Biological Conservation 253 (2021) 108915

Contents lists available at ScienceDirect

Biological Conservation

journal homepage: www.elsevier.com/locate/biocon

Reduction in seabird mortality in Namibian fisheries following the introduction of bycatch regulation

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ARTICLE INFO

Keywords:
Albatross
Bycatch
Mitigation
Seabirds
Trawl
Longline

ABSTRACT

Many industrial activities impose a threat on biodiversity, and it is unclear to what extent environmental regulations can reduce the threat of such activities. Bycatch in industrial fisheries is one of the greatest sources of mortality for seabirds, but a threat for which effective mitigation exists. Here we quantify whether the introduction of a new regulation that required the use of bird-scaring lines reduced seabird mortality in two of the most hazardous fisheries in the South Atlantic. The Namibian hake demersal trawl and longline fisheries, estimated to be killing 20,000–30,000 birds/year, have been required to use bird-scaring lines since 2015. We used data from BirdLife International's Albatross Task Force and the Namibian Fisheries Observer Agency to quantify changes in seabird mortality in these fisheries before and after the introduction of these regulations. Our estimated bycatch rates in the longline fleet were 0.468 birds/1000 hooks (95% confidence interval 0.067–1.450) before regulations and 0.004 birds/1000 hooks (0.001–0.013) following their introduction, a 98.4% reduction. Our estimate suggests that 215 (1–751) seabirds were killed across this fleet in 2018 compared to 22,222 (3187–68,786) in 2009. In the trawl fleet, observers recorded seabird mortality resulting from interactions with trawl cables. The average rate of heavy interactions was 1.09 interactions/h (0.81–1.39) before the regulation came into effect, and 0.49 interactions/h (0.23–0.84) since then. Extrapolations based on the number of observed fatal interactions suggest 1452 (0–3865) birds were killed by this fleet in 2017 compared to 7030 (0–16,374) in 2009. The lower mortality reduction in the trawl fleet is likely due to incomplete implementation of regulations and highlights the importance of adequate enforcement for effective bycatch mitigation. Overall, we demonstrate that regulations that mandate that well-tested safeguards are used during industrial operations can have enormous benefits for the conservation of threatened species.

1. Introduction

Seabirds are one of the most threatened groups of birds in the world, with 52% of pelagic species declining and 28% globally threatened (Dias et al., 2019; Croxall et al., 2012). Of these, albatrosses are in the most perilous state, with 15 of 22 species currently threatened with extinction (IUCN, 2019). Seabirds, and particularly albatrosses, are long-lived birds, with delayed sexual maturity, high adult survival and low fecundity (Warham, 1990). These traits contribute to adult mortality having a disproportionally large effect on population growth rates (Robertson and Gales, 1998; Saether and Bakke, 2000; Furness, 2003).

Incidental mortality in fisheries threatens 41% of seabird species and is considered one of the main drivers for albatross declines (Croxall et al., 2012; Dias et al., 2019). Seabird bycatch in longline fisheries was

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https://doi.org/10.1016/j.biocon.2020.108915
Received 22 January 2020; Received in revised form 22 November 2020; Accepted 1 December 2020
Available online 19 December 2020

first identified as a conservation issue in the early 1980s (Croxall et al., 1984), and subsequent global bycatch estimates suggested that longlines kill 160,000–320,000 seabirds each year (Anderson et al., 2011). Birds are primarily captured and drowned when they attempt to remove baits from longline hooks when these are being deployed behind a fishing vessel (Brothers, 1991; Ashford et al., 1995). Trawl fisheries were not recognised as a major source of seabird mortality until the 1990s, due to the cryptic nature of seabird interactions associated with trawling. Seabird mortalities around trawlers occur primarily through collisions with the trawl cables or net monitoring cables at the stern of the vessel (Bartle, 1991; Sullivan et al., 2003) but also through net entanglement (Watkins et al., 2008). Since most birds killed are not recovered or hauled aboard, quantifying mortality rates is difficult (Weimerskirch et al., 2000). The discarding of offal, which attracts seabirds to the stern of the vessel to forage, increases the risk of interactions with fishing gear (Sullivan et al., 2006; Watkins et al., 2008; Abraham et al., 2009).

Mitigation measures which dramatically reduce seabird bycatch have been developed for both trawl and longline vessels. Bird-scaring lines (BSLs; also known as tori lines) consist of colourful streamers which act as visual deterrents through erratic motion to keep birds away from the stern of the vessel, where birds are at highest risk of fatal interaction with fishing gear (Bull, 2009; Løkkeborg, 2011; Tamini et al., 2015). BSLs are among the most effective mitigation measures and have been shown to reduce seabird bycatch by more than 90% in demersal longline and trawl fisheries when correctly implemented (Maree et al., 2014; Melvin et al., 2019).

For demersal longline fisheries, best practice advice from the Agreement on the Conservation of Albatrosses and Petrels recommends the deployment of BSLs in combination with night setting (when fewer birds are actively foraging) and appropriate line weighting (to quickly sink hooks beyond seabird foraging depths) to minimise seabird bycatch (ACAP, 2017a). To reduce the risk of collisions with cables in trawl fisheries, this agreement also recommends ending the use of net monitoring cables, managing of offal and discards and deploying BSLs during fishing operations (ACAP, 2017b). Successful implementation of these measures has led to significant reductions in seabird bycatch in several fisheries (Croxall and Nicol, 2004).

