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# Long-term spatiotemporal distribution, abundance, and priority areas for manatees and calves (*Trichechus manatus* Sirenia: Trichechidae) in Guatemala

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**ABSTRACT**

**Introduction:** The Antillean manatee (*Trichechus manatus manatus*) is an endangered species found throughout the Caribbean, and the coastal waters of Central and northeastern South America. Their low numbers are the result of a variety of human-related pressures. A small population of manatees has been identified in Guatemala; however, their spatial and temporal dynamics remain unclear.

**Objective:** To examine long-term trends in the spatiotemporal distribution and abundance of manatees in Guatemala. This included identification of priority areas for manatees including the presence of calves, assessing whether distribution areas are inside protected areas, and studying the relationship between manatee sightings and human activities.

**Methods:** Nine years of standardized aerial surveys were conducted along the Atlantic coast (1992, 2005-2008, 2010-2011, 2014, 2022). Quantitative approaches to detect priority areas, specifically the Kernel density estimation and the Getis-Ord Gi* statistic, were used in the spatiotemporal analysis. A Spearman rank correlation analysis tested for significant correlations between human activities, coastline topographies, and manatee numbers along coastline segments. Manatee abundance across years, survey sections, and protected areas were also examined.

**Results:** A total of 293 sightings and 518 manatees were observed including 476 adults (92 %) and 42 calves (8 %). Manatees were most frequently observed as solitary individuals (60 %). Most manatee (61 %) and calf (68 %) sightings occurred inside protected areas where several priority areas were identified. The two priority areas were Refugio de Vida Silvestre Bocas del Polochic (Bocas del Polochic) and Refugio de Vida Silvestre Punta de Manabique, which were identified as important manatee habitats in 1992. Bocas del Polochic had the highest manatee abundance of all protected areas ($p < 0.05$). However, a shift in manatee distribution was recorded in 2014, although the cause is unclear. No annual significant differences in manatee abundance were found over time ($p = 1.0$), but significant differences in abundance were detected between survey sections and protected areas ($p < 0.05$). Manatee numbers had positive significant correlations with ecological and human parameters. The highest correlation was between manatees and rivers ($p < 0.01$), and the weakest correlation was between manatees, motorboats, and fishing nets ($p < 0.01$).

**Conclusions:** The results indicate that the local manatee population remained relatively stable for over 20 years, although changes in overall distribution were noted. It is unclear if the changes are temporary or permanent. As a sentinel species, manatee distribution shifts can be used as early warnings about the health of the environment and can depict current or potential impacts on individual- and population-level animal health.

**Key words:** Antillean manatee; mammal; conservation; endangered species; Central America.

**RESUMEN**

**Distribución espacio-temporal a largo plazo, abundancia y áreas prioritarias para manatíes y crías (*Trichechus manatus* Sirenia: Trichechidae) en Guatemala**

**Introducción:** El manatí antillano (*Trichechus manatus manatus*) es una especie en peligro de extinción que se encuentra en todo el Caribe y las aguas costeras de Centro América y noreste de América del Sur. Su bajo número es el resultado de una variedad de presiones relacionadas con los humanos. Se ha identificado una pequeña población de manatíes en Guatemala; sin embargo, su dinámica espacial y temporal sigue sin estar clara.
**Objetivo:** Examinar las tendencias a largo plazo en la distribución espacio-temporal y la abundancia de los manatíes en Guatemala. Esto incluyó la identificación de áreas prioritarias para los manatíes y las crías, la evaluación de si las áreas de distribución se encuentran dentro de áreas protegidas y el estudio de la relación entre los avistamientos de manatíes y las actividades humanas.
**Métodos:** Se realizaron nueve años de censos aéreos estandarizados a lo largo de la costa atlántica (1992, 2005-2008, 2010-2011, 2014, y 2022). En el análisis espacio-temporal se utilizaron métodos cuantitativos para detectar áreas prioritarias, específicamente la estimación de la densidad Kernel y el estadístico Getis-Ord Gi*. Un análisis de correlación de rangos de Spearman probó correlaciones significativas entre las actividades humanas, las topografías costeras y el número de manatíes a lo largo de los segmentos de la costa. También se examinó la abundancia de manatíes a lo largo de los años, las secciones de estudio y las áreas protegidas.
**Resultados:** Se observaron un total de 293 avistamientos y 518 manatíes, incluidos 476 adultos (92 %) y 42 crías (8 %). Los manatíes se observaron con mayor frecuencia como individuos solitarios (61%). La mayoría de los avistamientos de manatíes (61 %) y crías (68 %) ocurrieron dentro de áreas protegidas donde se identificaron varias áreas prioritarias. Las dos áreas prioritarias fueron el Refugio de Vida Silvestre Bocas del Polochic (Bocas del Polochic) y el Refugio de Vida Silvestre Punta de Manabique, que fueron identificados como importantes hábitats para manatíes en 1992. Bocas del Polochic tenía la mayor abundancia de manatíes de todas las áreas protegidas ($p < 0.05$). Sin embargo, se registró un cambio en la distribución del manatí en 2014, aunque la causa no está clara. No se encontraron diferencias significativas anuales en la abundancia de manatíes a lo largo del tiempo ($p = 1.0$), pero se detectaron diferencias significativas en la abundancia entre las secciones de estudio y las áreas protegidas ($p < 0.05$). El número de manatíes tuvo correlaciones positivas significativas con parámetros ecológicos y humanos. La correlación más alta fue entre los manatíes y los ríos ($p < 0.01$), y la correlación más baja fue entre los manatíes y las lanchas motoras y las redes de pesca ($p < 0.01$).
**Conclusiones:** Los resultados indican que la población local de manatíes se mantuvo relativamente estable durante más de 20 años, aunque se observaron cambios en la distribución general. No está claro si estos cambios son temporales o permanentes. Como especie centinela, el cambio en la distribución del manatí se puede utilizar como advertencia temprana sobre la salud del medio ambiente y puede representar los impactos actuales o potenciales en la salud animal a nivel individual y poblacional.


**Palabras clave:** manatí Antillano; mamífero; conservación; especies amenazadas; Centroamérica.

## INTRODUCTION

Identifying spatiotemporal patterns of distribution and abundance is important for understanding the status of a population. This information can be used to identify areas of importance and to evaluate the effectiveness of established protected areas since animals must utilize or concentrate in those areas if they have conditions that are important for their survival (e.g., food resources, habitat characteristics, etc.; Roberts et al., 2021). Spatiotemporal information is also useful for identifying whether anthropogenic activities impact animals, particularly when their habitat overlaps with these activities as it does in coastal environments (Halpern et al., 2008). Understanding these complex interactions is crucial for the design and implementation of an effective conservation management plan (de Souza et al., 2021; Yoccoz et al., 2001).

