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Standardization of CPUE of loggerhead sea turtle (*Caretta caretta*) caught by pelagic longliners in the Southwestern Atlantic Ocean

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Abstract – The population abundance estimates used in stock assessments or required to establish management measures, depend on the sampling of the entire demographic spectrum of a population resident in a given area. However, for sea turtles, most population estimates are based mainly on nesting beach survey data and only consider a fraction of the population. The Southwest Atlantic Ocean (SWA) is an important foraging and development area for juveniles of the loggerhead sea turtle *Caretta caretta* where reproductive stocks from various nesting beaches mix. Declines in *C. caretta* populations have been observed in many parts of the world and bycatch rates of this species in the SWA are among the highest worldwide. This study standardizes the catch rates of loggerheads caught by pelagic longline fisheries in the region, using data collected by observer programs from Brazil and Uruguay. Generalized linear models (GLM) with a delta lognormal approximation were used. The variables used in the model take into account spatial and temporal variations as well as the characteristics of the fleet. In total, 6 272 344 hooks were observed between 1998 and 2007, with minimum effort registered in 2000 (12 010 hooks) and maximum effort in 2005 (1 989 431 hooks). During this period 3778 loggerheads were incidentally captured. The catch rates of loggerheads by the Uruguayan and Brazilian pelagic longline fisheries show oscillations through the years without a clear tendency; however, a low negative trend was observed from 1998 to 2005 with an increase in the last two years (2006 and 2007). The capture per unit of effort (CPUE) values varied between 0.38 to 1.78 ind/1000 hooks in 2005 and 2007, respectively. Distinct zones with differential catch rates were identified, with the higher CPUE values over the continental slope of Uruguay and adjacent waters. The incidental catch rates of this species are influenced, not only by fishing area, but also by year, season, sea surface temperature and gear type. In consequence, these variables and other potential ones should be considered in bycatch estimates by different fisheries because the loggerhead sea turtles are not uniformly distributed. This study intends to contribute not only to the general knowledge of loggerhead sea turtles in the SWA but to a future assessment of their populations at a global scale.

Key words: Sea turtle / bycatch / longline / GLM / Southwestern Atlantic Ocean

Résumé – Les estimations d'abondance de population utilisées dans l'évaluation des stocks ou demandées pour établir des mesures de gestion, dépendent de l'échantillonnage du spectre démographique entier d'une population résidente dans une zone donnée. Cependant, pour les tortues de mer, ces estimations sont basées principalement sur des relevés des nids observés sur les plages et considèrent une fraction seulement de la population. L'Atlantique sud-ouest (SWA) est une zone importante de nourriture et de développement pour les juvéniles de la tortue caouanne *Caretta caretta* où des stocks de diverses plages de nidification sont mêlés. Le déclin des populations de *C. caretta* a été observé en de nombreux points du globe et les taux de captures accessoires de cette espèce en SWA sont parmi les plus élevés du monde. Cette étude standardise les taux de capture de cette espèce capturée lors de la pêche à la palangre, utilisant des

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des données collectées par des observateurs des programmes du Brésil et de l'Uruguay. Des modèles linéaires généralisés (GLM) avec une approximation delta log normale ont été utilisés. Les variables utilisées dans le modèle prennent en compte les variations spatiales et temporelles ainsi que les caractéristiques de la flotte. Au total, 6 272 344 hameçons ont été observés entre 1998 et 2007, avec un minimum d'effort enregistré en 2000 (12 010 hameçons) et un maximum en 2005 (1 989 431 hameçons). Durant cette période 3778 tortues caouannes ont été capturées. Les taux de capture de ces tortues par les palangriers uruguayens et brésiliens montrent des oscillations selon les années sans tendance évidente ; cependant, une faible tendance négative a été observée de 1998 à 2005 avec une augmentation en 2006 et 2007. Les valeurs de captures par unité d'effort (CPUE) varient de 0,38 à 1,78 ind/1000 hameçons en 2005 et 2007, respectivement. Des zones distinctes avec différents taux de capture sont identifiées avec des valeurs plus élevées de CPUE sur la pente continentale de l'Uruguay et les eaux adjacentes. Les taux de captures accidentelles de cette espèce sont influencés non seulement par la zone de pêche mais aussi selon l'année, la saison, la température de surface et le type d'engin de pêche. En conséquence, ces variables et autres critères potentiels devraient être considérés dans l'estimation des captures accessoires des diverses pêcheries car la répartition de cette tortue n'est pas uniforme. Cette étude tente de contribuer non seulement à la connaissance de la tortue caouanne en SWA mais à une estimation de leur population à un niveau mondial.

1 Introduction

The pelagic longline fishery in Uruguay and Brazil targets swordfish (*Xiphias gladius*), tunas (*Thunnus obesus, T. alalunga* and *T. albacares*) and some shark species (especially *Prionace glauca*). The Brazilian tuna fleet has been operating since 1956, with national as well as foreign leased vessels (Hazin et al. 1998), while the Uruguayan fleet has been operating without interruption since 1981. Both fleets operate in an extended zone in the southwestern Atlantic (SWA), often concentrating their effort on the continental slope and adjacent waters.

The pelagic longline fisheries are one of the main known causes of juvenile and adult sea turtle bycatch worldwide (Spotila et al. 2000; Yeung 2001; Lewison et al. 2004; Lewison and Crowder 2007). In the SWA the interaction of this fishery with sea turtles has been reported by various previous studies (Kotas et al. 2003; Pinedo and Polacheck 2004; Domingo et al. 2006; Lopez-Mendilaharsu et al. 2007; Giffoni et al. 2008; Sales et al. 2008). The loggerhead (*Caretta caretta*) is the most frequently captured sea turtle species, and its bycatch rates in the SWA are among the highest worldwide (Domingo et al. 2006; Lopez-Mendilaharsu et al. 2007; Giffoni et al. 2008 and Sales et al. 2008 where catch rates are compared with studies of other longline fisheries). The loggerhead bycatch by the Uruguayan and Brazilian longline fleets has been registered principally in waters over the continental slope, and also over the Rio Grande Rise (Lopez-Mendilaharsu et al. 2007; Giffoni et al. 2008; Sales et al. 2008).

