Strategic discarding reduces seabird numbers and contact rates with trawl fishery gears in the Southwest Atlantic

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Abstract

Incidental mortality in trawl fisheries is a serious threat to seabird sustainability. Driven primarily by seabirds attracted to discards, limiting discard discharge through strategic batching is a best practice mitigation measure recommended by the Agreement on the Conservation of Albatrosses and Petrels (ACAP). However, studies supporting the efficacy of batch discarding are rare, limited to the southwest Pacific, and assess seabird numbers attending vessels only, not gear contact rates. The effectiveness of batch discarding in areas with different seabird communities, fishery assemblages, and natural prey availability is therefore unknown. Here we quantify both seabird numbers and gear contact rates in response to strategic discard discharge in the Falkland Islands trawl fleet for two high-risk species groups: black-browed albatross (*Thalassarche melanophris*) and giant petrel species (*Macronectes spp.*). Specifically, we test the effect of three different discharge treatments (zero, batch and continuous discarding) at two vessels. Bird abundance and contact rates were positively related, but zero discarding consistently reduced seabird numbers attending trawlers and eliminated contacts with warp cables and tori-lines. Batching significantly reduced bird abundance and contact rates at the vessel that stored all discards between batches. At the other vessel, however, intermittent release of hashed viscera diminished the mitigation effect. Our findings validate the generality of batch discarding as an effective mitigation measure in trawl fisheries where zero discarding is not possible, while highlighting the importance of complete waste storage.

1. Introduction

Death by fisheries bycatch is one of the greatest threats to seabird populations worldwide (Dias et al., 2019), driven primarily by gillnet (~400,000 mortalities year $^{-1}$; Žydelis et al., 2013) and long-line fleets (160–320,000 mortalities year^{-1}; Anderson et al., 2011). However, collision with trawl gears can also lead to significant mortality. For instance, South Atlantic trawl fisheries accidentally kill ~10–34,000 seabirds per annum (Da Rocha et al., 2021; Kuepfer et al., 2018; Maree et al., 2014; Tamini et al., 2015) primarily from collisions with warp cables or via net entanglement (Kuepfer et al., 2018; Sullivan et al., 2006). Reducing seabird bycatch in trawl fisheries is therefore key for biodiversity and sustainable fisheries.

Seabirds are attracted to trawl fisheries primarily because they generate large quantities of waste (Sullivan et al., 2006; Watkins et al., 2008; Wienecke and Robertson, 2002). These discards can subsidise millions of seabirds (Sherley et al., 2020), benefiting some populations (Church et al., 2019) but can also result in death through entanglement, hooking or colliding with fishing gear (Clay et al., 2019). Managing discards is therefore important for mitigating seabird bycatch.

Strategic discard management may take several forms. A discard ban is the most successful mitigation tool (ACAP, 2019), but this may be unfeasible due to vessel design, processing speed or for political reasons (Bicknell et al., 2013). Storing waste temporarily and releasing it in batches is recommended as the next best mitigation measure for trawlers (ACAP, 2019). Batch discarding reduces seabird numbers attending some New Zealand fisheries (Pierre et al., 2012b, 2010), although direct effect on collision rates has not been assessed. Further, many factors influence seabird-vessel interactions including gear type (Phillips et al., 2016), seabird assemblage composition (Dias et al., 2019; Votier et al., 2010), or environmental factors such as food availability, season, fishing area or weather (Clark et al., 2019; Phillips et al., 2016; Sullivan et al., 2006). It may therefore be inappropriate to assume that discard management approaches apply across different locations, communities or metiers.

Albatrosses and large petrels (Order Procellariiformes) are particularly vulnerable to trawler mortality. They feed extensively on discards - their size enabling them to swallow large discards and also to dominate scavenging interactions behind vessels. In addition, their long wings have a tendency to wrap around warp cables when struck, resulting in birds being pulled underwater and drowned (Løkkeborg, 2011; Sullivan et al., 2006). Fatal strikes can easily go undetected, however, because corpses are not always retained in the cables, making it difficult to quantify this type of mortality (Parker et al., 2013). Quantifying and mitigating impacts of discard management on large Procellariiformes is a conservation priority.

In the Falkland Islands trawl fleet, annual bycatch averaged over 600 seabirds (range: 174–976) between 2004 and 2018, predominantly of black-browed albatross (*Thalassarche melanophris*) but also various petrel species (Kuepfer et al., 2018). Tori-line entanglements accounted for a maximum of 12.5% of observed seabird mortalities in some years (Kuepfer, 2016), highlighting the need for an improved long-term solution to help safeguard or attain a favourable conservation status of internationally protected seabirds. Sullivan et al. (2006) found that the absence of discards almost eliminated contacts with the warp cables but did not find a significant difference in contact rates of black-browed albatrosses between different levels of discharge. The effectiveness of strategic discard management through batch discarding is therefore unknown in this fleet.

Our aim is to quantify the number and collision rates of two high risk species groups – black-browed albatross and giant petrel species (*Macronectes spp.*) – following trawlers in response to three different fish waste treatments: (1) zero discarding, (2) batch release discarding and (3) continuous discarding. Based on previous studies in New Zealand (Pierre et al., 2010, 2012b), we expect that zero discarding has the ability to eliminate seabird bycatch during trawling, and that batch release, though less effective than zero discarding, will still significantly reduce the risk of bycatch. By focussing on the Falkland Islands trawl fleet we not only test these mitigation methods where a very large fishery co-occur with ~72% and ~43% of the global populations of black-browed albatross and southern giant petrels (*M. giganteus*, Crofts and Stanworth, 2021), respectively, but for the first time also assess the generality of such an approach to fisheries operating outside the south-western Pacific.

2. Materials and methods

2.1. Study area and experimental set-up

Our study was conducted in the Southwest Atlantic over the Patagonian Shelf and slope, predominantly in the west and north of the Falkland Islands Conservation Zones (FICZ) 48°S–56°S and 52°W–63°W (**Figure 1**). These waters are trawled throughout the year by demersal freezer factory vessels targeting a variety of finfish, squid and skate (Falkland Islands Government, 2019).

Experimental data were collected aboard two similar-sized trawlers but with differing hold capacities during four separate commercial finfish fishing trips (**Table 1**). For logistical reasons, the two vessels could not be observed simultaneously. Both vessels used obligatory tori-lines during all trawling activities. The factories of the two vessels had been retrofitted with 3 m^3 discard storage tanks designed to receive, store and batch release discards. Once full, the tanks empty directly into the sea. On Vessel A, a design fault meant that viscera were not collected in the tank, but instead passed through two scuppers, hashed (coarsely cut in a hasher pump), and discharged automatically and intermittently in approximately 2-minute intervals whilst all other waste was stored. This was different from Vessel B where all discards were stored.

Three experimental discarding treatments were implemented during net towing:

(1) Continuous – Discards discharged on a continuous/*ad-hoc* basis when available, with tank doors left open and no waste stored.
(2) Batch – Discards temporarily stored before being batch discharged. Once empty, storage resumed. Batch discharges occurred as and when the tanks reached capacity or when factory work was complete. Between batch discharges, filtered factory water continued to be discharged at a continuous rate for practical and safety reasons. At Vessel A, intermittent discharge of hashed viscera continued to occur as well.
(3) Zero – No discards or factory water discharged due to absence of ongoing factory processing during net towing.

Effects of these treatments on seabird-vessel interactions were measured using (a) the abundance of high-risk seabird groups in defined zones at the vessel stern, and (b) contact rates with warp cables and tori-lines. Commercial fishing practices continued throughout the observation periods.

2.2. Data collection

Data were collected by a single observer (AK), who conducted seabird observations from the vessel stern in daylight hours using the naked eye. Use of binoculars was unnecessary given the proximity of the birds to the observer. Although observations were conducted throughout the fishing operation (shoot, trawl, haul), experimental data for the current study were collected during net towing only. For reasons of safety and practicality, observations were not conducted in hours of darkness or at wind speeds exceeding 35 knots.

2.2.1. Environmental and operational parameters

A suite of environmental and operational variables considered relevant to bird interactions (Phillips et al., 2016) was recorded at the start of every observation period: wind speed and sea state (Beaufort scale), wind direction relative to trawling direction, and the number of other vessels operating in the vicinity (as visible by eye). Further, discard level (the volume of discard discharged, based on a subjective assessment of intensity of discharge) and discard rate were recorded to establish compliance with treatment. Observations were combined into sample periods of similar environmental and operational parameters. A new sample period was started whenever one of these parameters changed, or after a maximum of 60 minutes.

