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Conservation status of the loggerhead sea turtle in Brazil: an encouraging outlook

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ABSTRACT: The loggerhead turtle *Caretta caretta* is one of the large and long-lived species that comprise the charismatic marine megafauna. The loggerhead is considered endangered, especially in the Pacific Ocean, where there have been substantial declines in all the major nesting populations. On the other hand, some loggerhead nesting populations in the northwest Atlantic are apparently increasing, but the conservation status of loggerheads in the Atlantic-Mediterranean is not well known. Here we report on a long-term and geographically extensive study of the nesting abundance of the Brazilian loggerhead genetic stock resident in south Atlantic waters. We show that there has been a substantial long-term increase in nesting abundance of this once depleted Atlantic stock following the cessation of egg and turtle harvesting in the 1980s. We estimated that the 2003/2004 austral summer nesting season in Brazil encompassed more than 4800 loggerhead nests or >1200 nesters or >0.57 million eggs. National conservation efforts have contributed significantly to the improving status of the Brazilian loggerhead stock since the mid-1980s, but there are emerging threats such as incidental capture in coastal and pelagic fisheries that might limit any further recovery. Moreover, we found that the Brazilian nesting population is probably one of the largest remaining loggerhead nesting populations in the world. Hence, continued protection of the Brazilian loggerhead stock is of paramount importance for the global conservation of this species.

KEY WORDS: Endangered species · Loggerhead sea turtle · Seasonal nesting activity · Long-term increase · Brazil

INTRODUCTION

Human exploitation and habitat destruction have caused major declines in the abundance of the marine megafauna such as sea turtles (Troëng & Rankin 2005), whales (Roman & Palumbi 2003) and pelagic sharks (Baum & Myers 2004). There is increasing concern that the widespread decline of the marine megafauna will have unexpected and grave consequences for the long-term viability of the world's coastal ecosystems (Jackson et al. 2001). However, it has been shown that some seriously depleted sea turtle populations can recover quite quickly following protection from human exploitation (Dutton et al. 2005, Broderick et al. 2006, Chaloupka & Balazs 2007).

The loggerhead sea turtle *Caretta caretta* is one of the large, long-lived and late-maturing species that comprise the marine megafauna. There have been serious and widespread declines in loggerhead nesting abundance, especially for the Pacific Ocean populations (Chaloupka & Limpus 2001, Kamezaki et al. 2003, Limpus & Limpus 2003) and for several populations in the Indian Ocean (Baldwin et al. 2003). On the other hand, loggerhead populations nesting along the southern US Atlantic coast have generally increased over the past 25 yr or so (Ehrhart et al. 2003). However, there are several other genetic stocks of loggerheads in the Atlantic Ocean about which very little is known; one of these is the Brazilian stock which is resident mainly in south Atlantic waters (Bowen et al. 2005).

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Loggerheads have a long history of exploitation in Brazil, where prior to 1980 nearly all loggerhead eggs laid along the Brazilian coast were removed, and most nesting females were taken for meat (Marcovaldi et al. 2005). In more recent years, the Brazilian loggerhead has become exposed to other hazards such as marine debris (Bugoni et al. 2001) and coastal gillnet and pelagic longline fisheries operating in southern Brazilian waters (Soto et al. 2003, Kotas et al. 2004). Despite increasing fishery-induced mortality, the conservation status of the Brazilian loggerhead is less well known than other stocks resident in north Atlantic and Mediterranean waters (Ehrhart et al. 2003, Margaritoulis et al. 2003).

Reliable estimates of abundance are, therefore, urgently needed to help evaluate the current status and population trends of the Brazilian loggerhead turtle stock. Nearly all assessments of sea turtle abundance have been undertaken using trawl based catch-per-unit-effort estimation, aerial survey-based density estimation or, more commonly, by monitoring the number of females that come ashore each year to nest at stock-specific nesting beaches known as rookeries (Chaloupka & Limpus 2001). The Brazilian loggerhead is one of the few sea turtle stocks that has been continuously monitored for many years over an extensive geographic area by the same research program (Projeto TAMAR-IBAMA), and so this stock is especially suitable for population assessment using nesting beach surveys (Marcovaldi & Laurent 1996).

We report the results of a 16-yr Projeto TAMAR-IBAMA study of the conservation status and nesting activity of Brazilian loggerheads dispersed along >1100 km of the Brazilian mainland coastline. This long-term study provides a basis for regional sea turtle conservation planning (Marcovaldi et al. 2006), genetic interpretation of nesting loggerhead population contribution to mixed-stock Atlantic foraging areas (Bowen et al. 2005), assessment of global loggerhead status, and for assessing the long-term viability of the loggerhead stocks exposed to multiple anthropogenic hazards (Chaloupka 2003).

MATERIALS AND METHODS

Monitoring program and data description. Brazil has 8000 km of coastline with loggerhead nesting occurring mainly along the mainland coast from the states of Rio de Janeiro in the south to Sergipe in the north but with the peak nesting concentration along the north, coast of the state of Bahia (Marcovaldi et al. 2005, their Fig. 1). Since 1982, Projeto TAMAR-IBAMA has progressively established a national network of 21 field stations located across 9 Brazilian states and covering >1100 km of the Brazilian mainland coast and oceanic islands. Most of these stations are staffed year-round and are located in the main sea turtle nesting areas or in nearby major coastal foraging grounds where there has been a history of incidental capture in coastal fisheries (Marcovaldi & Laurent 1996, Baptistotte et al. 2003).

