of organisms (N) and density (N per km coastline).

MPAs	Area (km^2/segment)	Main habitat	N/Density per segment			Spearman correlation		
			Manatees	Dolphins	Sea turtles	Manatees	Dolphins	Sea turtles
Delta do Rio Parnaíba	3.14/16	Extensive Mangroves	6/0.4	4/0.3	12/0.8	0.004	n.s.	n.s.
Recifes de Corais	1.8/14	Offshore Reef Patches	3/0.2	0/0.0	41/2.9	n.s.	n.s.	0.0008
Barra do Rio Mamanguape	0.15/6	Coastal Reef Lines	5/0.8	2/0.3	8/1.3	0.0007	n.s.	n.s.
Costa dos Corais	4.14/26	Coastal Reef Lines	4/0.2	24/0.9	22/0.8	n.s.	0.024	n.s.
All MPAs	Total: 9.23/62		18/0.3	30/0.5	83/1.3	0.001	n.s.	n.s.
Outside MPAs	Total: −/232		23/0.1	48/0.2	203/0.9			

n.s: not significant at $\alpha = 0.05$.

4.1. Spatial distribution

Manatees, dolphins and sea turtles occurred more or less continuously along the study area. The only extensive area with virtually no sightings of animals was the Potiguar Basin, located at the northwestern coast of Rio Grande do Norte state. This region presents extremely harsh conditions due to the high energy of winds, waves and tides, with strong alongshore currents in westerly direction (Silva and Amaro, 2008). It is also considered one of the most oligotrophic regions of Brazil and has the lowest estuarine influence of the entire coastline, with virtually no freshwater input (Júnior et al., 2010). Furthermore, intensive resource exploration and coastal degradation have persisted for many decades due to the activities of the offshore oil industry, salt works and shrimp farming (Silva and Amaro, 2008), as observed during the survey. Seismic surveys associated with the offshore industry may cause severe physiological and behavioral changes in several organisms, especially in marine mammals (McCauley et al., 2000; Early, 2001). However, the present study and earlier assessments (Parente et al., 2006; Parente and Araújo, 2011) are still insufficient to evaluate the influence of offshore activities on the distribution and behavior of marine mammals and sea turtles in northeastern Brazil. The distribution of manatees, that forage on macrophytes and seagrass beds and are known to actively seek freshwater to drink, seems to be fundamentally determined by the availability of freshwater and food sources, and shelter in estuaries for reproduction (Hartman, 1979; Reynolds et al., 2009). However, the extreme harshness of the dynamic coastline, the scarcity or absence of freshwater sources and foods, the scarce and inaccessible sand bar estuaries, the absence of any shelter provided by barrier reefs and the intense human exploration may together explain the absence of manatees in the Potiguar Basin. This area and the eastern portion of the state of Ceará show the largest numbers of cases of manatee strandings, especially neonates, probably related to these factors (Parente et al., 2004; Meirelles, 2008; Lima et al., 2011).

The coexistence of manatees and sea turtles found in this study has been recorded in various other locations worldwide (Fertl and Fulling, 2007). This positive relationship is a function of the ecological requirements of both taxa, which may share common shelter and coastal foraging areas. Herbivory is a common trait among sirenians and *C. mydas*, feeding on seagrass beds and macroalgae (Hartman, 1979; Borges et al., 2008; López-Mendilaharsu et al., 2008; Guebert-Bartholo et al., 2011). There is a correlation of both taxa and fishing boats, both being concentrated close to shore, in the same, productive areas. This proximity implies a high risk of collision, accidental capture and habitat destruction, mainly by shrimp trawlers (Borges et al., 2007; Meirelles, 2008; Eguchi et al., 2010; Guebert-Bartholo et al., 2011). In Florida, most of the reported mortalities and serious mutilations of manatees (*T. m. latirostris*) are due to collisions with motor boats (Nowacek et al., 2004; Rommel et al., 2007). In northeastern Brazil, previous reports indicate that the interaction of *T. m. manatus* with motor boat traffic represents a direct threat for this species, causing lesions and deaths (Borges et al., 2007; Meirelles, 2008). In San Diego Bay, an intensively urbanized coastal area, frequent strandings of green turtles have been reported, probably related to collisions with motor boats (Eguchi et al., 2010).

