Herpetological Conservation and Biology 17(3):593–601.
Submitted: 5 October 2021; Accepted: 24 October 2022; Published: 16 December 2022.

Long-term Trend of Olive Ridley Sea Turtles (*Lepidochelys olivacea*) Nesting in Brazil Reveals One of the Largest Rookeries in the Atlantic

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Abstract.—**Northeastern Brazil supports an important population of Olive Ridley Sea Turtles (*Lepidochelys olivacea*) that was historically depleted due to several human activities. Here, we present the long-term trends in numbers of Olive Ridley Sea Turtles nests observed throughout 16 y of beach surveys. From 2003/2004 until 2018/2019 nesting seasons, we recorded annual nest counts along coastline of Bahia and Sergipe states between September and March. These data were compared with previous published data collected between 1991/1992 and 2002/2003 nesting seasons. We also estimated the minimum number of females nesting annually based on clutch frequency. Our results indicate an upward trend in annual nest counts between 2003/2004 and 2018/2019 with a significant increase in annual clutch counts every 2 y. We also observed a 50-fold increase in nesting numbers when comparing the 12,709 nests estimated in 2018/2019 season to the 252 nests counted in 1991/1992. Based on the average number of nests laid in the last three nesting seasons, we estimated that about 11,923 females nested annually over the study area. Our results highlight that Brazil currently supports the second largest population of Olive Ridley Sea Turtles in the Atlantic. The increase in annual nest counts observed between 1991/1992 and 2018/2019 is probably due to conservation actions that maximized hatchling output from the nesting beaches and reduced threats at sea. Despite this increasing trend, a high level of mortality of mature Olive Ridley Sea Turtles due to incidental catch in trawl fishery has been reported and is a matter of concern for the conservation and population stability in Brazil.**

Key Words.—Bahia; conservation; population recovery; sea turtles; Sergipe

Introduction

The conservation status of sea turtles is usually assessed based on long-term monitoring of females and their nests at the nesting grounds because these animals exhibit a long and complex life cycle, characterized by the use of different habitats by different life stages, which makes it difficult to monitor turtle numbers in the ocean (Rees et al. 2016). Only adult females use the terrestrial environment during the nesting season (Bolten 2003). Thus, the abundance of females and/or their nests usually serve as the primary metrics to monitor trends in sea turtle populations (National Research Council 2010; Rees et al. 2016).

Habitat destruction, direct exploitation, and fisheries interactions have caused a decline in most sea turtle populations worldwide (Lutcavage et al. 1997; Rees et al. 2016). With the implementation of measures to protect eggs and adult females on nesting beaches, however, and regulations to reduce fisheries bycatch of turtles in the ocean, the recovery of some depleted populations has been possible, and results are encouraging (Rees et al. 2016; Mazaris et al. 2017). A previous study compiled trends of sea turtle species worldwide based on Regional Management Units (RMUs) and indicated that 12 RMUs exhibit upward trends against five RMUs with downward trend (Mazaris et al. 2017). Olive Ridley Sea Turtles (*Lepidochelys olivacea*; hereafter, Olive Ridley), for example, have increased in abundance within RMUs from the Western Atlantic and Northeast Indian Ocean (Mazaris et al. 2017). For the Atlantic Basin, an upward trend has also been observed in French Guiana since the 2000s (Kelle et al. 2009; Lasfargue et al. 2021). In the eastern Atlantic Ocean, the population of Gabon

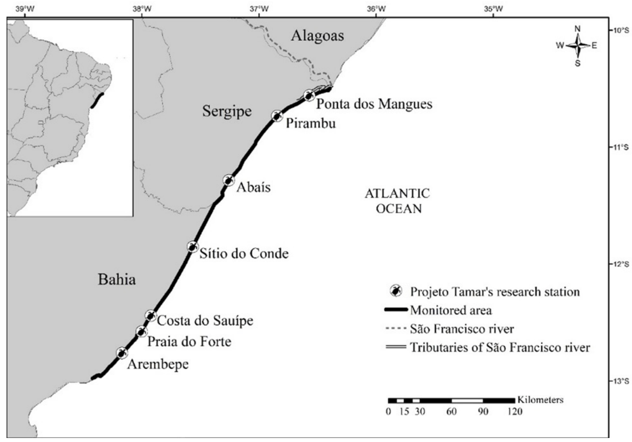

Figure 1. Nesting areas of Olive Ridley Sea Turtle (*Lepidochelys olivacea*) in Brazil.

was previously identified as the largest Olive Ridley population (Metcalfe et al. 2015), but a recent study revealed that Angola currently hosts the largest Olive Ridley nesting population in the Atlantic (Morais and Tiwari 2022).