TAMAR staff at each station are responsible for maintaining a daily program of nesting beach monitoring during the austral summer nesting season. The beach monitoring program involves the location of loggerhead clutches laid each night and, where necessary, protection of clutches until hatching using either in-situ mesh fencing or relocation — usually to nearby open-air hatcheries (Marcovaldi & Laurent 1996, Baptistotte et al. 2003). These interventions are required in some areas to protect the clutches from fox predation and poaching, or from human impact, where there is extensive coastal development (Marcovaldi et al. 2005). TAMAR field staff are supported by an extensive community-based beach monitoring program that comprises local fishermen who are employed, trained and supervised by TAMAR (Marcovaldi et al. 2005). The TAMAR monitoring program operating from the 21 stations comprises 16 management areas that are stratified into 79 beach sampling units, ranging from ca. 3 to 37 km in length, and which are mainly accessed using 4-wheel drive vehicles (Marcovaldi & Laurent 1996, Baptistotte et al. 2003). This hierarchical sampling scheme now ensures that comparable monitoring effort and sampling coverage has been maintained year-round since 2002 over most of the Brazilian mainland coastline where suitable sea turtle nesting habitat occurs.

When the TAMAR monitoring program started in 1982 it only covered the major sea turtle nesting beach at Praia do Forte in Bahia, which has the highest loggerhead nesting density in Brazil (Marcovaldi & Laurent 1996). The national sampling network then expanded progressively over a number of years to include all other nesting beaches across the 9 states, including the loggerhead nesting states of Rio de Janeiro, Espírito Santo, Bahia and Sergipe. Hence, comparable temporal and geographic coverage was only available from 1988 for 22 sampling units in Bahia and Espírito Santo (Fig. 1), a region which accounts for >75% of loggerhead nesting in Brazil (Table 1). After 1988 long-term loggerhead trends were based on monthly nesting activity recorded at the 22 sampling units in Bahia and Espírito Santo over a 16-yr sampling period from the 1988/1989 to the 2003/2004 austral summer nesting season.

These data comprised monthly time series for 10 contiguous sampling units in Bahia covering 93 km of

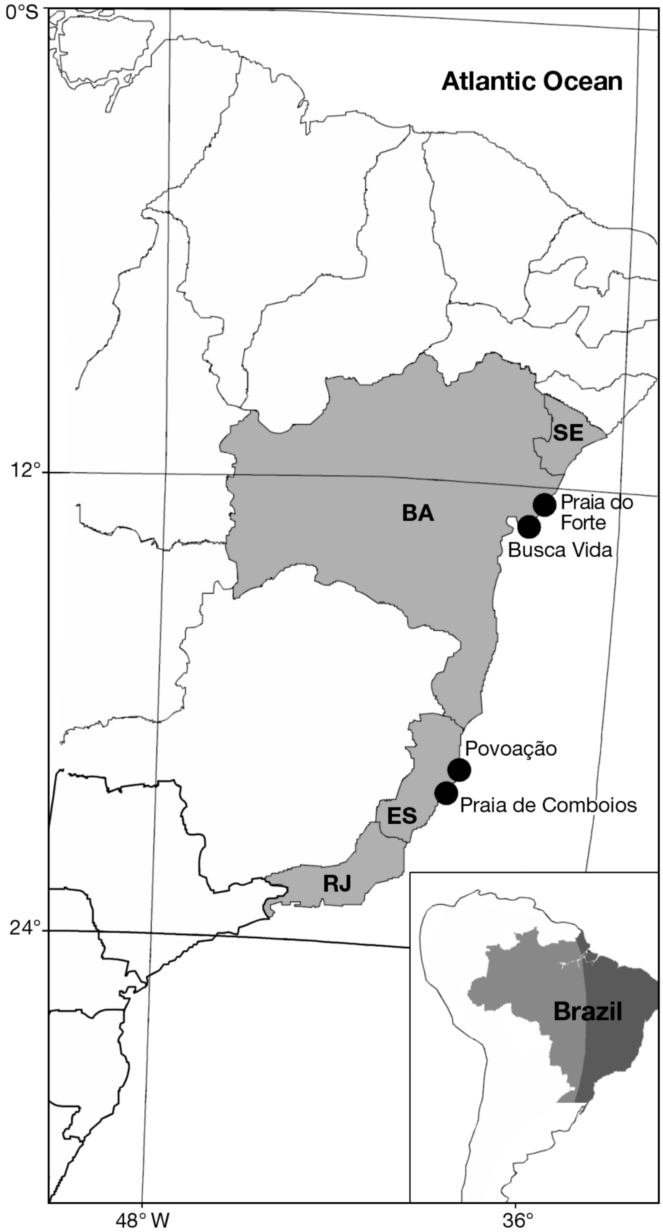

Fig. 1. Location of some of the major loggerhead sea turtle nesting beaches in Brazil. SE = Sergipe, BA = Bahia, ES = Espírito Santo, RJ = Rio de Janeiro

nesting beach and 12 contiguous sampling units in Espírito Santo covering 162 km. The 10 units in Bahia were Arembepe, Berta, Busca Vida, Jauá, Santa Maria, Praia do Forte, Itacimirim, Guarajuba, Barra do Jacuípe, Santo Antonio. The 12 units in Espírito Santo were Praia de Comboios, Cacimbas, Degredo, Monsarás, Povoação, Guriri, Campo Grande, Barra Nova, Barra Seca, Ipiranguinha, Ipiranga and Pontal do Ipiranga. As mentioned above, there was comprehensive geographic coverage from 2002 onwards, so we were then able to estimate nation-wide loggerhead nesting activity for the 2 nesting seasons, 2002/2003 and 2003/2004, on >639 km of nesting beach habitat along the Brazilian mainland coastline (Table 1). More detailed descriptions of the national sea turtle monitoring program, nesting beach characteristics, sampling protocols, nest protection practices and the history of Projeto TAMAR-IBAMA can readily be found elsewhere (Marcovaldi & Laurent 1996, Baptistotte et al. 2003, Marcovaldi et al. 2005).