The Antillean manatee (*Trichechus manatus manatus*, Linnaeus, 1758) is an endangered species found throughout the Caribbean, and in the coastal waters of Central and northeastern South America (Self-Sullivan & Mignucci-Giannoni, 2008; Quintana-Rizzo & Reynolds, 2010). Their low numbers are the result of human-related pressures including poaching, habitat loss, entanglement in fishing/shrimp nets, chemical contamination, and watercraft collisions (Jiménez, 2002; Lefebvre et al., 1989; Reynolds & Powell 2002; U.S. Fish & Wildlife Service, 2001). Poaching, specifically, has caused an extensive reduction in manatee populations throughout most of the species' range (Lefebvre et al., 1989).

A small population of manatees has been identified in Guatemala. The most recent population estimate is 150 manatees (Quintana-Rizzo & Reynolds, 2010). Poaching resulted in the death of 20 manatees between 2003 and 2016. A more comprehensive update details 48 deaths between 1992 and 2022, although this number includes undetermined causes of mortality (Machuca-Coronado et al., 2023). Different mechanisms exist to protect the species, such as The National Strategy for the Conservation of the Manatee, whose objectives are to monitor and protect manatees, manage and protect their habitat, and promote the cultural and ecological value of the species throughout its range in the country (Herrera et al., 2004). Their recommendations include collecting long-term data on population distribution and identifying the effects of anthropogenic activities on manatees and their habitats. There are also protected areas including the "Biotopo para la Conservación del Manatí Chocón-Machas". This is the first protected area for manatees in Latin America (Lefebvre et al., 1989), although it is mostly terrestrial (Consejo Nacional de Áreas Protegidas [CONAP], 2022).

Marine protected areas (MPAs) can be effective tools for the conservation of species at risk. The protection of manatees could result in the protection of many aquatic organisms. This is because aquatic mammals typically live in large areas where, if effective protection measures are established, numerous other species could be conserved and protected, as well as the ecosystem itself (Hooker & Gerber, 2004; Quintana-Rizzo et al., 2021; Roberts et al., 2021). However, ensuring the effectiveness of MPAs requires a thorough understanding of species distribution, abundance, and habitat relationships (Hunt et al., 2020). In simple terms, it requires knowing where animals are distributed, what areas are important to them and why, how many animals are there, and how they are negatively impacted by human activities.

In the case of aquatic mammals, implementing effective protective measures poses a challenge. They typically have long-range movements, are hard to see at the surface, and have long lives, which bolster the need for multi-year studies. Some field techniques are better suited for the challenge. Aerial surveys can cover large areas in short periods, allowing for the observation of animals from above and the simultaneous examination of human activities. They have been widely used to determine manatee abundance, distribution, and habitat use in the Wider Caribbean, and are one of the most suitable field methods for monitoring sirenian populations in the world (e.g., Edwards et al., 2007; Garrigue et al. 2008; Hagihara et al., 2018; Morales et al., 2000; Olivera-Gomez & Mellink, 2002, Olivera-Gomez & Mellink, 2005).

In Guatemala, a 9.8-hour aerial survey detected nine manatees along the Atlantic coast in 1991 (Ackerman, 1991). A more comprehensive set of monthly aerial surveys were used to generate the first population estimate of 53 manatees in 1992 (Quintana-Rizzo, 1993). In 2005 and 2014, regional surveys were conducted with the objective to examine the manatee numbers in the Belize-Guatemala-Honduras and Mexico-Belize-Guatemala regions (Quintana-Rizzo, 2005a, Quintana-Rizzo, 2005b). Annual aerial surveys were conducted between regional surveys (Machuca-Coronado & Quintana-Rizzo, 2011; Quintana-Rizzo & Machuca-Coronado, 2008), but none of the studies looked at trends in spatiotemporal patterns of manatee distribution and abundance. They did not examine the relationship between manatee sightings and human activities even though earlier studies recognized that manatees must travel through areas of high boat traffic to move between preferential habitats. Here we present a comprehensive assessment of the data collected during all of the aerial surveys conducted since

1992 and a depiction of long-term trends in the spatiotemporal distribution and abundance of manatees in Guatemala. Priority areas, or areas of particular importance for conservation, for the species were identified including the presence of calves, a determination of whether they are using protected areas, and the co-occurrence of manatee sightings and human activities. The results fill a critical gap in knowledge to ensure that the protection of this endangered species is based on a foundation of the most inclusive data available.

## METHODS

**Study area:** The study area included the entire Atlantic Coast of Guatemala, located along the state of Izabal (Fig. 1.1). It is bordered

