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Towards mitigation of seabird bycatch: Large-scale effectiveness of night setting and Tori lines across multiple pelagic longline fleets

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ABSTRACT

Bycatch in pelagic longline fleets remains a considerable source of mortality for threatened seabirds. Despite efforts to implement mitigation measures, the effectiveness of their application across multiple fleets and wide spatio-temporal scales remains poorly understood. We analyse about 15,800 sets and 36.4 million hooks observed during 583 trips aboard 132 vessels from five pelagic longline fleets (Brazil, Portugal, South Africa, Uruguay and foreign charter-vessels) operating in the south Atlantic and southwestern Indian Oceans (2002–2016) to assess the large-scale effect on bycatch rates of the implementation over time of night-setting and Tori (bird-scaring or streamer) lines. There was a highly significant decrease in standardised bycatch rate from 2002 to 2008 to 2009–2011 and a further reduction in 2012–2016, as consequence of an increased use of mitigation measures. This reduction on fleet-wide bycatch rates temporally coincides with the progressive implementation of mitigation measures in the two relevant Regional Fishery Management Organisations. Night-setting significantly reduced bycatch rates under all conditions, particularly for albatrosses. Surprisingly, bycatch rate during daylight was higher when Tori lines were deployed. Inconsistencies in Tori line deployments, entanglements with the fishing gear and the non-use of this measure with low seabird abundance may explain this pattern. At night, relative moon illumination increased bycatch rate, especially of petrels, but Tori lines significantly reduced seabird bycatch. Our results imply that a major reduction in global bycatch of threatened seabirds could be achieved, if night setting and Tori lines are correctly applied and extensively implemented by fleets operating south of 25°S.

1. Introduction

Incidental captures in fisheries, termed bycatch, particularly by industrial longline and trawl fleets, has long been identified as a considerable source of seabird mortality (Sullivan et al., 2006; Anderson et al., 2011) and a conservation concern for several globally threatened species of albatrosses (Diomedeidae) and petrels (Procellariidae) (Gales, 1998; Phillips et al., 2016; Dias et al., 2019). This has resulted in increased efforts to quantify (Brothers, 1991; Watkins et al., 2008; Anderson et al., 2011) and mitigate against this threat in various fisheries (Løkkeborg, 2011; Maree et al., 2014; Melvin et al., 2014). Yet, reducing seabird bycatch, especially in pelagic longline fisheries, remains a challenge.

In longline fisheries incidental mortality occurs mainly during setting, when the birds attempt to feed on the baited hooks, get hooked or entangled and drown as the gear sinks to its fishing depth (Brothers, 1991). The relatively slow sink rate of pelagic longlines, compared with demersal, allows the birds to more easily take the bait (Jiménez et al., 2012a). A variety of strategies have been developed to avoid seabird bycatch during longline setting (Bull, 2007). Aside from two recent emerging technologies, i.e. the hook-pods (Sullivan et al., 2018) and the underwater bait-setter (Robertson et al., 2018), currently, the most effective and feasible mitigation measures in pelagic longline fisheries are the deployment of bird scaring or “Tori” (bird-scaring or streamer) lines, setting the hooks at night, and specific branch-line weighting to increase sink rates of the baited hooks (Løkkeborg, 2011; Melvin et al.,

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2014). None of the aforementioned mitigation measures alone is likely to reduce seabird bycatch to negligible levels, consequently, the Agreement on the Conservation of Albatrosses and Petrels (ACAP) recommends the simultaneous use of the three mitigation measures (ACAP, 2019). Guided by evidence-based research, all major tuna Regional Fishery Management Organisations, which are responsible for the management of over 90% of tuna fishing in the global oceans, have implemented Conservation Management Measures to reduce seabird bycatch in these fisheries. Current Conservation Management Measures require the simultaneous use of two of the three aforesaid mitigation measures in areas of high seabird abundance; i.e. below the latitude 25° S in the Atlantic and Indian Oceans and the 30° S in the Pacific Ocean (ICCAT, 2011; IOTC, 2012; WCPFC, 2018).

Whereas there is considerable effort to refine the design and to test the effectiveness of the mitigation measures during controlled experiments (Sato et al., 2013; Melvin et al., 2014; Domingo et al., 2017; Jiménez et al., 2019), ascribing a reduction of seabird bycatch to the application of a measure through analyses of large-scale fisheries data remains challenging. This is due to the variability in data quality, the lack of spatially and temporally representative observer coverage, heterogeneity in longline fishing operations, the inconsistencies in the design and deployment of mitigation measures, and the lack of consistent reporting of the implementation of individual measure at a set-by-set level (Anderson et al., 2011; Phillips, 2013).

The south Atlantic and Indian Oceans host large numbers of globally important breeding sites of many threatened albatrosses and petrels, located at remote archipelagos; e.g., Falkland/Malvinas, South Georgia, Tristan da Cunha, Gough, Marion, Kerguelen, Crozet, among others (Phillips et al., 2016). These species are exceptionally wide-ranging and frequently cover large distances in search of particular habitats or environmental conditions (Wakefield et al., 2009; Louzao et al., 2011) which generally coincide with areas of high industrial fishing activity (Jiménez et al., 2016; Clay et al., 2019). The nutrient-rich waters around the continental shelves of southern Africa and the eastern coast of South America are known to harbour some of the highest concentrations of pelagic seabirds (Crawford et al., 1991; Veit, 1995; Jiménez et al., 2011), thereby increasing the probability of interactions with pelagic longline fleets and in turn, bycatch of related mortality of albatrosses and petrels. This not only affects many threatened species from the aforementioned breeding sites but also migrating species from elsewhere, including Oceania (Bugoni et al., 2008; Petersen et al., 2009; Yeh et al., 2013; Jiménez et al., 2014).

Here we analyse observer data from pelagic longline fisheries obtained by scientific observer programmes onboard several longline fleets operating in the south Atlantic and southwestern Indian Oceans over a period of 15 years (2002–2016). The compiled dataset comprised > 15,000 longline sets (i.e. fishing events) with detailed set-by-set information, including on the use of two seabird bycatch mitigation measures, namely night setting and deployment of a Tori line, in addition to seabird bycatch data at species level. The main objective of the paper was to test the operational effectiveness of the large-scale implementation of the two mitigation measures. After exploring the importance of covariates related to fleet, area, time and environmental conditions on the bycatch rate of seabirds, we assessed the large-scale effect of the implementation of the two mitigation measures, over time, taking into account variables affecting bycatch rate.

2. Materials and methods

2.1. Observer data

Data were obtained from scientific observer programmes for longline fisheries from Brazil, Portugal, South Africa and Uruguay. Brazilian data came exclusively from the non-governmental observer programmes maintained by Projeto Albatroz, while data from Portugal and Uruguay were collected by national on-board observer programmes and from South Africa by a governmental- and industry-funded observer programme. Joint Venture fishing operations under Japanese flag in the economic exclusive zones of South Africa and Uruguay were also included. In regard to seabirds, all the onboard programmes recorded at longline set level the total number of individuals captured by species. Other minimum required information for analyses from each setting operation was extracted. The final dataset included the vessel and fishing trip IDs, and for each longline set, the date, time and geographical coordinates at the start of setting, the observed number of hooks, the species-specific seabird bycatch numbers and the deployment of bird scaring lines (Tori lines) as a binary variable (yes/no).