Long-term nesting trend estimate. We estimated the underlying trend in observed annual nesting activity for Bahia and Espírito Santo (Fig. 2a) using a generalized smoothing spline regression approach implemented in the gss package (Gu 2002), which is available for the statistical modelling program R (Ihaka & Gentleman 1996). Smoothing spline regression uses the data to determine the underlying linear or nonlinear trend without assuming any specific functional form. Confidence bands are derived using cross-validation (Gu 2002). We estimated the long-term linear trend in the observed annual nesting activity using a linear regression model with first order moving average error (MA(1)) to derive a linear growth parameter estimate while accounting for any temporal correlation (see Chaloupka & Limpus 2001 for details). The response variable (annual nests) was in natural log form so that the parameter estimate for year (1988–2003) was interpretable here as a constant annual nesting population growth rate. This MA(1) linear regression model was implemented here using program SHAZAM (White 1997).

Seasonality and time-varying seasonal trends. We investigated seasonality in the observed monthly nesting activity (Bahia, Espírito Santo) and any time-varying seasonal trends using the statistical procedure known as stl; Seasonal and Trend decomposition using loess (Cleveland et al. 1990). This robust statistical procedure decomposes a time series using nonparametric smoothing into additive frequency components of variation (1) trend, (2) cyclical or quasi- periodic, (3) seasonal and (4) the residual or remainder. We implemented this time series decomposition procedure using the stl function in R (Ihaka & Gentleman 1996). stl has been used previously (Chaloupka 2001) to investigate spatial synchrony in egg productivity at green turtle rookeries in the Southeast Asian region and also by Balazs & Chaloupka (2004) to evaluate long-term trends in green turtle nesting abundance in the Hawaiian Archipelago.

Regional nester abundance estimate. The number of nesters can be derived from the recorded nesting activity if the expected clutch frequency per season is known. As there are no reliable clutch frequency data available for Brazilian loggerhead nesting populations we estimated nester abundance in Brazil during the

Table 1. Summary of loggerhead sea turtle nesting activity in Brazil for the 2002/2003 and 2003/2004 austral summer nesting seasons. km sampled: km of continuous nesting beaches sampled during each season (mean value of the 2 seasons for Rio de Janeiro)

State	km sampled	Nests per season 2002/2003	2003/2004	Total	Mean annual nesting density (nests km^{-1})
Sergipe	106	193	162	355	1.7
Bahia	212	2320	2678	4998	11.8
Espírito Santo	186	941	1007	1948	5.2
Rio de Janeiro	135	779	990	1769	6.6
Total	639	4233	4837	9070	7.1

2003/2004 season using a simple Monte Carlo simulation experiment (Vose 1996) given the number of nests in 2003/2004 (Table 1) and the expected annual clutch frequency derived using prior information for other loggerhead populations. Expected clutch frequency was assumed to be sampled from a binomial probability mass function as ~bin(n = 7, p = 0.52), which fitted well the clutch frequency data for the Florida (Frazer & Richardson 1985) and Australian loggerhead populations (Limpus 1996). Expected clutch frequency was then 4 clutches laid per nesting female per season and the maximum number of clutches observed per season was 7. There are no other data available for loggerhead populations that were suitable for fitting a probability mass function, as most published clutch frequency data are summarized as means and standard deviations, which is inappropriate for count data. Nester abundance in Brazil during the 2003/2004 nesting season was then assumed to be adequately sampled from a Poisson probability mass function as

$$\sim\text{Pois}(\text{nests}_{2004} \times \text{clutch frequency}^{-1})$$

given 1000 Monte Carlo trials. Binomial and Poisson probability mass functions are the appropriate sampling distribution functions to use for proportion and count data, respectively (Vose 1996). Expected nester abundance in the 2003/2004 season was then estimated by the 50th percentile (median) of the 1000 Monte Carlo trials, while uncertainty was summarized as a 95% empirical percentile confidence interval using the 2.5th and 97.5th percentiles. For further details of the Monte Carlo simulation and sampling methods adopted here see Vose (1996). We then calcu-