Although technical solutions exist to reduce incidental seabird mortality in fisheries, the uptake of mitigation measures is unlikely to be high in the absence of effective enforcement mechanisms and solutions that address the practical implementation and economic concerns of fishers. Evidence from Regional Fisheries Management Organisations suggests that the existence of regulations requiring the use of best-practice mitigation measures are not sufficient to ensure implementation and consequent bycatch reductions in target fleets (Gillman et al., 2013; CCSBT, 2019). Instead, effective seabird bycatch reductions have been shown to require additional favourable conditions beyond the existence of regulations alone, such as training and awareness campaigns, including on-board demonstrations of seabird bycatch mitigation measures (Maree et al., 2014; Melvin et al., 2019). Here we examine whether regulations requiring the use of BSLs have reduced seabird mortality in both longline and trawl fleets in a large jurisdiction in the South Atlantic Ocean, where legal mitigation requirements coincided with practical bycatch mitigation training and the establishment of a BSL supply-chain to ensure that fishers were well equipped to adhere to the new regulations.

Namibia is situated in south-west Africa between 17^0S and 30^0S and has a coastline of 1572 km. The Benguela Current transports nutrient-rich water from the southern coast of South Africa, past Namibia and north to Angola. Within 30 nautical miles of the Namibian coast the continental shelf drops to a depth of >1000 m. Prevailing winds drive the upwelling of cold nutrient rich waters, supporting abundant marine resources. The fishery sector plays a vital role in the Namibian economy and contributed 3.9% to the country's GDP in 2012 (MFMR, 2013); shallow-water Cape hake (*Merluccius capensis*) and deep-water Cape hake (*M. paradoxus*) are the most valuable species commercially fished in Namibian waters, though horse mackerel (*Trachurus capensis*) is fished in greater volume (MFMR, 2013). The abundant marine resources also attract high densities of seabirds, including several globally threatened species, which forage in the highly productive waters off the Namibian coast (Ludynia et al., 2012; Dias et al., 2017).

BirdLife International's Albatross Task Force - an international team of seabird bycatch mitigation experts – estimated that ~20,000 seabirds were being killed annually in Namibian demersal longline operations (Paterson et al., 2017) and approximately 8000 birds in the hake demersal trawl fishery (BirdLife International, 2013). The Albatross Task Force has worked with Namibian fishers and relevant government agencies since 2008 to increase awareness of seabird mortality and provide practical advice on how to implement effective mitigation measures that are both operationally and economically feasible. In addition to establishing a domestic supply of bird-scaring lines, the Albatross Task Force has further supported industry in bycatch mitigation measure adoption, through provision of standardised 5 kg steel weights to replace the slower-sinking concrete weights that are commonly used by this fleet (Paterson et al., 2017). In November 2015, the Ministry of Fisheries and Marine Resources in Namibia passed regulations requiring the deployment of at least one BSL during demersal longline fishing (MFMR, 2015a) and two BSLs during demersal trawling (MFMR, 2015b) to reduce seabird mortality in these fisheries. In this study we use data from on-board observers to compare seabird bycatch rates in the Namibian hake demersal longline and trawl fisheries before and after the introduction of regulations requiring the use of BSLs. We estimate seabird mortality rates for both fisheries and demonstrate how the introduction of legal requirements to adopt bycatch mitigation measures, supported by high levels of observer coverage and outreach activities to raise awareness among key stakeholders, can dramatically reduce the mortality of globally threatened seabirds in an important foraging hotspot in the South Atlantic.

2. Methods

In 2018, the Namibian hake demersal longline fleet consisted of 13 vessels with an average length of 29.4 m, which primarily fished between 21°S and 25°S, with low, patchy effort further south (Fig. 1, MFMR, unpublished data). The fleet preferentially started setting operations before nautical dawn and used a double line Spanish system with alternate dropper lines and weights placed at intersections (as described in Paterson et al., 2017). Since 2015, the Albatross Task Force gradually distributed steel weights to all fishermen, which sank faster and presented a lower bycatch risk to seabirds compared to the traditionally used concrete weights (Paterson et al., 2017). However, steel weights lost during fishing operations were gradually replaced with cheaper and more readily-available concrete weights, which was not in line with best practice (ACAP, 2017a).

In 2018, the hake demersal trawl fleet was made up of approximately 40 wet-fish (mean length 36.8 m) and 25 freezer vessels (mean length 68.9 m), which fished along the whole Namibian coastline at depths greater than 200 m (Fig. 1, MFMR, unpublished data). The wet-fish portion of the fleet made up approximately 65% of the annual fleet effort and used trawl nets with a minimum of 110 mm stretched mesh at the cod end and a vertical aperture of 3.5 to 5 m. Net monitoring cables were not used by vessels in this fleet.