The SWA is an important foraging and development area for juveniles of *C. caretta* (Domingo et al. 2006), where individuals belonging to reproductive stocks from various nesting beaches mix. From 43 loggerheads sampled from Uruguayan longline and coastal trawl fisheries bycatch, Caraccio et al. (2008) found that on the continental shelf and slope there was a predominance of the haplotype found on Brazilian nesting beaches, while off the slope in the open ocean, other haplotypes from nesting beaches in various locations, such as the USA, Mexico, Greece, Turkey and Brazil could also be found. Meanwhile, another study (Reis et al. 2009) found six distinct haplotypes among 125 loggerhead turtles sampled from Brazilian longline bycatch. According to these authors, only 47.2% of those loggerhead turtles had the Brazilian haplotype. The others turtles come from distinct rookeries different from the Brazilian ones.

All sea turtle species in the Atlantic Ocean are catalogued as either endangered or critically endangered by the International Union for the Conservation of Nature (IUCN). Loggerheads are specifically listed as endangered in the IUCN Red List of Threatened Species (IUCN 2008). The declines in numbers and critical situation faced by many sea turtle populations worldwide (Spotila et al. 2000; Kamezaki et al. 2003; Limpus and Limpus 2003; Witherington et al. 2009) and their life history characteristics (Bolten et al. 1998; Heppell et al. 1999) require serious conservation and management measures, a number of which are currently underway. However, for these to be successful, the trends in sea turtle populations should first be determined.

The population abundance estimates used in stock assessments or required to establish management measures depend on the sampling of the entire demographic spectrum of a population resident in a given area (Chaloupka et al. 2004). Most status and trend assessments of sea turtle populations are based on nesting beach survey data and therefore only take into account adult females. Although this information is very useful, it is insufficient because it leaves out the majority of the population: immature individuals of both sexes, adult males and non-reproductive females (Chaloupka and Limpus 2001). Small decreases in adult or large juvenile age-classes can drastically reduce population growth rates and are unlikely to be compensated by an increase in newborn production or survival (Heppell et al. 1999).

The models used in fisheries stock assessments require information on annual abundance variations of the species in question. The capture per unit of effort (CPUE) is traditionally used as a relative index of fish stock abundance (Hilborn and Walters 1992). This index is biased due to the variability in fishing operations, gear efficiency and different spatial and temporal distribution of resources (Maunder and Punt 2004). In consequence, it is desirable to remove those factors that can influence the CPUE, but which are not related to abundance. This procedure is commonly known as CPUE standardization (Maunder and Punt 2004), a process for which various models are used. The most common are generalized linear models (GLM) (McCullagh and Nelder 1989; Maunder and Punt 2004) where the CPUE is computed as a linear combination of explanatory variables, which can be continuous or categorical. We used these models to identify the factors that influence the capture rates of loggerheads in the SWA and develop a standardized index of relative abundance that can contribute to future population assessments that may be of assistance in the development of conservation and management strategies.

For the past few years, Uruguay and Brazil have been working together, combining efforts in research and conservation of sea turtles (Domingo et al. 2006; López-Mendilaharsu et al. 2007; Giffoni et al. 2008). This study attempts to give a regional perspective on catch trends of juvenile loggerheads in the SWA, standardizing the catch rates of *C. caretta* captured by the pelagic longline fleets of Uruguay and Brazil using data collected by scientific observers from observer programs of both countries. We also analyzed how each factor influenced the variability in catch rates of loggerhead sea turtles in the SWA.

2 Materials and methods

2.1 Characteristics of the fleets

The Brazilian and Uruguayan pelagic longline fleets present some differences in target species, operational area, vessel features, product processing and conservation, and gear configuration (e.g. number of hooks between buoys, depth of the gear, etc.) Such differences can also be found among vessels of the same fleet (Domingo et al. 2005; Bugoni et al. 2008; Jiménez et al. 2009). Beyond these differences, this study analyzes data from both countries taking into consideration only some of the vessels' features (engine power in HP, length in meters, Gross Registered Tonnage – GRT) and the type of fishing gear utilized (monofilament or multifilament mainline). A total of 48 vessels were observed.

2.2 Database

The data analyzed were collected by observers of *Programa Nacional de Observadores a Bordo de la Flota Atunera Uruguaya* (PNOFA) from Uruguay, since 1998, and *Programa Nacional de Observadores de Bordo da Frota Pesqueira do Brasil* (PROBORDO), and by observers of Fundação Pró-TAMAR, *Instituto ALBATROZ* and *Núcleo de Educação e Monitoramento Ambiental* (NEMA) from Brazil, since 2001.

We analyzed a total of 4276 fishing sets deployed between April 1998 and November 2007 in the area located between parallels 19° S and 37° 30' S, representing a total effort of 6 272 344 hooks by the two fleets. For each set, the observers recorded the date, geographic position (latitude and longitude) and sea surface temperature (SST in °C) at the beginning of the set, the effort (in number of hooks) and the number of loggerhead turtles captured. Nominal CPUE was calculated as the number of individuals captured every 1000 hooks (ind/1000 hooks). Seasons were considered as year quarters: 1^{st} (January-March), 2^{nd} (April-June), 3^{rd} (July-September) and 4^{th} (October-December).

2.3 Data selection

We conducted a Pearson correlation analysis between engine power, vessel length and GRT of the vessels to avoid the inclusion of variables in the model that could be highly correlated, and instead use a single variable that reflects the efficiency of the fleet.

The continuous explanatory variables SST and vessel characteristics were first evaluated with non-parametric smoothing functions (splines) to determine the type of relationship between the variables and the dependent catch rates (log CPUE). Those continuous variables that did not have a linear relation with the log CPUE were split into categories before inclusion in the GLM, because it would be incorrect to include them in the GLM model as linear covariates.