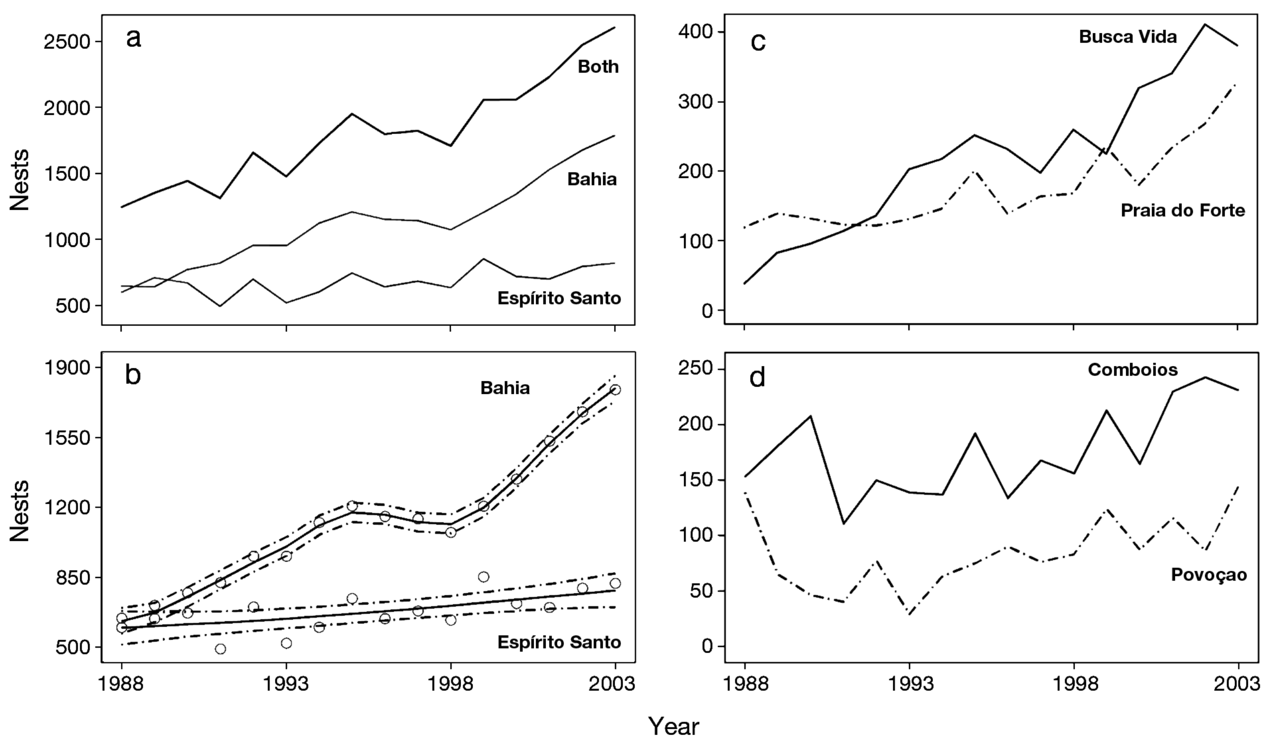

Fig. 2. (a) Annual number of loggerhead nests recorded in the states of Bahia and Espírito Santo over the 16-yr period from 1988 to 2003 (1988/1989 season to 2003/2004 season). Both: combined nesting for Bahia and Espírito Santo. (b) Underlying long-term trends in annual number of nests recorded in Bahia and Espírito Santo. Solid curves show generalised smoothing spline fits (Gu 2002), dashed curves show 95% Bayesian confidence intervals and open circles show the data from (a). (c) Annual number of loggerhead nests recorded for the 2 major beaches comprising the Bahia trend (a). (d) Annual number of loggerhead nests recorded for the 2 major beaches comprising the Espírito Santo trend (a)

lated the expected egg production for Brazil in the 2003/2004 nesting season as either a crude estimate:

$$[\text{eggs} = (\text{clutches} \times (\text{expected eggs per clutch}))] \quad (1)$$

or as a simple Monte Carlo estimate:

$$[\text{eggs} = (\text{bin}(n = \text{nesters} \times 7, p = 0.52) \times (\text{expected eggs per clutch}))] \quad (2)$$

where 'expected eggs per clutch' = 127 (Marcovaldi & Laurent 1996) and, again, 'nesters' ~Pois(nests_{2004} × clutch frequency^{-1}). All Monte Carlo simulations were conducted using Crystal Ball (Decisioneering 1996). The crude estimate of egg production is the approach commonly used in sea turtles studies, while the simple Monte Carlo approach is more robust and provides one way to account for uncertainty in the estimate.

Expected nester size trend. We investigated the expected size distribution of female loggerheads nesting each year at the Praia do Forte rookery using schematic box plot summaries (Cleveland 1993). Long-term size distribution data are only available for this rookery, which is one of the most important loggerhead nesting beaches in Brazil.

RESULTS

Long-term nesting trends

The recorded annual nesting activity summed for all the sampling beach units in Bahia and Espírito Santo over the 16-yr sampling period is shown in Fig. 2a, where it is apparent that nesting at the Bahia beaches has been increasing more quickly since 1988 than in Espírito Santo. The combined nesting activity for Bahia and Espírito Santo, which accounts for >75% of loggerhead nesting in Brazil (Table 1), has shown a significant increase since 1988, which is mainly due to the Bahia trend (Fig. 2a). The estimated Bayesian smoothing spline annual trends show that there have been significant long-term increases in nesting activity in Bahia and Espírito Santo over the 16-yr sampling period (Fig. 2b). However, the nesting in Bahia leveled off during the mid-1990s before increasing rapidly from ca. 1998 onwards, while the nesting in Espírito Santo seems to have increased progressively, though slowly, since 1988 (Fig. 2b). The expected linear trend for Bahia nesting activity was 6.4% per annum (95% CI: 5.2 to 7.5%), while the expected Espírito Santo nesting trend was 1.9% per annum (95% CI: 1.0 to 2.8%). Fig. 2c shows the annual nesting activity at the 2 most important nesting beaches (Busca Vida, Praia do Forte) in Bahia, where loggerhead nesting has increased significantly since 1988. The annual nesting activity at the 2 most important nesting beaches (Povoação, Praia de Comboios) in Espírito Santo is shown in Fig. 2d, where trends at both beaches have also been towards an increase in activity, but with significantly more inter-annual fluctuations than at the main beaches in Bahia (Fig. 2c).

Seasonality

The recorded monthly nesting summed for all the sampling beach units in Bahia and Espírito Santo over the 16-yr sampling period is shown in Fig. 3a. Fig. 3b shows that there has been a long-term increasing trend in monthly nesting activity in Bahia and Espírito Santo since 1988 (see Fig. 2a for the annual trend). The combined monthly nesting series for Bahia and Espírito Santo also display a distinct seasonal cycle (Fig. 3c) — note that the seasonal cycle is also a relatively more significant component of the series than the long-term trend (Fig. 3b,c). Fig. 4a shows the seasonal cycle subseries of loggerhead nesting in Bahia and Espírito Santo. The horizontal line is the fitted midmean (25% trimmed mean) value of the seasonal component for each month and shows the historical seasonal nesting pattern for each state. Nesting activity was highly seasonal (September to February) with peak nesting during November in both states (Fig. 4). However, the nesting season is slightly longer in Bahia, with significant nesting occurring during September at the start of the season and then again in February at the end of the season (Fig. 4b,c). The fitted values for each year (ends of the vertical lines) associated with each midmean in Fig. 4 show the pattern of interannual variation of the monthly subseries from the historical seasonal pattern. If the annual values display a trend about the midmean, this means the monthly pattern is changing over time (it is then nonstationary or time-varying). There was little inter-annual variability in the nesting season over the 16-yr sampling period for Bahia (Fig. 4b) and Espírito Santo (Fig. 4c). This suggests that the seasonal nesting cycle for Brazilian loggerheads was stable and consistent over the 16-yr sampling period (1988/1989 to 2003/2004) — in other words the seasonal nesting pattern in both states was stationary.