2.1. Fishing operations

On longline vessels, fishing trips typically lasted 5–10 days with lines set in a latitudinal direction. Longlines on sets observed by dedicated Albatross Task Force seabird bycatch observers on average consisted of 16,572 baited hooks on a single line approximately 30 km in length, with the setting operation lasting 2–3 h in total. Setting was on average completed within 22 min after nautical dawn across the study period, with hauling beginning between 10 AM and 12 PM and lasting for

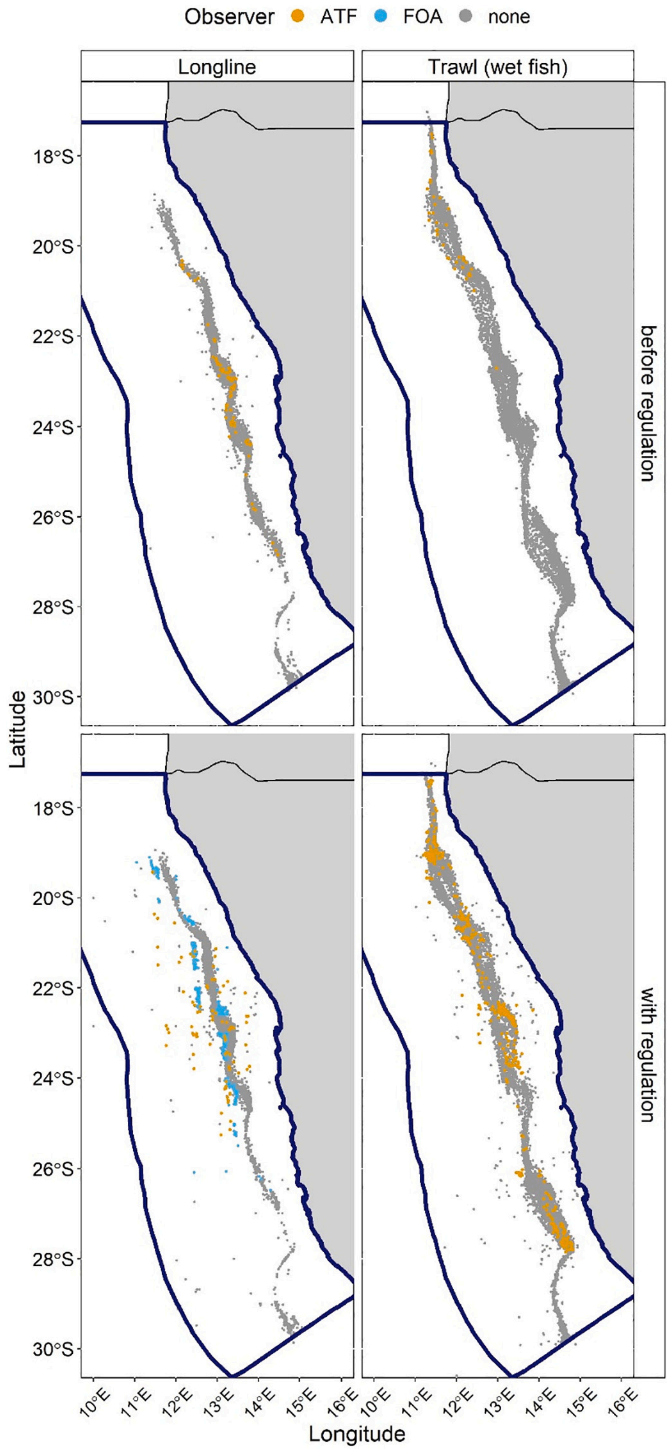

Fig. 1. Spatial distribution of fishing positions for demersal hake longline vessels and trawl vessels in the pre and post-regulation period (provided by the Namibian Ministry of Fisheries and Marine Resources, 2019), as well as the location of sets monitored for seabird bycatch by Albatross Task Force (ATF) and Fisheries Observer Agency (FOA) observers.

11–13 h. Discarding did not coincide with setting operations but lasted throughout the duration of the haul in most cases.

On wet-fish trawl vessels, fishing trips lasted on average 6 days. During observations, trawls were set at an average speed of 5 knots, with the first trawl beginning around 7:00 AM and lasting for approximately 2 h. Once the net is at fishing depth, vessel speed slows to 1–2 knots. Two to four trawls were typically deployed during the day, and two at night, and time between daytime trawls was typically 45–60 min as nets were emptied, cleaned and deployed again. Setting was ~15 min and offal discarding commenced immediately after the first net of the day had been hauled and continued throughout the setting operations of the subsequent trawl. Vessels from the freezer-portion of the demersal trawl fleet perform fishing trips that typically last 30–60 days, because the caught fish can be frozen on board.