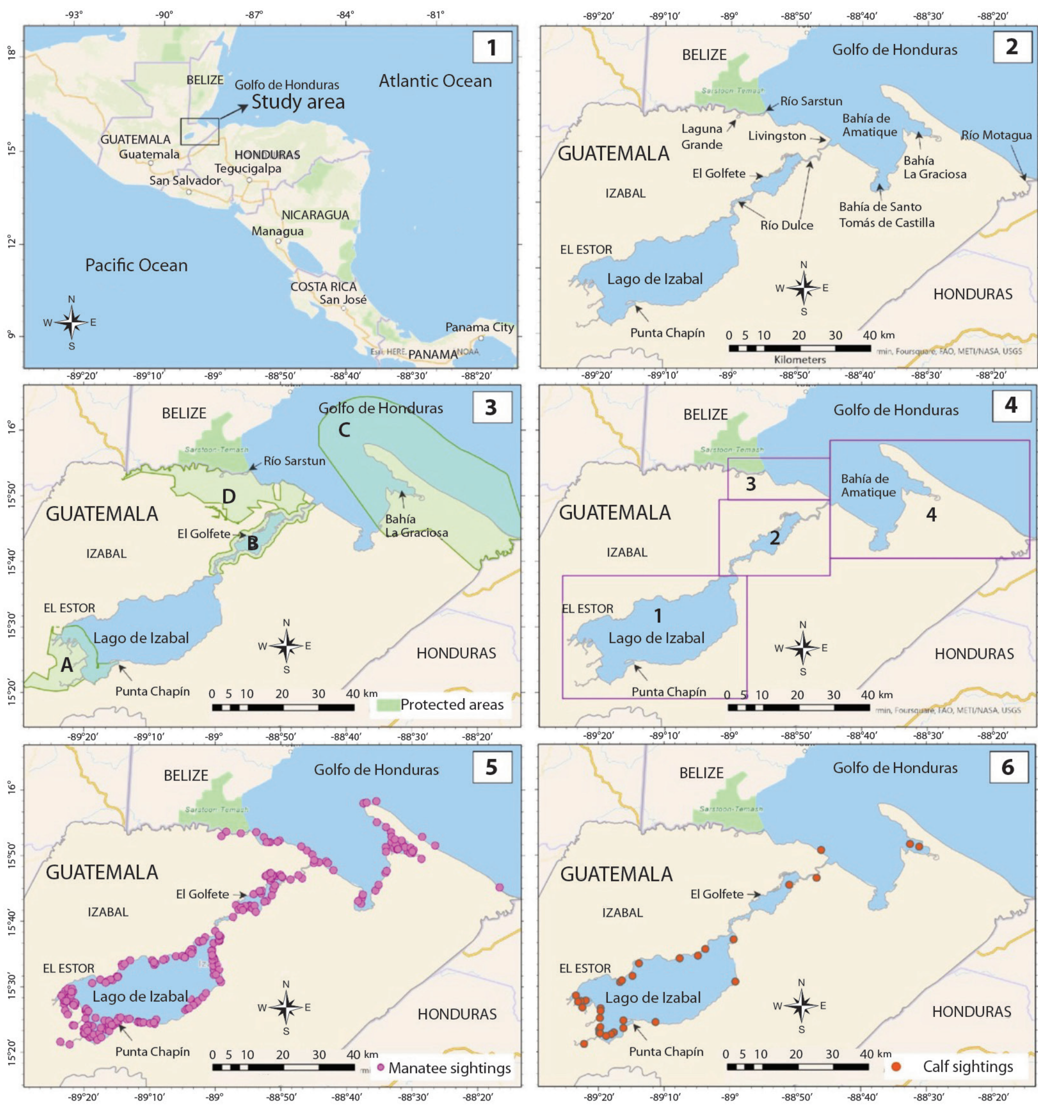


**Fig. 1.** (1) Location of the study area along the Atlantic Coast of Guatemala including (2) important geographical points, (3) protected areas, (4) survey sections, and location of (5) manatee sightings and (6) calf sightings between 1992 and 2022. Protected areas evaluated: A) Refugio de Vida Silvestre Bocas del Polochic, B) Parque Nacional Río Dulce, C) Refugio de Vida Silvestre Punta de Manabique, and D) Área de Usos Múltiples Río Sarstún.

to the north by the Caribbean Sea and to the east by the Gulf of Honduras. The study area encompasses distinctive aquatic ecosystems. Lago de Izabal is the largest freshwater lake in Guatemala (area = 717 km$^2$; Fig. 1.2). It connects to the Gulf of Honduras in the Caribbean Sea by Río Dulce. It has an average depth of 12 m and a maximum depth of 18 m (Arrivillaga, 2002). The southwestern part of the lake includes the protected area "Refugio de Vida Silvestre Bocas del Polochic" (Bocas del Polochic, Fig. 1.1). This RAMSAR site is a wetland of great ecological importance, providing food for more than 250 species of birds, both resident and migratory (Fundación Defensores de la Naturaleza, 1997). Midway between the lake and the sea is Río Dulce, a tidal river that broadens into a large and shallow area (4.5 m depth) known as El Golfete (Brinson et al., 1974). Both Río Dulce and El Golfete are part of a protected area called "Parque Nacional Río Dulce" (Fig. 1.3), which has terrestrial and aquatic zones (CONAP, 2005).

The Atlantic Coast forms a semi-enclosed bay called Bahia de Amatique. This bay includes a complex ecosystem of coastal lagoons, marshes, and swamps influenced by tides and the Río Dulce-El Golfete riverine systems. It is part of the protected area "Refugio de Vida Silvestre Punta de Manabique" (Punta de Manabique), a RAMSAR site located in the Gulf of Honduras (Fig. 1.3). Punta de Manabique is one of the most important ecosystems in the country as it is composed of multiple marine, coastal, and terrestrial areas (Yañez-Arancibia et al., 1999). Río Sarstún is another important site, located on the borderline between Guatemala and Belize. Two protected areas are partially located within this basin, the "Área de Usos Múltiples Río Sarstún", a RAMSAR site, located in Guatemala, and the Sarstoon-Temash National Park located in Belize (Fundación para el Ecodesarrollo y la Conservación [FUNDAECO], 2005) (Fig. 1.3).

**Survey methods:** Standardized aerial surveys were selected as an efficient and cost-effective method to collect data on the distribution and number of manatees (Reynolds et al., 2012). In 1992, April 2005, and 2022, aerial surveys were conducted by two observers who sat on each side of the aircraft and maintained their position throughout the survey. The 1992 surveys covered the center of Lago de Izabal, although since manatees were never sighted there, this portion of the lake was not included in the analysis or future surveys. The May 2005, 2006-2011, and 2014, surveys involved three observers. Two observers sat in the rear seats, while a pilot and another observer sat in the front seats. The front observer (EQR) was the more experienced, participated in all surveys, and was responsible for confirming total manatee numbers. Each observer scanned an area approximately 400 m wide (Olivera-Gomez & Mellink, 2002, 2005). Surveys were conducted parallel to the coast at altitudes of 150 to 200 m and at an average airspeed of 160 km/h from a Cessna 337 or Aero Commander (1992), or a Cessna 335 and Cessna 206 (2005-2022). A GPS continuously recorded the survey path during each survey.

The study area was divided into four sections: Lake Izabal, El Golfete, Livingston-Río Sarstún, and Livingston-Río Motagua (Fig. 1.4). A survey of the entire study area generally took a day, however in cases of unfavorable weather conditions some surveys were conducted over two days. A given section of the survey area was fully surveyed on the same day. Each sighting was considered to be independent because it was impossible to determine whether the manatees moved to different sections of the survey area on different days. When manatees were sighted, the aircraft circled to obtain the most accurate count (number of individuals) possible (Lefebvre & Kochman, 1991). Manatees within close proximity of one another and displaying similar behavior were grouped as one sighting. For each sighting, individuals were classified as adults or calves. Calves were defined as smaller animals up to 1/3 of the adult size (Hartman, 1979) and closely associated with a larger manatee (Irvine, 1982; Reynolds & Wilcox, 1994). One or more manatees were considered a group (Morales-Vela et al., 2000).

Observers recorded the number of manatees (calves and non-calves) and the location of each sighting. For each section of the survey area, environmental conditions such as the percentage of cloud cover and water surface conditions were estimated and recorded by the observers. To ensure that visibility was acceptable for efficient spotting of manatees, surveys were conducted only when sustained winds were < 10 knots and surface conditions scored ≤ 3 on the Beaufort wind scale.

