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Original Article

Bird scaring lines reduce seabird mortality in bottom and mid-water trawlers in Argentina

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Seabird bycatch in fisheries, and the development of effective mitigation to minimize this, have been subject to increasing research attention over the past three to four decades. Trawl fisheries represent a particular challenge, as bird mortalities (especially highly threatened albatrosses and large petrels, Procellariforms) occur primarily through difficult-to-detect collisions with warp and net monitoring cables. Effectiveness of bird-scaring lines (BSLs) as a mitigation measure can be fleet-specific, and studies relating specifically to reducing collisions with the net monitoring cable are rare. To support improved assessment and mitigation of seabird bycatch in trawl fisheries, we studied the mortality associated with mid-water and bottom factory trawl vessels along the southern tip of the Argentine Patagonian shelf, across 2144 trawls from 2012 to 2019, with three specific objectives: (i) inform improved bycatch management in this (and other) trawl fisheries by analysing differences in seabird collision rates and outcomes between net monitoring and warp cables, as well as the effect of mitigation measures in reducing collisions; (ii) explore the effects of key fishing operation variables on seabird impact outcomes; and (iii) estimate the annual seabird mortality in the study fleet. We tested the efficacy of BSLs as a mitigation measure to reduce seabird mortality, on warps and net monitoring cables. Our results show that seabird mortality increases in the presence of a net monitoring cable. Our estimation of fishery-wide mortality without the use of BSLs includes 108 [31–186] Southern royal albatross (*Diomedea epomophora*) and 279 [108–456] Black-browed albatross (*Thalassarche melanophrys*) killed annually. We demonstrate the efficacy of BSLs in reducing the number of collisions and in combination with no discarding of fishes, seabird interactions fell to *c.* zero. Our study builds the case for better bycatch data collection in trawl fisheries, the strong influence of discarding, and the feasibility of simple mitigation measures to reduce seabird bycatch, including on the net monitoring cable.

Keywords: bycatch, collisions, Patagonian shelf, seabird conservation

Introduction

Fisheries management has, at least in some cases, shifted emphasis from purely stock assessment to encompassing the unintended consequences of fishing, such as habitat destruction, changes to ecosystem structure, and the bycatch of non-target species (Zhou *et al.*, 2010). This anthropogenic activity is the primary at-sea threat to several large marine vertebrate populations, including sea turtles, seabirds, and marine mammals (Lewison *et al.*, 2014). These long-lived species (characterized by delayed maturity and low reproductive rates) are particularly sensitive to even small increases in mortality resulting from incidental capture in fisheries (Lewison *et al.*, 2014). The entire process of minimizing bycatch of non-target species—from identifying mortality levels to testing and then implementing mitigation measures—is often incomplete. Moving from characterization to minimized bycatch levels is likely to require incentive-based and/or command-and-control measures (Boyd, 2014; Maree *et al.*, 2014).

Seabird bycatch is widely recorded across a broad range of different fisheries and occurs at a rate considered unsustainable for many vulnerable seabird populations, particularly pelagic species like albatrosses and petrels (Procellariiforms, Dias *et al.*, 2019). The cumulative impact of global fisheries on seabird populations became a major conservation concern in the late 1980s (Weimerskirch and Jouventin, 1987; Brothers, 1991; Murray *et al.*, 1993). Although attention focused initially on demersal and pelagic longlining, bycatch in trawl fleets has also been identified as a major source of mortality for many albatrosses and petrels (Sullivan *et al.*, 2006b; Favero *et al.*, 2011; Croxall *et al.*, 2012; Maree *et al.*, 2014), first recorded in the early 1990s (Bartle, 1991).

In trawl fisheries, mortality occurs due to collisions with warp cables (WC) (metal cables used to tow fishing nets), the net monitoring cable (third wire, sonde cable, or netsonde cable), or by entanglement in the nets (Weimerskirch *et al.*, 2000; González-Zevallos and Yorio, 2006; Sullivan *et al.*, 2006b). Birds captured in nets or injured/killed after colliding with trawl cables and subsequently hauled onboard are considered to represent the minimum number of those killed during trawling—a large proportion of these birds fall into the water and are not recovered in fishing operations (Weimerskirch *et al.*, 2000; Sullivan *et al.*, 2006a; Parker *et al.*, 2013).

The net monitoring cable, which electronically monitors several fishing variables during trawling, poses a particular risk, as it has a greater aerial extent with respect to the WC (Sullivan *et al.*, 2006b; Løkkeborg, 2011; Tamini *et al.*, 2016).

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Several authors have identified elevated bycatch risk from the net monitoring cable compared to WC alone in trawl fisheries around the world (Weimerskirch *et al.*, 2000; Sullivan *et al.*, 2006b; Tamini *et al.*, 2016; Adasme *et al.*, 2019). For this reason, these cables have been banned—or only permitted in a controlled and defined way—in fishing operations in a number of Southern Hemisphere jurisdictions, *e.g.* New Zealand, Uruguay, and the CCAMLR convention area (see Ministry for Primary Industries, 2013; Dirección Nacional de Recursos Acuáticos, 2020; Commission for the Conservation of Antarctic Marine Living Resources, 2021). However, these bans are currently being reconsidered (Fisheries New Zealand, 2022).

There have been a number of research efforts to demonstrate potential measures to mitigate the impact of the net monitoring cable. In Alaska, Melvin *et al.* (2011) demonstrate that seabird strikes by net monitoring cables (NMC) can be reduced by combining the use of paired BSLs deployed on the port and starboard sides of the WC alongside the use of a snatch-block that works to draw the net monitoring cable closer to the water at the stern. This means that BSLs can reduce strikes with both types of cables. However, this can prove difficult to manage in high winds, and in some cases, individual streamers can warp cable around the NMC, compromising mitigation potential (Melvin *et al.*, 2011). In addition, tangles with the BSL can damage the expensive and sensitive NMC. Captains and crew therefore often resist mitigation measures that might interfere with the net monitoring cable (Melvin *et al.*, 2011). This is a substantial barrier to the implementation of mitigation measures supporting greater catch efficiency (Melvin *et al.*, 2011; Tamini *et al.*, 2016).

Seabirds are attracted to trawl fisheries by discards and offal, and several studies have shown that seabird mortality through collisions with cables increases in the presence of discards (Sullivan and Reid, 2003; Kuepfer *et al.*, 2022). Thus, discard management is the most effective method to reduce cable interactions (ACAP, 2021b). However, since fishery and vessel characteristics dictate the extent to which discards and offal can be managed, where this method is limited or impractical, cable collisions can be prevented by protecting them with other mitigation measures (ACAP, 2021b).