2.2. Data collection

2.2.1. Demersal longline

Seabird bycatch was recorded during hauling operations on demersal longline vessels, in two distinct sampling periods: 2009–2012 (pre-regulation) and 2016–2018 (post-regulation). Seabird bycatch data were combined from three sources. The data used by Paterson et al. (2017) collected by the Albatross Task Force in 2009–2012 (pre-regulation), data collected by observers from the Namibian Fisheries Observer Agency (hereafter, FOA) 2017–2018, and data collected by Albatross Task Force (hereafter, ATF) instructors 2016–2018 (post-regulation). For the pre-regulation period, seabird bycatch rates were observed on 72 sets deployed without BSLs during 14 trips on five vessels between July 2009 and July 2012, and the number of hooks deployed on these trips represented 1.5% of the total fishing effort in Namibia during that time (Table 1). For the post-regulation period, a total of 465 longline sets were observed during 78 trips on 8 vessels between November 2016 and October 2018 by either ATF ($n = 92$ sets) or FOA ($n = 373$ sets) observers, representing 8.2% of the number of hooks deployed in Namibian fisheries during that time. The presence/absence of BSLs was also recorded for each set during this sampling period. Recorded seabird mortalities were identified to species level by ATF observers, but not by FOA observers.

ATF observers were fully dedicated to seabird bycatch monitoring and estimated fishing effort observed by counting the number of line weights observed during hauling, thus providing information on the total number of hauled hooks that were observed for bycatch (mean = 56%, range 14–97% of hauled hooks were observed). FOA observers recorded the number of hooks that were retrieved by the fishing vessel and the number of seabirds caught, but did not identify the species of bycaught birds nor record the number of hooks monitored for seabird bycatch as they were also engaged in other data collection tasks during the haul. The uncertainty relating to the fishing effort monitored for seabird bycatch by FOA observers was accounted for during data analysis, under the assumption that the proportion of retrieved hooks that were inspected for seabird bycatch did not differ between ATF and FOA observers. This assumption is realistic because both observers were dedicated to the task of recording seabird bycatch and were provided with the same training and data collection protocols. However, due to the uncertainty over FOA observation effort we also conducted an analysis without any FOA data, which yielded almost identical results (Table S1) and confirmed that uncertainty in FOA observation effort did not affect our conclusions.

Table 1
Annual seabird mortality estimates for the Namibian demersal longline fleet for the pre-regulation (2009–2012) and post-regulation (2016–2018) period. Bycatch estimates calculated based on average seabird bycatch rates for each sampling period and annual fleet effort.

Year	Regulation	Annual fleet-wide fishing effort (total number of hooks set)	Bycatch estimate (seabirds killed per year)
2009	No	47,481,331	22,222 (3187–68,786)
2010	No	33,071,604	15,478 (2220–47,911)
2011	No	26,131,173	12,230 (1754–37,856)
2012	No	31,225,687	14,614 (2096–45,237)
2016	Yes	31,057,371	119 (1–417)
2017	Yes	42,381,792	163 (1–568)
2018	Yes	56,067,456	215 (1–751)

2.2.2. Demersal trawl

Seabird interactions with trawl cables were recorded by six Albatross Task Force observers on board industrial wet-fish demersal trawl vessels in two discrete sampling periods: 2009–2010 (pre-regulation) and 2016–2019 (post-regulation). Observations were conducted from the stern deck of the vessel, above the warp cable, to maximize the view of the danger zone. Observation periods only occurred during daylight hours, starting ~45 min before sunrise at the earliest and ending ~45 min after sunset at the latest. These observations included the monitoring of seabird interactions with both trawl cables. No observations were conducted on vessels from the freezer portion of the demersal trawl fleet, due to their comparatively long trips.

Individual seabird interactions with the trawl cables were recorded by species and interaction intensity along with the outcome. As in Maree et al. (2014), seabird-cable interactions were classified as either light (when no apparent impact on the bird was observed) or heavy (when the bird was dragged under water or a marked change in the direction and/or behaviour was observed). The outcome of each heavy interaction was classified as either 'uninjured' when the bird did not sustain any visible injuries, 'fatal', when the bird had broken its wings, was observed dead or did not resurface after being dragged under water (and therefore presumed dead), or "unknown", similar to other studies of seabird–trawl interaction (Sullivan et al., 2006; Watkins et al., 2008). Fishing operations were recorded as setting, trawling and hauling for all observed trawls. For the post-regulation period, data were also collected on the deployment of paired BSLs during fishing operations.

Between July 2009 and August 2010 (pre-regulation), 126 trawls were monitored on 10 vessels, with a total of 139 h and 45 min of seabird-trawl cable interactions observed on 13 trips, which represented 0.4% of the trips in Namibia during that period. Between July 2016 and August 2019 (post-regulation), 260 trawls were monitored on 15 vessels, equating to 120 h and 24 min of observation across 24 trips, representing 0.5% of the number of trips in the trawl fleet for this period. One trip was removed from the dataset due to inconsistencies in the data collection procedures used by a single observer, who was not deployed on any other trips.

2.3. Data analysis

2.3.1. Demersal longline

Since observation effort was quantified differently among the different data sources used for the demersal longline fleet, a simple quantification of bycatch rate was not possible. We therefore used a hierarchical Bayesian model which first estimated the observation effort for Fisheries Observer Agency observers, and then seabird bycatch rates based on the estimated observation effort. This model was based on a model to estimate bycatch of sea-turtles with similar data properties (Gardner et al., 2008). To examine the effect of the regulation, all data for the post-regulation period were included in the model irrespective of whether mitigation measures were used or not. We also grouped data across years, under the assumption that there were no systematic changes in fishing gear, operation, distribution or seabird assemblage between years within the two sampling periods (Paterson et al., 2017; Reid et al., 2013; Carneiro et al., 2020).