4.1.1. Antillean manatee

Studies on the distribution of manatees in Brazil have been conducted since the 80s, based on information from fishermen and stranding data (Parente et al., 2004; Luna et al., 2008; Lima et al., 2011). Only one single study in the eastern part of Ceará state used an aerial survey, however with difficulties associated to the observation of these animals in turbid waters during the rainy season and flight logistics (Costa, 2006). Conversely, the aerial methodology used in this study was very favorable for the detection of manatees, highlighting its importance for the conservation of this endangered species.

The detection of some manatees has been hampered due to the following factors: (1) solitary habit, (2) barely visible exposure on the surface, and (3) cryptic brownish color surrounded by turbid waters near estuaries. These limitations may make counting and identification inaccurate (Edwards et al., 2007), one alternative being the use of a side-scan sonar (Gonzalez-Socoloske et al., 2009). During periods of cold weather, aerial surveys conducted in Florida uncovered large groups of manatees in areas of warm and transparent water, which facilitated the counting (Edwards et al., 2007). In the study area, the almost constant temperature of coastal waters prevents this type of phenomenon (Lima et al., 2011).

The social structure of manatees, predominantly solitary or in couples, was also found in other studies in this region (Borobia and Lodi, 1992; Paludo and Langguth, 2002; Costa, 2006). The presence of calves on Barreta beach, Rio Grande do Norte state, was also recorded by other researchers (Oliveira et al., 1990; Paludo, 1998), suggesting the existence of a nursery area. The mating period of manatees in northeastern Brazil is the dry season, from October to May (Paludo, 1998; Parente et al., 2004; Meirelles, 2008; Lima et al., 2011). The observation of a single calf only within the reproductive season (March) during the aerial survey may be considered worrisome for the conservation of this species, which is threatened by the destruction and degradation of its estuaries (Parente et al., 2004; Meirelles, 2008). Furthermore, these few records may be due to lack of sampling within the estuaries, which are ecosystems using for reproduction and parental care of manatees (Hartman, 1979; Lima et al., 2011), or detection difficulty related smaller size.

The presence of manatees in shallow coastal waters, generally with less than 12 m depth, seems to be related to the availability of food sources (Hartman, 1979; Olivera-Gómez and Mellink, 2005; Rodas-Trejo et al., 2008; Langtimm et al., 2011). Furthermore, these are often shallow sheltered sites that allow animals to spend less energy in respiratory intervals (Smethurst and Nietschmann, 1999; Bacchus et al., 2009). The access to shallow foraging areas at high tide only introduces additional variability to the depth range of manatees. In previous studies conducted in northeastern Brazil with observations from shore or on boats, water depth of manatee sightings varied between only 0.4 and 5.6 m (Borobia and Lodi, 1992; Paludo and Langguth, 2002; Costa, 2006), which is much shallower than the range observed in our study (most frequently within 6–8 m, reaching 14.8 m). This difference is probably due to the more efficient coverage of deeper waters in this aerial survey as compared to earlier studies. The most common seagrass in this region, Halodule wrightii, which is considered one of the main food sources for this species (Borges et al., 2008; Lima et al., 2011), is found from the intertidal zone down to 10 m depth (Laborel-Deguen, 1963).

Furthermore, the occurrence of manatees near well-preserved mangrove estuaries located in the northern part of the study area reflects the use of these types of habitats for breeding and foraging (Olivera-Gómez and Mellink, 2005; Rodas-Trejo et al., 2008; Lima et al., 2011). In many other estuaries surveyed in this study, the visible deforestation of mangrove vegetation due to the expansion of shrimp farms, salt works, and urbanization has caused the closing of estuaries with sand bars, hampering the access by manatees (Lima et al., 2011).

The positive correlation between manatees and medium-sized cities highlights the intense human occupation of the coastal zone around estuarine and sheltered areas that are important for this species. The attractiveness of bays and estuaries for human populations in Brazil resulted in a long process of intense urban development, fisheries, ports, industries and recreational activities in these areas, which are major threats for coastal ecosystems (Cunha, 2005) and many endangered species.

4.1.2. Dolphins

Even under ideal conditions of water transparency and swimming in groups, the identification of dolphins was difficult due to their quick movements in opposition to the speed of the aircraft. The small morphological variations between some cetaceans make aerial identification difficult (Preen, 2004). *S. guianensis* was diagnosed by the morphology of the rostrum and melon, pink–gray coloration and its triangular dorsal fin (Flores, 2002).