Since loggerheads are not uniformly distributed in the SWA (Domingo et al. 2006; Giffoni et al. 2008) different zones were identified based on catch rate distribution for each set. To do this we used a non parametric analysis of classification and regression tree (CART) (Breiman et al. 1984). CART is a powerful and modern statistical tool for analysis of complex ecological data, which has been utilized to analyze, explain and predict the distribution patterns of different species (De'ath and Fabricius 2000; Vayssiéres et al. 2000; Benito Garzón et al. 2006). CART trees explain variation of a response variable by repeatedly splitting the data into more homogeneous groups, using combinations of explanatory variables that may be categorical and/or numeric. The homogeneity of nodes is defined by impurity, a measure which takes the value zero for completely homogeneous nodes, and increases as homogeneity decreases. Many measures of impurity (splitting criteria) exist. We used sums of squares of the means because are more suitable for ecological data dominated by zeros (Breiman et al. 1984; De'ath and Fabricius 2000). The explanatory variables used were latitude and longitude, on the decimal scale, and the response variable was the loggerhead CPUE. This was conducted in order to incorporate these 2 covariates into one categorical variable, called "*Area*", to then be included in the GLM.

2.4 Lognormal delta model

Many species, especially non-target species (or bycatch) have a high proportion of zero catches with positive effort. In order to deal with this type of highly skewed data, methods that deal with zero catch observations are required. The Poisson or the negative binomial distributions explicitly include zeros in the probability density distribution, however the Poisson function is usually restrictive, as the observed variance is normally greater than the mean (Ortiz and Arocha 2004). Other approaches include the use of the delta type two-step models, such as the delta lognormal (Pennington 1996; Lo et al. 1992; Stefansson 1996; Ortiz and Arocha 2004) or the zero-inflated models (Lambert 1992; Shono 2008). The delta model analyzes separately the positive observations and the probability that a null or positive observation occurs, and consists of two GLM, one assuming a lognormal and the other a binomial distribution. Given that the proportion of zero observations for the turtle bycatch is moderate (20–60% annual average), we opted

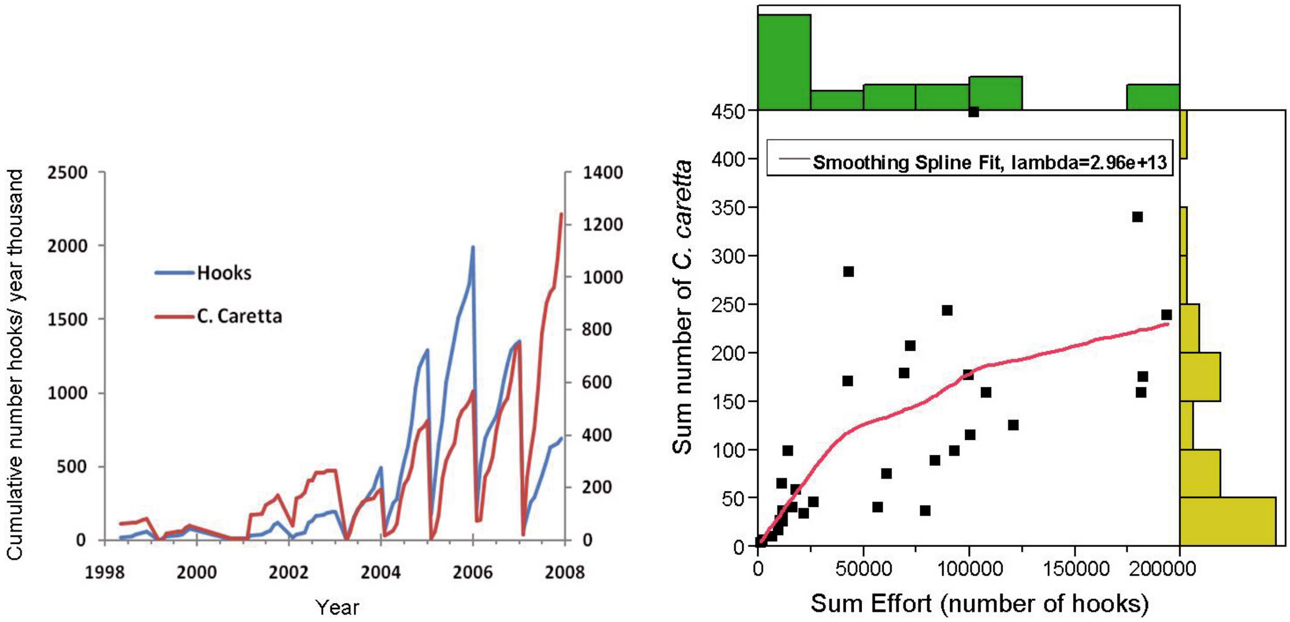

Fig. 1. A: Time series trends of the year-cumulative effort (number of hooks deployed) and catch of *C. caretta* in the Uruguayan and Brazilian pelagic longline fleets (1998-2008). B: Scatter plot of the catch per year-quarter of *C. caretta* (y-axis) and the number of hooks deployed per year-quarter (x-axis) from the same fleet and period. The line represents a smoothing spline fit, indicating the positive trend of the data and lateral histograms show the distribution of the data for each variable.

to use the delta-lognormal model as recommended by Shono (2008).

Following Ortiz and Arocha (2004), deviance tables (for both components of the delta model) were used to select the explanatory factors and interactions that explained most of the variance in the data. The maximum model included all single term factors and first-order interaction(s) that could provide a solution. The effect of each factor/interaction was evaluated following two criteria: first, the result of the χ^2 test between two nested models (in the case of models with interactions, the χ^2 test was between a model with and without the interaction), using an alpha value of 0.05, and a number of degrees of freedom given by the number of extra parameters estimated in the complex model minus one (McCullag and Nelder 1989); and second, the percent of deviance explained by the factor/interaction in reference to the total deviance for the maximum model. Factors and interactions that explained 5% or more of the variability were considered significant and included in the final model. The first criterion was a more formal statistical test, while the second criterion has been suggested in situations when, due to the large number of observations in the data, there is a tendency to favor over-parameterized models by including factors or interactions with little explanatory contribution overall (Maunder and Punt 2004).