The above-mentioned issues are all present in the Argentine mid-water and bottom factory trawl fleet targeting Hoki (*Macruronus magellanicus*), the focus of the present study. Seabird bycatch has already been characterized in the industrial Argentine Hake (*Merluccius hubbsi*) trawl fleet (Tamini *et al.*, 2015), and since 2017, there have been regulations requiring the use of BSLs to prevent seabird collisions with WC in both fleets [Resolution 03/2017 (Consejo Federal Pesquero, 2017)]. However, no net monitoring cable mitigation measures are defined under those regulations. The Hoki catch of the study fishery is certified under the Marine Stewardship Council (MSC) sustainable seafood scheme (Morsan *et al.*, 2017). A number of seabird species (especially albatrosses and petrels) were identified as potentially impacted by the fishery when it was undergoing re-certification against the MSC standard in 2017 (Morsan *et al.*, 2017). Concerns around seabird bycatch impacts—particularly collisions with the net monitoring cable—resulted in the fishery receiving a so-called "condition of certification" to address this issue (Morsan *et al.*, 2020). This process was a launchpad for Birdlife International's "Albatross Task Force (ATF)" to engage with the fleet to support improved compliance with the use of warp cable BSLs, and to assist in research to develop effective bycatch mitigation for the net monitoring cable.

This study characterizes seabird bycatch and mitigation in the Argentine mid-water and bottom factory trawl fleet with the following specific objectives: (i) inform improved bycatch management in this (and other) trawl fisheries by analysing differences in seabird collision rates and outcomes between net monitoring and WC, as well as the effect of mitigation measures in reducing collisions; (ii) explore the effects of key fishing operation variables on seabird impact outcomes; and (iii) estimate the annual seabird mortality in the study fleet.

Methods

Data source

Assessment of seabird interactions with factory trawlers, and the effects of BSL use, was conducted by ATF instructors on vessels from 2012 to 2019. The study fishery operates south of 50°S in the Argentine Sea and is comprised of four vessels (length = 64–120 m) using both bottom and mid-water trawl nets, which are monitored by a net monitoring cable. This fleet is a small segment of the entire Argentine trawl fleet (~190 offshore trawlers), primarily targeting demersal and sub-Antarctic species, namely Hoki, Southern blue whiting (*Micromesistius australis*), and Patagonian toothfish (*Dissostichus eleginoides*). Other non-targeted but commercially valuable species are also landed, including Southern Hake (*Merluccius australis*), Patagonian Cod (*Salilota australis*), Grenadier (*Coelorhynchus fasciatus*), Silver Warehou (*Seriolella porosa*), Kingklip (*Genypterus blacodes*), and Notothens (*Notothenia* sp.). Depending on the target species, discards may include whole fish, or processing offal (heads, tails, and guts), which may be thrown overboard "as is" or after mincing. No storage or other forms of discard management are used in this fishery.

Our hauling observations cover 2144 trawls of 16 fishing trips between 50°–57°S and 60°–68°W along the Southern Patagonian shelf (Figure 1). In addition, we conducted 3130 cable observation periods (totalling 1096.8 hours) on 654 trawls. From 3130 observations, 1869 were made when the target species was Hoki, 608 for Southern blue whiting, and 653 for Patagonian toothfish. The duration range of trips was 40–70 days, comprising 100–220 trawls/trip. The total observed effort represents 2.8% of the trawls and 10.6% of the total fishing days of this fleet during the study period. Monitored trips were concentrated south of 52°S, where vessels fishing Hoki and Southern blue whiting dispersed more widely, compared to the more restricted operations when the primary target is Patagonian toothfish.

Seabird species composition

Seabird abundance associated with fishing vessels was estimated by conducting 10 min counts from the stern gantry in a 200 m semicircular sampling area (see, Favero *et al.*, 2011). This information was gathered onboard during 1798 censuses from 757 trawls by two experienced seabird observers (authors LNC and RFD). The censuses were made at least once per trawl during active trawling (*i.e.* not setting or hauling). When it was possible, seabirds attending the observed vessels were identified to species level using photographic identification when necessary (*i.e.* particularly for some species e.g. skuas). We define frequency of occurrence as the percentage of

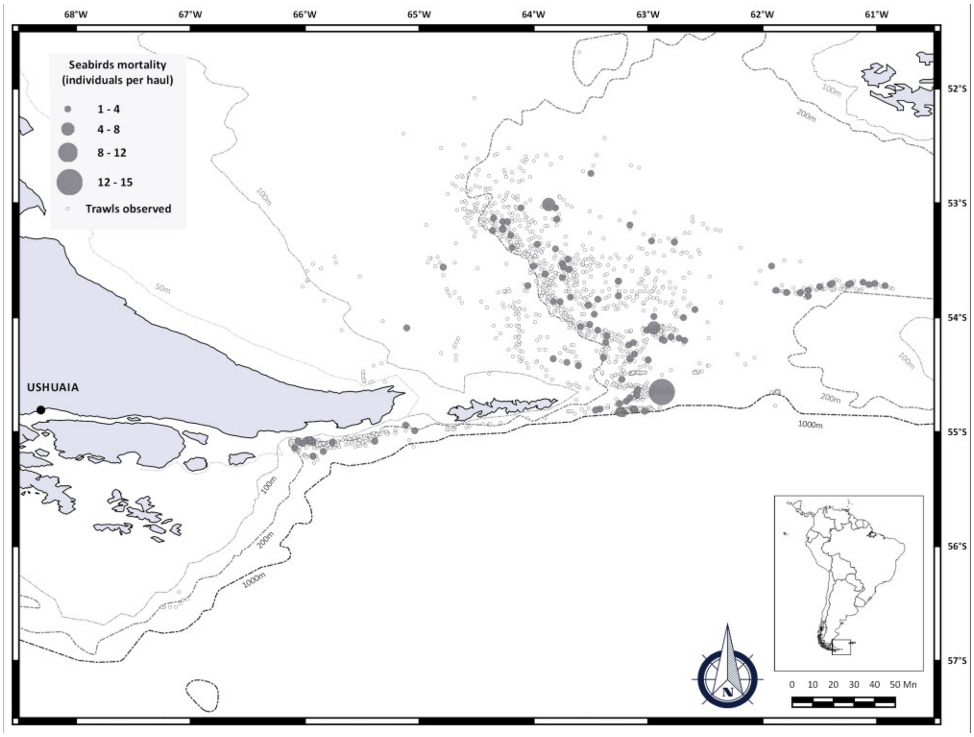

Figure 1. Observed trawls of mid-water and bottom trawlers fleet from 2012 to 2019 (white circles) and trawls with incidental capture of seabirds (grey circles).

trawls in which a particular seabird species was observed. The overall abundance (total number of individuals in all counts) and abundance per species was calculated.