In Brazil, sea turtle conservation efforts began with nesting beach surveys from 1980 to 1982 by Projeto Tamar. Data were gathered along Brazilian coast through beach patrols and interviews with local fishermen, turtle hunters, and egg poachers, known in northeastern Brazil at that time as *tartarugueiros*. Based on these 2 y of surveys, field stations were established in Sergipe and Bahia states, which were identified as important nesting grounds for sea turtles, including Olive Ridleys, and recognized for conservation priority since rookeries were extensively exposed to directed take of either eggs or adult females (Silva et al. 2016). After that, Projeto Tamar approached the local communities and proposed a non-consumptive alternative income and made the *tartarugueiros* allies in sea turtle conservation, providing capacity building and income generation opportunities (Marcovaldi and Marcovaldi 1999; Silva et al. 2016). Also, relocation of nests to hatcheries was a common strategy to promote protection and hatchling success, and to help mitigate several years of poaching (Marcovaldi and Marcovaldi 1999; Silva et al. 2016).

The results of conservation efforts since the 1980s were observed in previous studies, which revealed an increasing trend in the estimated number of nesting of sea turtle species (Marcovaldi and Chaloupka 2007; Marcovaldi et al. 2007; Silva et al. 2007). The Olive Ridley population experienced a 10-fold increase in nesting events from 252 nests in 1991/1992 to 2,606 nests in 2002/2003 (Silva et al. 2007). Despite this increasing trend coupled with a decrease in direct exploitation on the nesting beaches in Brazil, a high level of mortality of mature Olive Ridleys due to incidental catch in trawl fishery has been reported by Projeto Tamar over the past decade (Silva et al. 2010, 2011); a matter of concern for the conservation of Olive Ridleys in this region. Given the persistence of threats around reproductive areas, here we reassess and update the distribution and abundance of Olive Ridleys in Brazil using female and nest numbers as estimator, to see if the previously observed upward trend was sustained from 2003/2004 until the 2018/2019 seasons.

Material and Methods

Study area.—We surveyed 330 km of Brazilian coastline located between latitudes 10°51’S and 12° 96’S (Fig. 1). In Sergipe state, we monitored nesting events at three research stations: Ponta dos Mangues (27 km), Pirambu (53 km), and Abaís (36 km), covering 116 km. In Bahia state, we recorded nesting activities along four locations: Sítio do Conde (81 km), Costa do Sauípe (56 km), Praia do Forte (30 km), and Arembepe (47 km), covering 214 km of beach (Fig. 1; Supplemental Information Table S1).

Annual nest counts.—Our study includes 16 nesting seasons from 2003/2004 to 2018/2019. We carried out fieldwork annually from 15 September to 31 March, the main nesting period for Olive Ridleys in this region (Silva et al. 2007; Matos et al. 2012). We surveyed the study area daily at dawn to identify and record the reproductive events (nesting and non-nesting emergences). Nests were left *in situ* whenever possible and marked with numbered stakes, then monitored throughout the incubation period following the standard methodology adopted by Projeto Tamar (Marcovaldi and Laurent 1996; Marcovaldi et al. 2007). If necessary, the nests were dug up and sent to a hatchery or to a safe point on the beach. We identified the species in monitored nests by nest excavation after hatchlings emergence. In some cases, it was not possible to record species due to total hatchling emergence, predation, or poaching. In these cases, we estimated how many nests with unknown species could be Olive Ridley nests, to have the total number of nests to this species. The total number of Olive Ridley nests was defined as:

$$N_t = N_{obs} + N_{est}$$

where, N_{obs} is the number of nests known to belong to Olive Ridley turtles and N_{est} the number of Olive Ridley nests estimated from nests for which the species was not identified (unknown nests). The equation to estimate the number of Olive Ridley nests took the form:

$$N_{est} = N_{ni} (N_{obs} N_{sp}^{-1})$$

where, N_{ni} is the number of unknown nests, N_{obs} is the number of nests known to belong to Olive Ridleys, and N_{sp} is the number of nests of known species.