2.2.2. Seabird abundance

All seabirds within 500 x 500 m from the vessel stern were recorded at the start of each sample period, and high-risk black-browed albatrosses (hereafter BBA) and giant petrel species (hereafter GP) were allocated a position relative to the stern (modified from Abraham et al., 2009; **Figure A1**): (1) 40 m-radius semi-circle of birds on the water; (2) 40 m-radius semi-circle of birds in the air; (3) area between the tori-lines (c. 10 x 30 m) of birds on the water.

Sweep counts were conducted once at the start of every 10-minute subsample period inside the 40 m areas, and five times during a 10-minute subsample period inside the tori-line area. The latter was implemented only from Trip 2 onwards. The observer spent no more than 30 seconds on each sweep count. Sub-sample periods were always 10 minutes, except when the sample period changed before the completion of a sub-sample period. As such, a sample period contained a maximum of 6 x 10-minute sub-sample periods.

2.2.3. Contact rates

During trawling, seabird contacts with warp cables and tori-lines were recorded and classified as heavy or light based on Sullivan et al. (2006; **Table A1**) and assigned one of five fates (no apparent harm, minor injury, major injury, death or unknown).

2.3. Statistical analysis

All data exploration and statistical analyses were conducted in R (R Core Team, 2019). Variables of interest were explored for outliers using Cleveland plots, and the presence of collinearity and correlation of variables assessed using multi-panel scatterplots, Pearson correlation coefficients and variance inflation factors (VIF) (Zuur et al., 2010). To avoid numerical estimation problems and improve interpretation of the parameters, continuous explanatory variables were z-score standardised (Harrison et al., 2018).

A series of models were built using the glmmTMB package (function glmmTMB; Brooks et al., 2017) to determine (a) the effect of discard treatment on seabird abundance and contact rates, and (b) the relationship between contact rate and bird abundance. Count data were modelled using a Poisson error distribution except where over-dispersed, in which case we used a negative binomial error with a log-link function (Hardin and Hilbe, 2007; Magnusson et al., 2020). For seabird abundance, individual models were built separately for BBA and GP in each of the three count areas behind vessels, using respective abundance counts as the response variables. Contacts models were built for (a) all contacts and (b) heavy contacts individually for BBA and GP, with numbers of contacts used as the response variables, and the natural log of observation duration as the offset (log min) (Zuur et al., 2014).

We generally used sample period (see section 2.2.1) nested in trawl as our random effects with a common slope to account for the fact that bird abundance and contact rates within a sample period and a trawl are not independent. For the tori-line area abundance models, the nested random effects were under-dispersed, thus these were simplified by removing the nested component of the random effect. In all cases, model residuals were checked for autocorrelation (function acf) and there was no evidence of an influence of discard treatment in one trawl on seabird abundance and contact rates at subsequent trawls.

Models assessing discard treatment as the main variable of interest included a range of environmental variables with the potential to influence seabird-vessel interactions (**Table 2**). In abundance models, data from the two vessels were combined for analyses, with Vessel_id and the interaction of Vessel_id and Treatment included (**Table 2**). In contact models assessing treatment effect, high variance and the absence of certain factor levels at Vessel B meant that the data were analysed separately for the two vessels. However, additional models confirmed that treatment effects on contact rates remained the same at the two vessels when data were analysed jointly, using exclusively Vessel_id, Treatment and their interaction as fixed factors (**Table A7**). A stepwise backwards model selection procedure was conducted to determine the final set of covariates for each model, using the lowest Akaike's Information Criterion (AIC) to choose between alternative models.

Where we assessed the relationship between contacts and abundance, data from the two vessels were combined, as exploratory analyses revealed no changes in the overall direction of the relationship between contacts and abundance at the two vessels. The fixed effects in alternative models included exclusively abundance counts in the various sweep count areas (40 m on the water, 40 m in the air, tori-line area) and counts of the 40 m areas combined. The lowest AIC was used to then choose between alternative models.

Model fit was assessed using appropriate diagnostics (Zuur and Ieno, 2016) with tools provided by the DHARMa package in R (Hartig, 2019), and included assessment of residuals for dispersion, uniformity and zero-inflation (functions testDispersion, simulateResiduals, testZeroInflation). Influential outliers as assessed through residual plots were removed, and whilst this generally improved model fit, it never changed the significance levels of individual parameters. Significance level for all tests was $\alpha = 0.05$.

3. Results

3.1. Experimental summary

Experimental observations were conducted for a total of 216 hrs, comprising 58 fishing days and 106 experimental trawls (Vessel A: 68; Vessel B: 38) (Table 3). The numbers of trawls per discard treatment were 23 trawls during zero discarding, 51 trawls during batch discarding, and 32 trawls during continuous discarding. Mean discard storage time was 33 min (9–120 min) on Vessel A, and 18 minutes (3–42 min) on Vessel B, with batch discharge events taking a mean of 1.1 and 1.6 min, respectively. During batching events, bird abundance inside the count areas changed too quickly to conduct abundance counts, as numbers first increased when discards appeared, and then decreased as the vessel moved forward and the birds remained with the discard patch (**Figure 2**).

3.2. Seabird abundance

During the experiments, 14 seabird species were observed within 500 m of the vessel with BBA most abundant and frequent, followed by Cape petrels (*Daption capense*) and GP (**Table A2**). BBA and GP were present on 100% of occasions (BBA: 10 to > 500 birds; dominant abundance class = 201–500 birds; GP: 10 to 200 birds; dominant abundance class = 51–200 birds). Other procellariiformes recorded were royal albatross species (*Diomedea* *pomophora/sanfordi*), white-chinned petrel (*Procellaria aequinoctialis*), grey-headed albatross (*Thalassarche chrysostoma*), wandering albatross (*Diomedea exulans*), great shearwater (*Puffinus gravis*), sooty shearwater (*Ardenna grisea*), Wilson's storm-petrel (*Oceanites oceanicus*), and southern fulmar (*Fulmarus glacialoides*).

3.2.1. Impact of discarding on seabird abundance

Relative to continuous discarding, zero discarding significantly reduced abundance of BBA and GP within 40 m of the vessel ($p < 0.05$; **Figure 3**), with none inside the tori-line area. Batch discarding reduced the number of BBA in all count areas, and significantly so for birds in the air ($z = -2.64$; $p < 0.008$) and within the tori-line area ($z = -10.02$; $p < 0.001$; **Figure 3**). The preferred model did not indicate an effect of vessel identity which might be expected given their difference in discard storage capacities. However, when the data for Vessel A and Vessel B were analysed separately, batch discarding significantly reduced BBA on the water within the 40 m area at Vessel B where all discards were stored ($z = -2.83$; $p = 0.005$), but not at Vessel A where intermittent discarding of viscera continued during storage periods ($z = -0.80$, $p = 0.424$). For GP, the batch treatment also reduced abundance in all count areas, and significantly so for birds on the water (40 m: $z = -2.46$; $p = 0.014$) and within the tori-line area at Vessel B only ($z = -2.43$; $p = 0.015$; **Figure 3**).

Other environmental variables that significantly affected bird abundance in at least one of the sweep count areas were wind speed (higher winds increased BBA abundance), relative wind direction (cross winds increased BBA abundance; tail and cross winds increased GP abundance), trawl duration (increased duration decreased BBA abundance), season (increased BBA abundance during winter; increased GP abundance during the egg laying season), and the number of other vessels visible (increased vessel numbers increased BBA abundance) (**Table A6**).

3.3. Contact rates

A total of 8,581 contacts by BBA and GP were recorded with warp cables and tori-lines, the majority of which were light, on the water and resulted in no apparent damage (78%; **Table A4**). Heavy warp contacts, which have the potential to cause harm, were predominantly incurred by birds on the water (82%). Almost 10% of heavy contacts resulted in harmful or potentially harmful outcomes (death, major injury or unknown fates), although this varied between species (BBA: 11.3%; GP: 7.5%). Sixteen mortalities occurred during experimental observations (15 BBA and one grey-headed albatross), from heavy warp strikes ($n = 14$) and entanglement with the tori-line ($n = 2$). At least 13 of these mortalities occurred during continuous discarding, whilst two occurred during batch discarding.

