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Nonlethal capture of green sea turtles (*Chelonia mydas*) in fishing weirs as an opportunity for population studies and conservation

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ABSTRACT

Green sea turtles (*Chelonia mydas*) switch habitats during their development, moving from pelagic to neritic areas and then commuting between nesting and foraging grounds during adulthood. Due to their predominantly coastal habitats, they are under a range of anthropogenic threats. We monitored turtles incidentally captured in fishing weirs in Ceará state, northeastern Brazil, over a decade and provided an overview of capture rates in the fishery during previous decades. Between 2008 and 2018, 2335 captures were recorded, 76% were only once. Most recaptures (86%) occurred up to six months after the first capture, with a mean growth rate of 6.7 ± 3.6 cm year^{-1}. Capture rates varied between years, with the highest rates during the historical period, peaking in 1962 (0.16 turtles day weir^{-1}). Between 2008 and 2018, the daily capture rate was 0.07 turtles day weir^{-1}. Similar to other areas, the use of turtles as a fishery resource seems to have reduced population sizes in the Atlantic Ocean. On the other hand, the intensive monitoring of local weirs provided an opportunity to mobilize the community regarding their conservation, which in turn could have supported the recovery of turtles from a number of distant colonies. The relatively constant and year-round capture of green sea turtles reflects the presence of individuals from different rookeries and demonstrates the importance of the region as a developmental ground for juveniles from different nesting areas, with high growth rates compared with other feeding areas. Partnership with local fishermen and the long-term monitoring of passive nonlethal fishing weirs are key tools in supporting sea turtle conservation.

1. Introduction

Incidental capture in fisheries is the largest cause of mortality of sea turtles globally and occurs in a range of fishing gear, such as gillnets (Pingo et al., 2017), longlines (Swimmer et al., 2017), and trawling (Silva et al., 2010). Despite the negative impacts of fishing activities on populations, fixed fishing gear, such as some pound nets, fish traps and weirs, is an opportunity to work with fishermen toward conservation, as turtles remain alive inside traps (Lima et al., 2013; Silva et al., 2017). Most weirs are used in coastal regions, thus overlapping with the feeding and developmental areas of green sea turtles (*Chelonia mydas*), a mainly herbivorous species at the juvenile and adult phases (Bjorndal, 1997; Arthur et al., 2008). Thus, monitoring incidental capture in this type of fishing provides an efficient and favorable opportunity to obtain information on demographic parameters, habitat use, biological sampling and population trends over long periods (Gallo et al., 2006; Silva et al., 2017; Jang et al., 2018). In addition, it represents an opportunity to raise awareness in local communities, including those of fishermen.

In recent decades, intense conservation efforts regarding the green sea turtle subpopulation of the South Atlantic Ocean have reduced some local threats, such as egg harvesting and the intentional capture of adults, which has led to the current classification, Least Concern (LC) (Broderick and Patricio, 2019). Notwithstanding, this species is still listed as Endangered (EN) globally on the Red List of Threatened Species (IUCN, 2019) and as Vulnerable (VU) on the Brazilian Red List (MMA , 2014). Throughout its developmental period, green turtles have ontogenetic changes in feeding habits and distribution and are recruited from oceanic to neritic areas (Bjorndal, 1997). The neritic zones are used by

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juveniles as developmental and feeding areas, where individuals can remain until they reach a certain size or sexual maturity (Bjorndal et al., 2005).

Studies in foraging and developmental areas complement studies carried out on nesting areas that are limited to adult females, nests and offspring (Almeida et al., 2011; Weber et al., 2014). Understanding population patterns and trends is critical to implementing conservation measures adjusted to populations throughout their range (Wallace et al., 2013; Kameda et al., 2017; Shimada et al., 2020). In Brazil, studies on green turtle foraging areas demonstrate the importance of long-term monitoring programs for the conservation of the species (Gallo et al., 2006; Colman et al., 2015; Silva et al., 2017).

The coast of Ceará state, northeastern Brazil, was recognized decades ago as an important feeding area for green turtles from Ascension Island (Pritchard, 1973; Carr, 1975), Suriname and Guyanas (Schulz, 1975; Pritchard, 1976). The capture of turtles in fishing weirs along the Ceará coast have also been well documented since the 1960s (Paiva and Nomura, 1965; Almeida, 1974; Silva, 1994). Used earlier as a 'fishing resource', despite not usually being a main target, turtles captured in weirs were documented in production logbooks, which provides an unprecedented opportunity for comparison over decades. Although many turtles are captured in weirs, direct mortality by gear is negligible, which, coupled with the tradition of eating turtle meat, results in fishermen killing turtles for consumption or selling in local markets (Pritchard, 1976; Silva, 1994).

Understanding the urgency to initiate sea turtle conservation action in Ceará and attempting to reduce capture for consumption, the Tamar Project Foundation established a sea turtle research and conservation station in Almofala in 1992 (Marcovaldi et al., 2001). Educational programs with local communities and monitoring of incidental captures and turtle strandings along the beaches were implemented (Lima, 2001). These actions provided a key opportunity to raise awareness and avoid the killing of turtles for meat consumption or trade in local markets (Marcovaldi et al., 2001). Despite the absence of long-term monitoring in the area, the analysis of sea turtle capture in fisheries, of which sea turtles were a fishing resource from a historical perspective, provides clues on population changes, as well as on cultural and economic changes in human communities. It also provides the magnitude of the impact of the activity on the turtle population in the long term (Early-Capistrán et al., 2017).

This study aims to determine temporal variations in capture rates, residence time, size classes and growth rates based on recaptures of green turtles captured in weirs along the Ceará coast (2008–2018) and to compare capture rates with historical logbooks since 1962 in some weirs at the same location.