After selecting the set of fixed factors and interactions for each error distribution, all interactions that included the factor *year* were treated as random interactions. This allows for the estimation of the annual indices of CPUE while taking into consideration the variability associated with year-interactions (Cooke 1997). This will convert the basic model from GLM into a generalized linear-mixed model (GLMM). The significance of the random interactions was also evaluated using three different criteria; the likelihood ratio test (Pinheiro and Bates 2000), the Akaike information criteria (AIC), and Schwarz's Bayesian criterion (BIC) (Littell et al. 1996). Models with smaller AIC and BIC values are preferred to those with larger values. The indices of abundance were estimated as the product of the least squares means (LS means) of the factor *year* for the selected models (lognormal and binomial) (Lo et al. 1992; Stefánsson 1996).

All the analyses were conducted using R software (R Development Core Team 2007) and Glimmix and Mixed procedures from the SAS® statistical computer software (Littell et al. 1996).

3 Results

3.1 Observed data

Figure 1a shows the relationship between number of turtles caught and the number of hooks deployed by the Uruguayan and Brazilian pelagic longline fleets. The cumulative annual trends indicate that as number of hooks increased, the number of turtles caught also increased. This positive correlation is evident in Figure 1b, which plots the number of hooks and turtles caught by year-quarter.

In total, 3778 loggerhead turtles were captured during the study period (mean annual catch = 378 individuals, min = 7 and max = 1242). The number of observed sets increased from 1998 to 2005, and decreased from 2005 to 2007. The percent of positive loggerhead captures with respect to the total sets was 31% for the entire period with a minimum of 19% in 2005 and a maximum of 59% in 2006. These minimum and maximum agree with those observed for nominal CPUE, namely 0.31 and 2.25 ind /1000 hooks, respectively (Table 1).

Table 1. Number of vessels, effort (number of sets and hooks observed), number of loggerhead captures and the proportion of positives of this capture respect to the total sets deployed, Nominal CPUE, standardized CPUE, 95% confidence intervals (CI) and standard error (SE) estimates by year.

Year	Observed vessels	*N* sets	*N* hooks	*N* loggerheads	% positives	Nominal CPUE	Standard CPUE	CI low	CI high	SE
1998	4	59	57 905	82	42	1.50	0.63	0.30	1.30	0.24
1999	3	87	75 790	56	36	0.70	1.13	0.58	2.19	0.38
2000	3	15	12 010	7	33	0.58	0.45	0.15	1.36	0.27
2001	6	119	119 751	170	34	1.47	0.81	0.44	1.49	0.25
2002	10	197	191 837	265	45	1.43	0.61	0.34	1.10	0.18
2003	12	281	494 134	192	37	0.54	0.39	0.22	0.69	0.11
2004	16	700	1 292 354	454	35	0.49	0.57	0.35	0.93	0.14
2005	27	1 434	1 989 431	564	19	0.31	0.38	0.23	0.62	0.10
2006	16	945	1 349 928	746	27	0.74	0.70	0.44	1.14	0.17
2007	17	439	689 204	1 242	59	2.25	1.78	1.14	2.79	0.41

Table 2. Pearson correlation analysis between vessel characteristics.

Vessel characteristics	Mean (range)	*n*	Motor power	Length	GRT
Motor power (hp)	567 (115-1 450)	31	1		
Length (m)	28 (15-48)	43	0.85	1	
GRT (tons)	219 (31-411)	30	0.72	0.87	1

3.2 Selection of explanatory variables

Vessel characteristics. As expected, we observed a strong correlation among the characteristics of the fishing vessels (length, engine power and GRT) (Table 2), and therefore used only the length as explanatory factor as it was the variable with the highest number of corresponding data. The vessels range between 15 and 48 m in length.

Figure 2a shows the smoother spline of the vessel size (length) and log transformed catch rates for *C. caretta*. There is no a clear trend however, the smoother plot may suggest that vessels <24 m had higher catch rates for *C. caretta*, compared to the larger ones (Fig. 2a). Therefore, this variable was split into two categories: over and below 24 m.

Sea surface temperature. The loggerhead captures occurred in a wide range of SST between 11 and 29 °C. The SST also shows a non linear relationship with the log transformed loggerhead CPUE (Fig. 2b). The catch rates increased slightly with temperature up to 20 °C, although there was large variation due to the low number of observations. Between 20 and 25 °C most of the data indicate a rather constant catch rate, while above 25 °C the data suggest a decline in the catch rates at higher temperatures. Therefore, the SST variable was split into three categories, below 20 °C, between 20 °C and 25 °C, and over 25 °C.

Spatial distribution. Through the CART analysis we identified three areas as a result of the distribution of loggerhead CPUE (Fig. 3a,b):

- Area 1, with the highest CPUE value (1.9 ind/1000 hooks), comprising Uruguayan jurisdictional and adjacent international waters, over the continental shelf and slope, south of 30.5 °S and west of 51.3 °W;
- Area 2, with intermediate CPUE values (1.1 ind./1000 hooks), also south of 30.5 °S and east of zone 1, comprising Brazilian and oceanic waters, including waters over the Rio Grande Rise;
- Area 3, with the lowest CPUE value (0.2 ind/1000 hooks), north of zones 1 and 2 encompassing a larger area including the region of the Vitória-Trindade seamount chain.

Table 3. Variables used in the delta model for standardized loggerhead catch rates.