When a specific beach was not monitored in a given period of a nesting season, the number of nests laid on that beach (or stretch of beach) for that period was estimated as the average of the total number of Olive Ridley nests laid on that area for the same season period on previous and following nesting seasons (Silva et al. 2007). Furthermore, between 2013/2014 and 2018/2019 nesting seasons, we reduced the survey effort in some beaches. In these beaches, we counted all nests, but we did not excavate them all. To estimate number of Olive Ridley nests, we used the long-term database of 24 y of Projeto Tamar, which made it possible for us to identify the proportion of nests per species on each beach over time. We identified beaches with similar proportions of species over time series and grouped them into sampling units (Santos 2016). Within each sampling unit, there was a reference beach, where we excavated and collected data of all the nests. We used the proportion of species found on this beach to estimate the total number of Olive Ridley nests on the other beaches with reduced effort.

***Estimating female abundance*.**—We estimated the minimum number of females nesting by dividing the average number of nests laid in the last 3 y of nesting by clutch frequency (number of nests laid/female/season). We determined clutch frequency from approximately 5,000 individual nesting females, monitored during night patrols, over 16 y in Sergipe, which indicated that 88.4% of females nest once in a season, 11% nest twice in a season, and 0.6% nest three times in a season. We also estimated female abundance through satellite telemetry data from 39 females (Santos et al. 2019), which indicated that at least 21 females (54%) possibly nested twice, and the others probably nested once. The number of breeding females in the population was also determined based on the remigration interval of 1.5 y observed in others Olive Ridley populations (Miller 1997; Metcalfe et al. 2015).

***Statistical analysis*.**—Given that remigration intervals in the literature for Olive Ridley is 1.5 y (Miller 1997; Metcalfe et al. 2015), we evaluated the nesting trend using a Generalized Least Square Model with log transformed nest counts and autocorrelation errors to account for any temporal correlation using the nmle package in the R software version 4.1.1 (R Core Team 2021). We tested for first order autocorrelated error structure as well as for higher order autocorrelation. The best model was selected based on the difference in Akaike Information Criteria (AIC) values. The significance level for all tests was $\alpha = 0.05$.

Results

Trends in annual nest counts.—The best model of nesting trends in Olive Ridleys was the first-order autocorrelation (AIC = -4.901) with the second-order of autocorrelation (AIC = -4.353). This supported a significant increasing trend in nesting over the 16 y of this study ($P < 0.05$; Fig. 2) and corresponds to the

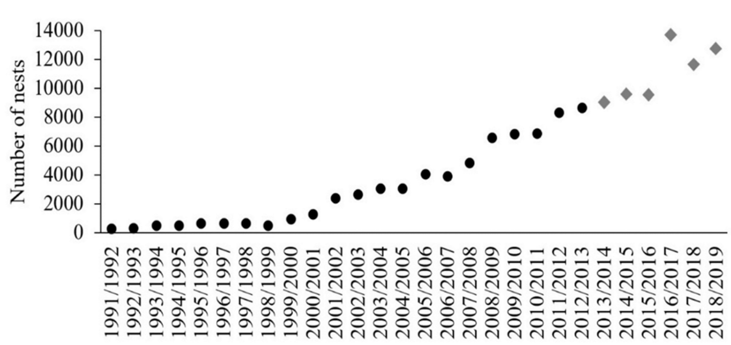

Figure 2. Number of Olive Ridley Sea Turtle (*Lepidochelys olivacea*) nests recorded during each reproductive season in northeastern Brazil between 1991/1992 and 2018/2019 (Silva et al. 2007 and present study). Closed circles are nesting counts along study area between 1991/1992 and 2012/2013 nesting seasons. Grey diamonds represents number of nests estimated between 2013/2014 and 2018/2019 nesting seasons.