2. Methods

2.1. Study area and sampling

The coast of Ceará state in northeastern Brazil is 573 km long (Araújo and Pereira, 2015), with a predominance of artisanal fishing and tourism as economic activities (Araújo and Pereira, 2015; Masih-Neto et al., 2017). Data from long-term monitoring fishing weirs by the Tamar Project Foundation, with voluntary collaboration of local fishermen, occurred in Almofala, Boca da Barra and Guajiru in the municipality of Itarema and in Volta do Rio in the municipality of Acaraú (Fig. 1).

Several fishing techniques are used along the Ceará coast, such as hook-and-line, bottom-set nets, and weirs (Lima et al., 2013). Among the different techniques, fishing weirs have a wide distribution and are common throughout the coast of the state (Paiva and Nomura, 1965; Araújo and Pereira, 2015), and are locally known as *currais*. These weirs are fixed nonselective passive traps made of wooden piles surrounded by wire mesh and tied together to form a net (Fig. 1) (Lima et al., 2013; Araújo and Pereira, 2015). In general, they are arranged in lines toward the sea with the number of units being variable and installed between 0.5 and 18 km from the coast (Fig. 1) (Paiva and Nomura, 1965; Lima et al., 2013; Araújo and Pereira, 2015). In the monitoring areas, fishing weirs had lengths from 80 to 313 m and depths ranging from 2 to 8 m (Paiva and Nomura, 1965; Rocha, 1980; Lima et al., 2013), but in the state, there are records of weirs with lengths of up to 700 m at depths of up to 20 m (Araújo and Pereira, 2015).

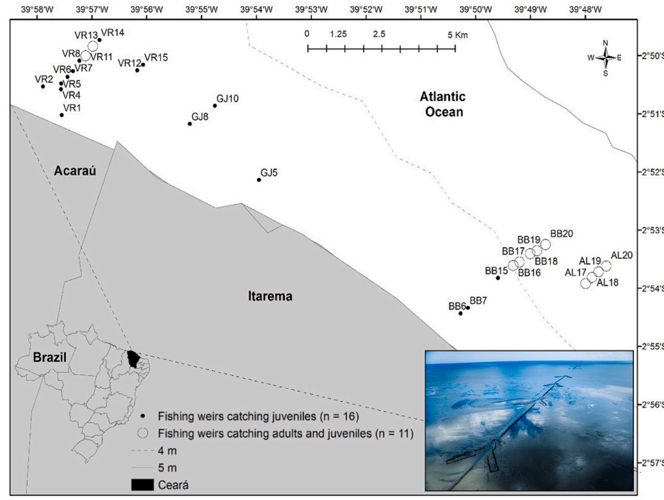

Fig. 1. Map of the study area in Ceará state, northeastern Brazil, with the distribution of fishing weirs from 2008 to 2018. Weirs installed in the same localities in different years overlapped and were represented as a single symbol. Codes indicate weirs: AL - Almofala, BB - Boca da Barra, GJ - Guajiru, and VR - Volta do Rio. Inset - aerial view of fishing weirs during low tide. Photo: Gentil Barreira.

Capture depends on the active movement of the animals inside the trap and tidal fluctuations, allowing the entry of fish and turtles during high tide (Tavares et al., 2005; Araújo and Pereira, 2015; Masih-Neto et al., 2017). When swimming parallel to the shore, the animals come across the "espia" of the weirs (a set of stakes installed linearly that lead the animals to the entrance of the trap) and follow this barrier toward the bottom penetrating the semicircular rooms, which are compartments from which they cannot escape, and remain until they are removed by the fisherman (Silva, 1994). Although sea turtles are nontarget species, they are often captured in weirs (Paiva and Nomura, 1965), which makes weir monitoring an opportunity to run mark-recapture studies and biological sampling and to promote community-based conservation.

Between 2008 and 2018, 27 fishing weirs were monitored (Table 1). Weirs were identified with the abbreviation of the community where they were built, and numbers indicate increasing distances from the coast. Researchers checked weirs daily onboard canoes with fishermen during hauling operations. In situations such as unfavorable environmental conditions, crowded canoes, or maintenance in the weirs, the turtle's handling procedures were carried out on the beach. The maintenance of monitoring over the years and the implementation of conservation actions in partnership with the fishing community led to an increase in fieldwork effort, strengthening the bonds of trust between fishermen and researchers and increasing the number of fishermen partners and weirs monitored (Table 1).

Most turtles captured during monitoring had biometry, information on health and body condition, collected at the time of capture and they were released. In cases of animals captured outside the monitoring period, management was carried out by the team on the beach. Turtles were marked with metal tags on the trailing edge in both front flippers. For each captured turtle, the curved carapace length (CCL, in cm) was measured with flexible plastic tape to the nearest 0.1 cm from the anterior point at the midline (nuchal scute) to the posterior tip of the supracaudal scutes.

The coast of Ceará is used by green turtles from different nesting

Table 1
Variation in fishing effort measured as the number of weirs and green sea turtles incidentally captured in Ceará state, northeastern Brazil, from 1962 to 2018. NI - noninformed, SD - standard deviation, and * - extracted directly from publications.