**Data analysis:** The data were divided into two sets based on the available survey effort (e.g., total kilometers) at the time of the analysis. Data with no survey effort (DNS) included surveys conducted in 1992 and April 2005. Data with survey effort (DWS) included surveys conducted from May 2005 on.

**Manatee groups:** size, calf presence, and sighting distance from shore. Group size across years were examined using a two-tailed Kruskal–Wallis test, and multiple Mann-Whitney U post hoc tests were used to compare differences between years. The 2-tailed statistical tests were conducted using the SPSS 28.0.1.1 package (2021) at a significance level of 0.05. The percentage of groups with calves inside and outside of protected areas was reported as descriptive statistics (mean ± standard error). Distance of manatee sightings and calf sightings from shore were calculated in ArcGis Pro 3.0.0.

**Spatial distribution:** two metrics were used to quantify the spatial distribution of manatees and identify priority areas: (1) a hotspot analysis, and (2) Kernel density estimation (Roberts et al., 2020). The first metric allows the use of DWS data as sightings per unit effort, and therefore, the evaluation of sections with uneven coverage. Thus, statistically, a priority area was defined by this study as one that was identified as either a "hot spot" or "cold spot", which are areas of statistically significant spatial clustering (see Hotspot analysis), or an area where the manatee density is more than 85 % of the estimated density in a given year (see Kernel density analysis).

A Hotspot analysis tests for statistically significant spatial clustering using the Getis-Ord Gi* statistic (Getis & Ord, 1992), which determines the spatial clustering of grid cell values that are higher (hot spot) or lower (cold spot) than is expected by random distribution. The study area was divided into 4 km x 4 km grid cells resulting in 246 cells. A 4 km width was chosen because it covered the survey flight path, the meandering sections of the study area, and the mouths of large and medium rivers flowing into the coastline (also referred to as secondary rivers). Medium and large rivers were defined based on the contribution of their streams as >10 to 100 $m^3/s$ and > 100 to 500 $m^3/s$, respectively (Spillman et al., 2000). Within each grid cell, the total number of manatees and the total length of survey tracks were calculated. If no sightings occurred in a grid cell that was surveyed, the grid cell was attributed a value of zero, but the cell was considered part of the survey effort. A spatial map was created at three levels of confidence (99 %, 95 %, and 90 %), and all clusters that were within the 90 % confidence level were considered hot spots or cold spots.

The second metric used was the Kernel density estimation to identify core activity areas. This nonparametric method estimates density curves, where each observation is weighted by the distance from a central value or core, also named kernel, generating a smoothed surface that describes a likely distribution at a given time (Worton, 1989). The analysis allows the use of data regardless of effort (e.g., both DNS and DWS), and thus, the examination of temporal patterns across the 8 years of surveys. A buffer with a 4 km extension over the coastline was created to include river mouths and delimit the analysis boundaries. The 4 km extension is of a similar size to one side of the grid cells used in the Hotspot analysis. Predicted density rasters were generated using a cell size of 1 $km^2$. All spatial analyses were conducted using ArcGis Pro 3.0.0.

Relationship between sightings, coastline features, and human activities: A Spearman rank correlation analysis tested for significant correlations between human activities, coastline features such as rivers, and manatee numbers per segment (Alves et al., 2013) in the study area and in each protected area. This correlation analysis was chosen due to the non-linear nature of relationships and the non-normality and heteroscedasticity of most distributions (Alves et al., 2013). The coastline was divided into 4 km segments for a total of 122 segments. For each analysis and segment, the occurrences of five ecological and human parameters were examined: (1) manatee numbers, (2) fishing activity (fishing nets), (3) tourism activity (transiting motorboats, kayaks), (4) commercial traffic (merchant or cargo ships), and (5) rivers. Fishing activity was recorded during the 2006-2008 and 2010 surveys, and tourism activities were recorded during the 2006-2011 surveys by the left rear observer. Since the final sample size of the commercial traffic parameters was small and confined to a specific area, we only reported descriptive statistics. The fifth parameter was based on cartographic and bibliographic analyses and it included the presence of large/medium size rivers in each segment. These are secondary rivers as sections of the coast such as El Golfete and Río Sarstún are part of the main rivers. Thus, for the correlation between manatees and rivers, one protected area was excluded from the analysis (Area de Usos Múltiples Río Sarstún) because no secondary rivers flow into the portion of the main river (Río Sarstún) that was surveyed. All analyses were performed using SPSS 28.0.1.1 package (2021) at a significance level of 0.05.

Manatee abundance: Abundance was measured as density (Krebs, 2014) or the number of manatees per square kilometer to account for incomplete surveys (e.g., the entire study area was not surveyed but individual surveyed sections were fully covered) and an unequal number of surveys per section. Periods of circling were excluded from this and all other analytical calculations. DWS data were used to examine manatee abundance across years, survey sections, and protected areas using a non-parametric Kruskal-Wallis test. Years with incomplete coverage (e.g., 2010 and 2022) of the study area were excluded from this analysis. Multiple Mann-Whitney U post hoc tests were used to compare differences in abundance using the SPSS 28.0.1.1 package (2021) at a significance level of 0.05. Boundaries of the protected areas were extracted from the World Database of Protected Areas (United Nations Environment Programme World Conservation Monitoring Centre & International Union for Conservation of Nature [UNEP-WCMC & IUCN], 2021).

## RESULTS

**Distribution of sightings:** A total of 293 sightings were recorded between 1992 and 2022. This included 518 manatees, 476 adults (92 %) and 42 calves (8 %) (Table 1). Of the 293 sightings, 17 % included groups with calves. Further, 61 sightings were part of the DNS data and 232 sightings were part of the DWS data. Manatees were most frequently observed as solitary individuals (63 %), but a group of 12 individuals was sighted on one occasion. This large group included a calf. Calves were typically sighted in groups of 3 ± 0.30 (standard error) while the mean group size for all manatees, regardless of age class, was 2 ± 0.09 (Fig. 2). Significant differences in group size were found among years ($H = 18.02$, d.f. = 8, $p = 0.02$). Group size was smaller in 2005 than in 2007, 2014 ($p < 0.05$); it was also smaller in 2006 than in 2007 and 2014 ($p < 0.05$). However, group size was not significantly different between 2005 and 2006, and among all other years ($p > 0.05$).