Variable	Type	Observations
Year	Categorical (10)	Period: 1998-2007
Quarter	Categorical (4)	1: January-March 2: April-June 3: July-Sept. 4: Oct.-Dec.
Sea surface temperature (SST)	Categorical (3)	Range: 9–32 °C 1: < 20 °C 2: between 20 and 25 °C 25 °C 3: > 25 °C
Area	Categorical (3)	See Fig. 2
Length (vessel)	Categorical (2)	1: < 24 m 2: ⩾ 24 m
Fishing gear	Categorical (2)	1: monofilament 2: multifilament

Gear characteristics. The monofilament type gear presented catch rates higher than the multifilament type, with mean values of 0.78 ind/1000 hooks (range: 0-29.00 ind/1000 hooks) and 0.40 ind/1000 hooks (range: 0-6.00 ind/1000 hooks) respectively. The maximum CPUE value (29.00 ind/1000 hooks) corresponds to a fishing set that occurred on Area 2 where 32 turtles were captured with 1100 hooks.

The explanatory variables considered in the standardization model, including both main factors and first-order interactions, are summarized (Table 3).

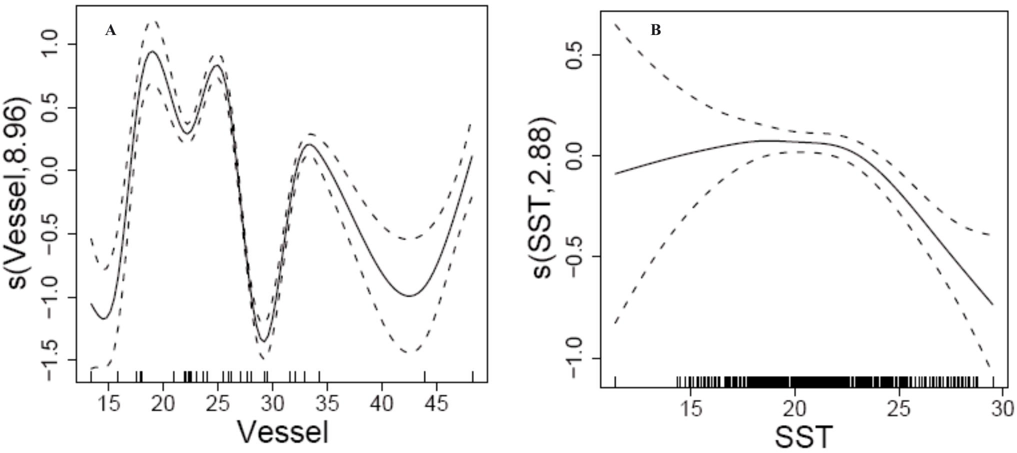

Fig. 2. Smoother spline plots of the *C. caretta* log CPUE (dependent variable), A: on vessel length (vessel) and B: on sea surface temperature (SST) from the Uruguayan and Brazilian pelagic longline fleets (1998-2008).

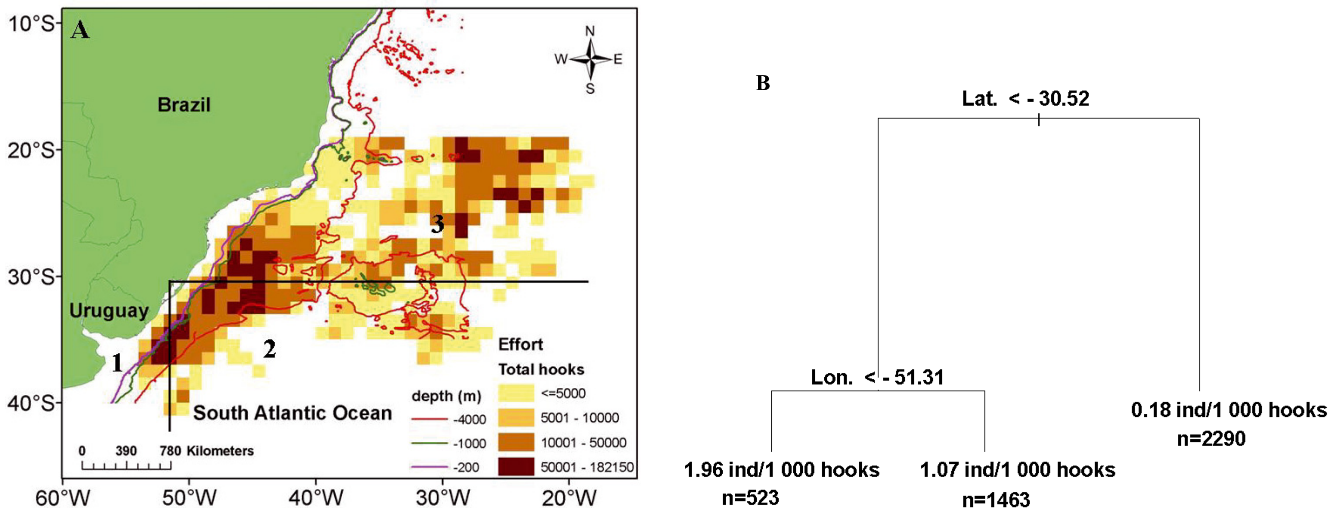

Fig. 3. A: Distribution of fishing effort (number of hooks in 1° × 1° grid squares) by the Uruguayan and Brazilian longline fleet (aggregated over 1998–2007). The numbers denote the fishing areas selected in the CART analysis (1-3). B: the tree obtained by CART for loggerhead CPUE in the southwestern Atlantic Ocean from the same period. Data with values of less than the splitting point go to the left daughter node; "*n*" is the number of data (sets) in each node.

3.3 Standardized loggerhead catch rates

The factors and interactions in the analysis were chosen through deviance table analysis, one for the lognormal and the other for the binomial model (Table 4a,b). However, since the χ^2 test depends on the order of the factors within the model formulation, importance was given to the percent of the deviance explained, rather than exclusively on the *p*-values (Ortiz and Arocha 2004), as mentioned in the methods.

Area is the variable that appears as the most significant in both, the lognormal and binomial models, followed by the *year*. The *gear* also appears to be significant in both models, and *SST* when modeling the proportion of positive catch. Also, the interactions *year*quarter* and *year*area* were significant in both models and *year*gear* and *area*gear* in the binomial model (Table 4).