Regional nester abundance and egg production

Prior to 2002 the geographic coverage of loggerhead nesting activity was incomplete, so we could only derive nation-wide estimates for the 2002/2003 and 2003/2004 nesting seasons. Estimates of annual loggerhead nesting activity along the Brazilian mainland coast since 2002 are summarized in Table 1. Logger-

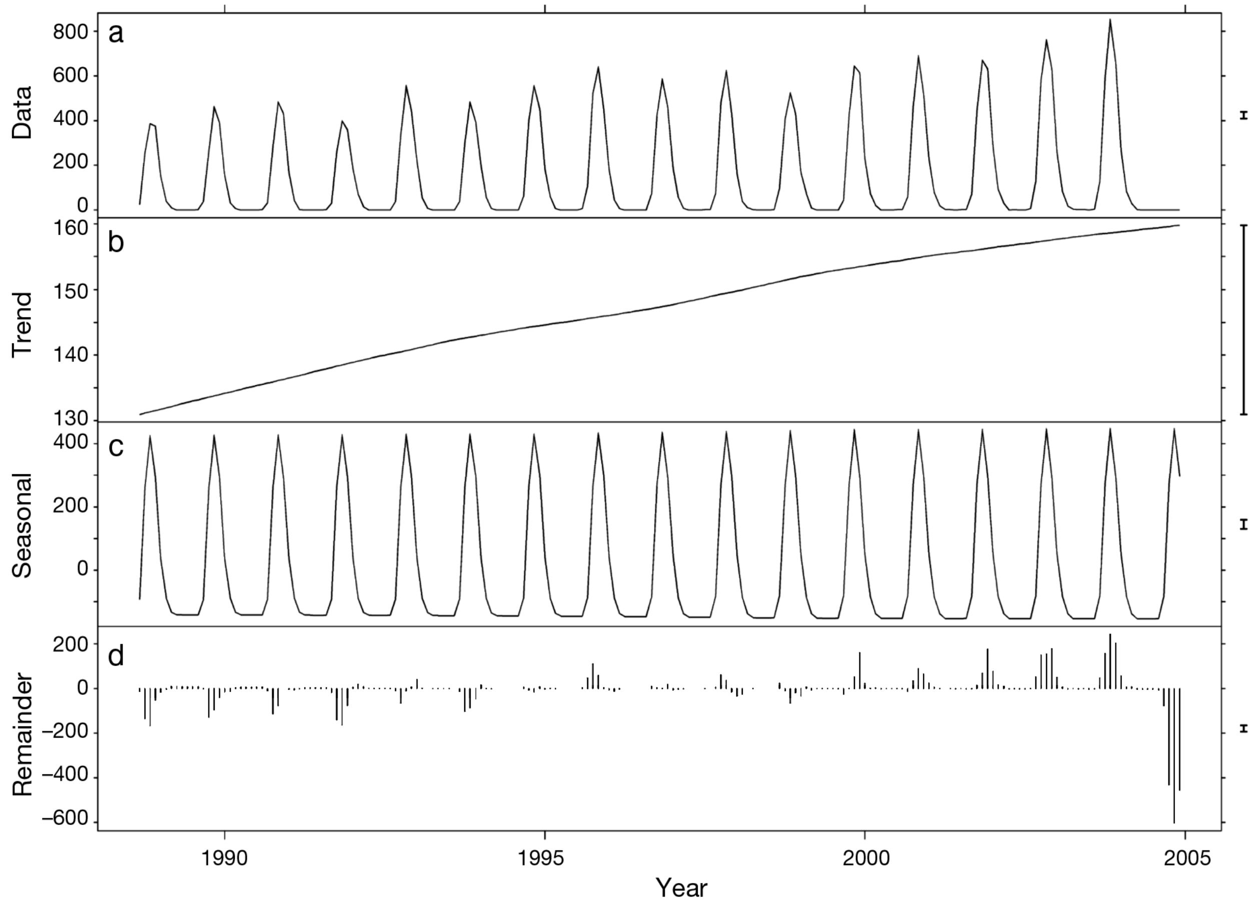

Fig. 3. stl decomposition plot of the combined number of loggerhead nests laid each month in Bahia and Espírito Santo over the 16-yr period (1988/1989 to 2003/2004). (a) Nests recorded each month. For annual time series see Fig 2a. (b) Fitted long-term trend or low-frequency variation in nests laid (bandwidth of trend filter = 9 yr). (c) Seasonal component that describes the variation in nesting at or near to the annual seasonal frequency. (d) Remainder or residual component remaining after the trend (b) and seasonal (c) components have been fitted to the series. The 3 components shown in (b–d) sum exactly to the series shown in (a). The panel scales are not the same, so the vertical bar at the right of each panel indicates the relative variation in scaling amongst the components and original data series

head nesting only occurs along the mainland coast but extends across a broad geographic range that includes (but not limited to) the following 4 contiguous States — Rio de Janeiro, Espírito Santo, Bahia and Sergipe (Fig. 1). Bahia in the tropical north accounts for ca. 55% of all loggerhead nesting in Brazil and has the highest nesting density in Brazil (Table 1), which is also consistent with previous relative density estimates (Marcovaldi & Laurent 1996). Importantly, Rio de Janeiro in the cooler temperate south has substantial loggerhead nesting (ca. 20% of all loggerhead nesting) that is equivalent to the nesting activity further to the north in Espírito Santo (Table 1). It was previously thought that Espírito Santo was the second most important nesting region after Bahia (Marcovaldi & Laurent 1996, Baptistotte et al. 2003). Only limited nesting activity occurs in Sergipe (<4%, Table 1), which is the most northern extent of loggerhead nesting in Brazil.