Analysis of sighting distribution from shore showed that manatees were most frequently sighted at distances ranging from 0.02 km to 2.6 km from the coast. Survey areas are depicted in Figure 1.3. Manatees were most frequently sighted at distances ranging from 0.02 km to 2.6 km from the coast. The mean and median distances from shore were 6.5 km and 5 km, respectively, followed by a continuous

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**Table 1**

Total number of manatees (including adults and calves) sighted per month, protected area, and survey section between 1992 and 2014 along the Atlantic coast of Guatemala.

| Year | Month | No. of manatees in study area | | | No. of manatees in protected areas | | | | No. of manatees in survey sections | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Total | Adults | Calves | RVSBP | PNRD | AUMRS | RVSPM | 1 | 2 | 3 | 4 |
| 1992 | January | 15 | 13 | 2 | 8 | 1 | 0 | 0 | 14 | 1 | 0 | 0 |
| | March | 28 | 24 | 4 | 19 | 0 | 0 | 0 | 21 | 0 | 7 | 0 |
| | April | 15 | 13 | 2 | 7 | 4 | 2 | 1 | 7 | 4 | 2 | 2 |
| | May | 15 | 15 | 0 | 3 | 2 | 0 | 1 | 3 | 2 | 0 | 10 |
| 2005 | April | 39 | 36 | 3 | 14 | 6 | 0 | 6 | 22 | 6 | 2 | 9 |
| | May | 49 | 43 | 6 | 15 | 2 | 0 | 8 | 35 | 2 | 2 | 10 |
| 2006 | July | 27 | 26 | 1 | 21 | 4 | 0 | NS | 21 | 4 | 2 | NS |
| | October | 53 | 48 | 5 | 8 | 7 | 0 | 10 | 25 | 7 | 6 | 15 |
| 2007 | January | 52 | 48 | 4 | 13 | 6 | 0 | 7 | 39 | 6 | 0 | 7 |
| | March | 38 | 35 | 3 | 5 | 7 | 2 | 20 | 8 | 7 | 2 | 21 |
| 2008 | February | 40 | 39 | 1 | 11 | 12 | 0 | NS | 28 | 12 | 0 | NS |
| 2010 | May | 26 | 23 | 3 | 26 | NS | PC | PC | 26 | NS | PC | PC |
| 2011 | March | 52 | 48 | 4 | 14 | 7 | 1 | 5 | 40 | 3 | 7 | 2 |
| 2014 | May | 45 | 43 | 2 | 4 | 7 | 0 | 10 | 20 | 14 | 1 | 10 |
| 2022 | August | 24 | 22 | 2 | 1 | 5 | NS | NS | 19 | 5 | NS | NS |
| | Total | 518 | 476 | 42 | 169 | 70 | 5 | 68 | 328 | 76 | 31 | 86 |
| | Range | 12-53 | 12-48 | 0-6 | 4-26 | 0-7 | 0-2 | 0-10 | 3-40 | 0-14 | 0-7 | 0-21 |
| | Percentage | 100% | 92% | 8% | 54% | 22% | 2% | 22% | 63% | 14% | 6% | 17% |

PC = poor conditions, NS = no surveyed. RVSBP = Refugio de Vida Silvestre Bocas del Polochic, PNRD = Parque Nacional Río Dulce, RVSPM = Refugio de Vida Silvestre Punta de Manabique, and AUMRS = Área de Usos Múltiples Río Sarstún. Survey sections: (1) Lago de Izabal, (2) El Golfete, (3) Livingston-Río Sarstún, and (4). Livingston-Río Motagua.

decrease in the sighting frequency toward open waters (Fig. 2).

**Spatial distribution:** Manatees were sighted throughout the study area, but they were unevenly distributed (Fig. 1.3, Fig. 1.4). Most manatee and calf sightings occurred inside protected areas (60 % and 68 %, respectively). Half of the groups with calves were observed in Bocas del Polochic, but in the overall Lago de Izabal, 82 % of groups with calves were sighted. No calves were observed in the coastal waters from Rio Sarstun to Rio Motagua.

A series of priority areas were identified and all occurred inside protected areas. This included three hot spots or areas of high clustering and two cold spots or areas of low clustering (Fig. 3). A hot spot was detected in the protected area Punta de Manabique while a large cold spot and two large hot spots were detected in Lago de Izabal (Fig. 3). In Lago de Izabal, one of the hot spots overlapped by approximately 1.5 $km^2$ with the protected area Bocas del Polochic. This protected area also overlapped with the cold spot by more than 50 $km^2$. A small cold sport was identified in the north side of Parque Nacional Río Dulce in El Golfete. No hot or cold spots were identified in other protected areas.

The location, number, and extension of predicted core activity areas for manatees varied across years (Fig. 4). However, some general patterns emerged. Lago de Izabal is a priority area for manatees as one or more core activity areas were detected there in each of the nine years of surveys. Within the lake, the southern corner, which covers the entire aquatic zone of Bocas del Polochic and Punta Chapin, was

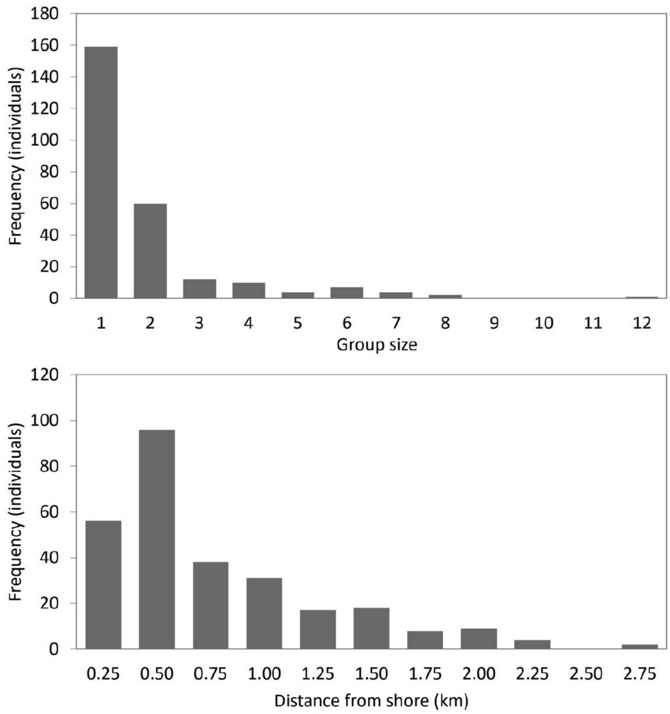


**Fig. 2.** Frequency distribution of group sizes of manatees and their distance from shore in Guatemala.

consistently identified as a core activity area, although this pattern shifted to the northern shoreline of the lake in 2014 and continued in 2022 (Fig. 4). Another core activity area was detected inside Punta de Manabique, near Bahia La Graciosa. In Parque Nacional Río Dulce, a core activity area was identified but only in half of the nine years of surveys (Fig. 4).