Seabird-vessel interactions

Seabird mortality based on hauling observations

Seabird interactions were counted in two ways: (1) birds hauled on board that had been killed by contacts with the net, warp, and NMC, and (2) through direct observations covering collisions with both the net monitoring and WC. To test the efficacy of BSLs in reducing both types of cable interaction, collisions were recorded in 3130 observation periods, separated between two treatments of ideally 15 min ($\overline{X} = 15$ min., SD = 5 min.) each: without mitigation measures (control) and with BSLs (experimental). In each observation period, instructors recorded:

1) observation time
2) number of interactions with the cables by species, age (when possible), type of interaction (flying collision or sea surface collision), direction of approach to the vessel, intensity of the interaction (light, medium, or heavy), and the outcome (not injured, injured, possibly dead, and dead).
3) characteristics of the trawl: latitude and longitude, date, use of BSLs and discard information (mixed, minced, and without discard), and quantity.

We define the categories of collision intensity and outcome as follows:

- light: touch that causes a little or no change in behaviour or direction
- medium: collision that causes change in behaviour and direction
- heavy: collision that shakes or drags the bird underwater
- not injured: no visible damage
- injured: bird with broken wings
- possibly dead: bird dragged under water and not seen again
- dead: bird visible dead on water or cable.

Discard information was recorded as follows:

- mixed: whole fish and offal discarded simultaneously
- minced: discards passed though mincer
- without discard: no discarding as there is no catch processing

BSLs covering WC were deployed from the port and starboard sides of the vessel, attached above and outside 2 m from blocks to maintain a minimum aerial extent of 20 m. The BSLs consisted of a main line/backbone (30 m of 10-mm coloured polypropylene) with seven streamers (brightly coloured and UV protected red hose) placed every 2.5 m. A buoy and the specially designed off-set towed device *Tamini Tabla*, to prevent entanglement between cables and BSLs were fixed at the terminal end to create drag and maximize their aerial extent (Tamini *et al.*, 2015; Jiménez *et al.*, 2022). As a mitigation measure for the net monitoring cable, another design of BSL was deployed 1 m above this cable sheave, approximately in the centre of the vessel. This BSL slides over the net monitoring cable through a heavy sheave (or with weight added, ~4 kg.) placed at the end of the BSL near the water, with the aim of achieving an aerial extent of at least 35 m. The net monitoring cable BSL consisted of ~37 m of 10-mm green and yellow polypropylene backbone with twenty 1 m bright red stream-

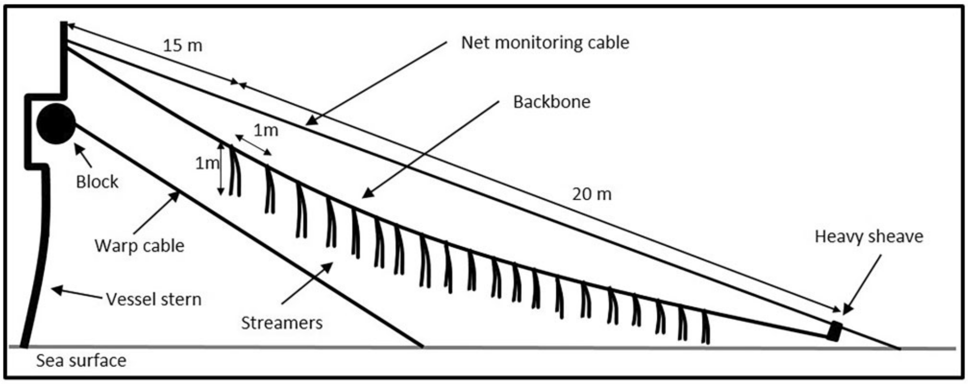

Figure 2. Diagram of front view of the bird scaring line (BSL) used to reduce the number of seabirds collisions against the net monitoring cable. Block (sheave that support the warp cable), backbone (main line of the bird scaring line), streamers (secondary lines of the bird scaring line), and heavy sheave (pulley with added weight).

ers every 1 m. The first streamer was at 15 m from the stern of the vessel [Figure 2, improved from Tamini *et al.* (2019)].

Factors affecting seabird interactions

To examine factors that might explain seabird interactions, we initially employed generalized linear mixed models. We initially tested count data as a response variable using a negative binomial distribution. As these models showed overdispersion, we recoded count data to 0 (no interaction) or 1 (interaction) with a Bernoulli distribution and logit link function (Richard and Abraham, 2013). All interactions with the cables were considered, including those where individuals were not injured. The objective of the analysis was to identify drivers of seabird interactions. In a preliminary model, the bird species was included as a fixed factor, but due to the high number of factor levels (12) relative to the number of observations we had, the model did not fit. Whilst the species type can influence the extent and nature of interactions (Weimerskirch *et al.*, 2000), by combining data for all species, we can focus on factors that affect and mitigate interactions more generally. Using the fishing operation variables, season, and seabird abundance, we separately analysed models on warp and net monitoring cable interactions. We included as fixed factors: streamer deployed (yes, no), discard details (mixed, minced, without discard), target species (Patagonian toothfish, Southern blue whiting, and Hoki), fishing gear (bottom trawl net, mid-water trawl net), season (winter, autumn, spring, and summer), and seabird abundance. To improve the fit of the model we used the square root transform for seabird abundance. In these models, year (2012, 2014, 2015, 2016, 2017, and 2019) and observer (two) were included as random effects.

$$\begin{aligned} logit\ (\mu_i) = \beta_o\ &+ \beta_1 Discard_i + \beta_2 StreamerDeployed_i \\ &+ \beta_3 Species_i + \beta_4 Gear_i + \beta_5 Season_i \\ &+ \beta_6 Abundance_i + a_{jObserver} + b_{jYear} + e_{ij}, \\ & Y_i \sim Bernoulli\left(\pi_{ij}\right), \\ logit\ (\pi_i) &= X_i\ \beta + Z_i + e_{j(i)}. \end{aligned}$$

Where β represents the vector of the regression coefficients, X is the matrix of covariates, Z_i are the random effects. Model selection was based on Akaike information Criteria (AIC, Zuur *et al.*, 2009). All models were performed using R software version 4.2.2 (R Development Core Team 2022) using package lme4 (Bates *et al.*, 2015). We subsequently used an odds ratio (OR) to indicate how many times a level of a factor increased based on a unit increase in another level of that same factor. The OR represents the probabilities but on a different numerical scale. We use the OR (exponential function of the regression coefficient) to indicate how many times a level of a factor increases based on a unit increase in another level of that same factor (Zuur *et al.*, 2009). In addition, we present the confidence intervals (CI) for each OR, where a wide CI implies that the number of events tested is quite small, while if the CI includes the number 1, the calculated OR is not statistically significant (Bland and Altman, 2000).