The Monte Carlo estimate of loggerhead nester abundance in Brazil during the 2003/2004 season was 1237 female loggerheads (95% empirical percentile confidence interval: 829–5096). The estimate of loggerhead nester abundance was based on the estimate of nests in Brazil during the 2003/2004 nesting season (Table 1). The crude 2003/2004 season egg production estimate for Brazil was 614 299 (= 4837 × 127, see Table 1; expected eggs per clutch = 127 from Marcovaldi & Laurent 1996), while the expected Monte Carlo estimate was 573 024 (95% empirical percentile confidence interval: 0.37 million to 2.2 million). It was most unlikely that every loggerhead nest in Brazil was recorded during the 2003/2004 nesting season, even though the geographic and temporal coverage was extensive. Therefore, all estimates of national nesting activity, nester abundance and egg production are minimum estimates.

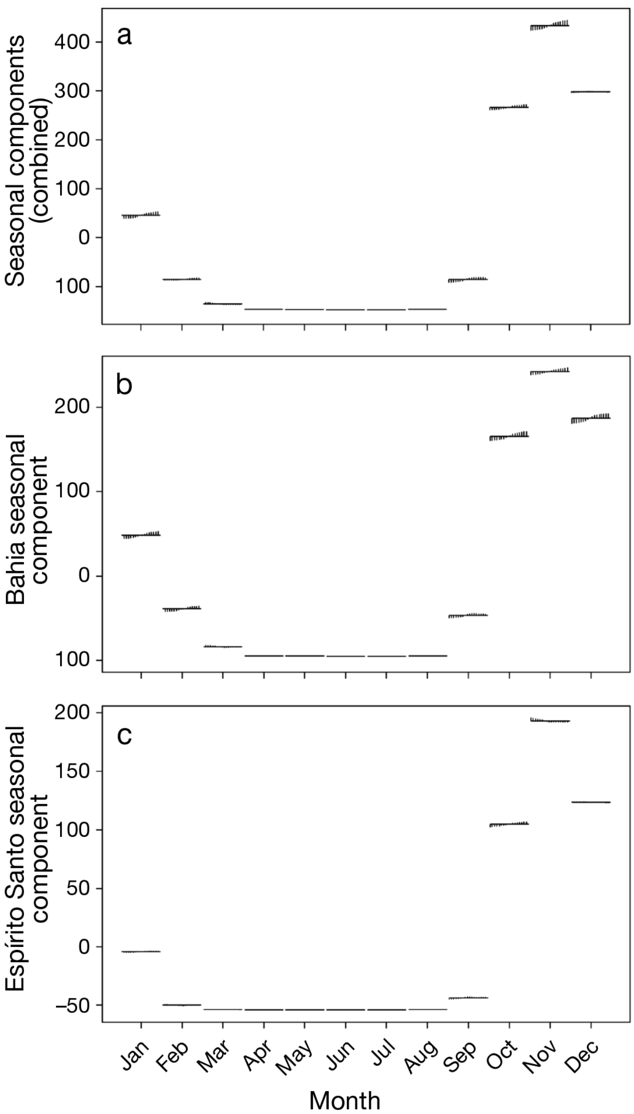

Fig. 4. Seasonal cycle monthly subseries plot of the estimated number of loggerhead nests laid each month over the 16-yr period (1988/1989 to 2003/2004) in (a) combined Bahia and Espírito Santo and then separately for (b) Bahia and (c) Espírito Santo. Plot in (a) shows the fitted seasonal component from the stl analysis (see Fig. 3c) that provided an assessment of the historical seasonal pattern as well as the temporal behaviour of each monthly subseries over the 16-yr sampling period. Plots in (b) and (c) show the fitted seasonal component from separate stl analyses for each state sample (not shown here).The horizontal line is the fitted mid-mean value of the seasonal component for each month

Expected nester size trend

Box plot summaries of the annual size distribution of loggerheads nesting over the 16-yr sampling period at the Praia do Forte rookery are shown in Fig. 5. The overall median for the 16-yr sampling period is shown by the solid horizontal bar, which is ca. 103 cm straight carapace length (SCL). The size distribution for each annual sample fluctuates around the overall median without any apparent long-term trend.

DISCUSSION

There are 5 species of sea turtle found in Brazil (Marcovaldi et al. 2005). The loggerhead is the most abundant nester of all 5 species along the Brazilian mainland coast, but prior to 1980 the loggerhead nesting populations were seriously depleted (Marcovaldi & Laurent 1996). Loggerhead nesting has increased significantly in Bahia and Espírito Santo since the late 1980s (Figs. 2a & 3b) following the creation of Projeto TAMAR-IBAMA by the Brazilian government in 1980 to help protect Brazilian sea turtle species. Egg and sea turtle harvesting was prohibited in the early 1980s and full legislative protection of all sea turtle species in Brazil was enacted in 1986 (Marcovaldi et al. 2005). One of the conservation responsiblities of Projeto TAMAR-IBAMA has been long-term community-based monitoring of sea turtle nesting activity and protection of nests from fox predation, poaching and beach habitat destruction (Marcovaldi & Laurent 1996, Baptistotte et al. 2003, Marcovaldi et al. 2005). These nation-wide conservation efforts have clearly contributed significantly to the improving status of the once-depleted Brazilian loggerhead stock (Fig. 2). The successful application of relatively simple and inexpensive conservation practices, such as nest protection and restricting egg poaching, to help recover depleted Atlantic sea turtles populations has also been shown recently for a green turtle nesting population at Tortuguero, Costa Rica (Troëng & Rankin 2005) and for a leatherback turtle nesting population at St. Croix, US Virgin Islands (Dutton et al. 2005). Moreover, Broderick et al. (2006) attribute the recovery of the green turtle stock that nests on Ascension Island in the mid-Atlantic to the efforts of Projeto TAMAR-IBAMA, which has protected green turtle populations that forage along the Brazilian coast and nest on Ascension Island.