Year	No. of days monitored	No. of green turtles captured	No. of recaptures	Capture rates turtles day weir^{-1} (mean ± SD)	Reference
1962	2487	400	NI	0.16	Paiva and Nomura (1965)
1963	3991	376	NI	0.09	Paiva and Nomura (1965)
1964	2162	187	NI	0.09	Paiva and Nomura (1965)
1965	1292	NI	NI	0.0*	Paiva and Fonteles-Filho (1968)
1966	664	NI	NI	0.1*	Paiva and Fonteles-Filho (1968)
1967	1580	NI	NI	0.1*	Paiva and Fonteles-Filho (1968)
1968	1530	NI	NI	0.0*	Collyer and Aguiar (1972)
1969	1687	NI	NI	0.1*	Collyer and Aguiar (1972)
1970	1687	NI	NI	0.0*	Collyer and Aguiar (1972)
1971	1353	NI	NI	0.0*	Almeida (1974)
1972	1454	NI	NI	0.0*	Almeida (1974)
1973	1164	NI	NI	0.0*	Almeida (1974)
1974	1972	NI	NI	0.1*	Ximenes (1980)
1975	2021	NI	NI	0.1*	Ximenes (1980)
1976	525	NI	NI	0.1*	Ximenes (1980)
1977	431	0?	–	–	Ximenes (1980)
1980	1123	62	NI	0.06 ± 0.04	Péres (1981)
2008	1764	88	6	0.04 ± 0.06	Present study
2009	2209	291	88	0.08 ± 0.08	Present study
2010	2734	240	34	0.07 ± 0.07	Present study
2011	2707	231	34	0.06 ± 0.07	Present study
2012	2486	209	24	0.07 ± 0.08	Present study
2013	2926	149	17	0.04 ± 0.06	Present study
2014	2952	237	34	0.07 ± 0.08	Present study
2015	3004	137	17	0.04 ± 0.06	Present study
2016	2595	180	18	0.06 ± 0.08	Present study
2017	2376	248	16	0.08 ± 0.12	Present study
2018	3325	325	42	0.08 ± 0.07	Present study

sites, such as those on Ascension and Trindade Islands, and also those in the Caribbean at Tortuguero, Matapica and Aves (Naro-Maciel et al., 2007); thus, the minimum CCL for adult individuals varies between colonies. Because most green turtles found in the region originate from Ascension Island (Naro-Maciel et al., 2007), individuals with CCLs equal to or greater than 97 cm (the minimum CCL registered for females in nesting activities on Ascension) were classified as adults (Weber et al., 2014).

2.2. Data analysis

The capture rate was defined as the number of green turtles captured per day per weir (days weir^{-1}), as unit effort for fishing weirs was based on the number of fishing days, thus representing an integrated period of several fishing days. All recaptures and records lacking individual identification (1.5%) or CCL measurements (0.6%) were excluded from calculations of capture rates and Generalized Linear Models – GLM, based on CCL.

Differences between months and years in capture rates and in CCL of the green turtles were assessed using one-way analysis of variance, followed by Tukey's HSD post hoc test using the 'base package' (R Core Team, 2020). To evaluate the relationship between the size of individuals, the depth of the area where fishing weirs were placed and the distance from shore, a multiple regression was performed (R Core Team, 2020). Data were transformed to meet linear model assumptions (normality, linearity and homoscedasticity of residuals) when necessary using a maximum likelihood function (boxcox, 'MASS' package, Venables and Ripley, 2002). Because the recapture rate data did not meet normality criteria after transformation, the nonparametric Kruskal-Wallis test was applied at $P < 0.05$ using the package 'agricolae' (Mendiburu, 2020). To perform this analysis, the monthly mean of each variable was used to compare the differences between years ($n = 12$). Similarly, monthly comparisons were conducted using the mean values of each variable during all monitoring periods in each year ($n = 11$).

The assessment of historical data of the green turtles captured in fishing weirs from 1960 to 1977 and 1980 was carried out using references providing the number of turtles captured and fishing effort in days (in this case, capture rate was calculated), or those where the fishing index had been calculated with fishing days as an effort measure (in this case, capture rate was extracted directly).

The determination of the explanatory variables influencing turtle size was identified by GLMs with factors for month, year, weir and the interaction among factors. As the normality criteria were not met in CCL measurements, data were log-transformed, and Gaussian distribution and link identity were used (R Core Team, 2020). Multiple linear regression was used to determine the relationship between the CCL of the captured turtles and the depth and distance from shore where weirs were located.

Growth rates were calculated (in cm per year; cm year^{-1}) for each turtle recaptured in intervals greater than 10 months. The mean annual growth rate was calculated as $(\Delta CCL/\Delta t) \times 365$, where ΔCCL was the CCL variation between recapture and first capture, and Δt was the number of days elapsed since initial capture (Rees et al., 2013; Colman et al., 2015). To determine the relationship between CCL in the first recapture and growth rate, linear regression was performed (R Core Team, 2020).

3. Results

Between 2008 and 2018, 2335 green turtles were captured in monitored fishing weirs. Most tagged individuals ($n = 2299$) were captured only once ($n = 1774$), while 195 individuals were recaptured up to 9 times, totaling 330 recaptures. Fishing effort ranged from a minimum of 1764 days weir^{-1} in 2008–2009 to a maximum of 3325 days weir^{-1} in 2018–2019; total fishing effort was 29,078 days weir^{-1} (Table 1).

Data from the historical period were revised, and the number of green turtles captured in fishing weirs refers to 1962, 1963, 1964 and 1980 (1025 turtles captured; Table 1). Fishing effort ranged from a minimum of 431 days weir^{-1} in 1977–1978 to a maximum of 3991 days weir^{-1} in 1963–1964; total fishing effort monitored was 27,123 days weir^{-1} (Table 1). At that time, turtles captured were used for consumption; thus, recapturing was not possible, making capture rates in historical vs. current times comparable.