However, when the interactions were included as random effects, only in the positive observations model the *year*area* and *year*quarter* were statistically significant according to the three criteria evaluated: the likelihood ratio tests and reductions in AIC and BIC values (Table 5). With the binomial model, the random interactions were not statistically significant; therefore the final model only included fixed factors (*year*, *area*, *quarter*, *gear* and *SST*). The estimated dispersion parameter of the binomial model was close to 1 (0.967) indicating no over-dispersion problems. The final models selected for the binomial and lognormal components for loggerhead CPUE were as follows:

For the lognormal: log CPUE = *year area gear quarter year*area year*quarter*
For the binomial: Success = *year area quarter gear SST*
where success equals 1 if the observer reported the catch of a

Table 4. Deviance analysis table of explanatory variables for loggerhead CPUE models (lognormal and binomial) from the Uruguayan and Brazilian pelagic longline fisheries. The models are fitted sequentially (single factors), and each interaction model compared to the corresponding model without the interaction. The columns give: degrees of freedom for each model (d.f.), residual deviance, resulting change in deviance, percentage of total deviance change compared with the deviance of the maximum model (model with the lowest deviance overall), and the *p* value for the χ^2 test between two consecutive models (single factors) or the model with and without interaction.

	d.f.	Residual deviance	Change in deviance	% of Total deviance	*p*
Model Factors Positive Catch Rates Values					
Null	1	969.4			
Year	9	826.7	142.6	28.4	< 0.001
Year Area	2	672.2	154.6	30.8	< 0.001
Year Area Gear	1	555.1	117.0	23.3	< 0.001
Year Area Gear Quarter	3	538.9	16.3	3.2	< 0.001
Year Area Gear Quarter SST	2	526.3	12.6	2.5	0.002
Year Area Gear Quarter SST Vessel	1	525.4	0.9	0.2	0.340
Year Area Gear Quarter SST Vessel Area*Gear	2	525.0	0.4	0.1	0.803
Year Area Gear Quarter SST Vessel Year*Vessel	8	519.6	5.8	1.2	0.669
Year Area Gear Quarter SST Vessel Gear*Quarter	3	519.5	5.9	1.2	0.118
Year Area Gear Quarter SST Vessel Area*Quarter	6	513.3	12.1	2.4	0.059
Year Area Gear Quarter SST Vessel Year*SST	12	512.4	13.0	2.6	0.370
Year Area Gear Quarter SST Vessel Year*Gear	6	509.0	16.4	3.3	0.012
Year Area Gear Quarter SST Vessel Year*Area	15	479.3	46.1	9.2	< 0.001
Year Area Gear Quarter SST Vessel Year*Quarter	21	467.8	57.6	11.5	< 0.001
Model Factors Proportion Positives					
Null	1	1497.9			
Year	9	1294.2	203.7	23	< 0.001
Year Area	2	1044.2	250.0	29	< 0.001
Year Area Gear	1	972.9	71.3	8	< 0.001
Year Area Gear Quarter	3	934.7	38.2	4	< 0.001
Year Area Gear Quarter SST	2	765.9	168.8	19	< 0.001
Year Area Gear Quarter SST Vessel	1	755.7	10.2	1	0.001
Year Area Gear Quarter SST Vessel Area*Vessel	2	752.2	3.4	0	0.179
Year Area Gear Quarter SST Vessel Year*Vessel	8	737.2	18.4	2	0.018
Year Area Gear Quarter SST Vessel Area*Quarter	6	721.6	34.1	4	< 0.001
Year Area Gear Quarter SST Vessel Gear*Quarter	3	720.0	35.7	4	< 0.001
Year Area Gear Quarter SST Vessel Year*Gear	6	695.2	60.5	7	< 0.001
Year Area Gear Quarter SST Vessel Area*Gear	2	695.2	60.5	7	< 0.001
Year Area Gear Quarter SST Vessel Year*Area	16	659.2	96.5	11	< 0.001
Year Area Gear Quarter SST Vessel Year*Quarter	22	627.5	128.2	15	< 0.001

Table 5. Analyses of alternative delta lognormal mixed model formulations for loggerhead catch rates from the Uruguayan pelagic longline fishery.

GLMixed Model	Log likelihood	Akaike's Information Criterion	Bayesian Information Criterion	Likelihood Ratio Test		Dispersion
Proportion positives						
Year Area Quarter Gear SST	14 085	14 087	14 093			0.9797
Year Area Quarter Gear SST Year*Area	14 279	14 282	14 285	–193.7	N/A	0.9777
Year Area Quarter Gear SST Year*Area Year*Quarter	14 393	14 399	14 403	–114.3	N/A	0.9689
Year Area Quarter Gear SST Year*Area Year*Quarter Year*Gear	14 526	14 534	14 540	–133.3	N/A	0.9849
Positives catch rates						
Year Area Quarter Gear	2 596	2 598	2 603			
Year Area Quarter Gear Year*Area	25 367	2 541	2 543	59.1	0.000	
Year Area Quarter Gear Year*Area Year*Quarter	2 499	2 505	2 509	37.8	0.000	