While national conservation efforts have contributed significantly to the improving status of the Brazilian loggerhead stock since the mid-1980s, there are now new emerging threats such as coastal development and incidental capture in coastal gillnet and pelagic longline fisheries that might limit any further recovery (Marcovaldi et al. 2006). Loggerhead strandings along southern Brazilian beaches have increased in recent years, with a significant proportion of strandings attributed to coastal fisheries-induced mortality (Soto et al. 2003). It is interesting to note that loggerhead beach strandings are rare except in southern Brazil, even

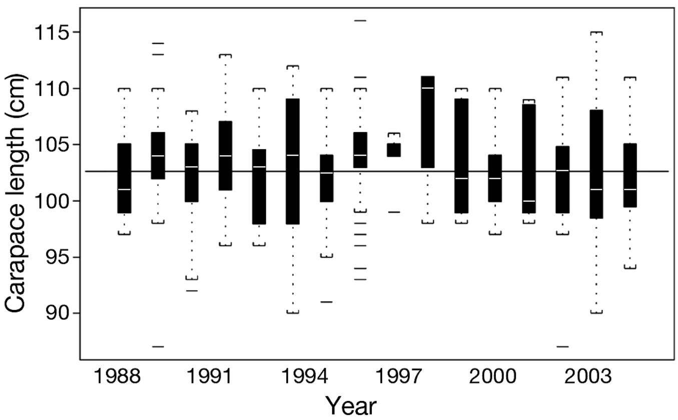

Fig. 5. Box plot summary of the annual size distribution of loggerheads nesting over the 16-yr sampling period at the Praia do Forte rookery. The white horizontal bar in each box shows the 50th percentile (median) of carapace size for each annual sample. The upper and lower boundaries of each box show the 75th and 25th percentiles, respectively. The top and bottom cap of the dotted vertical lines show the 90th and 10th percentiles, respectively. The extra horizontal bars shown for some boxes above the 90th percentile indicate extreme outliers. The overall median for the 16-yr sampling period is shown by the solid horizontal bar

though all nesting occurs further north. On the other hand, beach strandings of other sea turtles species (especially juvenile green turtles) are common in the 4 Brazilian states where loggerheads nest. This suggests that some of the main foraging grounds for Brazilian loggerheads are located in southern Brazilian waters and that mature females then migrate seasonally northward to nest on beaches in Rio de Janeiro, Espírito Santo, Bahia and Sergipe.

Incidental capture and drowning of loggerheads in pelagic longline fisheries operating in southern Brazilian waters has also increased in recent years (Kotas et al. 2004). Most loggerheads caught in longline fisheries operating in Brazilian waters are from the Brazilian genetic stock (Marcovaldi et al. 2006). An offshore region of particular concern is the Elevação do Rio Grande, which is a seamount chain located ca. 800 km off the southern Brazilian coast that rises to within 350 m of the sea surface (Marcovaldi et al. 2005). It is a major habitat for swordfish, tunas and sharks, which are heavily exploited by Brazilian and Uruguayan pelagic longline fleets. There is also high incidental capture of immature loggerheads, which suggests high loggerhead densities and that the Elevação do Rio Grande is an important oceanic developmental habitat for immature loggerheads in south Atlantic waters (Marcovaldi et al. 2006), similar to the seamount habitat around the Azores in north Atlantic waters identified recently for other Atlantic loggerhead stocks (Bolten 2003). Moreover, the size distribution of immature oceanic loggerheads caught in pelagic longline fisheries operating on the Elevação do Rio Grande (mean curved carapace length ca. 57 cm; Kotas et al. 2004) is similar to the size distribution of oceanic loggerheads from other stocks that are caught in pelagic longline fisheries elsewhere in the Atlantic, such as around the Azores (Bolten 2003). This suggests that pelagic longline fisheries pose a serious size-selective risk to immature oceanic loggerheads in the Atlantic that could have serious long-term demographic consequences for these loggerhead stocks (Chaloupka 2003). Reducing fishery-induced mortality of loggerheads in Brazilian coastal waters and also on the Elevação do Rio Grande should be a conservation priority for ensuring the long-term viability of the Brazilian loggerhead stock (Marcovaldi et al. 2006).

While long-term nesting trends are a useful measure of stock status (Balazs & Chaloupka 2004, Troëng & Rankin 2005) it is preferable to use ageclass-specific survival probabilities and abundance estimates to help diagnose sea turtle population status and trends (Chaloupka & Limpus 2001, 2002, Bjorndal et al. 2005, Dutton et al. 2005). Unfortunately, informative demographic information on, for example, survival probabilities is not available for most loggerhead turtle populations, including the Brazilian nesting populations (Chaloupka & Limpus 2002). Hence, morphometric trend indicators of nesting population status have been proposed, such as trends in the mean size of nesting loggerheads that might be indicative of some impending population decline (Hatase et al. 2002). Such indicators are far less informative than demographic parameters but often these are the only data readily available for many loggerhead nesting populations. We found no trend in the expected annual size distribution of nesting loggerheads at Praia do Forte in Bahia (Fig. 5), one of the most important loggerhead nesting beaches in Brazil (Fig. 2c). This indicates that the Brazilian nesting populations are increasing (Fig. 2) and there is no evidence of any impacts on the size composition of nesting females (at least for the Praia do Forte nesting population).