3.1. Capture rates

Overall, the daily capture rate during the monitored period was 0.07 turtles day weir$^{-1,}$ and 1/3 of the days had zero captures. Over the years, the mean capture rate ranged from 0.04 to 0.08 (2009 and 2013, $P < 0.05$, Fig. 2A). Capture rates were similar among months ($F = 1.13$, $P = 0.35$, Fig. 2B), with lower mean values from November to February (0.05 turtles day weir^{-1}) and higher from March to September (peak in May - 0.08 turtles day weir^{-1}).

Capture rates from 1962 to 1977, 1980 and from 2008 to 2018 varied from 0 to 0.16 turtles day weir^{-1} (Table 1). The highest capture rate was recorded in 1962, and an unknown number of turtles were captured in 1977. In years from the historical dataset, 38% had capture rates near zero. Notwithstanding, capture rates in this historical period were higher than those recorded between 2008 and 2018 (Table 1) because the highest rate recorded between 2008 and 2018 was 0.08 turtles day weir^{-1}, while in the historical period, the smallest rate was 0.1 turtles day weir^{-1} (excluding zero rates).

3.2. Size variation

Green turtles ranged in CCL at first capture from 24 to 123 cm (mean $= 49 \pm 17$ cm, $n = 1951$). Juveniles predominated with CCLs from 30 to 49 cm (66%, $n = 1296$) (Fig. 3), while adults (≥97 cm) represented 3% ($n = 49$) of individuals. Adults were recorded in 41% of the monitored weirs, mainly deeper weirs ($n = 11$, Fig. 1). Adults were absent in 2008, 2009, 2012 and 2015, while 2017 and 2018 had 69% of the records.

CCL varied among years ($F = 29.84$, $P < 0.05$, Fig. 4A), with the largest variation (SD) in 2017 and 2018. The lowest mean occurred in 2008 (44 ± 10 cm) and 2010 (44 ± 11 cm), and the highest mean occurred in 2017 (58 ± 23 cm). Until 2016, turtles presented a mean smaller than 50 cm, and in 2017–2018, turtles had a mean larger than 55 cm (Fig. 4A).

Monthly CCL had lower mean values during Austral winter (June to August) and peaked from late winter until summer (September to December). Most adults occurred during spring (57%). Another peak, despite being lower, resulting in bimodality, seems to have occurred in March (Fig. 4B), although the differences were not significant ($F = 0.62$, $P = 0.81$, Fig. 4B).

The GLM analysis with the variables "Weir", "Month", "Year" and their interactions explained 35.1% of the variability in CCL. The three variables of the model and their interactions were significant; however, "Weir" (20.2%) and the interaction "Weir:Month" (10.2%) had the greatest explanatory power in the GLM (Tables 2 and 3). This indicates that sizes at recruitment were affected mostly by local and secondarily by a combination of weir location and month.

Multiple regression to assess the relationship between the CCL of the captured turtles, depth and distance from shore where weirs were placed showed that the depth variable significantly explained most of the variance in turtle CCL. Considering CCL and depth, the adjusted model (Fig. 5) indicated a quadratic relationship between these two variables; therefore, it was observed that in shallower zones, there was a prevalence of juveniles with a CCL of approximately 45 cm, with a decrease in size at depths between approximately 3 and 4 m and larger juveniles (>50 cm) at depths greater than 5 m.

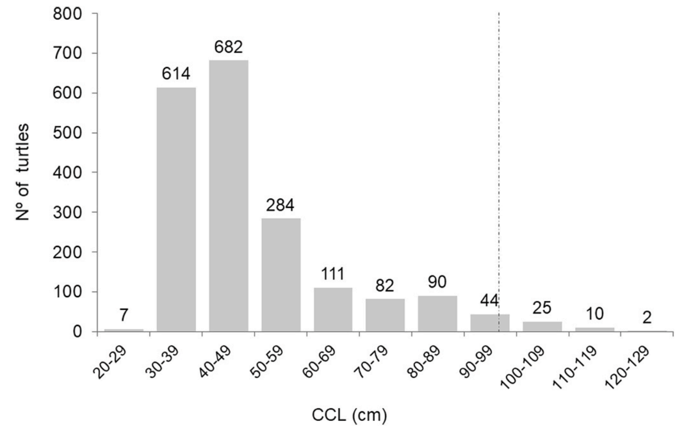

Fig. 3. Size class (CCL - curved carapace length) distribution of green sea turtles (*Chelonia mydas*) in fishing weirs in Ceará state, northeastern Brazil, from 2008 to 2018. The dashed line indicates a curvilinear carapace length of 97 cm, after which individuals were classified as adults.

3.3. Recaptures, residence and growth rate

A total of 330 recapture events of 195 individuals were recorded, ranging from once (129 individuals, 66.1%), twice (37 individuals, 19.0%), to three to nine times (14.9%). In 2009, the number of turtles