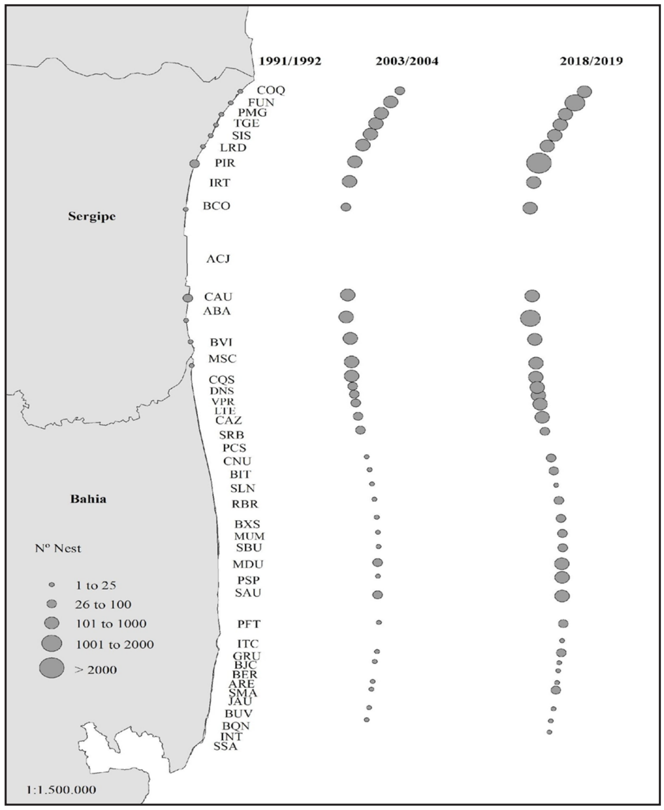

Figure 3. Estimated average number of nests of Olive Ridley Sea Turtles (*Lepidochelys olivacea*) during the 1991/1992, 2003/2004, and 2018/2019 nesting seasons in Brazil. The acronyms represent the nesting beaches: SSA = Salvador, INT = Itapuã, BQN = Buraquinho, BUV = Busca Vida, JAU = Jauá, SMA = Santa Maria, ARE = Arembepe, BER = Berta, GRU = Guarajuba, ITC = Itacimirim, PFT = Praia do Forte, SAU = Sauípe, PSP = Porto de Sauípe, MDU = Massarandupió, SBU = Subaúma, MUM = Mamucabo, BXS = Baixios, RBR = Ribeiro, SLN = Salinas, BIT = Barra do Itariri, CNU = Corre Nu, PÇS = Poças, SRB = Siribinha, CAZ = Costa Azul, LTE = Lote, VPR= Vapor, DNS = Dunas, CQS = Coqueiro, MSC = Mangue Seco, BVI = Boa Viagem, ABA = Abaís, CAU = Caueira, BCO = Barra dos Coqueiros, IRT = Ilha do Rato, PIR = Pirambu, LRD = Lagoa Redonda, SIS = Santa Isabel, TGE = Tigre, PMG = Ponta dos Mangues, FUN = Funil, and COQ = Cabeço.

average remigration interval of 1.5 y. Our results also indicated a pattern of increase in nesting numbers every two seasons (Fig. 2).

Between 2003/2004 (3,038 nests) and 2018/2019 (12,709 nests) we observed a four-fold increase in nesting. The exceptionally high nesting numbers in 2016/2017 alone (13,684 nests) showed a 4.5-fold increase over 14 y. The nesting numbers in 2018/2019 season was at least 50 times higher than the 252 nests counted in 1991/1992 (Silva et al. 2007; Fig. 3). Overall, the trend in nest density increased from south to north, with the highest nest density recorded consistently at Pirambu (PIR) in Sergipe with 100 nests/km, followed by nesting at Funil (FUN) with 73 nests/km, and then Tigre (TGE) and Ponta dos Mangues (PMG) beaches, both with 61 nests/km over the 16 nesting seasons. All the beaches of Sergipe state together account for 74% of the nesting, with two beaches (PIR and FUN) alone supporting 27% of the nesting.