3.3.1. Impact of discarding on seabird collisions

Zero discarding consistently incurred zero contacts (**Table A5**) and were therefore not analysed further. Compared to continuous discarding, batch discarding significantly reduced contact rates for both BBA and GP at Vessel B (all $p < 0.001$, **Figure 4**). Only heavy contacts of BBA were reduced significantly at Vessel A ($z = -3.02$; $p = 0.003$), although the effect was still significantly stronger at Vessel B where all discards were stored than at Vessel A where viscera continued to be released at an intermittent rate ($z = -2.49$; $p = 0.001$).

During the batch treatment, contact rates of GP and BBA combined declined significantly during storage periods relative to batching events (all contacts: $z = -9.79$; $p < 0.001$; heavy contacts: $z = -3.47$; $p = 0.001$). This difference in contact rates between storage and batching events was significantly greater at Vessel B compared to Vessel A ($p < 0.001$).

Other environmental variables that had a significant effect on contact rates included sea state (heavier sea states increased BBA and GP contacts), relative wind direction (cross and tail winds increased BBA contacts, cross winds increased heavy GP contacts) and season (winter and egg season saw higher overall contacts by both GP and BBA than the chick season), number of vessels visible (fewer heavy contacts of BBA with more vessels), and cumulative trawl duration (fewer contacts of BBA with longer trawl durations) (**Table A7**).

3.3.2. Seabird abundance and contact rates

The number of birds attending trawlers was positively correlated with contact rates for BBA and GP (all minimum: $p < 0.001$; **Figure 5**), although this relationship was not significant for GP in the air. Birds inside the tori-line area generally best explained contacts rates, except for heavy contacts of GP, where there was no significant difference between alternative models (**Table 4**).

4. Discussion

4.1. Effect of discard management on seabird-vessel interactions

In the current study, seabird abundance and contact rates were used to test the effect of strategic discard release on seabird-vessel interactions in a Southwest Atlantic trawl fishery. As hypothesised, when discards were absent, there were no birds within the tori-line area, and no contacts with warp cables or tori-lines. In addition, compared to the continuous discharge of discards, batch discarding significantly reduced seabird abundance and contacts. The high interaction rates of BBA is consistent with their dominance at comparable trawl fisheries operating across the wider Patagonian shelf (Favero et al., 2011; Seco Pon et al., 2015; Tamini et al., 2015), which in turn suggests our findings should generalise to trawl fisheries operating across the wider Southwest Atlantic.

The extent to which batch discarding reduced seabird interactions varied between the two vessels, being significantly greater at Vessel B where all discards were stored. As simultaneous data collection on Vessel A and Vessel B was not possible, we cannot entirely exclude the possibility of a temporal effect. However, the automatic and intermittent release of hashed viscera during storage at Vessel A provided obvious feeding opportunities thus reducing the effectiveness of batching. Birds are known to increase around vessels when food is present (Pierre et al., 2012a, 2010) and this observation was supported by additional analyses showing an incremental increase in seabird-gear interactions with increasing discard availability (rate and volume) at both vessels (**Table A8**). It confirms that reducing the temporal occurrence of discharges is a more effective form of bycatch mitigation for a wider array of seabird species than is discard manipulation such as hashing or mincing (Abraham et al., 2009; Pierre et al., 2010, 2012a).

The significant reductions in seabird-vessel interactions as a result of batch discarding were observed despite relatively short storage periods (average of 18 minutes on Vessel B). This is contrary to findings elsewhere where storage periods of 30 minutes reduced the abundance of small seabirds such as Cape petrels, but not significantly so for larger species such as BBA and GP (Pierre et al., 2012b). This difference may be influenced by operational and environmental factors such as seabird or vessel assemblage, or availability of natural prey. Nonetheless, batch discarding resulted in substantially higher seabird abundance and contact rates compared to the zero-discard treatment, particularly during batching events. Any discards, including factory water, increases bird abundance (Pierre et al., 2010), and the frequent batching events in our study likely contributed to keeping birds closer to vessels. The mitigation potential of discard management can therefore be maximised through prolonged storage periods and by minimising batch-discarding events during trawling activities (Pierre et al., 2010; 2012a,b).

4.2. Bird abundance and contact rates

We found that increased bird abundance generally resulted in higher contact rates (**Figure 5**). However, this relationship and the extent to which these individual measures of seabird-fisheries interaction were influenced by discard management, varied depending on the sweep count area and species considered (**Table 4**).

In general, contact rates were most strongly influenced by bird abundance inside the tori-line area where they are closest to warp cables. Within the 40 m count area, the number of GPs in the air had no effect on GP contacts, whilst BBA abundance in the air was as strongly correlated with collisions as was abundance on the water (**Figure 5**). This difference may be because, unlike BBA, GP rarely approach discards from the air. Moreover, bird abundance showed a greater response to the batch discard treatment than did contact rates in some instances. Batch discarding reduced BBA abundance inside the tori-line area and in the air, as well as GP abundance on the water (40 m) significantly at both vessels. However, contacts were only significantly reduced at Vessel B for both species. The discrepancy is likely the result of other interacting environmental variables influencing abundance and contacts (wind speed, wind direction, season, numbers of vessels visible, trawl duration).

Our results validate the use of bird abundance as a reliable estimate of collision rates in discard management studies where the latter cannot be collected for reasons of logistics or limited resources. In such events, we emphasise the use of multiple sweep count areas in order to maximise confidence in conclusions drawn about the effectiveness of the discard management system being tested (see also Abraham et al., 2009; Pierre et al., 2010, 2012a,b).

4.3. Implementing batch discarding

As well as being reliant on trained and cooperative crew, our study demonstrates that the efficacy of mitigation depends on the discard storage system – i.e., its capacity to store all discards before releasing them systematically in batches. Vessel design differences inhibit a one-size-fits-all solution; close collaboration between scientists, vessel architects and factory crew can help ensure that the deployment of any new equipment can safely and efficiently be built into the processing routine.

Importantly, our study shows that unlike zero discarding, batch-discarding during trawling does not eliminate bird interactions entirely. In addition, discard management cannot completely mitigate against net entanglements that can occur when birds scavenge from the net during shooting and hauling operations. This highlights the benefit of additional mitigation measures during fishing activities, including bird-scaring devices during trawling, effective net cleaning, and efficient deck procedures to minimise the time of shoot and hauling durations (ACAP, 2019).

Finally, while batch discarding does not eliminate this artificial food subsidy for seabirds, it is likely to make it less accessible nonetheless, depending on the sink rate of discards and the competitive abilities of scavenger species. Scavenging seabirds tend to be generalist and opportunist feeders, able to switch prey, so long as alternative prey are available (Bicknell et al., 2013). Monitoring of natural prey availability as well as dietary and demographic monitoring of affected seabird species will improve our understanding of their dietary flexibility, and potential demographic implications of reduced discard accessibility.

4.4. Study limitations

Collecting data aboard commercial vessels often presents logistical challenges that inhibit study design across multiple vessels or seasons (e.g. Abraham et al., 2009; Melvin et al., 2011; Pierre et al., 2010, 2012a), but provides a realistic assessment of mitigation measures under operational conditions. More research is required to assess how mitigation is influenced by other factors such as wind, trawl duration and season, probably best achieved via more studies on commercial vessels.

5. Conclusion

Our study shows that zero-discarding prevented seabird collisions with trawl gears and batch-discarding significantly reduced collisions, particularly when discards were stored effectively between batches. We also found that bird abundance provides a reliable proxy of collision rate, which is important for other studies unable to document bird strikes. Our results provide strong support for discard management as an effective bycatch mitigation tool in the Falklands and demonstrate that batch discarding can significantly reduce bycatch for trawl fisheries where a complete discard ban or prolonged discard storage is unfeasible. Given similar results from New Zealand, this result is likely to apply across a wide range of scenarios, although further research to confirm this is warranted. Differences in discard management designs that limit waste storage may also influence the mitigation potential of batch discarding. Thus, we recommend a re-appraisal of waste management across all fisheries that produce significant amounts of discards.