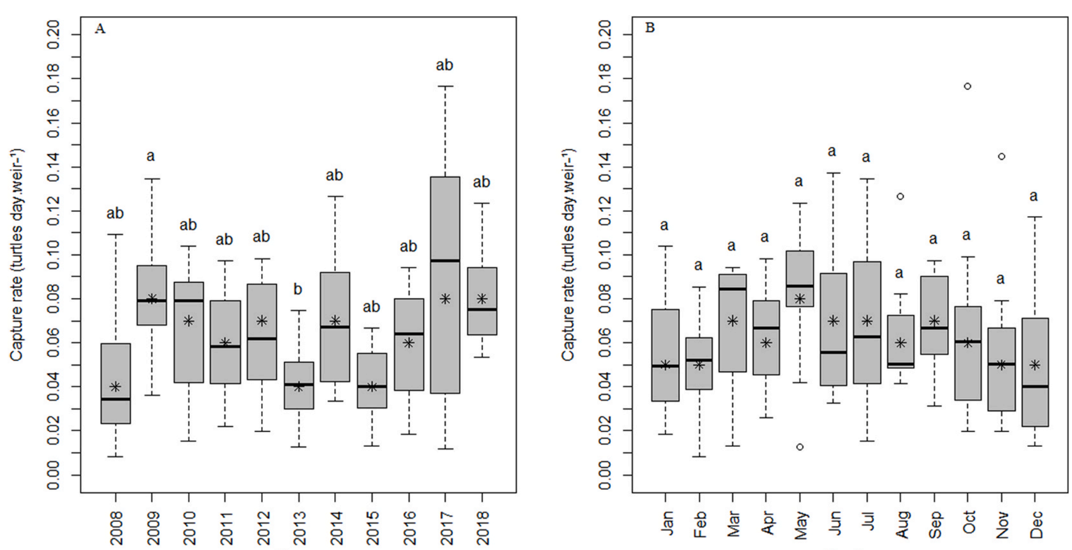

Fig. 2. Yearly (A) and monthly (B) variations in capture rates (turtles days weir^{-1}) of green sea turtles (*Chelonia mydas*) in fishing weirs in Ceará state, northeastern Brazil, from 2008 to 2018. Central line is the median, asterisk is the mean, upper and lower lines of the boxes represent the 75th and 25th quartiles, respectively, and whiskers are minimum and maximum in the 95th of cases. Different letters indicate significant differences among capture rates among years.

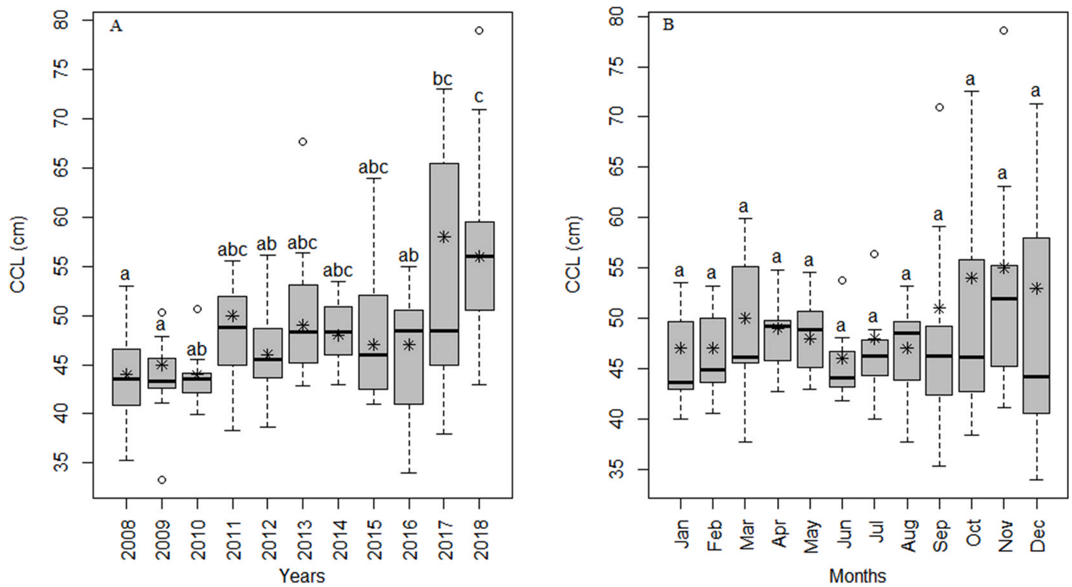

Fig. 4. Yearly (A) and monthly (B) variations in curved carapace length (CCL) of green sea turtles (*Chelonia mydas*) in fishing weirs in Ceará state, northeastern Brazil, from 2008 to 2018. Central line is the median, asterisk is the mean, upper and lower lines of the boxes represent the 75th and 25th quartile, respectively, and whiskers are minimum and maximum in the 95th of cases. Different letters indicate significant differences among CCLs in the years according to Tukey's test.

Table 2
Summary of the ANOVA results of the GLM for green sea turtle curved carapace length (CCL). The model was adjusted with a Gaussian distribution and identity link function, and the results are from the most parsimonious model (AIC = 525.9). % explained is calculated as deviance/residual deviance of the null model × 100, as in Ye et al. (2001). df - degrees of freedom.

Source of variation	df	Deviance	% explained	df of residuals	Residual deviance	*F*	*P*
NULL				1950	167.40		
Weir	26	33.84	20.2	1924	133.56	19.65	<0.001
Month	11	2.48	1.5	1913	131.08	3.41	<0.001
Year	1	0.90	0.5	1912	130.18	13.58	<0.001
Weir:Month	240	17.03	10.2	1672	113.16	1.07	0.232
Weir:Year	21	3.26	1.9	1651	109.90	2.34	<0.001
Month:Year	11	1.27	0.8	1640	108.63	1.74	0.059
Total Explained		58.77	35.1				

Table 3
Coefficients from the selected model with explanatory curved carapace length (CCL) of green sea turtles, explained by weir, month and year, as well as interactions between terms. The intercept represents the capture rate in weir AL1 in April in relation to which all other levels are compared. Only significant terms are shown.