Additional variables obtained for each longline set included: bathymetry (from GEBCO-30 arc sec grid, http://www.gebco.net/); spatial gradient of bathymetry by estimating the proportional change (PC) in depth within a surrounding 3 × 3 cell grid (90 × 90 arc sec [~3 km × 3 km]) using a moving window as follows: PC in depth = [(maximum value − minimum value) × 100]/maximum value]) (Louzao et al., 2009); the fraction illuminated of moon, a continuous variable which takes values from 0.0 (new moon) to 1.0 (full moon) (Agafonkin and Thieurmel, 2018); time of setting in three categories (night = entire set between nautical dusk and dawn; daylight or day = at least part of the setting between the sunrise and sunset, and twilight = setting between the sunset and sunrise and at least part conducted either between sunset and nautical dusk or between nautical dawn and sunrise). Breeding and non-breeding seasons were defined as the periods from October to April and May to September, respectively. This was based on the breeding/non-breeding seasons of the main by-caught species, which are year-round distributed in the southern hemisphere. These periods were also representative of the breeding/non-breeding seasons for many other species, except for great albatrosses (*Diomedea* spp.), which were captured in few numbers. The data were restricted to the Atlantic and Indian Ocean areas south of 15° S and west of 80° E. A total of 110 sets with missing information on Tori line were excluded. The final dataset comprised 15,779 individual fishing sets representing 36.4 million hooks observed during 583 trips aboard 132 pelagic longline vessels.

2.2. Statistical analyses

2.2.1. Effects on seabird bycatch composition

Multivariate Regression Trees (were used to explore the relationship between all available variables (see Table 1) and observed seabird species composition caught per longline set. The Multivariate Regression Trees approach was chosen because it is considered a robust method that can handle non-linear relationships and higher-order interactions between multivariate response variables and predictors (De'ath, 2002). The process employs recursive partitioning of data to cluster longline set observations according to species similarity. Data partitioning occurs via a series of binary splits of the predictor variables and the highest within-group similarity is achieved by minimizing the sum of square Euclidean distances within each resultant group. The regression tree starts with a single binary split at the top and 'grows' with each subsequent split, with each split resulting in two new nodes. The terminal nodes of the tree represent the final groups termed 'leaves' De'ath, 2002. In the Multivariate Regression Trees analysis, the species composition of sets where seabird bycatch occurred was related to year, latitude, longitude, time of setting, bathymetry, spatial gradient of bathymetry (i.e., change in depth as described above), moon illumination, season and vessel flag (Table 1). The percentage contribution of each species (frequency of occurrence > 3%) to the seabird bycatch composition of each terminal group was calculated.

2.2.2. Variable importance

A 'Random Forest' algorithm (Breiman, 2001) was employed to explore the relative importance of possible predictor variables (see Table 1) on Bird Capture per Unit of Effort (birds/ 1000 hooks;

Table 1
Details of covariates used in the Multivariate Regression Trees (MRT), Random forest (RF) and Generalized Additive Mixed Models (GAMMs).

Covariates	Model		
	MRT	RF	GAMM
Type	Non-parametric	Non-parametric	Semi-parametric
Spatial - Continuous	Lat + Lon	Lat + Lon	s (Lat, Lon, by = Season)
Season - Categorical (Breeding; Non-Breeding)	+ Season	+ Season	Interaction with Spatial
Year - Continuous	+ Year	+ Year	–
Period - Categorical (2002–2009; 2010–2011; 2012–2016)	–	–	+ Period
Bathymetry - Continuous	+ Bathymetry	+ Bathymetry	s (Bathymetry)
Depth change - Continuous	+ Depth change	+ Depth change	s (Depth change)
Moon Illumination - Continuous	+ Moon illumination	+ Moon illumination	s (Moon Illumination)* and s(Moon Illumination, by = Setting Time)***
Flag - Categorical (BR; JAP; POR; SA; UY)	+ Flag	+ Flag	–
Setting type - Categorical (Shallow; Deep)	–	–	+ Setting type
Tori line Use - Categorical (Yes; No)	+ Tori line Use	+ Tori line Use	+ Tori line Use
Setting time - Categorical (Day; Twilight; Night)	+ Setting time	+ Setting time	+ Setting time** and Interaction with Spatial Moon Illumination ***
Mitigation Interaction	–	–	+ Tori line Use: Setting Time**
Vessel ID - Categorical	–	–	Random Effect

"s" refers to splines and "+" refers to fixed factors in the model formulations. BR = Brazil, POR = Portugal, JPN = Japan, SA = South Africa and UY = Uruguay. * excluded from the final GAMM fitted to the complete dataset; ** excluded from the final GAMM fitted to nocturnal sets; *** excluded from both final GAMM models (complete dataset and nocturnal sets).

hereafter BCPUE). Random Forest is an extension of the Classification and Regression Tree approach (Breiman et al., 1984), whereby large numbers of classification trees (forest) are constructed from randomly selected subsets of the original data and grouped (Lawler et al., 2006; Lennert-Cody et al., 2008). One of the outputs of Random Forest calculations is a measure of variable importance. Random Forest quantitatively estimates the importance of each variable based on cross-validation, on BCPUE (Table 1).

2.2.3. Predictive modelling

Generalized Additive Mixed Models (GAMMs) with quasi-Poisson error structure and a log-link function were employed to investigate the effects of several combinations of covariates (see Table 1) on the number of birds caught per set (BCPS).

The models were of the general form of.

$$\mathrm{BCPSi} \sim \mathrm{quasi} - \mathrm{Poisson}\ (\lambda, \Phi) \quad (1)$$

$$\mathrm{Log}(\lambda) = \alpha + s(\beta i) + \varepsilon j \quad (2)$$

with λ and Φ being the mean and the dispersion parameters of the quasi-Poisson, α the intercept, s the smoothing spline, β the slope for the factor i and εj the random effect, in this case the individual vessel effect, indexed by the number of included strata j. In order to consider the bycatch rate as response, the number of hooks was included as an offset. The quasi-Poisson error distribution better reflected the data structure with large number of sets without seabird bycatch combined (85% of the sets) with high overdispersion.

BCPSi is affected by latent effects that introduce additional variability and potential bias when investigating the relative effects of the variables of interest. These factors can be ecological, like changes in seabird population size over time or spatial shifts in bird densities, as well as gear modifications, including the branch-line weighting regime (weight and distance from hook), which could not be included as covariates. Various combinations of covariates were included during the initial model selection process (Table 1). The factors month and breeding season were included one at a time. Pre-selection of models was conducted considering parsimony and feasibility to isolate the effects of the variables of interest (e.g., Tori line, night setting, moon illumination, implementation period; see below) and their combinations. Lastly, the effects of these variables were predicted for a reference set of standard conditions. The reference datasets were selected by fixing all the categorical variables to an individual stratum in the dataset and the continuous variables to the median (Maunder and Punt, 2004). Consequently, the results represent the bycatch rate under fixed conditions in a common time-area stratum. In the final models, year was divided into three implementation periods denoting pre-mitigation (2002–2008), phase-in of mitigation (2009–2011) and mitigation (2012–2016). These periods reflect the changes in current Conservation Management Measures from the International Commission for the Conservation of Atlantic Tunas (Table 2; see https://www.iccat.int/en/RecRes.asp) and the Indian Ocean Tuna Commission (Table 2; see https://www.iotc.org/cmms) and the development of controlled experiments, specification refinements, and technical advice on mitigation measures (Melvin et al., 2013, 2014; Domingo et al., 2017; ACAP, 2019; Jiménez et al., 2019; Santos et al., 2019). Because models accounted for the effects of mitigation methods, the factor Implementation period could also capture some effects not already included as covariates, i.e., changes in branch line-weighting regimes, diligence of the crew in properly deploying (and fixing tangled) Tori lines and changes in bird densities. Fleets were combined into two levels, "deep-setting" for Asian vessels with deep longline gear (Domingo et al., 2014) generally set in deeper depths (100 to 200 m, sometimes more) that target mainly tunas, versus "shallow-setting" for fleets with mixed targeting, mostly for swordfish and sharks, that generally operate with surface longlines (Domingo et al., 2014) in shallower depths (< 100 m). Spatial variables, bathymetry, change in depth, latitude and longitude were included as splines and individual vessel was retained as random effect. Analogous models we conducted separately for albatrosses and petrels to account for the differences in foraging behaviour. In addition, similar models for total seabirds, albatrosses and petrels were conducted only for nocturnal longline sets in order to assess the effect of the moon illumination.