Annual seabird mortality estimates

We estimated the total mortality of seabirds in the fleet using the total fishing effort from 2012 to 2019 (days and trawls by year) obtained from the Vessel Monitoring System (provided by the *Dirección Nacional de Planificación Pesquera, Subsecretaría de Pesca y Acuicultura de la Nación*) and the observed data. To convert fishing effort from trawls to fishing hours, we used information from our observed trips. Trawl duration was defined as the time from when nets reached operational trawl depth to the moment winches started hauling, which means our resulting bycatch estimates are likely to be conservative, as they do not include the hauling and setting periods. With this information, the total number of trawls made by the fleet was calculated from the average number of trawls per day observed and extrapolating to the total days of operation of the fleet. The estimated number of seabirds killed by the trawl fleet was calculated using the number of collisions recorded in the absence of BSLs. The distribution of data was assessed in three stages: for collisions that resulted in mortality (subsequently referred to as *dead*), collisions that resulted in mortality or lethal injury (*dead* and *injured*), and, finally, a third when the results of the collision were mortality, possible mortality, and lethal injury (*dead, possibly dead*, and *injured*). The collision rate was obtained as the sum of bird collisions in different observations divided by the sum of hours of observation:

$$\hat{B} = \left(\frac{\sum b_i}{\sum h_i}\right)\ \mathrm{H},$$

$\hat{B} =$ estimated total seabirds collisions
$b_i =$ seabirds collisions
$h_i =$ hours of observation

H = total of hours of trawl in the fishery.

For each rate obtained, the CI was calculated by resampling techniques since the data do not present a normal distribution (Crawley, 2007). For each frequency table (dead, dead + injured, dead + injured + possibly dead), the observation counting data were re-sampled and the proposed estimators were calculated for each new data set. The CI of the estimators was constructed from the 0.05 and 0.95 quartiles of all the estimators obtained in the simulation.

Results

Composition of seabird aggregations

Examining the composition of seabird flocks observed around vessels during fishing activities is essential to understand the nature of interactions and subsequent mortality. In total, 28 species of seabird were recorded foraging on discards aft of freezer trawlers (Table 1). The most frequently encountered species were Black-browed albatross and Southern giant petrel (*Macronectes giganteus*), followed by the Cape petrel (*Daption capense*), Southern royal albatross, Northern giant petrel (*M. halli*), and White-chinned petrel (*Procellaria aequinoctialis*). The remaining species were recorded in low numbers and in <50% of trawls (Table 1). Analysing the abundance and occurrence of *Diomedea* albatrosses, the high numbers of Southern royal albatross compared to Wandering albatross (*D. exulans*) were notable; the latter was only present at ~25% of trawls and in small numbers (up to 20). Northern royal albatrosses (*D. sanfordi*) were recorded very infrequently (Table 1).

Seabird vessel interaction

Seabird mortality based on hauling observations

The vast majority of the 294 albatrosses and petrels hauled dead onboard were killed by the net monitoring cable (85.7%), followed by net entanglement (both mid-water and bottom trawl, 12.2%) and warp cable collisions (2%) with an overall bycatch rate of 0.14 birds/trawl (see detailed numbers in Table 2). Notably, however, the two ATF instructors suggest that birds that ended up in the net were likely to have been killed by the NMC (90%) and WC, then subsequently entangled in the net. These observations are supported by examination of the corpses, which showed broken wings in the armpit or forearm, injuries consistent with cable collisions.

Analysis of the total collisions in the absence of mitigation measures shows the total number of collisions differs between the two cable types: 4.86 collisions/hr for NMC and 5.58 collisions/hr for WC (Table 3). However, excluding “not injured” birds and analysing the results of the collisions according to the three mortality outcomes (injured, dead, and possibly dead), mortality/injury is two times higher in net monitoring cable collisions compared to WC (0.11 and 0.05 collisions/hr, respectively, Table 3). Looking at the four most impacted species, Cape and Southern giant petrels were more impacted by the WC, while Black-browed and Southern royal albatrosses were most affected by the NMC (Table 3).

Factors affecting seabird interactions

The best models explaining the variation in the interaction with warp or NMC were those that included all factors: discard, BSL deployed, target species, fishing gear, season, and seabird abundance. All factors included in the models were statistically significant (Tables S1 and S2, supplementary material). The models with these factors explained 66% and 46% of the variation, respectively, and presented a good fit (residual deviation < degrees of freedom, Table S3, Fig. S1 and S2, Supplementary Material). The probability of interaction predicted by the model with both the warp and NMC was reduced to almost zero when there were no discards, and was lower when the target species was Patagonian toothfish and when BSLs were used (Figures 3 and 4, respectively). On the WC, the chances of interaction were greater when discards were minced (OR = 47.4) or mixed (OR = 203.1) compared to without discards and also greater when BSLs were not used (OR = 18.5). The interaction was also greater when the target species was Southern blue whiting or Hoki compared to Patagonian toothfish (OR = 9.3 and OR = 41.3). In addition, chances of interactions were higher during mid-water trawling compared to bottom trawling (OR = 2.4). Regarding the season, the chances of interaction were higher in the spring or summer than in autumn (OR = 8.2 and OR = 4.0, Table 4). Regarding seabird abundance, an increase results in the probability of interaction growing by 1.06 times.