Trends in female abundance.—According to clutch frequency data from approximately 5,000 individual females over 16 y in Sergipe, the average number of nests laid in the last three nesting years was 12,669 nests, suggesting that 11,923 females nested along the 330 km over the last three nesting seasons. Based on satellite telemetry data from 39 females tracked (Santos et al. 2019), we estimate a minimum of 9,248 females nesting between 2016/2017 and 2018/2019 seasons. Using the remigration interval of 1.5 y (Miller 1997; Metcalfe et al. 2015) and considering both estimates of clutch frequency, the estimated size of the female breeding population in northeastern Brazil ranged between 13,873 to 17,885 females in the last three years of nesting.

Discussion

Abundance and trends in the Atlantic basin.—Olive Ridley populations have historically been depleted worldwide, but decades of conservation efforts resulted in upward trends of some populations (Metcalfe et al. 2015; Mazaris et al. 2017; Lasfargue et al. 2021; Shanker et al. 2021). An increasing trend was reported

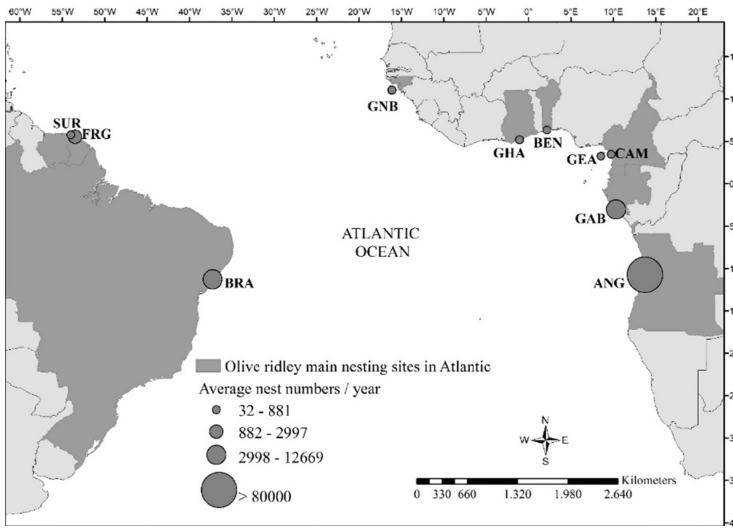

Figure 4. Nest numbers per year for the main nesting sites of Olive Ridley Sea Turtles (*Lepidochelys olivacea*) along the Atlantic Ocean. Locations are SUR = Suriname[1]; FRG = French Guiana1; BRA = Brazil[3]; GNB = Guinea Bissau[2]; GHA = Ghana[2]; BEN = Benin[2]; GEA = Equatorial Guinea[2]; CAM = Camaroon[2]; GAB = Gaboon[2]; and ANG = Angola[2]. ([1]Lasfargue et al. 2021, [2]Morais and Tiwari 2022, [3]this study).

for the Brazilian population in the early 2000s (Silva et al. 2007), but threats around reproductive areas are still a matter of conservation concern. In our study, we reassessed the population trend of the Olive Ridley Turtle in Brazil and observed a significant 50-fold increase in nesting numbers from 252 nests counted in 1991/1992 to an estimated 12,709 nests during the 2018/2019 season.

Because sea turtles exhibit significant variation in dispersion patterns and habitat use among life stages, as well as high fidelity as adults to their natal areas (natal philopatry; Bolten 2003; Jensen et al. 2013), population recovery is a complex puzzle that requires conservation actions both in terrestrial and marine environments and at an international scale (Rees et al. 2016; Mazaris et al. 2016; Lewinson et al. 2013) In our study, the significant increase achieved between the nesting seasons of 1991/1992 and 2018/2019 is probably the direct result of conservation actions carried out in the Atlantic region both at the foraging and nesting grounds (Silva et al. 2016; Giffoni et al. 2019). In Brazil, uninterrupted conservation actions were promoted over four decades by Projeto Tamar. These conservation actions were based on an adaptive threat management framework and community-based development strategy, through social integration and promotion of innovative educational and socioeconomic activities to achieve sea turtle conservation goals (Silva et al. 2016). For example, former poachers were hired to work as *tartarugueiros* to patrol the beaches and protect sea turtles, employment opportunities were generated through product/merchandise manufacturing and handicrafts, and to advocacy for the creation of a second period of shrimp trawl closures that overlapped with the peak of the Olive Ridley nesting season. Furthermore, uninterrupted conservation actions implemented directly on nesting beaches since the 1991/1992 season contributed to high hatchling production (Silva et al. 2007, 2016). Olive Ridleys reach sexual maturity around 16 y old (Petitet et al. 2015), which matches the time when a steep increase in the number of nests was observed after the 1991/1992 nesting season. It is possible that hatchlings from the early years nested for the first time in 2007, 2008 or 2009, contributing to the significant increase of nests observed since the 2007/2008 nesting season.