The statistical computing environment R (R Development Core Team 2015) was used for all statistical analyses. The Multivariate Regression Trees, Random Forest and GAMMs analyses were performed using 'mvpart' (De'ath, 2002), 'RandomForest' (Cutler et al., 2007) and 'mgcv' (Wood, 2006) libraries, respectively.

3. Results

A total of 8472 individual seabird captures (0.23 birds/1000 hooks) were included in the dataset, mostly albatrosses (*n* = 4183) and petrels (*n* = 3842). A total of 28 species were recorded, with white-chinned petrels (*Procellaria aequinoctialis*) and black-browed albatrosses (*Thalassarche melanophris*) being most frequently caught (*n* = 3402 and

Table 2
Implementation history of the current seabird bycatch mitigation measures in the International Commission for the Conservation of Atlantic Tunas (ICCAT) and the Indian Ocean Tuna Commission (IOTC).

RMFO	Year	Number and summary of the recommendation/resolution		Mitigation measures
ICCAT	2002	Rec. 02/14	CPCs shall inform the SCRS on the status of their NPOA and provide information on seabird interactions, including bycatch. SCRS should present a bycatch assessment.	None.
	2007	Rec. 07/07	The Commission shall develop mechanisms to enable CPCs to record data on seabird interactions, including regular reporting to the Commission. CPCs shall: 1) provide information on seabird interactions, including bycatch, and 2) seek to achieve reductions in levels of seabird bycatch.	All vessels fishing south of 20°S shall use BSL. Vessels targeting swordfish using monofilament longline gear are exempted from BSL on condition of night setting and 60 g ≤ 3 m of the hook.
	2011	Rec. 11/09	CPCs shall: 1) record data on seabird bycatch by species through scientific observers, 2) seek to achieve reductions in levels of seabird bycatch, and 3) collect and provide information on how they are implementing these measures and on the status of their NPOA.	All longline vessels fishing south of 25° S shall use at least two of following three mitigation measures: night setting, BSL, branch-line weighting. All vessels fishing in the area between 20°S to 25°S shall use BSL. Mitigation measures shall conform to the minimum technical standards. In the Mediterranean, mitigation measures should be implemented on a voluntary basis.
IOTC	2005	Res. 05/09	CPCs shall inform the IOTC Scientific Committee on the status of their NPOA and provide information on seabird interactions, including bycatch. IOTC Scientific Committee should present a bycatch assessment.	None.
	2006	Res. 06/04	The Commission shall develop mechanisms to enable CPCs to record data on seabird interactions, including regular reporting to the Commission. CPCs shall: 1) provide information on seabird interactions, including bycatch, and 2) seek to achieve reductions in levels of seabird bycatch.	All vessels fishing south of 30°S shall use BSL. Vessels targeting swordfish using monofilament longline gear are exempted from BSL.
	2008	Res. 08/03	CPCs shall seek to achieve reductions in levels of seabird bycatch. Fishing operations shall be conducted in such a way that baited hooks sink as soon as possible. CPCs shall collect and provide information on how they are implementing these measures and on the status of their NPOA.	All longline vessels fishing south of 30°S shall use at least two mitigation measures, selecting at least one from each of the following lists: A) night setting, BSL, branch-line weighting, and B) night setting, BSL, branch-line weighting, blue-dyed squid bait, offal discharge control, line shooting device).In all other areas, CPCs may require that longline vessels use at least one of the measures. Mitigation measures used shall conform to the minimum technical standards.
	2010	Res. 10/06	Idem to Res. 08/03.	Idem to Res. 08/03, but 30° S was modified to 25° S.
	2012	Res. 12/06	CPCs shall record seabird bycatch data by species through scientific observers and report these. Otherwise data from logbooks shall be reported. CPCs shall seek to achieve reductions in levels of seabird bycatch.	All longline vessels fishing south of 25° S shall use at least two of following three mitigation measures: night setting, BSL, branch-line weighting. Mitigation measures shall conform to the minimum technical standards.

Rec. = Recommendation.
Res. = Resolution.
CPCs = Contracting Parties and Cooperating non-Contracting Parties, Entities or Fishing Entities.
SCRS = Standing Committee on Research and Statistics.
NPOA = National Plan of Action.
BSL = Bird scaring line or Tori line.

Table 3
Species of seabirds incidentally captured during 583 fishing trips observed aboard 132 pelagic longline vessels in the south Atlantic and Indian Oceans (2002–2016). Their IUCN status is also provided: CR: Critically Endangered, EN: Endangered, VU: Vulnerable, NT: Near Threatened, LC: Least Concern (see details in www.birdlife.org/datazone/species/search). N = number of individuals.

Species	Scientific name	IUCN status	N
Albatrosses			4183
Wandering albatross	*Diomedea exulans*	VU	48
Tristan albatross	*Diomeda dabennena*	CR	11
Southern royal albatross	*Diomedea epomophora*	VU	47
Northern royal albatross	*Diomedea sanfordi*	EN	72
Unidentified royal albatross	*Diomedea epomophora/ sanfordi*		20
Unidentified great albatross	*Diomedea* spp.		20
Shy-type albatross	*Thalassarche cauta/steadi*	NT*	717
Black-browed albatross	*Thalassarche melanophris*	LC	1937
Campbell albatross	*Thalassarche impavida*	VU	4
Atlantic yellow-nosed albatross	*Thalassarche chlororhynchos*	EN	542
Indian yellow-nosed albatross	*Thalassarche carteri*	EN	169
Yellow-nosed albatross	*Thalassarche carteri/ chlororhynchos*		150
Grey-headed albatross	*Thalassarche chrysostoma*	EN	26
Unidentified mollymawks	*Thalassarche* spp.		4
Sooty albatross	*Phoebetria fusca*	EN	13
Light-mantled albatross	*Phoebetria palpebrata*	NT	7
Unidentified albatrosses	*Diomedeidae*		396
Petrels			3842
Southern giant petrel	*Macronectes giganteus*	LC	20
Northern giant petrel	*Macronectes halli*	LC	6
Giant petrels	*Macronectes spp.*		25
White-chinned petrel	*Procellaria aequinoctialis*	VU	3402
Spectacled petrel	*Procellaria conspicillata*	VU	28
Grey petrel	*Procellaria cinerea*	NT	1
Cape petrel	*Daption capensis*	LC	44
Southern fulmar	*Fulmarus glacialoides*	LC	8
Great-winged petrel	*Pterodroma macroptera*	LC	10
Great shearwater	*Ardenna gravis*	LC	84
Sooty shearwater	*Ardenna grisea*	NT	3
Flesh-footed shearwater	*Ardenna carneipes*	NT	10
Unidentified shearwater	*Ardenna/Puffinus* spp.		16
Unidentified petrels	*Procellariidae*		185
Other seabirds			115
Magellanic penguin	*Spheniscus magellanicus*	NT	2
Cape gannet	*Morus capensis*	EN	109
Subantarctic skua	*Stercorarius antarcticus*	LC	4
Unidentified seabirds			332
Total seabirds			8472

*The two species of albatrosses are listed as NT.

n = 1937, respectively) (Table 3). The observed fishing effort was distributed in two main clusters: one off Brazil, Uruguay and adjacent international waters between 19° and 48° S, and one around the South African Atlantic and Indian ocean coasts (Fig. 1). These main areas were connected by a relatively sparse band of scattered fishing effort across both ocean basins between 25° and 35° S and few isolated patches around West Africa off the Angola-Mozambique border (Fig. 1). The two general areas with high seabird bycatch were associated with the continental shelves and shelf edges and few isolated locations on the high seas, often denoted by seamounts and submarine ridges (Fig. 1). The BCPUE distribution varied between breeding and non-breeding seasons (see Fig. S1, Fig. S2 and Figs. S3 for all seabirds, by albatrosses and petrels, and by main species, respectively). The proportion of night setting and Tori line use increased from 49.5% and 52.0% to 79.8% and 85.1%, respectively, from the first to the third period (Table 4).