	Estimate	Standard error	*t*	*P*
Intercept	−40.210	28.550	−1.408	0.159
Main Effects				
Weir 19 BB	−508	166.20	−3.056	0.002
Weir 2 VR	1181	554.9	2.129	0.033
Interactions				
Weir 10 GJ:August	−0.585	0.275	−2.127	0.034
Weir 18 BB:December	−0.539	0.165	−3.260	0.001
Weir 20 BB:July	0.684	0.342	2.003	0.045
Weir 18 AL:November	−0.503	0.215	−2.338	0.020
Weir 17 BB:November	−0.367	0.175	−2.097	0.036
Weir 18 BB:November	−0.417	0.164	−2.547	0.011
Weir 11 VR:November	−0.653	0.226	−2.888	0.004
Weir 5 VR:November	−0.737	0.350	−2.107	0.035
Weir 7 VR:November	−0.373	0.183	−2.037	0.042
Weir 19 BB:October	0.511	0.256	1.998	0.046
Weir 19 BB7:Year	0.252	0.824	3.056	0.002
Weir 2 VR:Year	−0.588	0.276	−2.130	0.033

recaptured (n = 88) was at least double the number of recaptures in other years, except in 2017 (Table 1). In contrast, 2008 had the lowest number of recaptures (n = 6) and sampling effort (Table 1).

Most recaptured individuals had moved between the fishing weirs that were monitored, with only 18% of recaptures occurring at the same weir where the turtle had last been captured. The shortest recapture interval occurred one day after capture, and the longest occurred after approximately 3 years. Although recapture intervals varied, most occurred within a month from release (52%, n = 172), with 86% (n = 285) occurring up to six months (Fig. 6). Recaptured turtles ranged in size from 31 to 85 cm (mean = 44 ± 9 cm, n = 330).

A subset of 33 recaptures had intervals ≥10 months (Table 4), with initial CCLs ranging from 30 to 56 cm. Most individuals (70%) changed size class between the first and last recapture (Table 4). The annual mean growth rate among the recaptured juvenile green turtles was 6.7 ± 3.6 cm year^{-1} (range = 1.29–19.95 cm year^{-1}). The linear regression indicated a correlation between the CCL of the first recapture and the growth rate (r^2 = 0.27, P < 0.001). In general, individuals with smaller lengths in the first recapture had the highest growth rate, while larger individuals grew slower (Fig. 7).

4. Discussion

Long-term monitoring of sea turtles captured in fishing weirs along the Ceará coast confirmed that the region is an important feeding and developmental area for juvenile green turtles. In the area, turtles grow

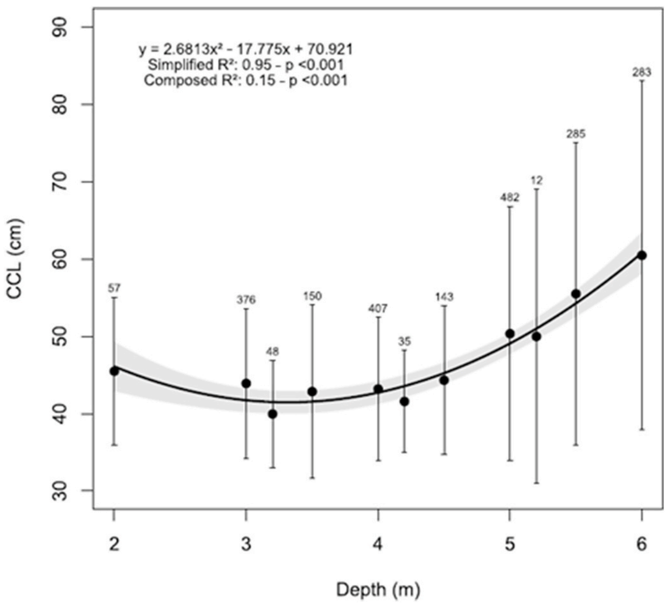

Fig. 5. Regression between the curved carapace length (CCL) of the green sea turtles (*Chelonia mydas*) captured and the depth during high tide where each fishing weir was placed. The bars show the standard deviation, and the number above represents the total number of turtles captured at each depth. Shading is the 95% confidence interval of the regression model. The simplified R^2 value represents the mean tendency of the CCL at each depth, and the composed R^2 value represents the probability of a single individual captured to have the CCL predicted by the model.

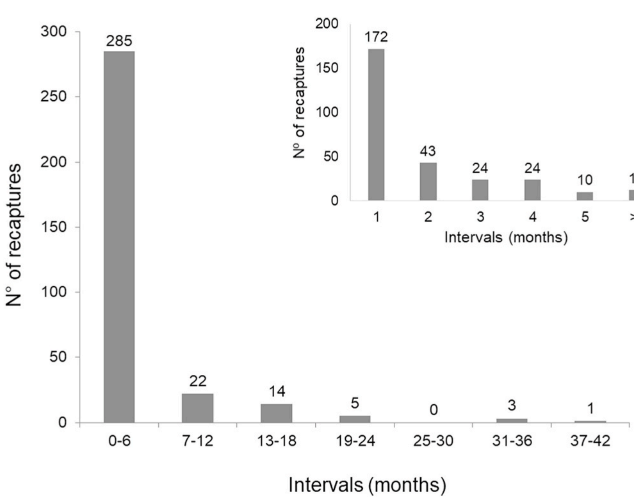

Fig. 6. Intervals of recaptures of green sea turtles captured in weirs in Ceará state, northeastern Brazil, from 2008 to 2018. The inset shows details of the first interval, from 0 to 6 months.

faster than in other feeding areas, with adults remaining in deeper waters. Some fishing weirs have been installed over *Halodule wrightii* meadows (Barros, 2013); this is the most common seagrass along the Brazilian coast and is often consumed by green turtles (Guebert-Bartholo et al., 2011; Gama et al., 2016), which could explain the high capture rate in the fishing weirs.