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Figures

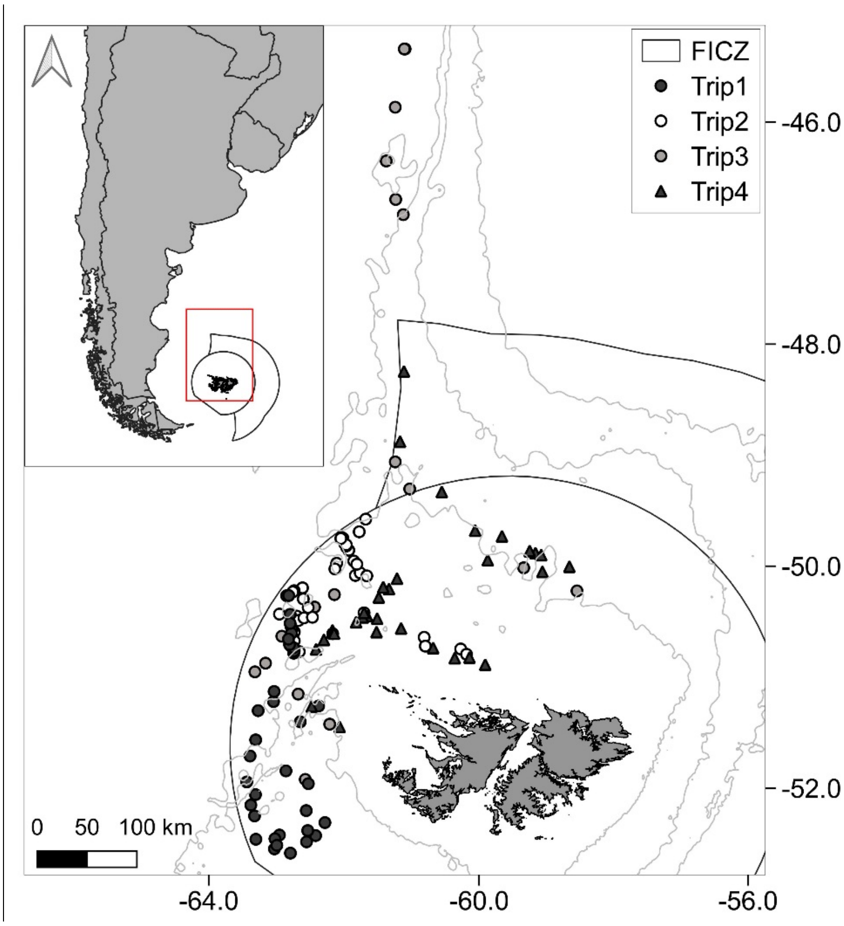

Figure 1. Fishing locations east and north of the Falkland Islands over the Patagonian Shelf during the individual experimental trips on Vessel A (Trips 1–3) and Vessel B (Trip 4). FICZ = Falkland Islands Conservation Zones. The 200, 500 and 1000 m depth contours are shown.

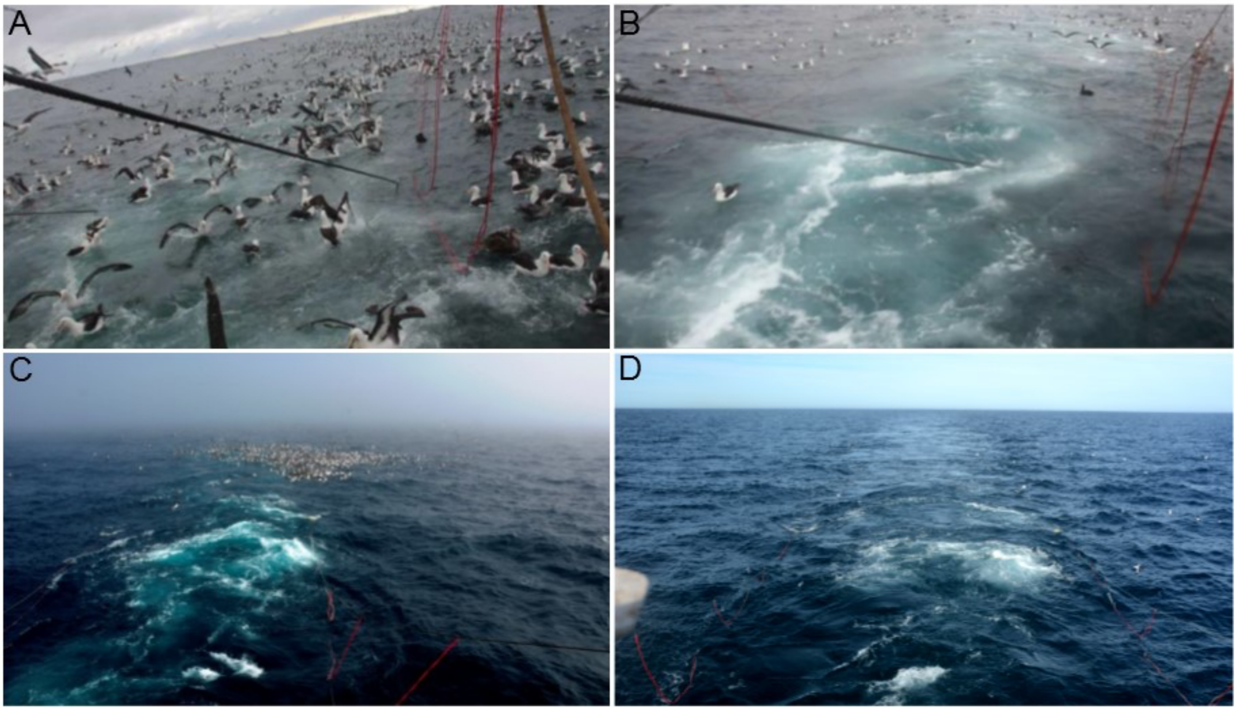

Figure 2. Typical view from the vessel stern during continuous discarding (A), discard storage (B), shortly after a batching event (C), and during zero discarding (D). The portside warp cable and tori-line are visible on A–C; both tori-lines are visible in D.

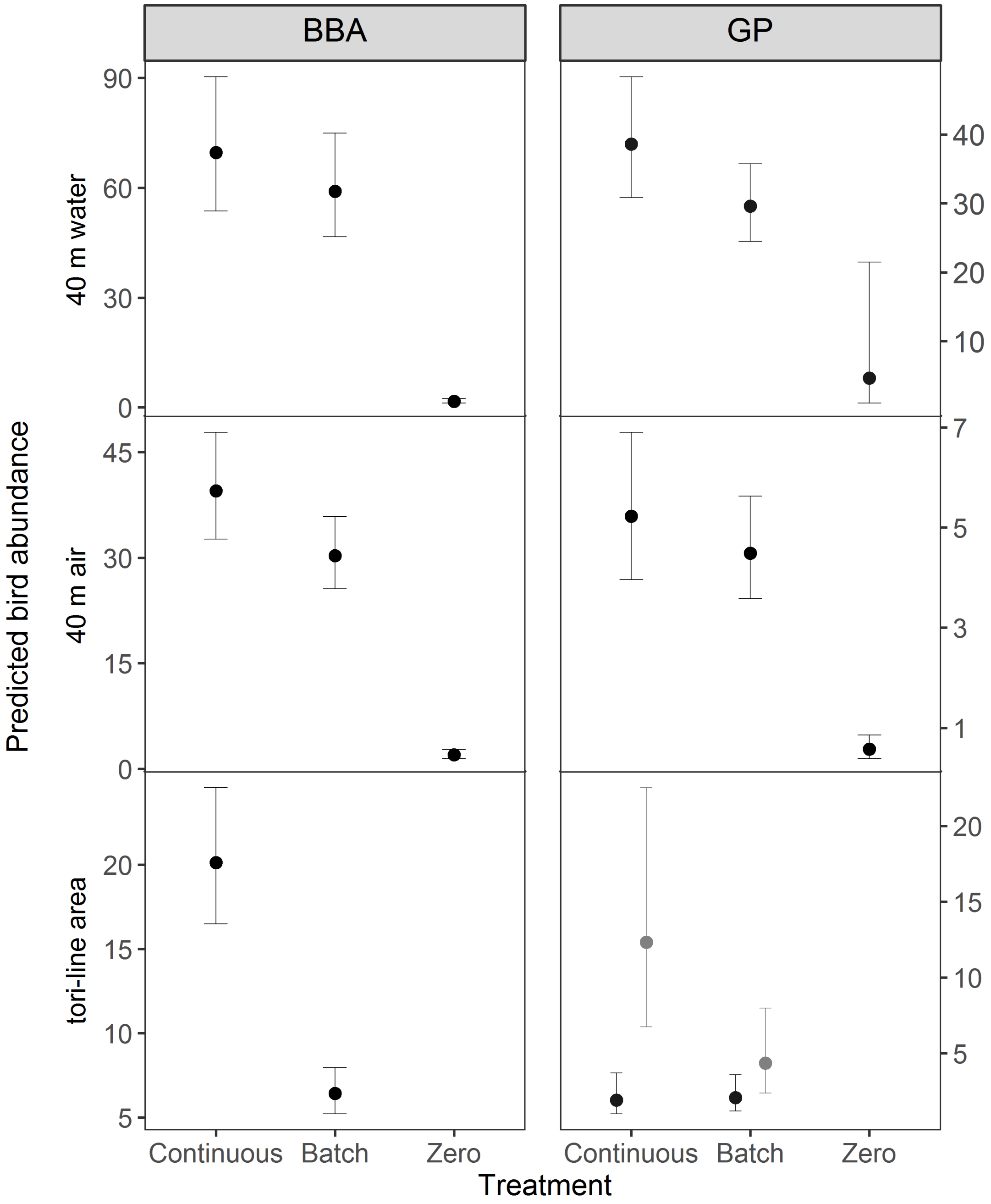

Figure 3. Predicted abundance (marginal mean ± 95% CI) of black-browed albatrosses (BBA) and giant petrel species (GP) relative to discard treatments. Bottom right panel shows predictions for Vessel A (black) and Vessel B (grey). Note the difference in scales between panels.