Data collected by Albatross Task Force (ATF) observers included the number of hooks retrieved and the number of hooks inspected for bycatch (observer effort), whereas Fisheries Observer Agency (FOA) data included the number of hooks set and retrieved, but not the number of hooks inspected for bycatch, which is critical for the estimation of bycatch rates. Thus, we estimated FOA observation effort based on the proportion of retrieved hooks that were observed by ATF observers (i.e. in ATF data the observation effort was calculated as n hooks observed/n hooks retrieved). We incorporated this estimation as a logistic regression into our model and included 'trip' as a random effect to account for random variation among observation rates on each trip. This approach ensures correct error propagation of the uncertainty in observation effort to the estimated bycatch rates.

Seabird mortality on longlines is observed as the number of dead birds per set (integer counts) with a large number of sets killing no birds. Because of the zero-inflated negative-binomial distribution of mortalities, we estimated bycatch rates before and after the regulation using a zero-inflated negative binomial model with a complimentary log-log link (Gardner et al., 2008). Briefly, this model first calculates the probability that any seabirds were caught during a given longline set, accounting for the observation effort, and random variation associated with the vessel and the trip. For trips in which bycatch is estimated to occur, the number of birds killed is then estimated in a second equation that also accounts for the observation effort, and random variation associated with the vessel and the trip. We included the seabird bycatch mitigation regulation as an independent fixed effect in both the occurrence and abundance parts of the model, and used diffuse normal priors centred on 0 for these effects. We fitted the seabird bycatch model in JAGS (Plummer, 2013) called from R 3.5.1 (R Core Team, 2013) via the package 'jagsUI' (Kellner, 2016). We ran four Markov chains each with 100,000 iterations and discarded the first 50,000 iterations. We tested for convergence using the Gelman-Rubin diagnostic (Brooks and Gelman, 1998) and confirmed that R-hat was <1.01 for all parameters.

Because the effects of the regulation in this model were on the log-scale (for abundance) and on the complimentary log-log scale (for occurrence), we estimated overall seabird bycatch rate per 1000 hooks before and after the regulation on the actual scale, accounting for uncertainty in observation effort and all model parameters. We present these estimates as means with 95% credible intervals and quantified the change as the difference between pre- and post-regulation bycatch rates divided by the pre-regulation rates.

To estimate the total seabird mortality for the Namibian demersal longline fleet, effort data for the years 2009–2012 and 2016–2018 were provided by the Ministry of Fisheries and Marine Resources. The estimated bycatch per unit effort obtained from the model was then multiplied with the relevant effort data before and after regulation to extrapolate a fleet-wide annual bycatch estimate.

2.3.2. Demersal trawl

We compared the number of heavy seabird-cable interactions and fatal interactions recorded by Albatross Task Force observers on wet-fish trawl vessels before and after the regulation came into effect.

To quantify the effect of regulation on seabird interactions, we estimated the mean and 95% confidence intervals of the number of interactions per hour of observation using a non-parametric bootstrap procedure (Crowley, 1992; Manly, 2018). Since BSLs may not be deployed immediately after trawl doors enter the water, as stipulated by regulations, we stratified the bootstrap samples by vessel activity and ensured that each bootstrap sample contained a similar proportion of samples from setting, trawling and hauling events. We drew 10,000 stratified random samples and quantified the number of all heavy and fatal interactions for the pre- and post-regulation periods. We quantified the change as the difference between pre- and post-regulation rates divided by the pre-regulation rates.

Total effort data, based on the number of hours trawled, for the years 2009–2010 and 2016–2017 were provided by the Ministry of Fisheries and Marine Resources. The observed fatal interaction rates in the wet-fish portion of the demersal trawl fleet were multiplied with the relevant effort data, to extrapolate an annual bycatch estimate for the demersal trawl fleet for the pre- and post-regulation periods. To provide a conservative estimate of the mortality in the freezer-portion of the demersal trawl fleet, for which no empirical data exist, we used the same fatal interaction rates as for the wet-fish trawl fleet. This extrapolation therefore assumes that the larger freezer vessels are operationally very similar to the wet-fish vessels on which observations were carried out. We caution that due to their larger size, the freezer vessels may pose a greater collision risk to seabirds and our extrapolations may therefore be a minimum figure.

3. Results

3.1. Demersal longline

During the pre-regulation period, a total of 46 (63.9%) of the 72 observed sets resulted in seabird bycatch and 573 birds were retrieved during hauling operations from these sets, of which 84.2% were white-chinned petrels (*Procellaria aequinoctialis*). Other bycaught species included Atlantic yellow-nosed albatrosses (*Thalassarche chlororhynchos*), black-browed albatrosses (*Thalassarche melanophris*), brown skuas (*Stercorarius antarcticus*), sooty shearwaters (*Ardenna grisea*) and Cape gannets (*Morus capensis*) (see Paterson et al., 2017).