Sea turtle captures from the 1960s to the 1980s allowed us to infer a depletion of stocks after an initial period of higher capture rates, probably due to the use of turtles as a fishing resource. The later increase in capture rates was possibly related to the recovery of populations nesting in distant rookeries and the reduction of intentional killing for meat consumption or market trade in Brazil. The historical overview

Table 4
Size-specific growth rates for green sea turtles recaptured at intervals ≥10 months (n = 33) in fishing weirs at a coastal foraging ground in Ceará state, northeastern Brazil, from 2008 to 2018. CCL - curved carapace length, SD - standard deviation, and n - number of turtles.

Size class at first recapture and size class last recapture (CCL cm)	Mean growth rate (cm year^{-1})	SD	Range (cm)	n	Range interval (days)
30–39.9	7.1	0.6	30–39	3	317–380
30–49.9	6.4	2.1	33–49	7	319–583
30–59.9	9.7	4.1	35–56	5	361–957
40–49.9	3.4	1.2	41–49	3	502–656
40–59.9	5.5	1.2	42–55	9	303–677
40–69.9	7.9	–	41–64	1	1112
40–79.9	20.0	–	45–74	1	549
50–59.9	4.0	3.1	50–59	3	322–564
50–69.9	8.3	–	56–68	1	531

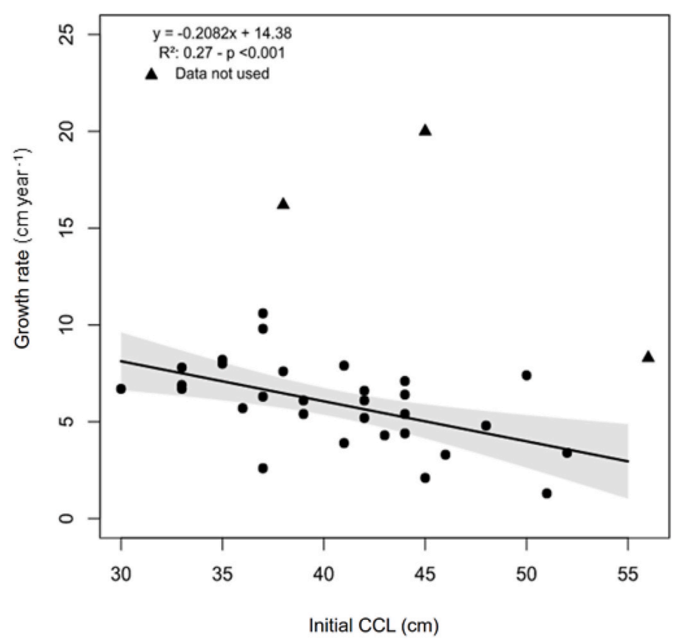

Fig. 7. Linear regression between curved carapace length (CCL) in the first recapture and the growth rate of green sea turtles (*Chelonia mydas*) in fishing weirs in Ceará state, northeastern Brazil, from 2008 to 2018.

demonstrated how conservation activities reflected positively on the actions of fishermen (Marcovaldi et al., 2001; Lima et al., 2013) and potentially in the recovery of populations, as indicated by the number of nesting females in source nesting grounds such as Ascension Island (Weber et al., 2014), Suriname and elsewhere (Mazaris et al., 2017). The development of trust in fishing communities has been key to avoiding turtle killing for consumption or market trade and thus for the successful conservation of sea turtles in several places (Risien and Tilt, 2008; Bretos et al., 2017). Transforming fishermen into conservation agents facilitates the favorable perception of communities toward turtles and reduces costs for monitoring, as fishermen themselves already perform daily monitoring. Moreover, it allows essential demographic and ecological data to be gathered (Silva et al., 2017).

4.1. Capture rates

Capture rates were similar among months. Possibly, the low variation in capture rates is related to the maintenance of fishing weirs in the same location over the years (Lima et al., 2013) in association with the mixed stocks, i.e., individuals from different nesting areas, such as Suriname, Ascension, Trindade and Aves Island (Naro-Maciel et al., 2007), which results in the arrival of turtle cohorts throughout the year and buffers interannual variations in nesting productivity. This pattern of similar rates over the months contrasts with that recorded in subtropical and temperate areas, where juvenile green turtles have a marked seasonal variation in abundance (Torezani et al., 2010; Silva et al., 2017; Piovano et al., 2020).

However, although not statistically significant, there was a clear seasonal variation, with approximately double the capture rate between March and October, suggesting that beyond the presence of mixed stocks, changes in environmental characteristics may reduce capture rates during summer. Higher capture rates have been reported in fall--winter since the 1960s (Paiva and Nomura, 1965; Collyer and Aguiar, 1972; Almeida, 1974). After July, strong trade winds make fishing more difficult and less productive (Ximenes, 1980), with weather conditions potentially leading to higher energy expenditure in juveniles swimming through waves and currents in the coastal region (López-Mendilaharsu et al., 2005; Hatase et al., 2006). This could cause spatial changes in turtle distribution and a local decrease in turtle numbers during spring and summer.

The period from 1962 to 1964 had the highest capture rates, and despite a decline from 1962 onwards, rates could reflect a stock reduction due to consumption and sale of turtle meat (Silva, 1994). Population declines in green sea turtles caused by human harvests have been reported, e.g., in Tortuguero and Ascension (Campbell and Lagueux, 2005; Weber et al., 2014). The decrease in capture rates in the first half of the 1970s may reflect the decline in the size of the population in nesting areas, mainly due to the lack of legislation and protective actions toward turtles. In Brazil, there was partial protection for green turtles with a CCL <80 cm in 1976, and only in 1986 was there total protection for all species and sizes (Marcovaldi and Marcovaldi, 1999). Similar capture rates between 2008 and 2018 may reflect the recovery of the population of green turtles nesting on Ascension Island (Weber et al., 2014). Given that turtles along the Ceará coast originate from different nesting areas (Naro-Maciel et al., 2007) and the strong influence of Ascension Island rookeries, conservation actions in this foraging area possibly contributed to the recovery of populations at Ascension, Suriname and elsewhere in the Atlantic Ocean.