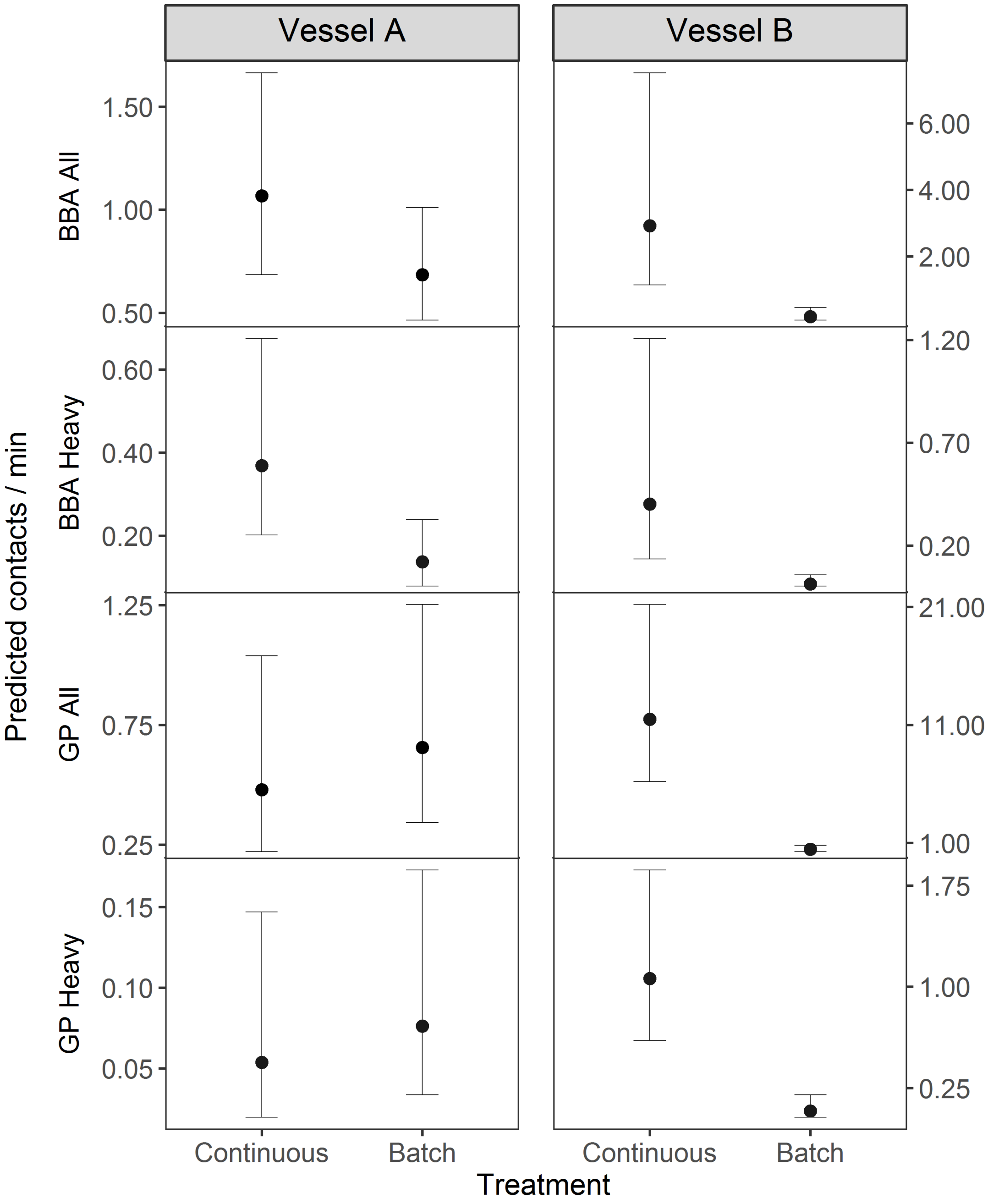

Figure 4. Contact rates per min (marginal mean ± 95% CI) for black-browed albatrosses (BBA) and giant petrel species (GP) relative to discard treatments at Vessel A and Vessel B. Note the difference in scales between panels.

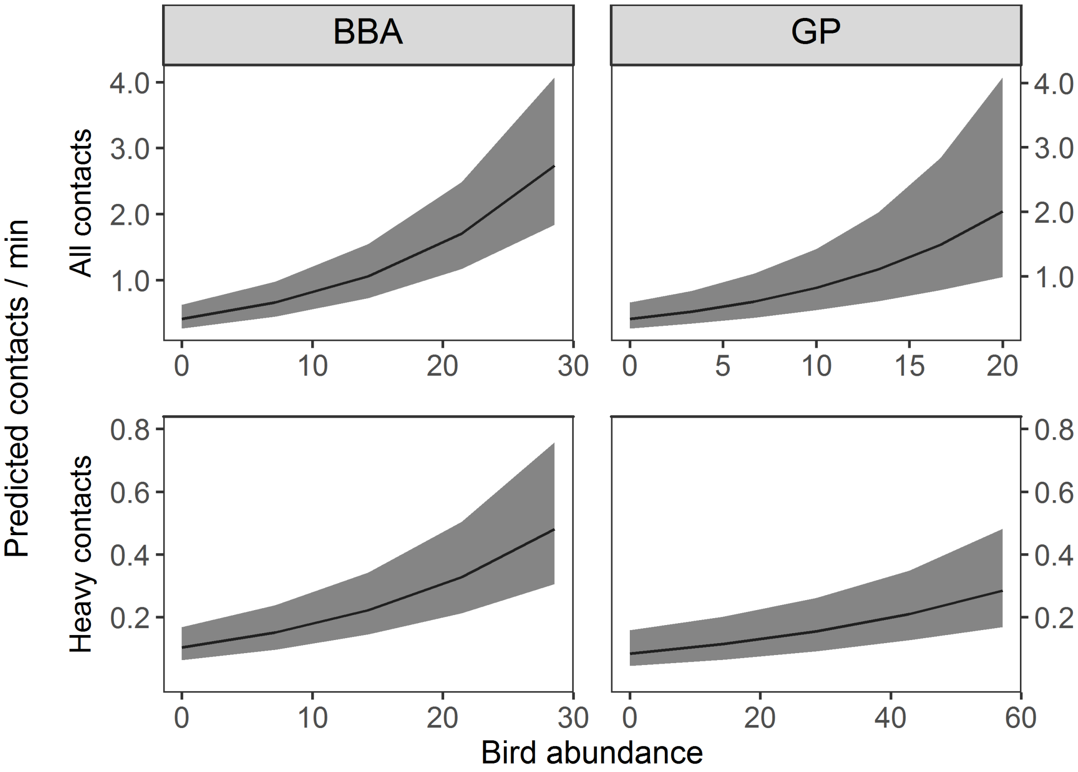

Figure 5. Contact rates per min (marginal mean ± 95% CI) in relation to bird abundance of black-browed albatrosses (BBA) and giant petrel species (GP). Best fit models (lowest AIC) shown only, hence bird abundance relates to the tori-line sweep count area in all plots, except for GP heavy contacts (bottom right), where bird abundance relates to the 40 m water sweep count area. The x-axes have been capped to assist visualisation of the relationship at more characteristic abundances of respective sweep count areas. Note the difference in scales between panels.

Tables

Table 1. Specifications of study vessels used.