**Correlations of coastal features and human activities:** For the entire study area, the Spearman rank correlation analysis identified significant correlations between manatees and ecological and human parameters (Table 2). The first and highest positive significant correlation was found between manatees and rivers ($r_s$ = 0.67, $p < 0.01$). A similar significant correlation was detected in the inshore protected areas (Bocas del Polochic and Parque Nacional Río Dulce) with the highest correlation ($r_s$ = 1.00) being between manatees and rivers of a protected area (Bocas del Polochic). Additionally,

**Table 2**
Spearman correlation ($r_s$) between numbers of manatees, selected coastal features, and human activities in the study area and individual protected areas.

| Parameters | Study area | Protected Areas | | | |
|---|---|---|---|---|---|
| | | RVSBP | PNRD | RVSPM | AUMRS |
| Coastal features (rivers) | $r_s$ = 0.67, p < 0.01* | $r_s$ = 0.99, p < 0.01* | $r_s$ = 0.52, p < 0.01* | NA | $r_s$ = -0.07, p = 0.75 |
| Fishing nets | $r_s$ = 0.04, p = 0.40 | $r_s$ = -0.06, p = 0.54 | $r_s$ = 0.27, p < 0.05 | NA | NA |
| Tourism activity | | | | | |
| Motorboats | $r_s$ = 0.07, p < 0.05* | $r_s$ = 0.19, p < 0.05* | $r_s$ = 0.19, p < 0.05* | $r_s$ = -0.15, p = 0.59 | $r_s$ = 0.14, p = 0.15 |
| Kayaks | $r_s$ = -0.40, p = 0.26 | $r_s$ = 0.06, p = 0.48 | $r_s$ = -0.15, p = 0.87 | $r_s$ = -0.31, p = 0.26 | $r_s$ = -0.06, p = 0.54 |

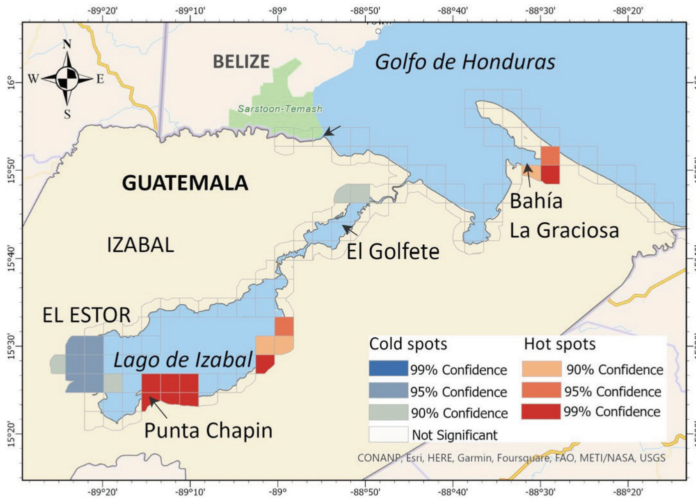


**Fig. 3.** Hotspots and cold spots of manatees based on sightings per unit effort. Additional details of the study area are shown in Figure 1.

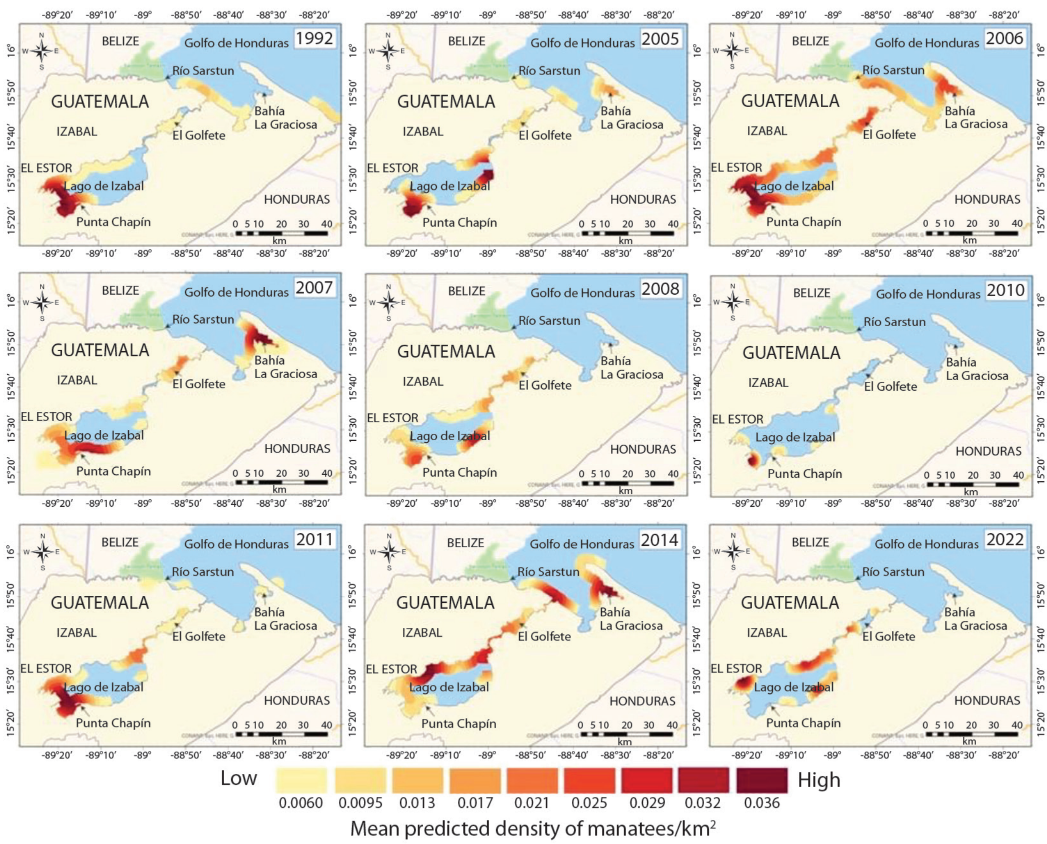


**Fig. 4.** Interannual variation in core activity areas of manatees in Guatemala between 1992 and 2022 using Kernel estimates. Each section of the study area was surveyed except in 2008 (no survey: Livingston-Río Motagua), 2010 (no survey: El Golfete; poor weather conditions: Livingston-Río Motagua, Livingston-Río Sarstún), and 2022 (no survey: Livingston-Río Motagua, Livingston-Río Sarstún).

manatee sightings were weakly positively correlated with the presence of motorboats ($p < 0.01$) in these two protected areas and with fishing gear ($p < 0.05$) in Parque Nacional Rio Dulce (Table 2). No other correlations were found for the entire study area or in the protected areas.