During the post-regulation period, a total of 42 (9.0%) of the 465 observed sets resulted in seabird bycatch, and a total of 94 birds were killed, with the maximum number of birds killed in a single set being 17. Most of these mortalities were recorded by Fisheries Observer Agency observers which did not identify bird species. Photographic evidence confirmed that some of the birds caught in the post-regulation period were endangered juvenile Atlantic yellow-nosed albatrosses. Bycaught birds recorded by Albatross Task Force observers included three white-chinned petrels and one sooty shearwater.

Our model accounting for uncertainty in observation effort and random variation among vessels and trips indicated that the regulation had a major effect on the occurrence (mean parameter estimate −4.87; 95% credible interval −18.1–15.2) and abundance (−3.63; −5.8 to −1.8) of seabird mortality. BSLs were deployed on 95% of all longline sets observed after the regulation came into effect, and the estimated seabird bycatch rate decreased from 0.468 birds/1000 hooks (95% credible interval 0.067–1.450) in the pre-regulation period to 0.004 birds/1000 hooks (0.001–0.013) in the post-regulation period, corresponding to a 98.4% (93.8–99.9%) reduction in seabird mortality in this fishery since regulations came into effect. Assuming that our observed bycatch rates are representative of the overall Namibian longline fleet, extrapolation of our bycatch rates across all longline fishing operations in Namibia suggests that 215 (95% CrI 1–751) birds were killed in 2018 compared to 22,222 (95% CrI 3187–68,786) in 2009 (Table 1).

3.2. Demersal trawl

Seabird mortalities resulting from collisions with trawl cables were recorded during setting and trawling operations on wet-fish demersal trawl vessels, but never during hauling. Less than 1% of the observed interactions were recorded as having an unknown outcome. Of the 458 observed seabird interactions, 268 (58.5%) were classified as light interactions, and 190 (41.5%) were classified as heavy interactions.

In the pre-regulation period we recorded on average 1.09 (0.81–1.39) heavy interactions with the trawl cable per hour, which declined to 0.49 (0.23–0.84) heavy interactions/h after the regulation came into effect, a reduction of 54% (40–72%). The reduction of interactions was twice as large during the trawl phase (before 1.17, after 0.425; reduction of 63.8%; 95% CI 45.7–86.3%) than during the setting phase (before 1.14, after 0.778; reduction of 31.5%; 95% CI 18.2–59.2%).

The 13 fatal interactions that were observed during the pre-regulation period (Table 2) were spread across eight trawls on five trips and included black-browed albatrosses, Atlantic yellow-nosed albatrosses, white-chinned petrels and a cape petrel (*Daption capense*). In the pre-regulation period, albatrosses and white-chinned petrels constituted 77% of the heavy interactions observed. This proportion was reduced to 30% following the introduction of regulations requiring the use of BSLs. In the post-regulation period, all seabird mortalities were recorded on a single trip and were exclusively kelp gulls (Table 2).

BSLs were used on 91% of the observed trawls during the post-regulation period, but only deployed immediately after trawl doors entered the water on 52% of these. In the remaining cases, BSLs were deployed after winches stopped or once trawling activity had commenced.

Table 2
Heavy seabird interactions and mortalities recorded by Albatross Task Force observers onboard wet-fish demersal trawlers during the pre (2009–2010) and post-regulation (2016–2019) period. IUCN status refers to the species category on the IUCN red list (VU: vulnerable, EN: endangered, LC: least concern).

Species	IUCN status	Number of heavy interactions (fatal interactions)	
		Pre-regulation: 2009–2010	Post-regulation: 2016–2019
White-chinned petrel *Procellaria aequinoctialis*	VU	102 (4)	13 (0)
Atlantic yellow-nosed albatross *Thalassarche chlororhynchos*	EN	37 (4)	None observed
Black-browed albatross *Thalassarche melanophris*	LC	27 (4)	None observed
Cape petrel *Daption capense*	LC	24 (1)	None observed
Kelp gull *Larus dominicanus*	LC	None observed	28 (3)

Fatal interactions with trawl cables constituted 3% of all observed seabird-trawl cable interactions on wet-fish demersal trawl vessels, and 7.3% of all heavy interactions. The rate of these decreased by 57.9% after the regulation came into force, with an average of 0.055 (0–0.13) mortalities/h recorded in the pre-regulation period and 0.023 (0–0.69) mortalities/h in the post-regulation period. Additional interactions with trawl cables, resulting in at least one black-browed albatross being killed, were recorded by video on a trip during the post-regulation period when no data were collected and no BSLs were deployed.

Based on these results, we estimate that 7030 (CI 95% 0–16,374) birds were killed by the Namibian demersal trawl fleet in 2010, compared to 1452 (CI 95% 0–3865) in 2017, but we caution that these extrapolations may be conservative because they assume that the mortality rate on freezer vessels is identical to those in the wet-fish trawl vessels (Table 3).

Our findings thus suggest that a total of 1615 (CI 95% 1–4433) birds were killed in the demersal hake fishery in Namibia in 2017 (year for which the most recent effort data is available for both the demersal trawl and demersal longline fleets).