3.1. Seabird bycatch composition

The recursive partitioning procedure employed by the Multivariate Regression Trees produced a tree with seven 'groups' explaining 21.4% of the variance in the species bycatch composition (Fig. 2). Longitude was the most important variable and explained 13% of the variance, with the split occurring at 14°26 E (Fig. 2a). Within the eastern Atlantic/western Indian Ocean branch, the secondary split occurred in the year 2011. Prior to 2011 in the eastern Atlantic Ocean, bycatch composition was split at a longitude of 22°75 east, while moon illumination best explains composition after 2011. The western branch comprises mostly the south Atlantic region. Time of setting was the secondary split in the south Atlantic; sets deployed at night differed from day/ twilight sets, and the latter branch was further split at 44°82 east (Fig. 2a). The bycatch species composition, as a proportion, is depicted for each terminal group (Fig. 2b).

3.2. Variable importance

The Random Forest analyses revealed that the time varying explanatory variables (year, moon illumination and season) and spatial ones (depth change, bathymetry, longitude and latitude), explained the most variation in BCPUE (Fig. 3). Notably, the mitigation measures (i.e., Tori line and setting time) were relatively less important for describing changes in seabird bycatch rates in the dataset. Vessel flag was the least important variable. The relevance of spatial and temporal variables was an expected result, as observed bycatch data cover heterogeneous regions from two oceans with distinctive seabird species assemblages (see above section) and contrasting seabird densities (e.g. shelf areas of global seabird relevance vs oceanic regions). Within these relevant areas, specific habitats such as the shelf-break (denoted by change in bathymetry) have the largest seabird abundance. Furthermore, large oceanic areas during the breeding season, especially at lower latitudes, have low seabird densities in contrast to the austral winter when migrating non-breeding seabirds are extremely abundant. In order to assess the effect of mitigations on bycatch rates, the results of the Random Forest analyses indicated the need of considered all the above-mentioned covariates (see next section). Although the year explained most of the variation (Fig. 3) and indicated a reduction over time of the BCPUE (Fig. S4), the observer data were unbalanced by year and spatial distribution in particular years covers relatively restricted regions; Therefore, further analyses considered periods of years. The partial dependency plots of the Random Forest algorithm are shown in Fig. S4.

3.3. Predictive modelling

The GAMM analyses confirmed the significant influence of the bathymetry and change thereof, general area, as well as time of setting, fleet and Tori line use. Moon illumination increased bycatch rate significantly. There was a highly significant decrease (approximately 50%) in standardised bycatch rate from period 1 (2002–2008) to period 2 (2009–2011) and a further reduction in period 3 (2012–2016) (Fig. 4). Night-setting significantly reduced bycatch rate, with a larger difference for albatrosses (Fig. 4). Surprisingly, combined bycatch rate was higher when Tori lines were employed during the day; when albatrosses and petrels were modelled separately this effect remained significant for albatross (Fig. 4). During the night the pattern reversed, with significantly lower bycatch when Tori lines were used (Figs. 4 and 5). The effectiveness of night setting decreased with the moon illumination; the bycatch rate increases almost linearly with the fraction illuminated of the moon in all seabirds aggregated and in petrels (Fig. 5). Deep-set longlines mainly targeting tunas had a higher bycatch rate for petrels (Fig. 4). The predicted bycatch rate distribution during the breeding and non-breeding season for aggregated seabirds, albatrosses and petrels are shown in Fig. 6, respectively. Overall, those predictions show

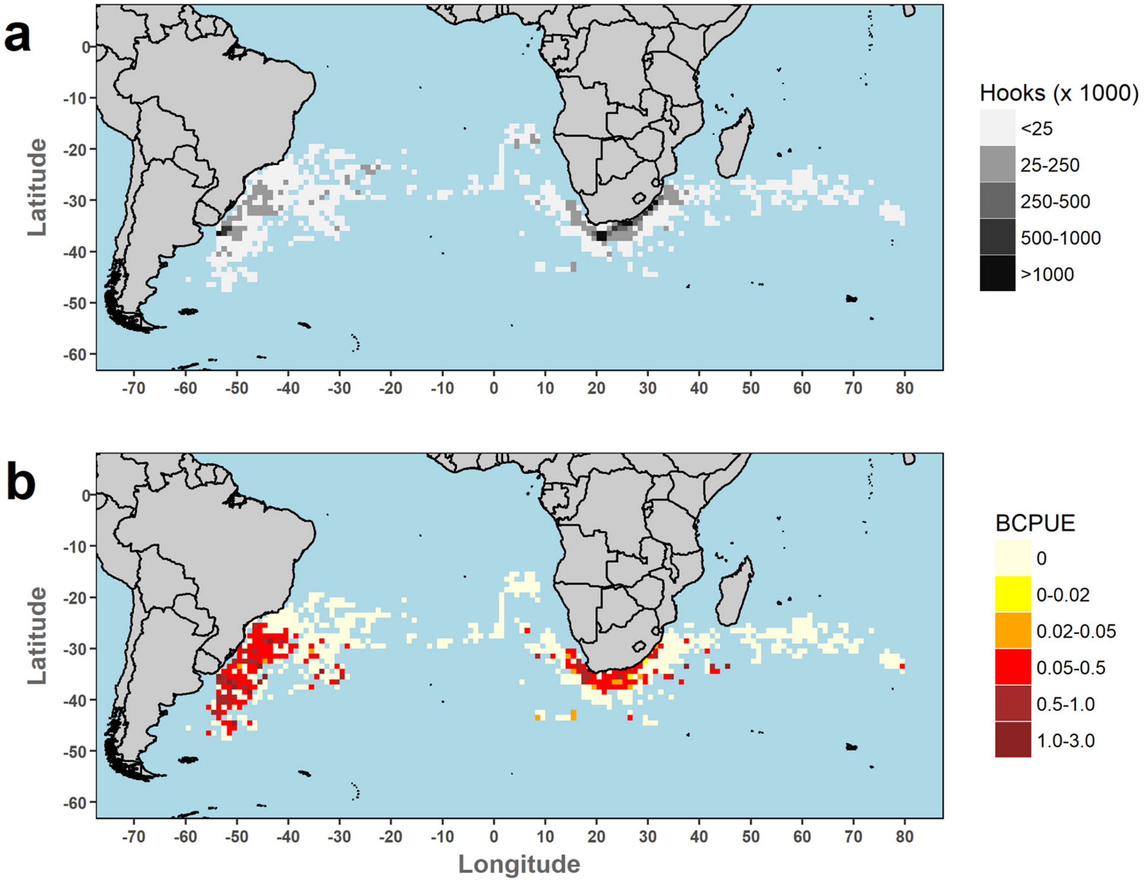

Fig. 1. Distribution (1 × 1° resolution) of a) nominal effort (number of hooks) and b) the nominal Bird Capture per Unit of Effort (BCPUE, birds/1000 hooks) observed for all seabirds aggregated in the southern Atlantic and south western Indian Oceans over a period of 15 years (2002–2016). Data were obtained onboard the pelagic longline fleets of Brazil, Portugal, South Africa and Uruguay and on Japanese longline vessels licensed to fish in the Economic Exclusive Zones (EEZ) of South Africa and Uruguay.