The median SCL for loggerheads nesting at Praia do Forte is 103 cm (Fig. 5). There is no geographic difference in expected carapace size among the Brazilian loggerhead nesting populations (Marcovaldi & Laurent 1996, Baptistotte et al. 2003) and neither is there any expected size difference between these and other Atlantic loggerhead nesting populations (Tiwari & Bjorndal 2000). However, Atlantic nesting loggerheads are on average much larger than loggerheads nesting in the Mediterranean (Margaritoulis et al. 2003) or the Pacific (Hatase et al. 2002, Limpus & Limpus 2003) and Indian Oceans (Luschi et al. 2003). Whether the larger expected size of loggerheads nesting in the Atlantic results in higher size-dependent reproductive output (shorter nesting season interval, larger clutch size, higher seasonal clutch frequency) is yet to be determined but warrants further investigation.

Loggerheads nest over a very broad contiguous geographic range in Brazil extending from cool temperate climates in the south to tropical climates in the north (Fig. 1, Table 1). This represents a contiguous nesting range for a single loggerhead stock that is perhaps unparalleled in the world. All the Brazilian nesting populations are from the same genetic stock (Bowen et al. 2005) but are exposed to different nesting beach temperatures, which affects the hatchling sex ratio because of temperature-dependent sex determination (Marcovaldi et al. 1997). Warmer beaches in the north of Brazil (Bahia, Sergipe) produce mainly female loggerhead hatchlings (Marcovaldi et al. 1997), while the cooler beaches in the south (Espírito Santo and presumably Rio de Janeiro) produce nearly equal proportions of male and female hatchlings (Baptistotte et al. 1999). Consequently, protecting only northern populations might result in far too few males, while protecting just the southern populations might result in too few females.

Inappropriate gender composition could lead to reduced mating encounters and thus reduced population growth, a density-dependent demographic process known as depensation or an 'undercrowding' or Allee effect (Dennis 2002). Reduced mating encounters have been implicated in several major population collapses including north Atlantic cod (Rowe et al. 2004) and saiga antelope (Milner-Gulland et al. 2003), and could also affect the recovery of a depleted sea turtle population (Chaloupka & Balazs 2007). Therefore, long-term conservation of the Brazilian loggerhead stock requires protection of many nesting beach regions in Brazil to ensure an appropriate gender composition (Baptistotte et al. 1999). It is clearly, important to maintain a national loggerhead monitoring and conservation program that samples from the full geographic range of nesting populations in Brazil. In other words, maintaining the high density nesting region of Bahia (Table 1, Fig. 2) would be necessary, but simply insufficient, to ensure the long-term viability of the Brazilian loggerhead stock.

Although loggerheads in Brazil nest over a broad geographic range, there was nonetheless similar seasonal nesting behaviour evident for the nesting populations in Bahia and Espírito Santo (Fig. 4b,c). Apparently, all loggerhead nesting populations, including Brazilian populations, display a distinct seasonal nesting pattern (Baldwin et al. 2003, Ehrhart et al. 2003, Kamezaki et al. 2003, Limpus & Limpus 2003, Margaritoulis et al. 2003), unlike some hawksbill and green sea turtle populations in the Pacific that nest year-round (Pilcher & Ali 1999, Chaloupka 2001). It is possible that the loggerhead nesting season in Brazil (Fig. 3c) could expand as the stock recovers and nesting population densities increase, forcing some turtles (especially first-time nesters) to nest earlier or later during the season, a pattern which is evident for recovering Southeast Asian green turtle populations (Chaloupka 2001). In our study, the residual component in Fig. 3d was also a major element in the nesting data series, which might reflect environmental variability due to sea-surface temperature fluctuations that are known to influence sea turtle breeding behaviour (Chaloupka 2001, Balazs & Chaloupka 2004).

The global importance of the recovering Brazilian loggerhead stock is clear when compared to the current status of all other major loggerhead nesting populations (Table 2). We estimated that Brazilian loggerhead stock in the 2003/2004 austral summer season comprised more than 4800 loggerhead nests (Table 1), equivalent to more than 1200 nesters or more than 0.57 million eggs. Moreover, all these estimates of national nesting activity, nester abundance and egg production are minimum estimates. Importantly, the nesting populations comprising the Brazilian loggerhead stock have been increasing since the late

Table 2. Summary of annual nesting activity at the major loggerhead nesting regions in the Atlantic, Pacific and Indian Oceans and Mediterranean Sea. Estimates derived assuming a clutch frequency of 4 nests per female per season (Frazer & Richardson 1985, Limpus 1996, Canbolat 2004)

Location	Nests	Nesters	Source
Atlantic			
Caribbean/Bahamas	<1000	ca. 250	Ehrhart et al. (2003)
Quintana Roo (Mexico)	<1000	ca. 250	J. C. Zurita et al. (2003, pers comm.)
Cape Verde Islands	>4000	ca. 1000	Ehrhart et al. (2003)
Brazil	>4837	>1237	Present study
Florida	>70 000	>17 500	Ehrhart et al. (2003)
Pacific			
Japan	ca. 2500	>625	Kamezaki et al. (2003)
Eastern Australia	<3000	<750	Limpus & Limpus (2003)
Indian			
Eastern South Africa	>1712	ca. 428	Baldwin et al. (2003)
Western Australia	<4800	<1200	Baldwin et al. (2003)
Oman	>100 000	ca. 25 000	Baldwin et al. (2003)
Mediterranean			
Cyprus	ca. 571	>143	Margaritoulis et al. (2003)
Turkey	ca. 2000	>500	Canbolat (2004)
Greece	ca. 3050	>762	Margaritoulis et al. (2003)

1980s, which is an encouraging outlook. The Brazilian nesting population is one of the largest remaining loggerhead nesting populations in the world after the super-aggregations at Masirah (Oman, Indian Ocean) and eastern Florida (Table 2). Hence, we contend that the continued protection of the Brazilian loggerhead stock is of paramount importance for the global conservation of this species.

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