	Vessel A	Vessel B
Length	54 m	53 m
Hold capacity	450 t	720 t
Discard management storage system	3 m^3 tank to temporarily store all discards *except* viscera. Batch release directly out to sea.	3 m^3 tank to temporarily store all discards, *including* viscera. Batch release directly out to sea.
Study dates	Trip 1 (05–22 Apr 2015) Trip 2 (14 May–02 Jun 2015) Trip 3 (29 Oct–10 Nov 2015)	Trip 4 (10–28 Apr 2017)

Table 2. Variables used for modelling seabird interactions. AT = Abundance models where Treatment is the main variable of interest; CT = Contacts models where Treatment is the main variable of interest; CA = Contacts models where Abundance is the only variable of interest. Interaction terms included in models are indicated by identical superscript numbers. BBA = Black-browed albatross. GP = Giant petrel species.

Effects	Explanatory variable	Definition	Type	Models
Fixed	Treatment[1,2]	Experimental discard treatment	Factor	AT, CT
	Vessel id[1]	Vessel A or Vessel B	Factor	AT
	Wind speed	Wind speed in knots	Continuous	AT
	Sea state	Sea state in Beaufort scale	Continuous	CT
	Season	Chick-rearing, winter and egg-laying	Factor	AT, CT (Vessel A only)
	Relative wind direction	Wind direction relative to trawling direction: 45˚, 90˚, 135˚, astern, into	Factor	AT,CT
	Vessels visible	The number of vessels counted around the experimental vessel	Continuous	AT,CT
	Abundance (BBA / GP)	Bird abundance inside sweep count areas, or combined 40 m areas	Continuous	CA
	Cumulative trawl duration[2]	Based on sample numbers 1, 2, 3, 4, etc.	Continuous	AT, CT
Random	Trawl	Trawl number	Factor	AT, CT, CA
	Sample (nested in Trawl)	A unique number representing the sample period given a particular trawl	Factor	AT (except tori-line area models), CT, CA
Offset	Log(min)	Duration in minutes of subsample period	Continuous	CT, CA

Table 3. Summary of data collected. (d) = days, (t) = trawls, (s) = samples, (c) = counts. Trip1, 2, and 3 were made on Vessel A; Trip 4 was made on Vessel B.

Treatm.	Trip	All observations				40m abundance data (water & air)			Tori-line area abundance data			Contacts data	
		N(d)	N(t)	N(s)	obs. (hrs)	N(s)	N(c)	obs. (hrs)	N(s)	N(c)	obs. (s)	N(s)	N(c)
Cont.	1	6	10	72	20.83	66	119	19.55	0	0	00.00	55	102
	2	6	9	73	23.12	72	142	22.95	71	141	22.93	67	142
	3	4	4	22	5.88	13	16	2.52	13	16	2.52	13	16
	4	9	9	29	18.97	28	113	13.80	24	97	12.33	28	114
Batch	1	10	17	228	41.65	191	280	38.30	0	0	0.00	206	307
	2	12	16	207	39.12	202	311	37.95	200	312	38.05	195	312
	3	5	5	48	10.95	37	53	6.70	37	53	6.7	36	52
	4	11	13	163	28.77	90	189	21.90	63	126	21.9	160	244
Zero	1	1	1	1	0.93	1	6	0.93	0	0	0	1	6
	2	0	0	0	0.00	0	0	0.00	0	0	0	0	0
	3	6	6	17	9.08	17	55	9.08	16	49	9.08	12	55
	4	14	16	22	17.08	21	105	16.82	21	105	6.82	20	104
Total				882	216.4	738	1389	190.5	445	899	130.3	793	1454

Table 4. Generalised linear mixed model outputs assessing seabird contact rates as a function of seabird abundance. BBA = black-browed albatross; GP = giant petrel species; TL = tori line; AIC = Akaike's Information Criteria. Significance level at $\alpha = 0.05$.

Response variable	Abundance area	Δ AIC	Estimate	Std. Error	z-value	p-value
BBA all contacts	TL area	0.0	0.948	0.084	11.280	<0.001
	40 m water + air	49.2	1.016	0.125	8.157	<0.001
	40 m air	62.9	0.863	0.122	7.090	<0.001
	40 m water	63.0	0.876	0.122	7.211	<0.001
BBA heavy contacts	TL area	0.0	0.770	0.097	7.952	<0.001
	40 m water + air	14.0	0.893	0.134	6.626	<0.001
	40 m air	20.7	0.803	0.134	5.996	<0.001
	40 m water	23.7	0.749	0.130	5.747	<0.001
GP all contacts	TL area	0.0	0.598	0.113	5.309	<0.001
	40 m water	12.9	0.541	0.130	4.153	<0.001
	40 m water + air	13.5	0.523	0.128	4.080	<0.001
	40 m air	27.3	0.142	0.085	1.664	0.096
GP heavy contacts	40 m water	0.0	0.610	0.134	4.570	<0.001
	TL area	3.4	0.402	0.095	4.229	<0.001
	40 m water + air	6.1	0.486	0.136	3.578	<0.001
	40 m air	16.7	-0.037	0.126	-0.293	0.77

Supplementary Information

6.1. Appendix 1: Data collection protocol – additional information

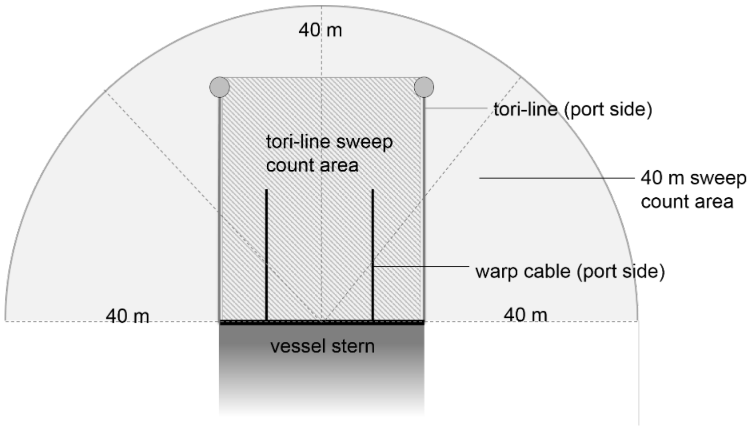

Figure A1. Specific areas behind the vessel stern in which black-browed albatross and giant petrel species were counted. Not drawn to scale.

Table A1. Seabird-cable /tori-line strike definitions adapted from Sullivan et al. (2006).

Location	Light strike	Heavy strike
Air	Bird in flight makes contact with the warp cable /tori-line but flies away in a controlled manner.	Bird makes contact with the warp cable /tori-line during flight and is deviated from its natural path or falls into the water.
Water	Bird sitting on the water makes contact with the warp cable /tori-line and, while bird seems unaffected, it may or may not fly away.	Bird sitting on the water makes heavy contact with the warp cable /tori-line and becomes deviated from its natural path, and at least partly submerged.

6.2. Appendix 2: Seabird abundance and contact counts – raw data

Table A2. Abundance classes for 500 × 500 m counts: 1 (1–10 birds), 2 (11–50 birds), 3 (51–200 birds), 4 (201–500 birds), and 5 (> 501 birds). P = present, for instances when it was too dark to collect abundance data. Modal class (class range), and the percentage of times the species was present during abundance counts are given.