Table 4
Number and percentage of longline sets using specific mitigation measures (Night setting and Tori line) by period.

Period	N of sets	Mitigation measure						
		Setting time				Tori line use		
		Day	Twilight	Night	% Night	No	Yes	% Yes
Pre-mitigation 2002 - 2008	6323	1963	1231	3129	49.5	3035	3288	52.0
Phase-in of mitigation 2009 - 2011	5495	640	335	4520	82.3	486	5009	91.2
Mitigation 2012 - 2016	3961	630	171	3160	79.8	590	3371	85.1

similar results to the observed spatial and temporal bycatch patterns (Figs. S1 and S2), indicating also acceptable model fitting in all cases.

4. Discussion

The study is the first to examine the operational effectiveness and implementation over time of mitigation measures to reduce seabird bycatch in pelagic longline fisheries, over a wide spatial and temporal scale, and across multiple fleets. The dataset analysed here represents an extensive fine-scale observer dataset with individual species seabird bycatch information in pelagic longline fisheries. The data are derived from observer programmes with high standards of training with regard to collection of seabird bycatch information, enabling us to interrogate data on species or functional group level. We found a significant decrease in fleet-wide seabird bycatch rates, and also separately for albatrosses and petrels, from period 1 (2002–2008) to period 3 (2012–2016), coinciding with the progressive implementation of the mitigation measures in the two relevant tuna Regional Fishery Management Organisations, the International Commission for the Conservation of Atlantic Tunas (ICCAT) and the Indian Ocean Tuna Commission (IOTC) (see Table 2).

The effect of night setting had a consistent positive effect in aggregated and disaggregated species models, meaning that night setting effectively contributes to lower bycatch rates. The effectiveness of night setting is well documented in regional studies (Murray et al., 1993; Brothers et al., 1999; Jiménez et al., 2009, 2014; Petersen et al., 2009) and our results corroborate these findings on a large spatial and temporal scale. Night setting was more effective for albatross than for

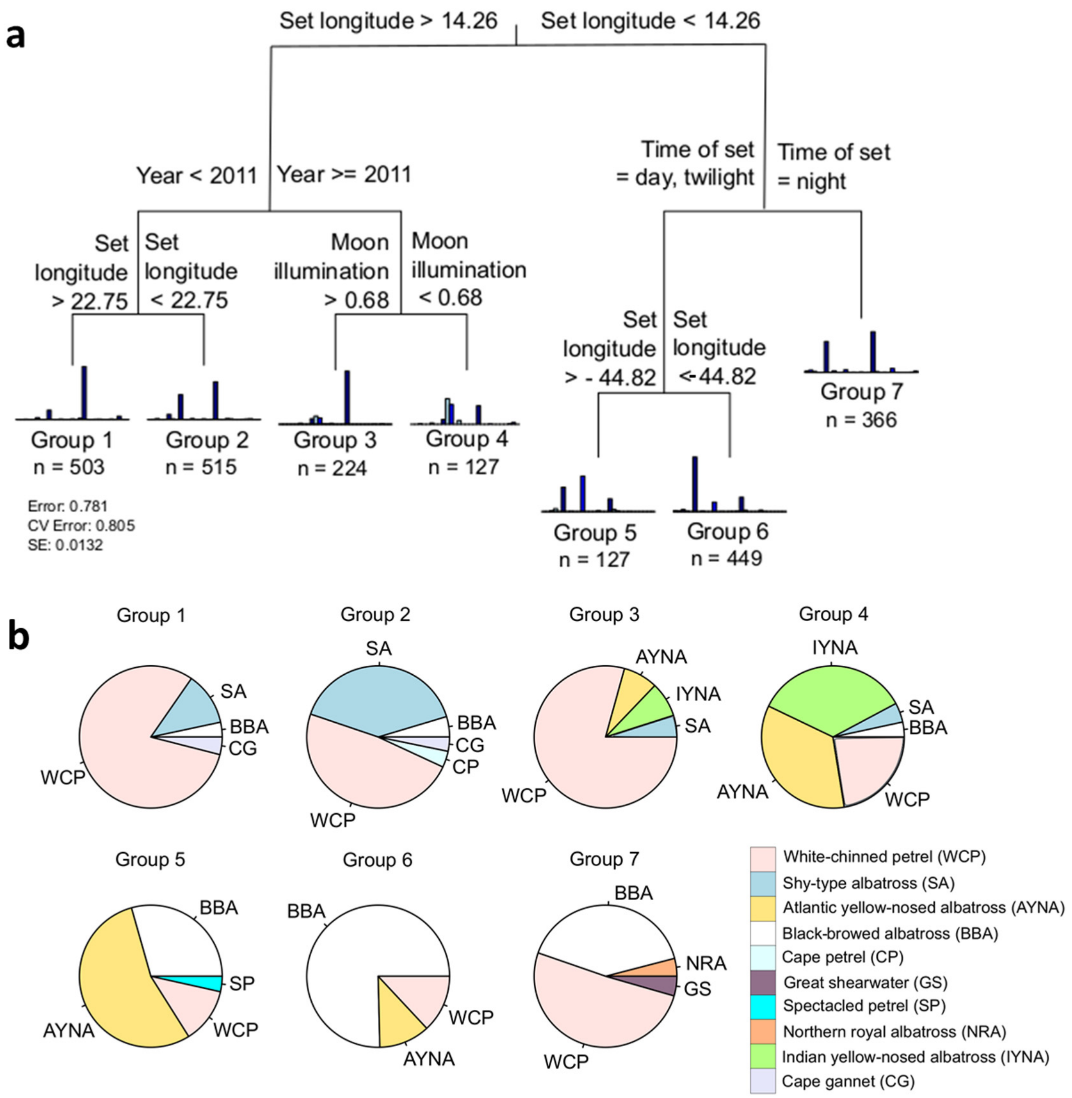

Fig. 2. (a) Analysis of the seabird bycatch distribution using Multivariate Regression Tree (MRT) to illustrate how the seven terminal groups differ by depicting observed binary splits in the explanatory parameter used, and (b) analysis of the seabird bycatch composition using observed species at each terminal group of the MRT and the relative species proportion (> 3%) within each group.

petrels because of the difference in foraging behaviour. Most of the medium-size petrels recorded as bycatch, and especially white-chinned petrels which represented the bulk of the bycaught petrels, are proficient divers that can access fishing baits to depth that albatrosses cannot reach (Rollinson et al., 2014). However, due to the larger body size, albatrosses easily and routinely displace petrels, which increases their access to baited hooks and therefore the likelihood of getting caught (Jiménez et al., 2012a). Albatrosses are less active at night, increasing their foraging activity only with a brighter moon (Phalan et al., 2007). White-chinned petrels are able to travel similar distances, and also forage, during the day and night without the influences of the moon phases (Weimerskirch et al., 1999; Mackley et al., 2011). Therefore, the decreased abundance of albatrosses at night may favour petrel foraging and in turn their susceptibility to bycatch. Moon illumination can facilitate the detection of sinking baits to albatrosses and petrels, which explains the observed reduction on the effectiveness of night setting in both groups. As expected, moon illumination has a greater (and linearly correlated) effect on the BCPUE of petrels. The nocturnal activity, independent of the moon phases, leads to a progressive increase of bait detection with moonlight. In contrast, with albatrosses the bait detection improves only when their nocturnal forage activity increases during the brightest period, explaining why bycatch rates in nocturnal sets only starts to increase after more than half of the moon is illuminated.