Commercial traffic in the form of merchant or cargo ships was only observed in the Livingston-Río Motagua section. Within this section, the commercial traffic happened near the Santo Tomas de Castilla port where 10 cargo ships were observed during surveys. A total of eight manatees were sighted in this area.

**Manatee abundance**: Manatee abundance was estimated for the entire study area, each surveyed section, and each protected area. For a given survey, the mean abundance was 0.10 ± 0.01 manatees/km$^2$ (range = 0.05 – 0.26 manatees/km$^2$) and the overall mean calf abundance was 0.01 ± 0.002 manatees/km$^2$ (range = 0.00 – 0.03 calves/km$^2$). No annual significant differences in manatee abundance were found among 2015 (May), 2006, 2007, 2008, 2011, and 2014 ($H = 0.82$, d.f. = 6, $p = 0.99$) or the years with complete surveys of the study area.

Manatee abundance was significantly different among sections surveyed and among protected areas ($p < 0.01$). In the first case, no statistical difference in manatee abundance was found between Lago de Izabal and Livingston – Río Motagua ($U = 9.28$, $p = 0.06$). Mean abundance was 0.18 ± 0.02 manatees/km$^2$ in Lago de Izabal and 0.10 ± 0.02 manatees/km$^2$ in Livingston – Río Motagua (Fig. 5). However, manatee abundance was significantly different between Lago de Izabal and El Golfete ($U = 12.20$, $p = 0.006$) and between Lago de Izabal and Río Sarstún ($U = 15.20$, $p < 0.001$). Further, manatee abundance was not statistically different among El Golfete and the two more coastal sections (Livingston – Río Sarstún, Livingston – Río Motagua; $p > 0.05$). In these three sections, mean abundance varied between 0.06 and 0.10 manatees/km$^2$ (Fig. 5).

In the case of the protected areas, Bocas del Polochic (Lago de Izabal) had the highest manatee abundance (1.52 ± 0.03 manatees/km$^2$) of all protected areas ($p < 0.05$; Fig. 5). Manatee abundance was not statistically different among the other three protected areas ($p > 0.10$).

## DISCUSSION

This study comprises the largest effort to quantify and correlate the distribution of manatees along the Atlantic coast of Guatemala, yielding important insights into the local status of the species. Our results show that manatees were nonuniformly distributed along the surveyed area with most sightings being recorded in protected areas (60 %).

**Spatiotemporal distribution and priority areas:** Our results agree with other studies that found that manatees tend to be located in areas near freshwater sources (Alvarez-Alemán et al., 2017; Castelblanco-Martínez et al., 2018; Favero et al., 2020; Lefebvre et al., 2001; Marsh et al., 2001; Olivera-Gomez et al., 2022; Powell & Rathbun, 1984; Rathbun et al., 1990), with shallow waters (Hartman, 1979; Olivera-Gomez & Mellink, 2005), close to shore (Olivera-Gomez & Mellink, 2005), where aquatic vegetation (Arrivillaga & Baltz, 1999; Poll, 1983; Yañez-Arancibia et al., 1999) known to be part of the species diet (Allen et al., 2018; Alves et al., 2013; Hurst & Beck, 1988) exists, and where there is minimum motorboat traffic and little to no coastal human development. Priority areas were identified in the southern corner of Lago de Izabal, from Punta Chapin to Bocas del Polochic, and the innermost corner of Punta de Manabique (Bahia de Amatique). The southern corner of Lago de Izabal has been an important area for manatees for nearly 30 years (Machuca-Coronado & Quintana-Rizzo, 2011, Machuca-Coronado & Quintana-Rizzo, 2014; Quintana-Rizzo, 1992), although a shift in manatee distribution occurred in 2014. Within the southern corner, manatees clustered in small groups (1-2 manatees) in the northern section and in large groups (up to 8 manatees) in the southern section (Punta Chapin). A high percentage of sightings that included calves was also reported there (50 %) and in coastal waters

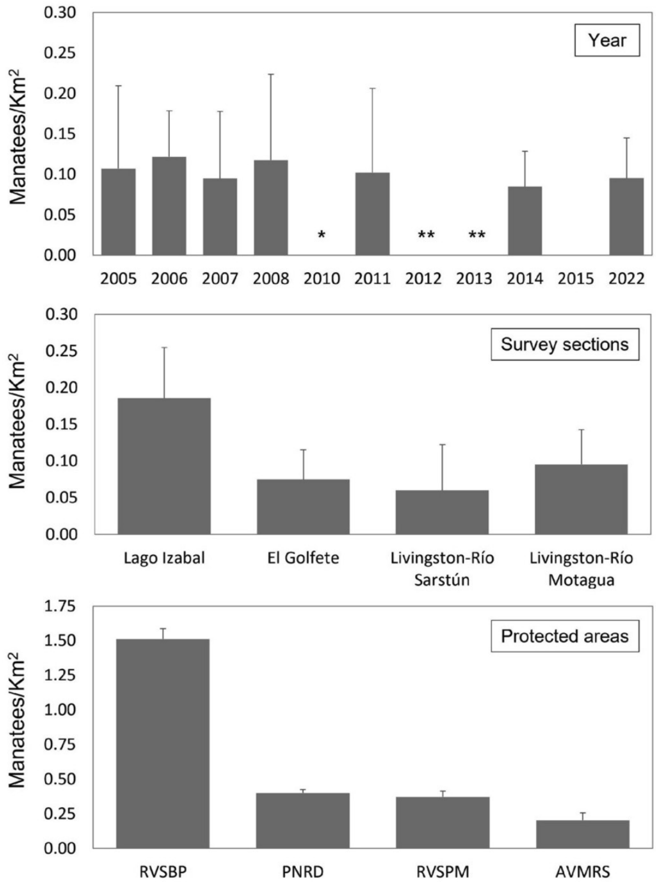


**Fig. 5.** Relative abundance of manatees for years 2005-2022 with survey effort of the entire study area, each section, and protected areas in Guatemala. Note: * = only one section was completed; thus, mean was not calculated, ** = no aerial surveys were conducted. RVSBP = Refugio de Vida Silvestre Bocas del Polochic, PNRD = Parque Nacional Río Dulce, RVSPM = Refugio de Vida Silvestre Punta de Manabique, and AVMRS = Área de Usos Múltiples Río Sarstún.

of the lake (82 %). This distribution may reflect habitat requirements specific to this social unit or demographic group (Gannon et al., 2007).