Regarding the net monitoring cable, as for the trawl cables, chances of interaction were greater when discards were minced (OR = 44.3) or mixed (OR = 64.2) and also greater when BSLs were not used (OR = 6.6). The interaction was also greater when the target species was Southern blue whiting or Hoki compared to Patagonian toothfish (OR = 3.0 and OR = 4.1), and no differences were found when the target species was Southern blue whiting or Hoki. In addition, chances of interactions were four times more likely when midwater trawling compared to bottom trawling (mid-water to bottom OR = 0.25). Regarding the season, the chances of interaction were higher in the spring or summer than in autumn (OR = 2.8 and OR = 4.4) and in the spring or summer than in winter (OR = 1.9 and OR = 3.0, Table 4).

Annual seabird mortality estimates

Our mortality estimates from data collected without BSLs and using fishery effort data from 2012 and 2019, suggest 148 [63–253] Black-browed albatross and 232 [105–379] Southern giant petrels are killed or injured per year by collisions with WC. Moreover, 279 [108–465] Black-browed albatross and 108 [31–186] Southern royal albatross are killed or injured per year by collisions with NMC (Table 5).

Discussion

This is the one of the most detailed fleet-wide studies of incidental capture and mitigation measures to reduce it in trawl fisheries, particularly with regard to the net monitoring cable. Although the study fleet is small, this in-depth examination means this is a highly timely contribution to understanding and mitigating the risks of this cable for seabirds globally, particularly as some jurisdictions consider relaxing bans (Fisheries New Zealand, 2022). Given the imperative need to reduce the bycatch of threatened seabirds in trawl fisheries (Dias *et al*., 2019), our results are a key information source for the fishing industry, managers, and conservationists alike.

Seabird species associated with the fishery

The seabird assemblages associating with this fleet were diverse, including coastal species such as cormorants, gulls,

Table 1. Abundance (total number of individuals in all censuses), frequency of occurrence (%), and mean (range in parentheses) per census of seabirds attending bottom and mid-water trawlers on the Patagonian shelf during 2012–2019.

	Species	Abundance (total number of individuals in all the census)	Frequency of occurrence (%)	Mean (range)
1	Black-browed albatross LC *Thalassarche melanophris*	156 704	99.7	207.5 (0–2400)
2	Southern giant petrel LC *Macronectes giganteus*	125 608	99.7	166.4 (0–1700)
3	Cape petrel LC *Daption capense*	171 226	88.1	256.7 (0–5350)
4	Southern royal albatross VU *Diomedea epomophora*	8563	85.7	13.2 (0–685)
5	Northern giant petrel LC *Macronectes halli*	6471	59.3	14.4 (0–760)
6	White-chinned petrel VU *Procellaria aequinoctialis*	5803	58.8	13.04 (0–85)
7	Wilson's storm petrel LC *Oceanites oceanicus*	8002	44.8	23.6 (0–250)
8	Wandering albatross VU *Diomedea exulans*	444	24.7	2.8 (0–20)
9	Southern fulmar LC *Fulmarus glacialoides*	1 824	24.6	9.8 (0–500)
10	Kelp gull LC *Larus dominicanus*	794	21.1	5 (0–50)
11	Grey-headed albatross EN *Thalassarche chrysostoma*	1 114	18.4	8.0 (0–80)
12	Sooty shearwater NT *Ardenna grisea*	386	13.9	3.7 (0–55)
13	Slender-billed prion LC *Pachyptila belcheri*	754	8,5	11.8 (0–115)
14	Great shearwater LC *Ardenna gravis*	129	8.3	2.05 (0–30)
15	South American tern LC *Sterna hirundinacea*	132	7.4	2.4 (0–8)
16	Brown skua LC *Catharacta antarctica*	47	3.6	1.7 (0–5)
17	Northern royal albatross EN *Diomedea sanfordi*	58	2.6	2.9 (0–5)
18	Snowy sheathbill LC *Chionis albus*	16	1.2	1.8 (0–3)
19	Westland petrel EN *Procellaria westlandica*	7	0.7	1,4 (0–2)
20	Imperial shag LC *Leucocarbo atriceps*	3	0.4	1 (0–1)
21	Shy/White capped albatross NT/NT *Thalassarche cauta/steadi*	2	0.3	1 (0–2)
22	Chilean skua LC *Catharacta chilensis*	2	0.1	1 (0–1)
23	Antarctic petrel LC *Thalassoica antarctica*	1	0.1	1 (0–1)
24	Common diving-petrel LC *Pelecanoides urinatrix*	1	0.1	1 (0–1)
25	Manx shearwater LC *Puffinus puffinus*	1	0.1	1 (0–1)
26	Pomarine skua LC *Stercorarius pomarinus*	1	0.1	1 (0–1)
27	Salvin's albatross VU *Thalassarche salvini*	1	0.1	1 (0–1)
28	Buller's albatross NT *Thalassarche bulleri*	1	0.1	1 (0–1)

After the species, we included the categories of the IUCN Red List, LC: Least concern, NT: Near threatened, VU: Vulnerable, and EN: Endangered (BirdLife International, 2021)

terns, and skuas in addition to the more "typical" trawl-associated pelagic species like albatrosses, shearwaters, and petrels. The species composition is different from that recorded for coastal trawl fisheries, which record gull-dominant assemblages, and the Argentine hake fishery, where seabird species diversity is lower (González-Zevallos *et al.*, 2007; González-Zevallos *et al.*, 2011; Seco Pon *et al.*, 2012; Seco Pon *et al.*, 2013). The number of recorded seabird species (28) associated with the southern freezer trawlers is also higher than for the industrial hake trawl fleets and side-

Table 2. Seabirds hauled aboard killed during 2144 trawls in mid-water and bottom trawlers on the Patagonian shelf during 2012–2019.

Species	WC	Net	NMC	Total
Black-browed albatross	3	23	173	**199**
Southern giant petrel	2	2	32	**36**
Southern royal albatross		8	16	**24**
Grey-headed albatross			23	**23**
Cape petrel	1	2	5	**8**
White-chinned petrel			2	**2**
Northern royal albatross			1	**1**
Southern fulmar		1		**1**
	6	**36**	**252**	**294**

Table 3. Number collisions by outcome for net monitoring (NM) and warp (W) cables in mid-water and bottom trawlers on the Patagonian shelf during 2012–2019 without the use of mitigation measures for 343.6 and 442.3 monitored hours, respectively.