Contrary to night setting, the effects of using Tori lines were inconsistent and indicated a slightly higher BCPUE during diurnal sets. This result was contrary to what was found in several controlled trials where the efficacy of Tori lines was tested (Melvin et al., 2013; Domingo et al., 2017). The ambiguous Tori line effect reversed during the night when Tori lines resulted in consistently lower BCPUE estimates for all models, with the combined species model showing the strongest effect. There are several possible explanations for this observed pattern. First, Tori line records could only be used as a binary variable (used or not), due to the inconsistency of available information on the specifications, number and if correctly deployed. In experimental studies, Tori lines were found to be effective to deter seabird attacks on baited hooks to a distance behind the vessel similar to its aerial coverage (~ 70–100 m) (Melvin et al., 2014; Domingo et al., 2017). This mitigation measure alone might be insufficient when it is not combined with correct branch-line weighting, as seabirds are still able to access baited hooks beyond the Tori line coverage (Melvin et al., 2014; Sato et al., 2016). Moreover, entanglements of Tori lines with the fishing gear are common and occurred in almost half (47%) and a third (31%) of all observed deployments on medium and large size vessels,

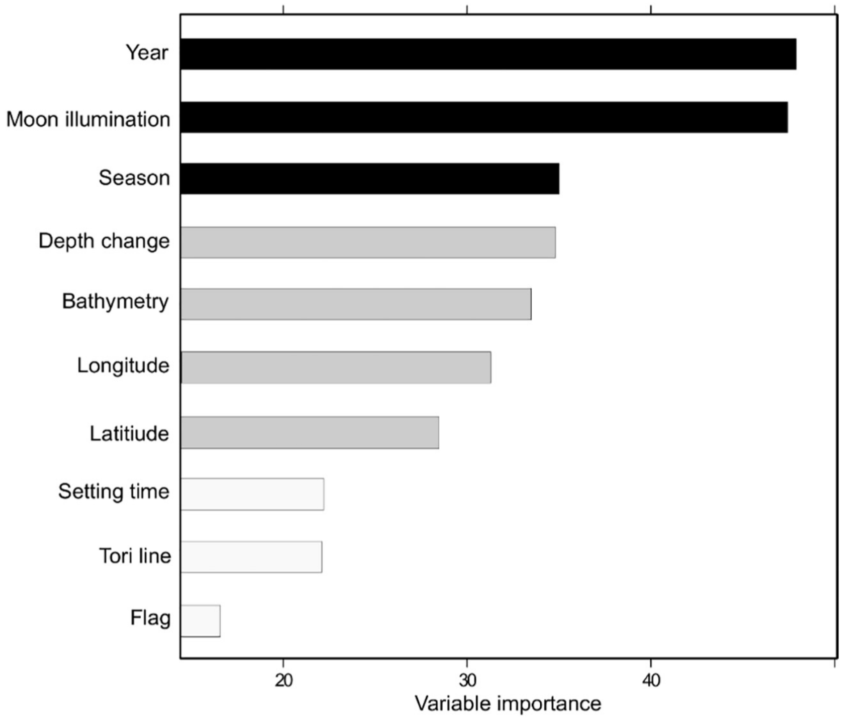

Fig. 3. Random Forest: Variable importance. The figure shows the estimate of the relative importance of predictor variables on Bird Capture per Unit of Effort (BCPUE, birds/1000 hooks). The black depicts temporal variables, the dark grey spatial or environmental variables and the light grey represents management variables.

respectively, under experimental conditions (Melvin et al., 2013; Domingo et al., 2017). Tori lines were still shown to be effective when deployed during night sets. This is consistent with the observation that visibility at night is reduced and Tori lines, even when damaged or not fully deployed, may still cover the critical area near the vessel where the bait remains easily accessible to seabirds. A second explanation could be that Tori lines are less likely to be deployed when there are few seabirds around vessels, resulting in low bycatch rates. An example of this, could be a reduced use of Tori line during the breeding season, when seabird abundance is low in most fishing areas. Tori line could be perceived as unnecessary when there are no birds around vessels and not be used to avoid complications caused by entanglements of Tori lines with the fishing gear (loss of time, materials, and sometimes the complete Tori Line). In addition, during October–April the days are longer, and the proportion of longline sets starting before twilight is likely to increase. In fact, shallow-set longlines mainly targeting swordfish had a higher proportion of set conducted during daylight and twilight during the breeding season in all the three analysed periods (see Fig. S5). Unlike deep-set longline vessels targeting tuna that were all large (~ 50 m length), the vessels classified under the category shallow-set longline mainly included a range of lengths from small (< 25 m) to medium-size vessels (~ 25–40 m length). Indeed, the small and medium-size vessels are those with greatest operational challenges of deploying Tori lines due to entanglements with the fishing line (including branch lines and buoy lines) (Domingo et al., 2017).

Data limitations curtailed our ability to accurately quantify the change in efficacy of implementing Tori lines use as mitigation measure. An unbalanced sampling design confounded analyses regarding Tori line use. Period 1 (2002–2008) had an acceptable distribution of sets with and without Tori lines deployed, however the mandatory adoption of using a Tori line as a mitigation measure resulted in a lack of contrast due to few observations without Tori lines in the latter periods (2009–2011 and 2012–2016) to allow for comparison. Furthermore, there was a general lack of standard Tori line specifications and guidelines for their correct implementation, particularly for the first period (2002–2008). The deployment of Tori lines without meeting the minimum standard specifications may have low effectiveness in reducing bycatch.

Overall, our results indicate a large reduction of seabird bycatch consistent with the implementation of seabird mitigation measures at the relevant Regional Fishery Management Organisations. Conservation Management Measures from these organisations now require mandatory use of two out of three mitigation measures. Individual mitigation measure effects were inconclusive for Tori line use but night setting significantly reduced seabird bycatch. Yet, night setting alone cannot explain the magnitude of the observed reduction. The dataset analysed here did not include any information on branch-line weighting, but the results suggest, in the absence of a clear population trajectory of the main seabird populations affected here (BirdLife International, 2019a) that in combination with night setting, branch-line weighting might be effective in reducing seabird bycatch in general and for both functional groups. According to our results, night setting is the most effective mitigation strategy when applied alone. However, moon illumination significantly increased seabird bycatch during the night, necessitating a combination of night setting with other mitigation measures during these sets. This is confirmed in our study based on an extensive dataset; the simultaneous use of night setting and Tori lines produced the most effective practice to reduce seabird bycatch.