4.2. Turtle size

The sizes of green turtles captured in fishing weirs indicated sharing of foraging areas by juveniles and adults, with a prevalence of juveniles in shallow waters. This pattern is common along the Brazilian coast (e.g., Jardim et al., 2016; Colman et al., 2015; Silva et al., 2017) and in the world's oceans (e.g., Arthur et al., 2008; Fukuoka et al., 2015; Kameda et al., 2017). Juveniles, due to their small size and growth, have higher energetic demands than adults (López-Mendilaharsu et al., 2005), and they establish themselves in calm and sheltered coastal areas as they recruit from the pelagic to the neritic phase (López-Mendilaharsu et al., 2005; Hatase et al., 2006). The low number of adults in this study (3%) is explained by larger turtles occupying deeper waters (Chambault et al., 2015; this study) outside the fishing weir depth.

The differences in the mean CCL of turtles captured over the years were due to the high mean in 2017 and 2018, years with a high number of adults, which increased the mean length. Despite this, the minimum and maximum lengths recorded in the last two years (24–122 cm) were similar to those recorded in previous years (27–123 cm) and to those recorded for the region from 2004 to 2006 (26.4–121 cm, Lima et al., 2013). Monthly variations in turtle sizes were not significant, but between September and December (spring), mean CCLs were over 50 cm, with an increase of approximately 5 cm compared with other months. This increase in CCL may have been related to the presence of adult females from Suriname and French Guyana moving to Brazil after the nesting period. According to Baudouin et al. (2015), regardless of their individual date of arrival in Brazil, all green turtles stayed on the Ceará coast between June and October.

The GLM analysis on CCL data indicated greater explicability according to weir and the interaction between weirs and months, which suggests that some weirs were more prone to capturing large (or smaller) turtles. Fishing weirs with greater depths (5–6 m) accounted for the capture of larger turtles, although females from French Guyana and Suriname tracked in the area had core areas >10 m and >22 km from the coast (Chambault et al., 2015); therefore, outside the operational depth of weirs (<6 m depth and <5 km from shore). In addition, the presence of adults could have been underestimated by the sampling weirs.

4.3. Recapture, residence and growth rate

Most turtles recaptured within six months between events could be explained by moving out of the area to deeper areas as they grow or weir avoidance behavior. To these nonexcluded possibilities could be added the possibility of potential movement outside the area and returning long afterwards, e.g., three years from tagging. Residence for days or a few months in feeding areas has been recorded elsewhere in Brazil (Gallo et al., 2006; Torezani et al., 2010; Jardim et al., 2016), Japan (Fukuoka et al., 2015), the United Arab Emirates (Robinson et al., 2017), Mexico (Karam-Martínez et al., 2017), and South Korea (Jang et al., 2018). However, when settled in a given area, juvenile green turtles could move to nearby areas and remain undetected, as demonstrated recently using satellite telemetry in the Caribbean (Godley et al., 2003; Robinson et al., 2017).

The mean growth rate of green turtles, 6.7 ± 3.6 cm year^{-1}, was higher than that of turtles in other feeding areas in Brazil, e.g., Bahia (12°S, 3.0 cm year^{-1}, Jardim et al., 2016), Espírito Santo at 20°S (3.1 cm year^{-1}, Torezani et al., 2010), Rio Grande do Sul at 29°–31°S (3.7 cm year^{-1}, Lenz et al., 2017), Akumal Bay in Mexico at 20°N (6.2 cm year^{-1}, Labrada-Martagón et al., 2017), and the Japanese archipelago of Ryukyu at 24°N (2.2 cm year^{-1}, Kameda et al., 2017). The high value could have been due to intrinsic individual factors (e.g., sex, size) or external factors (e.g., habitat, diet, water temperature) (Kubis et al., 2009; Eguchi et al., 2012; Velez-Zuazo et al., 2014); in addition, it could have been biased by the small number of recaptures with intervals ≥ 10 months.

In general, turtles with a CCL of 30 cm at first recapture had the highest growth rates, i.e., as CCL increased, growth rate decreased. In sheltered coastal waters, juveniles can maximize their growth rates by avoiding energy expenditures with deep dives and facing strong waves and currents (López-Mendilaharsu et al., 2005; Colman et al., 2015).

5. Conclusion

Our study shows that the incidental capture of green turtles in fishing weirs along the coast of Ceará state is high, most of which were juveniles with CCL <50 cm, while adults remained in deeper waters. Turtles had short residence times in the region and they grew faster than turtles in other feeding areas, particularly in smaller size classes. Capture rates varied throughout the historical period but were mostly homogeneous between years and months, followed by a recent increase. Environmental awareness by fishermen and their change in behavior, avoiding killing turtles for consumption or illegal sale, could have contributed to the trends that were detected and to the conservation of wide-ranging green turtles in this tropical foraging area along the Ceará coast.

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CRediT authorship contribution statement

Lima, EHSM: Conceptualization, research, writing - review and editing; Awabdi, DR: Conceptualization, formal analysis, writing - original draft; writing - review and editing; Melo, MTD: Conceptualization, research, writing - review and editing; Giffoni, B:

Conceptualization, writing - review and editing; Bugoni, L: Conceptualization, writing - original draft; writing - review and editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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