	Outcome									
	Dead		Injured		Possibly Dead		Not injured		Total	
Species	NM	W	NM	W	NM	W	NM	W	NM	W
Cape petrel			2			2	364	1105	**366**	**1107**
Black-browed albatross	1		3	1	14	6	724	508	**742**	**515**
Southern giant petrel			1	7	3	5	323	716	**327**	**728**
Southern royal albatross	1		1		6		89	6	**97**	**6**
Grey-headed albatross			1		3		27	50	**31**	**50**
Northern giant petrel			1				40	41	**41**	**41**
Southern fulmar							28	8	**28**	**8**
White-chinned petrel							33	15	**33**	**15**
Wandering albatross							3		**3**	
Great shearwater							1		**1**	
Wilson’s storm petrel							1		**1**	
Kelp gull								1		**1**
	2		**9**	**8**	**26**	**13**	**1633**	**2450**	**1670**	**2471**

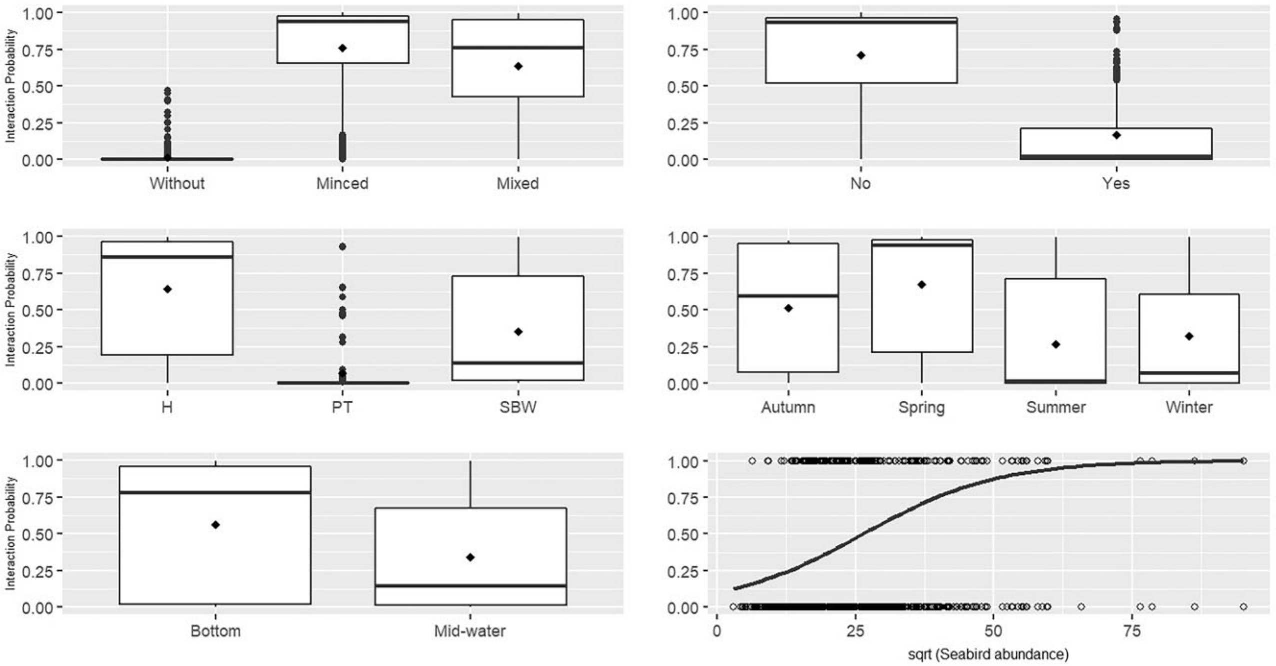

Figure 3. Probability of interaction with warp cable. Values predicted by the final model for each explanatory variable of the fishing operation. From left to right and top to bottom: discard details, streamer deployed, target species, seasons, fishing gear and seabird abundance. Median: horizontal line into the box plot. Mean: diamond. Upper and lower quartiles: boxes. Whiskers: vertical lines. Black dot indicates the data point values that lie beyond the ends of the whiskers.

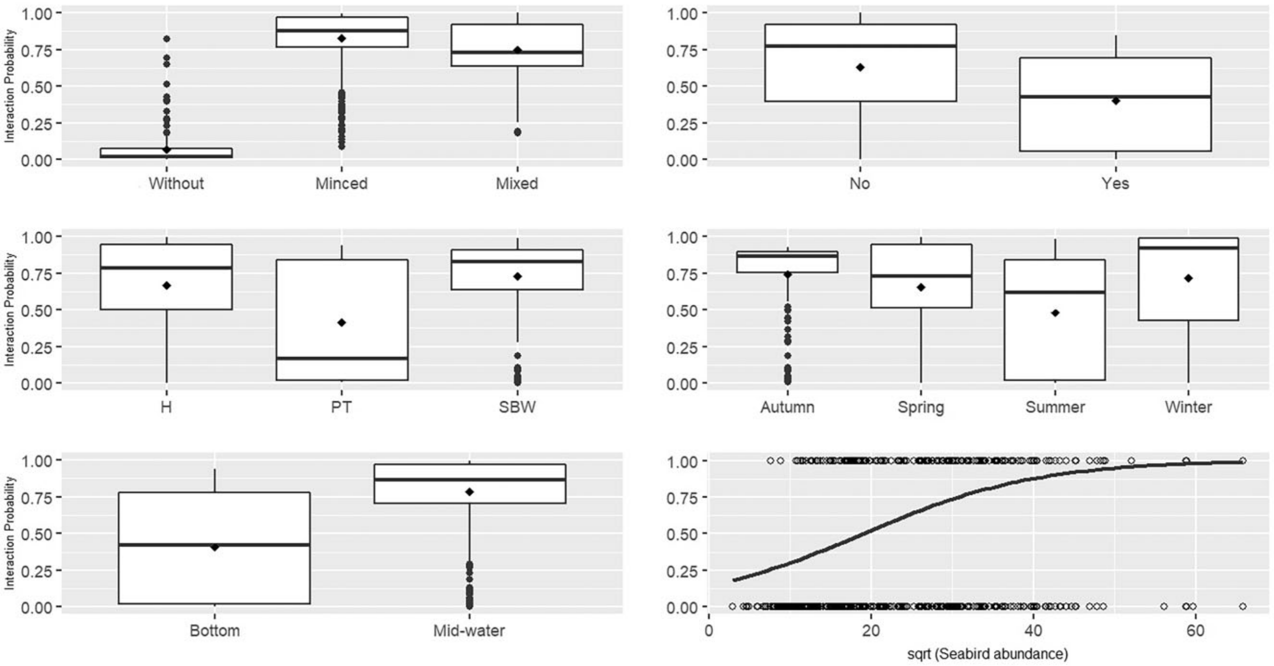

Figure 4. Probability of interaction with net monitoring cable. Values predicted by the final model for each explanatory variable of the fishing operation. From left to right and top to bottom: discard details, streamer deployed, target species, seasons, fishing gear, and seabird abundance. Median: horizontal line into the box plot. Mean: diamond. Upper and lower quartiles: boxes. Whiskers: vertical lines. Black dot indicates the data point values that lie beyond the ends of the whiskers.