Groups of two to eight Guiana dolphins found in this study are commonly observed in northeastern Brazil (Araújo et al., 2001, 2008), while groups of this species may reach 150 specimens in the southern region (Flores, 2002), where waters are more productive due to seasonal upwelling (Muehe and Garcez, 2005). This explains the tendency of large groups to inhabit the southern and southeastern region, and small groups to occur in the northeastern region (Araújo et al., 2008).

The higher frequency of dolphins in deep waters, reaching a depth of 17.1 m and at a distance of up to 4.4 km from the coast in the present study, is similar to findings of previous studies on Guiana dolphins in Brazil, with up to 16 m depth and four km from the coast (Bazzalo et al., 2008; Wedekin et al., 2010). Previous studies showed that the bathymetry is important for the distributions of dolphins, mainly due to the depth-related distribution of prey (Baumgartner et al., 2001; Certain et al., 2008). This may reflect their search for food, corroborated by the migration of fish to deeper areas and away from the coast due to environmental perturbations in nearshore reef ecosystems in northeastern Brazil (Frédou and Ferreira, 2005). The search of these animals for more offshore areas may suggest a strategy to find favorable foraging areas, and possibly to avoid the intense coastal artisanal fishing activity recorded in this study. Accidental capture in fishing nets is a main threat for Guiana dolphins in Ceará state, cetacean species with highest (62%) incidence of strandings (Meirelles et al., 2009). This species and bottlenose dolphins (*Tursiops truncatus*) have foraging as a determinant factor for habitat choice (Hastie et al., 2004; Wedekin et al., 2010).

The occurrence of dolphins close to estuaries may indicate the search for food sources that are associated to these important nurseries for crustaceans and fish, both for resident species and for marine migratory species (Blaber, 2000). In Brazil, *S. guianensis* frequently occurs in estuarine areas and their surroundings (Flores, 2002; Araújo et al., 2008), suggesting that many unidentified specimens are probably of this species.

4.1.3. Sea turtles

Sea turtles were the most abundant taxon in this study. This is the first aerial survey of sea turtles carried out in Brazil. This methodology has been shown to provide important abundance estimates of sea turtle populations, especially in foraging or nesting grounds (Epperly et al., 1995; Cardona et al., 2005; Roos et al., 2005; Witt et al., 2009).

Individuals from the family Cheloniidae have been identified by the greenish-brown shell coloration, that is distinct from Dermochelyidae, which have a black color and very prominent ridges. The detection of the specimens, even in moderate visibility conditions, occurred through the total body exposure and turbulence at the water surface caused by the fins during the dive, which could reveal the number of animals (McClellan, 1996). However, flight altitude and speed, and escape behavior caused by the noise of the aircraft, made the identification at species level difficult, as observed in other studies (Shoop and Kenney, 1992; Epperly et al., 1995; McClellan, 1996). The smaller size of sea turtles in relation to other taxa studied also contributed as a limiting factor for identification to species level. Previous studies based on aerial surveys suggested a minimum size of 30 (Epperly et al., 1995) to 75 cm (Shoop and Kenney, 1992) carapace width for a specific diagnosis of sea turtles. Conversely, in the present study, identification to species level was not possible even for large-sized specimens.

The high number of solitary sea turtles sighted could indicate that the areas studied did not include major breeding grounds, since mating occurs in large groups in shallow waters (Hirth, 1980). In Brazil, green turtles, for example, may be sighted in groups during the reproductive period from September to March, which includes the study period. This species uses oceanic islands for mating, being rarely sighted in large groups along the continental northeastern coast of Brazil. The northeastern coast harbors 12 of the 19 main breeding areas for sea turtles in country (Marcovaldi and Marcovaldi, 1999). However, none is included in the study area, although nesting areas along the coast have been recorded. Aerial and snorkel census techniques for estimating green turtle abundance in foraging areas identified small groups of 4–5 individuals, that apparently were randomly distributed (Roos et al., 2005). It is therefore likely that the study area is mainly used for feeding and resting.

In this study, varying depths (0.9–18.5 m) and distances from the coast (from the coastline up to 5 km) occupied by sea turtles showed the diversity of existing habitats. Their spatial distribution can be influenced by physical and biological parameters, and depth distribution is closely related to their feeding, breeding and resting behavior (Griffin and Griffin, 2003; Roos et al., 2005; Witt et al., 2010). In a previous study in Brazil, green turtles were sighted during scuba dives feeding at 6 m depth (Guebert-Bartholo et al., 2011), and swimming in areas with vegetation at 10 m depth and up to 10 km distant from the coast (Parente et al., 2006). These numbers are within the range recorded in this study, suggesting the occurrence of important foraging areas in northeastern Brazil.