Our results also highlight that Brazil currently supports the second largest population of Olive Ridleys in the Atlantic region with an annual average of 12,669 nests for the last three nesting seasons (2016/2017 to 2018/2019) and with the highest number of nests recorded during the 2016/2017 season (n = 13,684; Fig. 4). The largest Olive Ridley nesting population in the Atlantic (and also the largest non-arribada population globally) was recently recorded in Angola, with 83,024 nests counted (Morais and Tiwari 2022). Considering the maximum number of female Olive Ridleys estimated in Angola (83,024) and Brazil (17,885), the Angola population is 4.6 times larger than the Brazilian population.

Historically, the largest Olive Ridley populations in the western Atlantic were attributed to Suriname and French Guiana. In Suriname, however, the population declined significantly, and the latest population assessments reported only 150–200 nests/year (Hoeckert et al. 1996; Hilterman et al. 2008). In French Guiana, however, an increase in the number of nests was observed since the 2000s. About 1,716 to 3,257 nests were estimated annually between 2002 and 2007 (Kelle et al. 2009), but recent estimates indicated that between 2008 and 2016, an average of 2,997 nests were deposited annually (Lasfargue et al. 2021). In the eastern Atlantic region, the population of Gabon was previously identified as the largest Olive Ridley population in the Atlantic. The average annual number of nests varied between 2,370 and 9,814 and the highest number recorded was 14,033 nests during the 2013/2014 season (Metcalfe et al. 2015).

Current and potential threats.—Although conservation activities based on environmental education and social inclusion contributed to the upward trend of the Olive Ridley population, coastal development and increasing interactions between adult turtles and fisheries around the nesting areas are still issues of concern (Sales et al. 2008; Castilhos 2016; Oliveira 2016). Specifically, beaches in Bahia State have undergone a rapid change in recent years. Beaches that were once deserted or previously occupied by coconut farms or small communities of fishermen are now occupied by residential condominiums, hotels, and leisure areas with a significant increase in tourism, beach users, and light pollution (Lopez et al. 2014). Active real estate speculation and mischaracterization of coastal environments are some of the current threats to sea turtles in terrestrial habitats (Lopez et al. 2014; Silva et al. 2016). Nest predation by wild animals such as the Crab-eating Fox (*Cerdocyon thous*), the Nine-banded Armadillo (*Dasypus novemcinctus*), and the Six-banded Armadillo (*Euphractus sexcinctus*) is another threat that has been increasing in recent years both in Bahia and Sergipe (Gandu et al. 2013). Some nest protection strategies such as increased effort in night beach patrols and the use of flags near the nests to scare the predators have had good results in reducing egg loss (Longo et al. 2009). Additionally, due to illegal human occupation in coastal areas, a new and increasing threat has emerged: nesting Olive Ridleys have been attacked by Domestic Dogs (*Canis lupus familiaris*) primarily on the beaches of Sergipe (Castilhos 2016).

In addition to all these threats, the most significant impact faced by sea turtles is the incidental catch in fisheries. The shrimp bottom trawl has been identified as the major threat to Olive Ridley in Brazil (Silva et al. 2010). Since 1994, a Brazilian law has required the use of Turtle Excluder Devices (TEDs; https://www.icmbio.gov.br/cepsul/images/stories/legislacao/Portaria/1994/p_ibama_36_1994_egulamentausotednapescacamaraorosa.pdf); however, this law has been largely disregarded by fishermen along the entire Brazilian coastline, which makes the law ineffective (Duarte et al. 2019). The trawl fishing distance from the coast appears to be another problem contributing to the bycatch of Olive Ridley. In Sergipe, during the nesting season, there is an overlapping between the Olive Ridleys inter-nesting area and the main trawl fishing area with both occurring in shallow waters of 5–30 m depth (Silva et al. 2011). This overlap results in hundreds of Olive Ridley turtles stranded on the beaches every year, mainly on austral summer, when the females come to nest. Between March 2010 and February 2015, 1,971 Olive Ridley stranded on the beaches between the north coast of Bahia and south coast of Alagoas (including all coast of Sergipe state). More than 90% of these Olive Ridley were adults, with high reproductive values (Reis et al. 2019).