Table 4. OR and CI of interaction with WC and NMC.

	WC		NMC	
Variable	OR	CI	OR	CI
Discard details				
Without discard to minced	47.4	23.3–96.7	44.3	25.9–75.7
Without discard to mixed	203.1	95.3–432.9	64.2	37.0–111.3
Minced to mixed	4.3	2.4–7.5	NS	NS
Streamer deployed				
Yes to No	18.5	14.2–24.0	6.6	4.5–9.9
Target species				
H to PT	9.3	3.8- 22.9	NS	NS
SBW to PT	41.3	13.5–126.5	NS	NS
SBW to H	4.4	2.3–8.5	NS	NS
PT to H	NS	NS	3.0	1.8–4.9
PT to SBW	NS	NS	4.1	2.2–7.5
Seasons				
Autumn to Spring	8.2	3.9–17.0	2.8	1.3–6.2
Autumn to Summer	4.0	2.1–7.8	4.4	2.1–9.5
Winter to Spring	3.8	1.9–7.6	1.9	1.1–3.2
Winter to Summer	NS	NS	3.0	1.8–4.8
Spring to Summer	NS	NS	1.5	1.1–2.3
Summer to Spring	2.1	1.2–3.4	NS	NS
Fishing gear				
Mid-water to bottom	2.4	1.7–3.1	0,25	0.35–0.18

haul trawlers that fish further north on the Patagonian shelf (Tamini *et al.*, 2015; Tamini *et al.*, 2020). Black-browed albatross was the most frequently observed and most abundant species, followed by Southern giant petrel, Cape petrel, and Southern royal albatross. This is similar to other trawl fisheries in the area, with several studies identifying Black-browed albatross as the most frequent and numerous species associated with Patagonian shelf fishing vessels, particularly freezer trawlers (Sullivan *et al.*, 2006b; Favero *et al.*, 2011; González-Zevallos *et al.*, 2011; Tamini *et al.*, 2015; Jiménez *et al.*, 2022; Kuepfer *et al.*, 2022). In addition, we recorded two specimens of two species extremely uncommon for the Argentine Sea: the Buller´s and Salvin´s albatrosses (*Thalassarche bulleri* and *T. salvini*) (Tamini and Chavez, 2014; Dellacasa *et al.*, 2022). The conservation status of albatross species attending the austral fleet includes one that is Least Concern, two Near Threatened, three Vulnerable, and two Endangered, according to the IUCN Red List (see Table 1, BirdLife International, 2021).

Table 5. Numbers, rates, and estimation (with CI) of birds dead (D), injured (I), and possibly dead (PD) by the result of colliding against the warp cables (WC) and net monitoring cables (NMC).

				Birds/hour			Estimation		
WC	D	D + I	D + I + PD	D	D + I	D + I + PD	D	D + I	D + I + PD
BBA		1	7		0.002 [0–0.007]	0.017 [0.007–0.029]		21 [0–63]	148 [63–253]
CP			2			0.005 [0–0.012]			42 [0–105]
SGP		7	11		0.017 [0.005–0.032]	0.027 [0.012–0.044]		148 [42–274]	232 [105–379]
NMC									
BBA	1	4	30	0.003 [0–0.009]	0.012 [0.003–0.021]	0.088 [0.047–0.139]	10 [0–31]	62 [15–108]	279 [108–465]
CP		2	2		0.006 [0–0.015]	0.006 [0–0.015]		31 [0–77]	31 [0–77]
GHA		1	6		0.003 [0–0.009]	0.018 [0–0.041]		15 [0–46]	62 [0–186]
NGP		1	1		0.003 [0–0.009]	0.003 [0–0.009]		15 [0–46]	15 [0–46]
SGP		1	8		0.003 [0–0.009]	0.024 [0.012–0.038]		15 [0–46]	62 [15–109]
SRA	1	2	8	0.003 [0–0.009]	0.006 [0–0.015]	0.024 [0.009–0.041]	10 [0–31]	15 [0–46]	108 [31–186]

Birds/hour: sum of birds colliding/observed hours. Estimate: Rate x fishing effort in hours. Estimated total hours: 10210. Observed hours 2012–19: 411 (WC) and 339 (NMC). BBA: Black-browed albatross, CP: Cape petrel, SGP: Southern giant petrel, GHA: Grey-headed albatross, NGP: Northern giant petrel, and SRA: Southern royal albatross.

Seabird mortality based on hauling observations

Dead seabirds hauled on board generally offer a definitive but inaccurate measure of impact given that cable-related mortality is cryptic, as any individuals not observed colliding with cables and falling into the water are not recorded as dead (Parker *et al.*, 2013; Pierre *et al.*, 2014). Richard and Abraham (2013) consider that cryptic mortality in trawl fisheries could increase the observed mortality by up to eight times depending on the fishing method and the bird size (also see e.g. Adasme *et al.*, 2019). The seabirds hauled onboard dead tend to be medium- and large-sized species of albatrosses and petrels. Observed rates of dead seabirds hauled aboard, including mortality by net, warp, and NMC from bottom trawl fisheries along the Patagonian shelf, varies between 0.048 to 1.042 bird/trawl without mitigation measures (Sullivan *et al.*, 2006b; González-Zevallos *et al.*, 2007; González-Zevallos *et al.*, 2011; Tamini *et al.*, 2015; Tamini *et al.*, 2020). Rates found in our study fleet are around the average of these values, though it is important to highlight the presence of Grey-headed albatross and Southern royal albatross in higher numbers than previously recorded in the Patagonian shelf, given their conservation status.