The positive correlation of sea turtles with reef formations such as Northern Beach Rocks and Offshore Reef Patches, as observed by the high density of individuals in the MPA "Recifes de Coral" may be intimately related to the search for shallow sheltered areas and for areas with abundant macroalgae that grow on sandstone substrates. Likewise, an aerial survey carried out in Western Australia revealed a higher density of sea turtles in reef areas (Preen et al., 1997). In a study conducted in the South-West Indian Ocean, the distribution of these animals close to coral reefs and on the outer reef slopes was explained by the availability of shelter and food (Jean et al., 2010), similarly to the findings of the present study.

4.2. Marine protected areas (MPAs)

The high density of manatees in the MPAs "Delta do Rio Parnaíba" and "Barra do Rio Mamanguape" highlights the importance of these areas for the protection of this species and its habitats. These areas are mainly composed of a complex deltaic environment with well-preserved mangroves ("Delta do Rio Parnaíba") or estuarine mangroves with adjacent coastal reef lines ("Barra do Rio Mamanguape"), allowing for the occurrence of groups of manatees in sheltered, well-preserved areas and an open access to upstream environments for reproduction and resting (Borobia and Lodi, 1992; Lima et al., 2011). In the Persian Gulf, areas with high densities of dugongs and sea turtles were related to habitats that are rich in seagrass beds and coral reefs, and were chosen for the establishment of MPAs (Preen, 2004).

The occurrence of dolphins and sea turtles in MPAs characterized by linear coastal reef formations can ensure sheltered areas for foraging and resting. The MPA "Recifes de Coral", with high numbers of sea turtle sightings, has coastal and offshore reefs, as well as seagrass beds and banks of macroalgae, which likely represent food sources for these animals (Guebert-Bartholo et al., 2011). In the MPA "Costa dos Corais", the configuration of a large-scale barrier reef may allow for higher food availability and facilitate fish capture strategies by dolphins. The use of specific foraging techniques is commonplace for some species of delphinids, such as the bottlenose dolphin, that adapt its distribution patterns towards habitats that are favorable for prey capture (Hastie et al., 2004; Torres and Read, 2009). In Brazil, Guiana dolphins feed preferentially in bays, barrier reefs and estuaries, where they can direct fish schools to shallower waters (Araújo et al., 2001; Rossi-Santos and Flores, 2009). Such areas are widely found in the MPA "Costa dos Corais" (FAO, 2011).

It is noteworthy that there is a captive manatee reintroduction program within the MPA "Costa dos Corais", located in the northern part of the state of Alagoas. This very successful program has possibly provided an increase of the manatee population in this area (ICMBio, 2011). However, proximity and easy access of human populations to reef areas found in the study can directly affect the biological communities (Castro and Pires, 2001). Habitat loss and the degradation of feeding areas for sea turtles are a potential cause of population decline (López-Mendilaharsu et al., 2008; Guebert-Bartholo et al., 2011) and the presence of motor boat traffic and trawling can cause behavioral changes in dolphins (Constantine et al., 2004; Wedekin et al., 2010; Carrera et al., 2008).

The results of the present study cannot be used to test whether the existence of MPAs increases the density of endangered species in these areas, as in other studies (Witt et al., 2009; Panigada et al., 2011; Knip et al., 2012). All MPAs were delineated around special coastal features, such as outstandingly large or exceptionally well-preserved estuaries and barrier reefs, which create favorable and essential habitats for these and many other species. Rather than proving the effect of MPAs, the elevated density of these organisms shows the vital importance of protecting and adequately managing such unique ecosystems to ensure a sustainable future for the populations of severely threatened species.

5. Conclusions

The spatial distributions of manatees, dolphins and sea turtles show the different types of behavior of these species and the variety of ecosystems along the coast, with a preference for well-preserved foraging and resting habitats.

In northeastern Brazil, aerial monitoring in areas of occurrence of marine mammals and sea turtles, that are susceptible to habitat loss, can encourage the development of management, environmental conservation and recovery programs. The diagnosis and monitoring of ecosystems are essential for the survival of marine biodiversity, highlighting the role of MPAs for the protection of ecosystems and species.

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