Our large-scale analysis confirms areas of high seabird bycatch rates in the south Atlantic and southwestern Indian oceans, previously reported from regional studies (Petersen et al., 2009; Jiménez et al., 2010). Yet, some caution should be exercised with this generalization due to the lack of observed fishing effort from major distant-water longline fleets (Yeh et al., 2013), especially in international waters from the central Atlantic below 25° S and southern areas from both Atlantic and western Indian oceans. Bycatch species composition varied among ocean basins, with black-browed albatross, Atlantic yellow-nosed albatross (*Thalassarche chlrorhynchos*) and white-chinned petrel representing the largest proportion in the southwest Atlantic, and white-chinned petrel, shy-type albatross (*Thalassarche cauta/steadi*) and both Atlantic and Indian (*Thalassarche carteri*) yellow-nosed albatrosses being the main captured species in the southern Africa Atlantic coast and western Indian Ocean. Despite these differences, the functional groups were relatively similar, and in waters off south-eastern South America and southern Africa the bycatch composition dominated by albatrosses changed to medium-sized petrels with night setting and

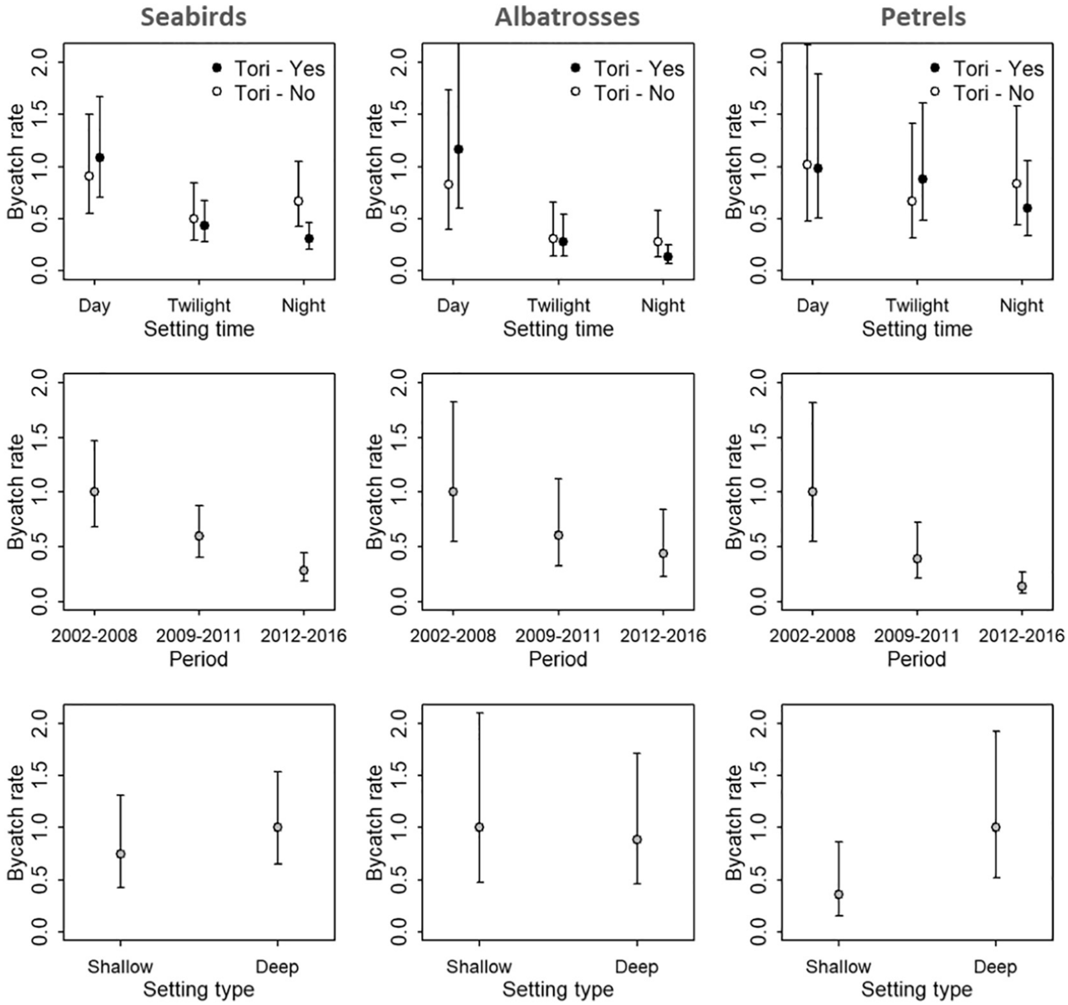

Fig. 4. Results of GAMMs (quasi-Poisson) showing the main effects (categorical variables) on the bycatch rate (number of birds caught as response variable and natural logarithm of the number of hooks as offset) of seabirds, albatross and petrels. To illustrate the relative effect size bycatch rates were normalized, such that the category with largest expected value was scaled to one. Error bars represent the 95% confidence intervals.

high moon illumination, again supporting that bycatch composition relates to differences in foraging strategies between functional groups. Interestingly, bycatch of petrels was higher in chartered vessels targeting tuna species; this is likely due to them using small tuna hooks compared to larger hooks used for swordfish and sharks, which increases catchability (i.e., probability of getting hooked) of petrels (Jiménez et al., 2012b).

Despite the observed reduction in bycatch rates based on a progressive and large-scale implementation of mitigation measures, a low proportion of the global pelagic longline fishing effort is sampled by onboard observers, suggesting a low compliance with Conservation Management Measures (see below). A large number of seabirds is presumed to be incidentally caught in pelagic longline fisheries around the world, with recent annual bycatch estimates in the order of several tens of thousands of albatrosses and petrels in the southern hemisphere (BirdLife International, 2019b). Our results imply that a major reduction in global bycatch of threatened seabirds could be achieved, if the mitigation measures analysed in this work are correctly applied and extensively implemented by fleets operating south of 25° S. A further bycatch reduction could be achieved by also adopting appropriate branch-line weighting regimes; the simultaneous use of these three mitigation methods is considered to be the best-practice (ACAP, 2019).

5. Conclusions

The results presented here indicated that if correctly applied, current mitigation practices are effective in reducing seabird bycatch under various conditions for a variety of fishing operations. Night setting proved to be effective under all conditions examined, and the combination of this measure with the employment of Tori lines produced the best mitigation scenario. The strengths of our conclusions are the result of a large percentage of observer coverage (up to 100% for some of the fleets analysed here), representative of most of the fishing areas, by scientific observers trained and experienced in seabird identification. This analysis was only possible due to the sharing fine scale of set-level information among several countries. We found convincing evidence that the large-scale implementation of mitigation measures under real commercial fishing operations can produce over time significant seabird bycatch reductions. It should be noted that our bycatch data are from vessels with observers, and that mitigation use is presumed to be much lower, and seabird bycatch rates much higher, on unobserved fishing trips in some of the fleets analysed here. In addition, we also note that observer coverage for most longline fleets in the ICCAT and IOTC areas constitute < 5% of the fishing effort, and is not stratified by area, vessel or season. Moreover, compliance with Conservation Management Measures related to bycatch mitigation is thought to be low in the absence of observers (Gilman, 2011). Therefore, the observed bycatch reduction is impossible to generalise to the