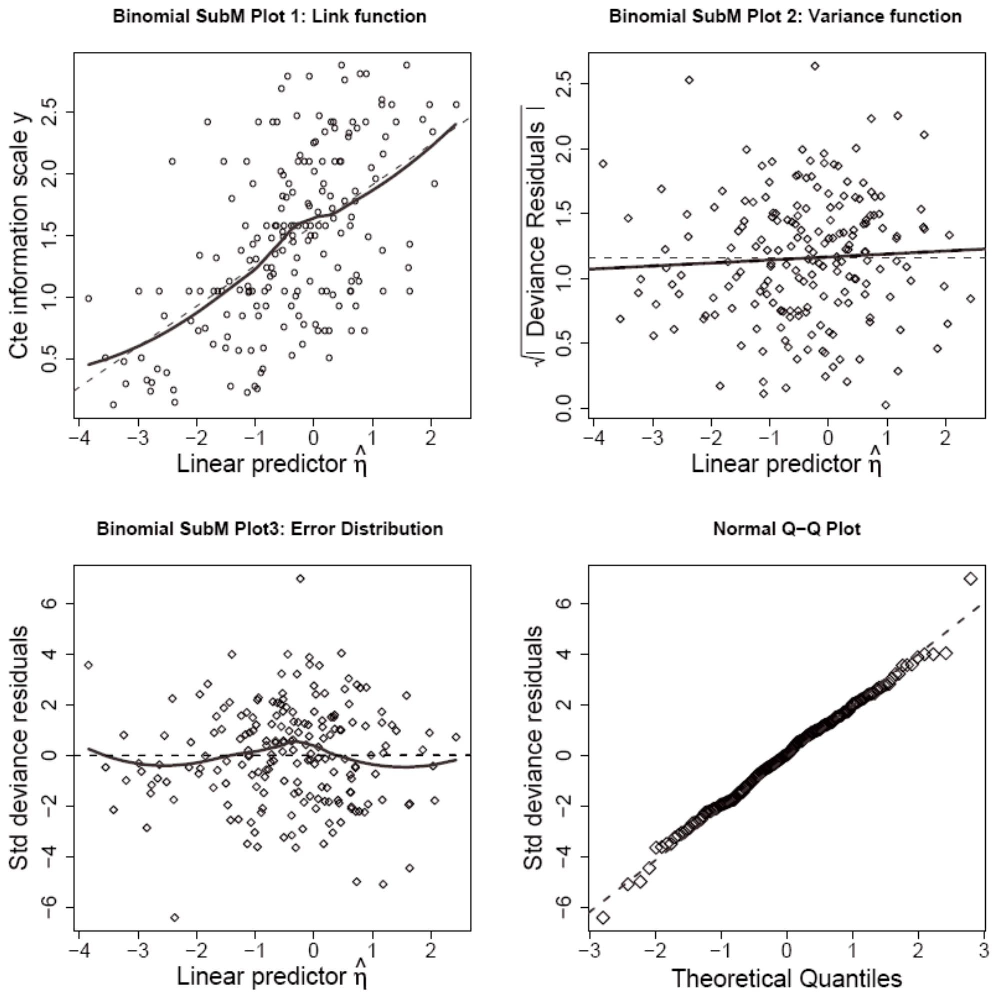

Fig. 4. Diagnostic plots for the positive loggerhead catch CPUE model. In all plots the broken line represents the expected pattern of observations, the solid line is the loess smoother of the actual observations. The link function and error distribution plots confirmed model assumptions of lognormal distribution for CPUE, however the variance and qq-plots indicated a higher than expected variability for larger catch rates.

turtle or 0 if no turtles were caught (modeled as a binomial response), and the interactions *year*area* and *year*quarter* were assumed to be random interactions. Overall the model explained about 52% of the observed variability in the proportion of loggerhead catch by set and 58% of the conditional observed catch rates.

Diagnostic plots are presented for the final models (Fig. 4). For the binomial model, the error distribution plot, link function plot, and variance function plot all followed the expected patterns confirming the model assumptions (McCullagh and Nelder 1989). For the lognormal model, the link function plot and the error distribution plot also followed the expected patterns. The variance function and qq-plots indicated a higher variance as catch rates increased and a greater observed fraction of extremely low catch rates than those predicted by the model, respectively. Overall model diagnostics confirmed the model fit and estimates.

The standardized and nominal loggerhead CPUE, including estimated 95% confidence bounds, are shown (Fig. 5, Table 1). No clear trend**s** are observed in the estimation of the loggerhead catch rates, but a small decreasing tendency was observed from 1998 to 2005 with an increase in the last two years (2006-2007). CPUE values varied between 0.38 ind/1000 hooks in 2005 and 1.78 ind/1000 hooks in 2007. Coefficient of variance ranged from 23 to 60%, larger confidence bounds were estimated for the early years (1998-2001), mainly due to the lower number of observations during those years. With the exception of 2007, annual estimates of CPUE overlap for most of the period, with lower catch rates in 2003-2005. The year 2007 shows the highest catch rates and confidence bounds, and although overall fishing effort decreased almost by 50% compared to 2007 (Table 1), the percent of sets that caught *C. caretta* increased from 27 to 59% in 2007, resulting in catching about twice the number of turtles compared to 2006.

4 Discussion

The effort observed during the study period increased notably from 2001, following the incorporation of data from the

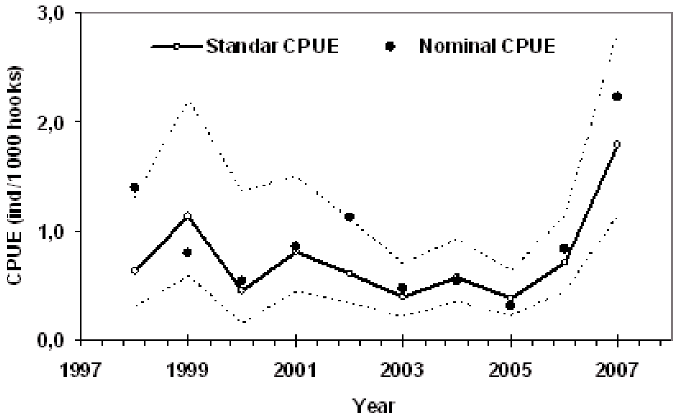

Fig. 5. Nominal and standardized catch rates for loggerhead sea turtles from Uruguayan and Brazilian pelagic longline fleets from 1998 to 2007. Dotted lines represent 95% confidence intervals for the standardized catch rates.

Brazilian observer programs. The highest captures started in the year 2001, corresponding with a higher observation effort that also started that year. The annual catch was highly variable, and is related to the fishing effort. The relationship between the effort and *C. caretta* catches by the Uruguayan and Brazilian longliners is not exactly linear (Fig. 1) because there are other factors affecting this relationship (variables identified in the standardization model as significant factors and interactions). Therefore, in our case using number of hooks deployed as the effort unit is consistent with the analysis and the observed data.