Species	Trip 1 (05/04 - 22/04/2015)	Trip 2 (14/05 - 02/06/2015)	Trip 3 (29/10 - 10/11/2015)	Trip 4 (10/04 - 28/04/2017)
Black-browed albatross *Thalassarche melanophris*	5 (1-5), 100%	4 (1-5), 100%	2 (1-5), 100%	5 (1-5), 100%
Giant petrel spp. *Macronectes spp*	3 (1-5), 100%	2 (1-4), 100%	2 (1-5), 100%	3 (1-5), 100%
Cape petrel *Daption capense*	5 (1-5), 100%	4 (1-5), 100%	2 (1-4), 98%	3 (1-5), 98%
Wilson's storm-petrel *Oceanites oceanicus*	P, 4%	P, 1%	P, 81%	P, 8%
Royal albatross species *Diomedea pomophora/sanfordi*	1 (1), 5%	1 (1-2), 51%	1 (1-2), 71%	2 (1-3), 88%
White-chinned petrel *Procellaria aequinoctialis*	3 (1-4), 68%	3 (1-4), 74%	1 (1-3), 41%	3 (1-3), 84%
Great shearwater *Puffinus gravis*	2 (1-3), 53%	1 (1-2), 28%	1 (1-2), 17%	1 (1), 33%
Kelp gull *Larus dominicanus*	0	1 (1), 24%	1 (1), 6%	0
Wandering albatross *Diomedea exulans*	1 (1), 10%	1 (1), 23%	1 (1), 1%	0
Southern fulmar *Fulmarus glacialoides*	2 (1-3), 59%	P (1-2), 41%	0	1 (1), 11%
Sooty shearwater *Ardenna grisea*	0	0	0	1 (1), 8%
Grey-headed albatross *Thalassarche chrysostoma*	3 (3-4), 71%	P (1), 8%	0	1 (1), 4%
Gentoo penguin *Pygoscelis papua*	0	1(1), 1%	0	0
South American tern *Sterna hirundinacea*	1 (1), 3%	0	1 (1-2), 14%	0
Unidentified giant albatross spp. *Diomedea spp.*	1(1-2), 40%	1(1), 22%	1 (1), 2%	0

Table A3. Abundance counts (mean ± sd) of black-browed albatross (BBA) and giant petrel species (GP) in the three count areas during the three discarding treatments.

Vessel	Treatm.	BBA			GP		
		40m water	40m air	tori-line area	40m water	40m air	tori-line area
A	Cont.	97.09 ± 59.3	55.13 ± 31.7	23.89 ± 14.1	28.17 ± 31.3	7.43 ± 13.2	3.75 ± 7.5
	Batch	66.23 ± 48.7	39.14 ± 28.9	12.41 ± 17.8	22.33 ± 22.6	4.64 ± 7.1	2.69 ± 5.9
	Zero	1.20 ± 2.0	2.25 ± 4.1	0.00 ± 0.0	1.18 ± 1.7	1.43 ± 2.0	0.00 ± 0.0
B	Cont.	98.12 ± 47.5	47.57 ± 20.9	24.72 ± 9.7	58.87 ± 26.1	8.67 ± 9.3	15.44 ± 8.6
	Batch	75.68 ± 45.4	37.25 ± 27.0	3.92 ± 4.2	40.62 ± 23.5	6.71 ± 6.7	3.36 ± 3.5
	Zero	2.22 ± 2.8	1.72 ± 1.7	0.00 ± 0.0	0.99 ± 1.7	0.84 ± 1.0	0.00 ± 0.0

Table A4. Summary statistics of seabird contacts with the warp cable and tori-lines during experimental trawls. CP = Cape petrel, GHA = grey-headed albatross, BBA = black-browed albatross, RA = Royal albatross species, SF = southern fulmar, GP = giant petrel species, WCP = white-chinned petrel, GS = great shearwater, SAT = South American tern. TL = tori-line, W = warp, NOA = no apparent damage, PMI = possible minor injury, PMA = possible major injury, D = death, U = unknown.

Spp	Contact Point	Fate	Trip 1				Trip 2				Trip 3				Trip 4			
			Water, light	Water, heavy	Flying, light	Flying, heavy	Water, light	Water, heavy	Flying, light	Flying, heavy	Water, light	Water, heavy	Flying, light	Flying, heavy	Water, light	Water, heavy	Flying, light	Flying, heavy
CP	TL	NOA	1	4	2	4	12			3								
	W	NOA	6	8	1	1	10	8	1	8								
		PMI						1										
GHA	TL	NOA	16	16	7	10	2											
	W	D		1														
		NOA	7	8	9	5												
BBA	TL	D														1		
		NOA	48	23	5	50	182	41	20	121	35	5	6	12		1		
		PMI		1														
	W	D		3				3								4		
		NOA	103	32	47	64	786	105	226	80	116	17	22	18	2332	277	43	23
		PMA		1												3		
		PMI		4						1				1				
		U		9				8				1				79	1	
RA	W	NOA														1		
SF	TL	NOA	2	1		1	4	1	1	1								
	W	NOA					1											
GP	TL	NOA	45	8	1	4	152	4	1	12	288	6	2	2				
	W	NOA	47	18			224	54	2		249	66		4	2146	245	2	1
		PMA														1		
		PMI												1		2		
		U						2				2				30		
WCP	TL	NOA	1	2	1	2	2											
	W	NOA				1			1									
GS	TL	NOA						1										
SAT	W	NOA									1							
Total			276	139	73	142	1375	228	252	226	689	97	30	38	4478	644	46	24

Table A5. Contact rates per hour ± sd of black-browed albatross (BBA) and giant petrel species (GP) during the three discard treatments.

Vessel	Treatment	BBA		GP	
		All	Heavy	All	Heavy
A	Continuous	28.98 ± 11.0	8.86 ± 4.1	8.15 ± 4.3	1.80 ± 1.5
	Batch	11.67 ± 3.1	2.71 ± 0.9	10.21 ± 5.8	1.29 ± 0.7
	Zero	0.00 ± 0.0	0.00 ± 0.0	0.00 ± 0.0	0.00 ± 0.0
B	Continuous	121.58 ± 31.6	16.29 ± 4.4	102.39 ± 21	11.39 ± 3.2
	Batch	15.92 ± 4.3	2.75 ± 1.1	16.86 ± 3.9	2.19 ± 0.8
	Zero	0.00 ± 0.0	0.00 ± 0.0	0.00 ± 0.0	0.00 ± 0.0

6.3. Appendix 3: GLMM outputs for models assessing the effect of discard treatment

Table A6. Results of GLMM, with **abundance** as the selected response variable, and **treatment** as the primary variable of interest. P = Poisson distribution. NB1 = negative binomial distribution with a log-link function, where the variance increases linearly with the mean as $\sigma 2 = \mu(1 + \alpha)$, with $\alpha > 0$ (where α is the overdispersion parameter, Hardin and Hilbe 2007; Magnusson et al., 2020). Significance level at $\alpha = 0.05$. BBA = black-browed albatross; GP = giant petrel species.

Model	Effects	Variable	Estimate	Std. Error	z-value	p-value
BBA		(Intercept)	4.03	0.16	25.71	< 0.001
(40m water)	Fixed	Ves. id Vessel B	0.30	0.18	1.69	0.092
Model: NB1		Treatment Batch	-0.16	0.12	-1.41	0.159
		Treatment Zero	-3.71	0.22	-16.62	< 0.001
		Cum. obs. dur.	-0.08	0.03	-2.94	0.003
		Wind speed	0.14	0.05	2.67	0.008
		Rel. wind 045°	0.21	0.10	2.12	0.034
		Rel. wind 090°	0.07	0.11	0.64	0.521
		Rel. wind 135°	-0.11	0.12	-0.92	0.358
		Rel. wind 180°	-0.02	0.15	-0.13	0.896
		Season Egg	-0.19	0.24	-0.79	0.427
		Season Winter	0.27	0.17	1.56	0.118
		Vessels visible	0.07	0.04	1.80	0.071
				Var		
	Random	Sample:Trawl	0.41	0.17		
		Trawl	0.55	0.30		
BBA		(Intercept)	3.40	0.12	28.04	< 0.001
(40m air)	Fixed	Treatment Batch	-0.27	0.10	-2.64	0.008
Model: NB1		Treatment Zero	-2.97	0.18	-16.58	< 0.001
		Wind speed	0.31	0.04	7.21	< 0.001
		Rel. wind 045°	0.34	0.09	3.77	< 0.001
		Rel. wind 090°	0.21	0.10	2.04	0.041
		Rel. wind 135°	-0.01	0.11	-0.12	0.907
		Rel. wind 180°	0.07	0.13	0.53	0.598
		Season Egg	0.08	0.18	0.46	0.648
		Season Winter	0.37	0.13	2.77	0.006
				Var		
	Random	Sample:Trawl	0.33	0.11		
		Trawl	0.48	0.23		
BBA		(Intercept)	2.76	0.19	14.42	< 0.001
(TL area)	Fixed	Treatment Batch	-1.14	0.11	-10.02	< 0.001
Model: NB1		Rel. wind 045°	0.48	0.18	2.65	0.008
		Rel. wind 090°	0.58	0.19	3.11	0.002
		Rel. wind 135°	0.20	0.22	0.92	0.358
		Rel. wind 180°	0.51	0.25	2.06	0.039
		Season Egg	-0.42	0.24	-1.79	0.074
		Season Winter	0.10	0.14	0.71	0.478
		Ves visible	0.12	0.05	2.33	0.020
				Var		
	Random	Trawl	0.35	0.35		
GP		(Intercept)	3.65	0.14	25.93	< 0.001
(40m water)	Fixed	Ves. id Vessel B	0.47	0.16	2.92	0.004
Model: NB1		Treatment Batch	-0.28	0.11	-2.46	0.014
		Treatment Zero	-2.03	0.84	-2.43	0.015
		Rel. wind 045°	-0.09	0.10	-0.88	0.382
		Rel. wind 090°	-0.22	0.11	-1.95	0.051