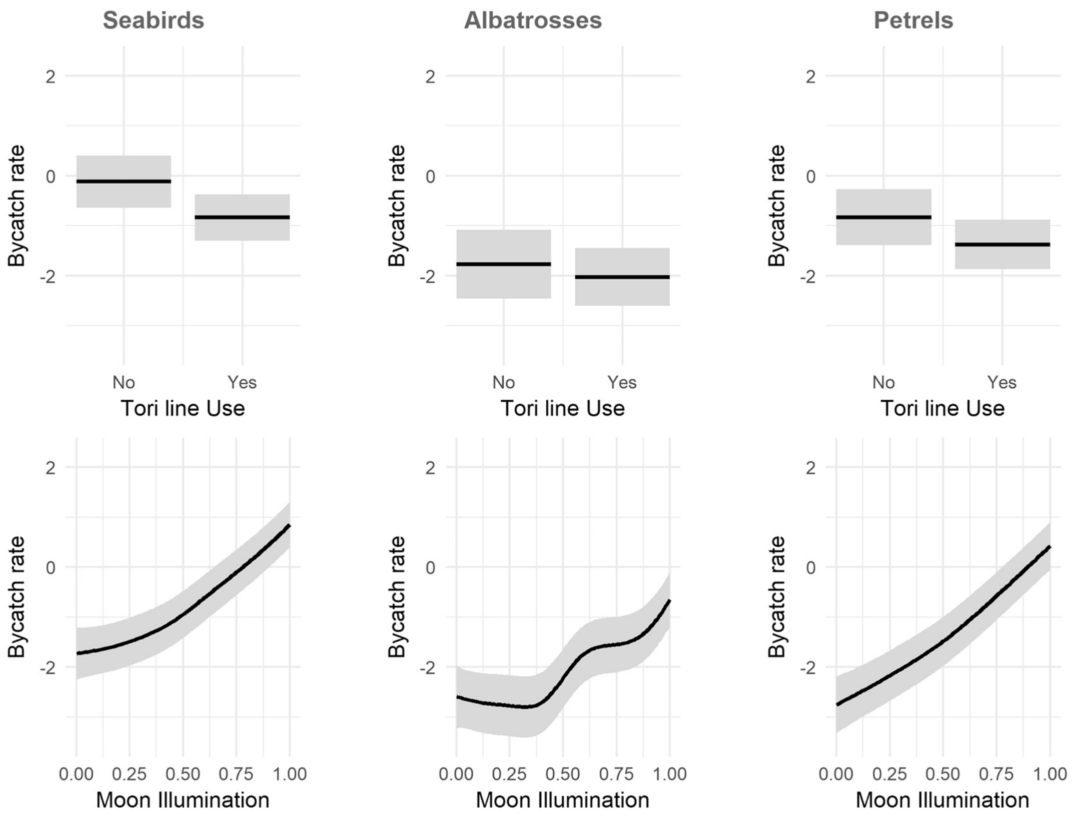

Fig. 5. Results of GAMMs (quasi-Poisson) on the effect of Tori line use and moon illumination on the bycatch rate (number of birds caught as response variable and natural logarithm of the number of hooks as offset) of seabirds, albatross and petrels during nocturnal longline sets, taking into account ancillary variables. Plots illustrate the relationship between the catch rate and the mentioned variables, fixing the remaining categorical covariates to a given stratum and the continuous ones to the median value (i.e. conditional plots). All plots are on the scale of the linear predictor (logarithm) of the models. Bands represent the 95% confidence intervals.

overall ICCAT and IOTC fishing effort. Our results further suggest that mitigation measures are only effective when applied correctly. An increase in observer coverage, appropriate spatial and temporal stratification and mandatory training and implementation of best practice for branch-line weighting and Tori line employment is imperative not only for the improvement of current Conservation Management Measures but also to further interrogate and refine the effectiveness of current measures globally.

Authorship statement

Sebastián Jiménez: Conceptualization; Data curation; Formal analysis; Methodology; Visualization; Writing - original draft; Writing - review & editing. **Andrés Domingo**: Conceptualization; Supervision; Project administration; Funding acquisition; Resources; Writing - review & editing**. Henning Winker**: Conceptualization; Data curation; Formal analysis; Methodology; Visualization; Writing - review & editing**. Denham Parker**: Conceptualization; Data curation; Formal analysis; Methodology; Visualization; Writing - review & editing. **Dimas Gianuca**: Conceptualization; Data curation; Writing - review & editing. **Tatiana Neves**: Conceptualization; Project administration; Resources. **Rui Coelho**: Project administration; Resources; Writing - review & editing. **Sven Kerwath**: Conceptualization; Project administration; Resources; Methodology; Writing- Original draft preparation; Writing - review & editing.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocon.2020.108642.

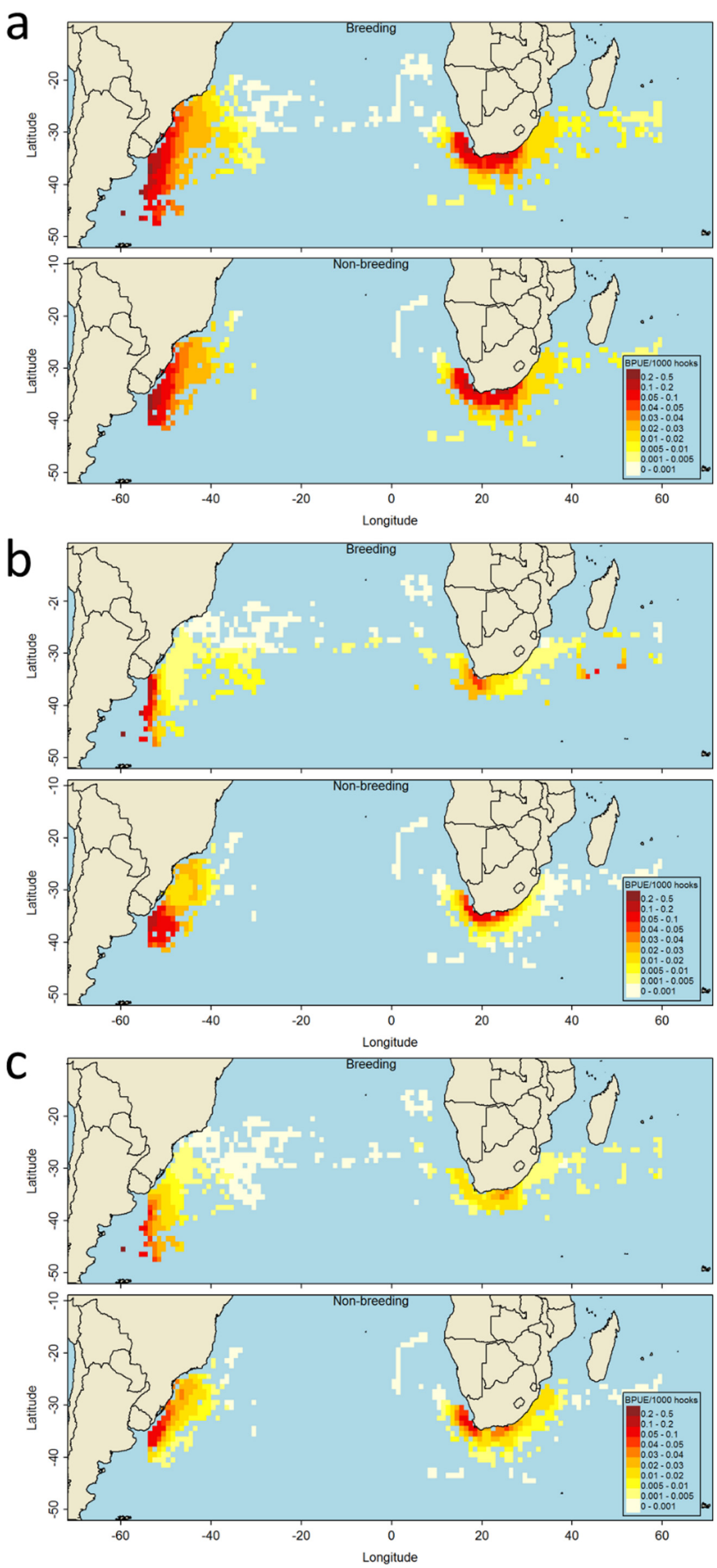

Fig. 6. Distribution of the bycatch rates (Bird Capture per Unit of Effort, BPUE = birds/1000 hooks) for (a) seabird (all species aggregated), (b) albatrosses (Diomedeidae) and (c) petrels (Procellariidae) predicted by GAMM for data observed during the breeding and non-breeding seasons in the southern Atlantic and south western Indian Oceans over a period of 15 years (2002–2016). Data were obtained onboard the pelagic longline fleets of Brazil, Portugal, South Africa and Uruguay and on Japanese longline vessels licensed to fish in the Economic Exclusive Zones (EEZ) of South Africa and Uruguay. Map units are degrees of latitude and longitude and cell size is 1 × 1°.

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