During the study period, loggerhead turtles were captured in 31% of the sets. This value is higher than the 3.8% reported by McCracken (2004) or the 7.5% registered by Gardner et al. (2008a) for the north Atlantic, where capturing a loggerhead sea turtle were considered as a "rare event".

It was clearly noted that the relationship between the analyzed variables and the loggerhead catch is not linear. Smaller vessels (< 24 m), which due to their reduced autonomy operate closer to shore, generally over the continental slope, exhibit higher bycatch rates than bigger boats. However, the significance of this variable was not reflected in the modelling of the loggerhead catch rates. Other variables, such as *area*, appear as significantly more important (Table 4).

Vessel length did not appear to be relevant in the final model, but the fishing gear type was found to be significant. For positive catches, the type of gear explained a high proportion of the variability in the loggerhead CPUE (Table 4). Higher bycatch rates were observed in those vessels which employed monofilament main lines. We can not be sure that the variable that affects the catch rate is the main line material itself, in case another variable associated with the utilization of different fishing modalities and fishing gears could be influencing the different catch rates observed with both gear types (number of hooks deployed, hook depth, bait type, etc).

The relation of the catch rates and the SST is not linear, and it is observed that the loggerhead catch rates increase together with the temperature, with the higher catch rates occurring between 20 °C and 25 °C. It is important to note that most of the effort is deployed on this temperature range. The SST appears as significant in the binomial model related to the success of catching turtles, but not to the magnitude of the catch rate (lognormal model, Table 4). Likewise, Gardner et al. (2008a), for leatherback sea turtles, found that temperature was not important in predicting the number of turtles captured but it was an important factor in predicting the zero-inflation parameter.

Previous studies observed different CPUE values associated with the spatial and temporal distribution of loggerhead sea turtles in the SWA (Domingo et al. 2006; López-Mendilaharsu et al. 2007; Giffoni et al. 2008; Sales et al. 2008). The CART analysis showed that there are distinct zones with differential catch rates, with the higher CPUE values over the continental slope of Uruguay and adjacent waters (Area 1) according to previous studies in the area (López-Mendilaharsu et al. 2007; Giffoni et al. 2008). Coincidentally, high CPUE values for marine turtles and other species (target and bycatch) have already been reported for this area (Domingo et al. 2007; Jimenez et al. 2009). This zone is under the influence of the convergence of the Malvinas and Brazil currents (Subtropical convergence) and the discharge of the Rio de la Plata estuary, as a result of which the zone is highly productive and supports high trophic levels (Acha et al. 2004). Also the deviances table (Table 4) shows that the area is the most important factor determining the different catch rates of loggerhead sea turtles in the SWA.

There are also temporal differences between years and quarters, and even their interaction (*year*quarter*) appears to be a significant explanatory factor (Table 4). A previous study on loggerhead bycatch of the same fleets observed that the highest bycatch rates occurred during the first and second quarter (summer and fall) (López-Mendilaharsu et al. 2007), while another study (Giffoni et al. 2008) found that the highest bycatch occurred during fall, but depended on the area considered.

Our results show that loggerhead CPUE is not uniformly distributed in the study area. Gardner et al. (2008b) also observed that sea turtle catch distributions vary over different spatial and temporal scales in the North Atlantic. It is influenced by areas and seasons (quarters) and by other variables associated with gear type. We know that other variables should be evaluated as well, including bait type, gear configurations and hook depth. Watson et al. (2005) found that the combination of hook type and bait have different effects on loggerhead sea turtles bycatch rates. Also, analysis of observer data collected by the Secretariat of the Pacific Community (SPC) demonstrates that shallow-set longline gear takes ten times more sea turtles than deep-set gear (SPREP 2001). These potential variables could be used in future studies.

The catch rates of loggerheads by the Uruguayan and Brazilian pelagic longline fisheries show oscillations through the years without a clear tendency; however a low negative trend was observed from 1998 to 2005 with an increase in the last two years (2006 and 2007). We should pay special attention to the higher catch rates of loggerhead sea turtles registered in 2007, when the CPUE was 2.35 times higher than the average of all years.

Previous studies have determined that the majority of the loggerheads captured by the pelagic longline fleets of both Uruguay and Brazil in the SWA are juveniles (average of

58.9 cm of curved carapace length, $n = 1730$) (Giffoni et al. 2008). Crouse et al. (1987) demonstrated by demographic analysis (use a Lefkovitch stage class matrix model) that the most vulnerable stages in loggerhead sea turtles were juveniles and subadults.

The present study provides the first standardization of catch rates of juvenile loggerhead sea turtles in the SWA as a proxy of annual relative abundance estimation. Abundance estimation for different age classes is important for the management of highly migratory species such as *C. caretta*. Consequently, it is important that future research takes into account standardized abundance estimates of different age classes so that, jointly, an assessment of *C. caretta* in the Atlantic Ocean can be made. Conserving sea turtles, and other global bycatch species, will require ocean-scale assessments.

To reduce the incidental capture of sea turtles, efforts are being conducted to test circle hooks as a mitigation measure, both in Uruguayan and Brazilian pelagic longline fisheries (for Uruguay see Domingo et al. 2009, for Brazil the data are unpublished), which have been found to be successful in the reduction of sea turtle bycatch in other parts of the world (Cooke and Suski 2004; Watson et al. 2005; Piovano et al. 2009). At the same time, there are ongoing studies on distribution, habitat use and environmental preferences of juvenile loggerheads through satellite telemetry (unpublished data).

Observer programs are, up to the present, the best and most reliable source of bycatch data for different species. These programs provide information about fisheries that would not otherwise be obtainable and that is fundamental for the conservation and management of marine resources. The continuity of these programs is of utmost importance for the collection of data and the developments of longer temporal series, as well as to test and promote mitigation measures to reduce incidental capture of many species. Also the use of regional databases allows a more effective management and conservation issues in this transzonal and highly migratory species such as *C. caretta*.

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