Annual seabird mortality estimates

This study provides the first estimate of total seabird mortality caused by the austral Argentine bottom and mid-water trawl fleet and proposes simple and economically feasible solutions to reduce collisions. This includes cryptic mortality which, because we use the direct counts of interactions against cables (vs. counts of dead birds hauled aboard), is generally not included in conventional estimates. The impact of the fishery on seabirds is evident, though lower than the impact recorded by the Argentine hake freezer trawlers operating on the Patagonian shelf, even when taking fleet size into account (Tamini *et al.*, 2015). Nevertheless, the impact of the fleet on Grey-headed albatrosses (population size: 95000 breeding pairs, Endangered status) and Southern royal albatrosses (population size: 7900 breeding pairs, vulnerable status) from collisions with the net monitoring cable represents a serious concern due to their conservation status (BirdLife International, 2021). If widespread non-compliance with mitigation measures present and future regulations occurred, mortality levels would likely be in the order estimated here (hundreds of birds). However, electronic monitoring aboard the fleet revealed an 85% compliance rate for MSC re-certified vessels in 2020 (Morsan *et al.*, 2021).

Efficacy of mitigation measures and associated recommendations

Our study shows clear evidence of the efficacy of BSLs in preventing seabird collisions with WC. To date, mitigating bycatch on NMC has been less-studied, though ACAP best practice exists, and firstly recommends removing the cable altogether. Failing that, the deployment of a bespoke BSL and installation of a snatch block to reduce the aerial extent of the cable is recommended (ACAP, 2021b). Our results show that seabird interactions with the NMC can be significantly reduced when BSLs are used. In addition, this research echoes previous findings that no discarding during trawling is the most effective tool to prevent bycatch, supporting the core recommendations of ACAP trawl bycatch mitigation advice. Using a combination of mitigation measures is likely the most effective means of reducing bird strikes (*e.g.* streamers on warps and NMC, snatch block for the net monitoring cable, elimination of discards, where this is practicably possible).

Countries in southern South America have included measures to reduce seabird bycatch on NMC in their National Plans of Action (NPOA-Seabirds) or government regulations (e.g. Dirección Nacional de Recursos Acuáticos, 2020). In 2019, Chile expanded the NPOA-Seabirds to include trawling and mitigation measures in several trawl fisheries, among which is the southern industrial freezer fleet where the use of BSLs, the removal of the net monitoring cable or the use of a snatch block are recommended (Suazo *et al*., 2014; Subpesca, 2019). In Uruguay, both the NPOA-Seabirds (Domingo *et al*., 2007) and its revision (Domingo *et al*., 2015) advise the use of mitigation measures adopted by CCAMLR. Recently, the mandatory use of BSLs was introduced for the whole Uruguayan trawl fleet, and the net monitoring cable was banned (Dirección Nacional de Recursos Acuáticos, 2020). Argentina's NPOA-Seabirds recognizes that the mitigation measures for the net monitoring cable are its elimination, the use of a snatch block and other third wire "scarers" such as buoys or colourful plastic nets (Consejo Federal Pesquero, 2010). These mitigation measures were proposed before the present study and followed the guidelines of previous research in other countries (Weimerskirch *et al*., 2000; Melvin *et al*., 2004; Consejo Federal Pesquero, 2010). As a contribution to the Argentinean NPOA-Seabirds and any future updates to regulations from the models and mortality estimates calculated, our results show:

a) no discards significantly reduced seabird interactions to near zero, and we therefore recommend this as the first option for mitigation in this trawl fleet.
b) use of BSLs significantly reduced interactions, and we therefore recommend their use in combination with zero discards. Where discard removal or management is not an option for operative/infrastructure reasons, we recommend the use of BSLs.
c) there were no significant differences between the probability of seabirds colliding with WC of mid-water trawls compared to bottom trawls, so we recommend the use of warp cable BSLs in mid-water trawls, as this is not presently required.
d) the probability of collision with the net monitoring cable is much higher when the mid-water net is used in comparison with the bottom trawl. The difference of depth between mid-water and bottom nets generates a larger cable angle in the former, and therefore a larger distance from the vessel where the cables enter the water, increasing the threat to seabirds. As such, whilst we recommend the use of a BSL for both fishing types, this is of particular importance in the mid-water fishery.
e) use of BSLs for the WC when the fleet fish for Patagonian toothfish can be dismissed due to the near absence of collisions in all situations (so long as the fleet maintain current fishing behaviours). The fleet fish this species at great depths (800–1800 m) and at lower trawl speeds (∼2.5 knots). This combination causes the cables to enter the water very close to the stern (Dellacasa & Chavez observations) minimizing the possibility of collision for seabirds.
f) there were no significant differences in seabird interactions with the net monitoring cable when the discards were minced and mixed and little difference in WC (OR = 4.3), suggesting that minced discards would not be an effective mitigation measure in this fishery.

The maximum sustainable number of fisheries deaths has been calculated at 854 [600–1 190] individuals/year for the entire Southern royal albatross population (Richard *et al*., 2020). With an estimate of 108 [31–186] birds killed annually, this fishery could be directly contributing to population declines of this ACAP-listed species, especially when the impacts of other fisheries in the region are considered (Jiménez *et al*., 2014; Adasme *et al*., 2019; Jiménez *et al*., 2020). With this in mind—and noting that the companies and crews of this fleet are working on this as part of a condition of their MSC certification—we suggest that fleet-wide implementation of mitigation measures is urgent: a zero discards policy, supported by the elimination of the net monitoring cable or use of a snatch block and the deployment of BSLs.

Final comments

The mitigation of seabird bycatch does not consist of a single *silver bullet* solution. The need for a combination of measures is extensively reviewed in various documents, most notably for longline and trawl fisheries (ACAP, 2021a; ACAP, 2021b; ACAP, 2021c). Globally speaking, a pragmatic strategy would be for quick implementation of simple mitigation measures (BSLs) on all trawl cables, with a longer-term aim of implementing discard elimination (or management) or the implementation of wireless technology (in the case of third wire). A permanent and dedicated observer or electronic monitoring program on seabird bycatch and mitigation measure performance, backed by a relevant fisheries regulation, is evidently necessary to ensure the efficacy of mitigation strategies. However, in the short term, sustainable certification schemes can act as a lever for management action.

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Supplementary Material

Supplementary material is available at the *ICESJMS* online version of the manuscript.

Author contributions

LLT, RFD, LNC, RC, and EF contributed to the conceptualization, design, and methodology of the study. RFD and LNC conducted the collection of onboard data. LLT, RFD, and LNC processed and interpreted the data. CJM and MEG led the analysis of the findings. All authors contributed to drafting. LLT, RC, and EF led the revising of the final manuscript.

Conflicts of interest

None declare.

Data Availability

The data underlying this article cannot be shared publicly due for the privacy of individuals and companies that participated in the study.

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