4. Discussion

Our study demonstrates that significant reductions in seabird bycatch can be achieved over a short period of time when best practice bycatch mitigation is implemented in a fishery. The introduction of regulations requiring the use of bird-scaring lines (BSLs) during fishing operations, coupled with a high level of uptake from industry facilitated by training and cooperation, has resulted in a 98.4% reduction in seabird bycatch rates in the Namibian demersal longline fishery. In combination with the widespread practice to start setting lines before nautical dawn already present in the fleet, the seabird mortality in this fishery therefore declined from >20,000 birds per year to <300 birds per year since the regulation came into effect. Our post-regulation estimate for the demersal longline fleet is the most comprehensive and up-to-date assessment of seabird bycatch for this fishery. The incorporation of government observer data into our analysis greatly increased confidence in the post-regulation bycatch estimates. This significant bycatch reduction, in one of the world's deadliest fisheries for seabirds (Anderson et al., 2011; Paterson et al., 2017), represents an important conservation achievement for the protection of seabirds foraging along the Benguela Current System.

We also found a reduction in seabird mortality in the demersal trawl fleet, but this reduction was of a lower magnitude (58%). Numerous studies have shown that the use of BSLs can reduce seabird-cable interactions by over 80% onboard demersal trawl vessels (Bull, 2009; Maree et al., 2014; Tamini et al., 2015). The relatively moderate

Table 3
Annual seabird mortality estimates for the Namibian hake demersal trawl fleet for the pre-regulation (2009–2010) and post-regulation (2016–2018) period. Bycatch estimates calculated based on the rate of fatal interactions with trawl cables recorded by Albatross Task Force observers on wet-fish demersal trawl vessels for each sampling period and annual fleet effort (hours of trawl). Bycatch rates from the wet-fish vessels were extrapolated to the freezer portion of the fleet, based on the assumption that these are operationally similar.

		Wet-fish portion of the fleet		Freezer portion of the fleet		Total
Year	Regulation	Effort (hours)	Bycatch estimate	Effort (hours)	Bycatch estimate	Seabird mortality
2009	No	90,323.63	4950 (0–11,549)	37,945.07	2080 (0–4852)	7030 (0–16,374)
2010	No	61,753.65	3384 (0–7896)	33,335.83	1827 (0–4263)	5211 (0–12,159)
2016	Yes	51,086.80	1179 (0–3537)	23,167.15	535 (0–1604)	1714 (0–5177)
2017	Yes	40,403.92	933 (0–2309)	22,472.5	519 (0–1556)	1452 (0–3865)

reduction in heavy and fatal interaction rates in our study may be explained by imperfect implementation of the regulation. Although BSLs were used on 91% of observed trawls, many were deployed after winches stopped rather than when trawl doors enter the water, as specified by the 2015 regulation (MFMR, 2015b). The reduction in heavy interactions during the setting process, when BSLs were often not deployed yet, was therefore much lower than during the trawling process. Late deployment of BSLs results in trawl cables being left exposed during setting operations when offal is discarded, thus posing a high collision risk to foraging seabirds. As such, BSLs were correctly deployed on <50% of all observed trawls in the post-regulation period, and this imperfect implementation may therefore lead to seabird interactions and mortality occurring on trawls reported to have used BSLs.

The primary driver of this imperfect implementation in the demersal trawl fleet appears to be fisher's concern about entanglements of BSLs with trawl cables during setting operations. Technical modifications that extend attachment points on either side of the vessel could reduce risks of entanglement with trawl cables. As stipulated by the regulations, stopping all offal discarding during trawl net setting could eliminate the risk of seabird bycatch (Abraham et al., 2009), since discards are the major driver of seabird attendance at vessels and affect the number of interactions with trawl cables (Weimerskirch et al., 2000; Sullivan et al., 2006). We therefore recommend that industry implement trials to examine the efficacy of extended BSL attachment points and delayed discarding, and that in future, cases of non-compliance be reported by observers to the Fisheries Inspectorate and acted on accordingly.

Night setting and line weighting – two additional primary mitigation measures recognised as best practice – are currently not legal requirements in Namibia's bycatch regulations for the hake demersal longline fleet. As an operational preference of the fleet, the majority of sets begin before nautical dawn (>90% since 2015), but they are regularly not completed before nautical dawn (only 43% completed before dawn since 2015). Thus, a potentially substantial number of hooks is not set at night as defined in best practice recommendations (ACAP, 2017a). Hence, it will be important for ongoing monitoring to highlight any move away from these preferential setting times, as this has the potential to increase seabird bycatch (ACAP, 2017a) and may risk affecting more diurnal albatross species if bird-scaring lines fail to work as intended (Paterson et al., 2017). Furthermore, the reported shift back to concrete weights from faster-sinking steel weights provided by the Albatross Task Force is a concern (Paterson et al., 2017) and may also have ramifications for bycatch levels in this fishery (ACAP, 2017a). We were, however, unable to assess the impact of changes in the line weighting regime, as data have not been systematically collected on weight type, mass and distribution along the line. Considering the changes in line weighting, and the potential for operational preferences for setting times to change, we suggest that updated regulations requiring the fishery to use line weighting and/or night-setting alongside BSLs would be advisable. While the use of BSLs appears to have been the primary driver of bycatch reductions in this fishery (Paterson et al., 2017), updating regulations to require night setting or line weighting in addition to BSLs would bring requirements more closely in line with best practice (ACAP, 2017a) and minimise risks inherent in the existing management regime. Further, we recommend that seabird bycatch data collection becomes mandatory and integrated into standard fishery data collection protocols (Paterson et al., 2017), to ensure that seabird bycatch rates are monitored and used to inform fisheries management in Namibia.