The southern corner of the lake is probably the most protected section for manatees of Lago de Izabal and the entire Atlantic coast, but the area is not free of human activities and interactions. Illegal gillnets of up to 4 km long are commonly sighted there (H. A. Garcia personal communication). An orphaned manatee was entangled in one of those nets in 2014. The calf was rescued from the net but died after a failed rehabilitation attempt (Machuca-Coronado & Quintana-Rizzo, 2014). Further, changes in land use and development have altered anthropogenic nutrient inputs resulting in an increase of raw sewage, strip mining flow, and agricultural fertilizers into the lake (Obrist-Farner et al., 2019). This has negatively impacted the water quality and overall health of the ecosystem. In the southern corner, water quality was classified as medium and good based on the National Sanitation Foundation Water Quality Index (a 100-point scale from excellent, good, medium, bad, to very bad; Aguirre Cordón et al., 2006). The lake has also started to undergo cultural eutrophication, which contributes to frequent harmful algal blooms, the proliferation of invasive species such as *Hydrilla verticillata*, and a decline in fish abundance (Obrist-Farner et al., 2019). Additionally, predictive models indicate that the temperature of the coastal surface waters will increase by 2 – 5 °C by 2100 and that this will be a biological stressor that could alter or harm the aquatic ecosystem (Marchese, 2015).

The 2014 shift in manatee distribution could have been caused by multiple factors. Since manatees are considered sentinel species of the overall health of the ecosystem (Bonde et al., 2004; Bossart, 2011), distributional changes could be used as early warnings about current or potential negative impacts on individual-level and population-level animal health; Bossart, 2011). Those warnings could help identify environmental stressors that could ultimately affect human health associated with the oceans (Bossart, 2011). The fact that a similar pattern was observed in 2022 suggests that the change in manatee distribution is permanent, and future studies will help to determine this. A multispecies approach could be useful in this case since other species like macroinvertebrates are also biological indicators of an aquatic ecosystem in stress (Roldán-Pérez et al., 2016).

Protected areas do not appear to be equally important for manatees as indicated by differences in the number, location, and temporal presence of priority areas. For example, the innermost section of Punta de Manabique is a priority area but its extension and persistence varied over time. No priority areas were identified in Área de Usos Múltiples Río Sarstún while they were only detected in some years in Parque Nacional Río Dulce. There is a high presence of human activities in the former. The demand for land leases in mangrove areas has increased considerably in Parque Nacional Río Dulce, which saw the construction of large tourist complexes (Arrivillaga, 2003). Parque Nacional Río Dulce is one of two coastal areas in the entire country where the transformation of mangrove areas by coastal development and tourist infrastructure is more evident (Arrivillaga, 2003). Notably, we recorded the highest number of motorboats (64 %) and kayaks (68 %) there along the entire Atlantic coast. Manatees that use this area must navigate through a busy intersection of fast-moving vessels, kayaks, and fishing gear. They appear to stay within the coastal waters as suggested by their high proportion of sightings (80 %) within a kilometer from the coast. Females with calves must pay attention in this busy environment for the safety of the calf, and few appear to remain there as suggested by the small percentage of calf sightings (6 %) in this protected area.

**Manatee abundance including calf presence:** Our manatee abundance estimates are within the lower confidence limit of abundance estimates reported in 1992 (Quintana-Rizzo, 1993). Nevertheless, early abundance estimates were calculated based on Schaeffer et al. (1986) and thus, differences in analytical procedures could account for the observed differences. New population modeling techniques based on aerial survey data could provide more reliable population estimates (e.g., Martin et al., 2015). However, those models require different collection protocols than the ones used in this survey, and observers that are trained in those protocols. A preliminary survey was conducted in this way, and there are plans to apply one of those models to the results.

Mean manatee abundance was comparable to that reported in other parts of Mesoamerica including Bahia de Chetumal, although the study was conducted at a different time of the year (Morales-Vela & Olivera-Gómez, 1994). The overall percentage of calf sightings (12 %) and number of calves sighted (8 %) were also comparable to other parts of Mesoamerica (Callejas-Jiménez, 2021; Edwards et al., 2014; Morales-Vela et al., 2000) and the Caribbean (Alvarez-Alemán et al., 2017).

Mean manatee abundance was not significantly different from 2005 to 2014. This represents approximately 10 years of relative stability, which is significant for a small population of an endangered species. Yet at least 20 manatees died around the same time (2003-2016; Machuca-Coronado & Corona Figueroa, 2019) representing 13 % of a minimum population of 150 manatees (Quintana-Rizzo & Reynolds, 2010). This begs the question of how the population could appear to remain stable at this mortality rate, which is likely underestimated. Possible explanations include that the population is higher than 150 manatees or that the survey methodology does not account for the re-sighting of individual animals (i.e., one individual could be sighted twice in the same survey). Alternatively, or in conjunction with this, there could be an influx of manatees moving to and from neighboring countries such as Belize, which has the largest manatee population of Antillean manatees in the Caribbean (Morales-Vela et al., 2000; O'Shea & Salisbury, 1991), and Honduras. This influx could counterbalance the effects of mortality. However, this assumes that mortality remains at a sustainable rate, which is unclear. Better population estimates and record keeping of mortality events are needed to understand the dynamics of the Guatemalan manatee population.

**Conservation and management:** The identification of priority areas for manatees should be used to better focus management efforts in the future. This level of information is needed to design and evaluate the effectiveness of protected areas for the conservation of the species. Manatee protection needs to be strengthened by ensuring that priority areas and critical resources (e.g., freshwater sources, feeding areas) are given special management consideration. It is urgent that the impact of human activities, such as those caused by the cultural eutrophication of Lago de Izabal, are minimized, and controlled. Similar actions are needed to minimize the use of fishing nets in protected areas. Motorboat speed restrictions need to be implemented to increase safety for manatees traveling through and between protected areas, considering the movement of animals between the inshore waters of the lake and the marine environment. This 150 km (round-trip) movement is well within the species capabilities since manatees can conduct 600-km$^+$ round-trip migrations (Deutsch & Barlas, 2016). Manatee movements among different parts of the coastline highlight the importance of connectivity between protected areas. The most effective conservation and management actions require a comprehensive understanding of animal movement patterns and habitat selection as depicted by this study.-

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

**Author Contribution:** E.Q.R conceived the original idea for this manuscript. E.Q.R, O.H.M.C, and H.A.G. expanded and agreed on the details of the publication. All authors collected data and helped secure funding for aerial surveys and related field work. E.Q.R. (lead) and O.H.M.C. processed and analyzed the data. E.Q.R. lead the manuscript writing with contributions to drafting, critical review, and editorial input from O.H.M.C. and H.A.G.

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