Although a law forbids trawl boats in Bahia, Sergipe, and Alagoas from fishing inside the first, second, and third nautical miles, respectively (https://www.icmbio.gov.br/cepsul/images/stories/legislacao/Instrucao_normativa/2004/in_mma_14_2004_regulamentapescacamaroesregiao_ne.pdf), this law is also ignored and, in practice, boats fish within a few hundred meters from the coast, increasing the probability of bycatch. In addition to trawl boats, longline fishing is another threat to the Olive Ridley population. Between 1999 and 2016, the Brazilian longline fishery incidentally captured more than 600 Olive Ridleys (Giffoni et al. 2017). Despite the big challenge associated with fisheries management to reduce bycatch, some strategies might be contributing to mitigate this impact. Besides the overlapping between the shrimp trawl time closure and the Olive Ridley nesting peak from 2004, another important change was related to longline fishery. In November 2018, the Brazilian Government forbid the use of J hooks for all longline fishing boats licensed to fish Swordfish (*Xiphias gladius*) and tuna (*Thunnus* sp.). Since then, those boats have to use only circle hooks bigger than 14/0 (https://www.icmbio.gov.br/cepsul/images/stories/legislacao/Portaria/2017/P_mdic_mma_74_2017_medidas_mitigadoras_tartarugas.pdf). Circle hooks have been suggested as an efficient mitigation measure to reduce the incidental capture of sea turtles in longlines (Sales et al. 2010; Andraka et al. 2013; Swimmer et al. 2017). It is likely that the number of Olive Ridley bycatch in pelagic longlines has decreased since then; however, at-sea verification is not possible because the Brazilian on board observer program has been suspended for improvement since 2012 by Brazilian government, and has not resumed (Zamboni et al. 2020).

Conservation concerns and future research.—It is important to note that there is a large gap in our ecological knowledge of Olive Ridleys, especially the juveniles, and many questions still need to be addressed about their population from the southwestern Atlantic, such as foraging grounds and composition of mixed stocks. This is crucial for understanding the significant population increase observed in our study and what spatial management measures are effective in promoting population recovery. Issues like the lack of TED adoption remains a challenge. The low enforcement capacity, especially related to fisheries, is still a problem not only for sea turtles but also other marine animals and needs to be urgently addressed by the Brazilian government. Also of concern is the rapid and unchecked coastal development, which brings problems such as light pollution and predation of nests and females. These problems need to be addressed and quantified to understand how the mortality of these individuals can impact the stability of the population in the near future.

Conclusions.—Our results highlight that Brazil currently supports the second largest population of Olive Ridleys in the Atlantic. The remarkable recovery of the Brazilian Olive Ridley population is probably due to the uninterrupted research and conservation work on the nesting beaches over 40 y, and also in-water actions during the last 18 y to lessen the incidental captures in fisheries (Silva et al. 2016). If the loss of mainly adult Olive Ridley with high reproductive values persists, this population may again decline in the next few generations. To avoid this and to maintain a healthy and stable population, it is critical that conservation actions in terrestrial and marine habitats are effectively implemented, monitored, and improved over the long-term. Equally important is to ensure that existing rules are followed, and for that it is necessary that the government has the capacity for strong enforcement. Without enforcement, the conservation efforts will be weakened, and expected population recovery may not be fully achieved.

Acknowledgments.—We would like to thank the local communities of the states of Sergipe and northern Bahia for their collaboration with the conservation program, and all trainees (university students) and Fundação Projeto Tamar staff members who helped to collect the data. Data collection by Fundação Projeto Tamar was authorized by Instituto Chico Mendes de Conservação da Biodiversidade (ICMBio), through license number 42760, issued by the Biodiversity Authorization and Information System (SISBIO). We thank Tomo Eguchi for statistical advice.

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Supplemental Information: http://www.herpconbio.org/Volume_17/Issue_3/deCastilhos_etal_2022_Suppl

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