Observer coverage in these two fleets is maintained at a high level with observers onboard approximately 40% of all demersal longline and 90% of demersal trawl trips in 2018 (Fisheries Observer Agency, personal communication, August 16, 2019), and this is likely to have had an important role in the effective implementation of bycatch mitigation measures (FAO, 2009). Fisheries management would however benefit from a better understanding of what seabird species are routinely killed in fishing operations. To date, data collected by government observers in the demersal longline fleet did not record the identity of bycaught seabirds. The Marine Resources Act 2000 states that albatrosses that are accidentally caught or injured during fishing operations should be reported, as they are legally protected from intentional killing and disturbance in Namibia (MFMR, 2001). An improved understanding of which species remain at risk will be important for customising further improvements, especially because there have been confirmed records of endangered Atlantic yellow-nosed albatrosses being caught in Namibian waters in the post-regulation period. Moreover, tracking studies have established that the foraging range of the Critically Endangered Tristan albatross and other globally threatened *Procellariformes* overlap with Namibian fishing fleets (Reid et al., 2013; Dias et al., 2017; Clay et al., 2019). Thus, the capture of even a small number of birds of these threatened species would be of great concern (Reid et al., 2013) and given the non-negligible bycatch mortality that persists in the Namibian hake demersal fishery it is important that the identity of affected species is documented.

Training is a central element of addressing accurate bycatch documentation, and this has formed the core of Albatross Task Force engagement in Namibia since its inception in 2008. In addition to at-sea mitigation trials to demonstrate the efficacy and feasibility of BSL use, the Albatross Task Force has delivered bycatch education, mitigation and data collection training aimed at skippers, fisheries observers and inspectors in the major ports of Lüderitz and Walvis Bay. Recent efforts have ensured that >75% of fisheries observers have been trained in key bycatch issues (Albatross Task Force Namibia, unpublished data) and the Fisheries Observer Agency has started to collect seabird bycatch data. Representatives from 12 of the 14 hake fishing companies in Namibia have attended training workshops, which have recently focused on relevant legal requirements. Furthermore, information leaflets regarding seabird bycatch mitigation in both English and Oshiwambo have been delivered to fishing crews and all government observers and active hake vessels have been provided with seabird identification guides. Nonetheless, ongoing training is clearly necessary to maintain awareness, improve compliance (particularly in the trawl fleet), data collection and enforcement. To this end, we recommend that seabird bycatch training become integrated into the national fisheries inspector and observer course syllabus, with similar training for new entrants into the fishing industry. Better implementation of regulations in this fishery would mark a substantial advance in the at-sea conservation of albatrosses and petrels off the coast of southern Africa.

Alongside the reductions reported in Alaskan fisheries (Melvin et al., 2019), the Namibian fleet is among a small number of demersal longline fisheries outside the Antarctic area (Cox et al., 2007) with demonstrable fleet-wide improvements. This success can be attributed to a combination of the introduction of regulations and long-standing relationships between non-governmental organisations (like the Albatross Task Force), key industry stakeholders, scientists and resource managers (Melvin et al., 2019). These relationships also facilitate evaluation of the regulation: since July 2017, approximately 60% of official government observers have been collecting seabird bycatch data in the Namibian hake demersal fleet.

In summary, we have shown that environmental regulations that mandate the adoption of technical mitigation solutions can have enormous benefits for biodiversity. Our example of Namibian fisheries shows that seabird mortality has been reduced by an order of magnitude since the introduction of regulations requiring the use of bird scaring lines in 2015. However, further improvements are possible with updated regulations and greater compliance, especially in the demersal trawl fleet. The adoption of a National Plan of Action for Reducing the Incidental Catch of Seabirds in Namibian Fisheries (Benguela Current Commission, 2017) provides an opportunity to track the progress of fisheries posing a threat to seabirds in Namibian waters, including those described here. To ensure the bycatch reductions reported above are sustained into the future, it is critical that fleet-wide compliance with the use of best-practice mitigation measures is achieved and that seabird bycatch becomes a core theme of fisheries management in Namibia and elsewhere. We therefore caution that ongoing engagement with and training of industry stakeholders is critical to ensure that measures stipulated by regulations are adopted and yield benefits to biodiversity.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocon.2020.108915.

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.

Acknowledgements

This work is dedicated to the memory of Ismael Kavela, who carried out at-sea data collection used in this study. The Albatross Task Force in Namibia is hosted by the Namibian Nature Foundation. The project is supported by the RSPB, the BirdLife International partner in the UK, and funded by a grant from the David and Lucile Packard Foundation. Previoius work under this project has also been funded by a grant from the Adessium Foundation through Vogelbescherming, BirdLife Nederland. We thank Tim Reid, Alex Bond and Adam Butler for their input into data collection and analysis, the Ministry for Fisheries and Marine Resources for provision of fleet data and the National Hake Association and Namibian Fisheries Observer Agency for their continued support.

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