		Rel. wind 135˚	-0.37	0.13	-2.89	0.004
		Rel. wind 180˚	-0.38	0.14	-2.76	0.006
		Treat. Cont. : Cum.obs.dur.	0.23	0.08	2.88	0.004
		Treat Batch: Cum.obs.dur.	0.04	0.03	1.38	0.167
		Treat. Zero: Cum.obs.dur.	1.88	0.96	1.96	0.050
				Var		
	Random	Sample:Trawl	0.29	0.08		
		Trawl	0.59	0.35		
GP		(Intercept)	2.28	0.18	12.79	< 0.001
(40m air)	Fixed	Treatment Batch	-0.15	0.15	-1.00	0.320
Model: P		Treatment Zero	-2.21	0.24	-9.26	< 0.001
		Wind speed	0.12	0.07	1.82	0.069
		Rel. wind 045˚	-0.22	0.15	-1.49	0.136
		Rel. wind 090˚	-0.84	0.16	-5.13	< 0.001
		Rel. wind 135˚	-1.35	0.19	-7.03	< 0.001
		Rel. wind 180˚	-1.28	0.21	-6.01	< 0.001
		Season Egg	0.62	0.23	2.69	0.007
		Season Winter	-0.29	0.19	-1.54	0.122
				Var		
	Random	Sample:Trawl	0.59	0.35		
		Trawl	0.57	0.32		
GP		(Intercept)	0.35	0.40	0.88	0.380
(TL area)	Fixed	Ves. id Vessel B	1.87	0.45	4.12	< 0.001
Model: NB1		Treatment Batch	0.07	0.43	0.17	0.863
		Rel. wind 045˚	0.53	0.29	1.86	0.063
		Rel. wind 090˚	0.06	0.33	0.17	0.866
		Rel. wind 135˚	0.33	0.34	0.96	0.338
		Rel. wind 180˚	0.55	0.42	1.32	0.187
		Ves. id Ves. B : Treatm. Batch	-1.12	0.46	-2.43	0.015
				Var		
	Random	Trawl	1.05	1.09		

Table A7. Results of GLMM, with **contact rate** (log contacts/min) as the selected response variable, and **treatment** as the primary variable of interest. P = Poisson distribution, NB1 = negative binomial distribution with a log-link function, where the variance increases linearly with the mean as $\sigma 2 = \mu(1 + \alpha)$, with $\alpha > 0$ (where α is the overdispersion parameter); NB2 = negative binomial where the variance increases quadratically with the mean as $\sigma 2 = \mu(1 + \mu/\theta)$, with $\theta > 0$ (where θ is the overdispersion parameter, Hardin and Hilbe, 2007; Magnusson et al., 2020). Significance level at $\alpha = 0.05$. BBA = black-browed albatross; GP = giant petrel species.

VESSEL A						
Model	Effects	Variable	Estimate	Std. Error	z-value	p-value
BBA	Fixed	(Intercept)	-3.37	0.36	-9.43	< 0.001
(All contacts)		Treatment Batch	-0.44	0.25	-1.77	0.077
Model: NB1		Sea state	0.30	0.12	2.38	0.017
		Rel. wind 045˚	0.36	0.36	0.99	0.320
		Rel. wind 090˚	1.31	0.37	3.58	< 0.001
		Rel. wind 135˚	0.93	0.38	2.45	0.014
		Rel. wind 180˚	0.93	0.47	1.99	0.046
		Season Egg	1.30	0.45	2.90	0.004
		Season Winter	1.40	0.26	5.39	< 0.001
		Vessels visible	-0.33	0.15	-2.28	0.023
				Var		
	Random	Sample:Trawl	1.22	1.49		
		Trawl	0.45	0.21		
BBA	Fixed	(Intercept)	-4.06	0.45	-8.96	< 0.001
(Heavy contacts)		Treatment Batch	-0.99	0.33	-3.02	0.003
Model: NB2		Rel. wind 045˚	0.79	0.48	1.66	0.097
		Rel. wind 090˚	1.76	0.47	3.76	< 0.001
		Rel. wind 135˚	1.61	0.49	3.27	0.001
		Rel. wind 180˚	1.81	0.59	3.08	0.002
		Vessels visible	-0.48	0.19	-2.60	0.009
				Var		
	Random	Sample:Trawl	0.98	0.97		
		Trawl	0.76	0.58		
GP	Fixed	(Intercept)	-4.28	0.47	-9.13	< 0.001
(All contacts)		Treatment Batch	0.31	0.44	0.72	0.471
Model: NB2		Season Egg	3.92	0.66	5.92	< 0.001
		Season Winter	1.04	0.45	2.30	0.022
				Var		
	Random	Sample:Trawl	0.63	0.39		
		Trawl	1.22	1.49		
GP	Fixed	(Intercept)	-5.88	0.61	-9.61	< 0.001
(Heavy contacts)		Treatment Batch	0.35	0.51	0.68	0.496
Model: NB1		Season Egg	2.39	0.75	3.21	0.001
		Season Winter	0.79	0.54	1.46	0.145
				Var		
	Random	Sample:Trawl	0.98	0.95		
		Trawl	1.21	1.48		

VESSEL B

Model	Effects	Variable	Estimate	Std. Error	z-value	p-value
BBA	Fixed	(Intercept)	-1.13	0.49	-2.31	0.021
(All contacts)		Treatment Batch	-2.82	0.49	-5.82	< 0.001
Model: NB2		Sea state	0.72	0.33	2.20	0.028
		Cum. obs. dur.	-1.61	0.54	-3.00	0.003
		Vessels visible	0.45	0.28	1.61	0.108
		Treatment Batch: Cum. obs. dur.	1.06	0.60	1.78	0.075
				Var		
	Random	Sample:Trawl	0.89	0.79		
		Trawl	1.37	1.88		
BBA	Fixed	(Intercept)	-3.21	0.59	-5.42	< 0.001
(Heavy contacts)		Treatment Batch	-3.41	0.64	-5.30	< 0.001
Model: NB2		Sea state	0.79	0.39	2.02	0.044
		Cum. obs. dur.	-1.22	0.42	-2.88	0.004
				Var		
	Random	Sample:Trawl	0.50	0.25		
		Trawl	1.54	2.38		
GP	Fixed	(Intercept)	0.17	0.32	0.54	0.592
(All contacts)		Treatment Batch	-3.24	0.38	-8.62	< 0.001
Model: NB2		Sea state	0.45	0.20	2.28	0.022
				Var		
	Random	Sample:Trawl	0.79	0.63		
		Trawl	0.84	0.70		
GP	Fixed	(Intercept)	-3.14	0.83	-3.77	< 0.001
(Heavy contacts)		Treatment Batch	-2.58	0.45	-5.69	< 0.001
Model: NB1		Rel. wind 045°	0.46	0.92	0.50	0.619
		Rel. wind 090°	1.72	0.86	2.00	0.046
		Rel. wind 135°	2.05	0.89	2.31	0.021
				Var		
	Random	Sample:Trawl	0.16	0.03		
		Trawl	0.52	0.27		

COMBINED VESSEL A + VESSEL B

Model	Effects	Variable	Estimate	Std. Error	z-value	p-value
BBA	Fixed	(Intercept)	-1.65	0.27	-6.12	< 0.001
(All contacts)		Ves. id Vessel B	1.30	0.44	2.92	0.003
Model: NB1		Treatment Batch	-0.48	0.34	-1.42	0.156
		Ves. id Ves. B: Treatm. Batch	-2.00	0.53	-3.74	< 0.001
				Var		
	Random	Sample:Trawl	0.90	0.82		
		Trawl	0.98	0.95		
BBA	Fixed	(Intercept)	-3.09	0.34	-9.00	< 0.001
(Heavy contacts)		Ves. id Vessel B	0.54	0.57	0.94	0.345
Model: NB2		Treatment Batch	-0.87	0.42	-2.06	0.040
		Ves. id Ves. B: Treatm. Batch	-2.49	0.76	-3.27	0.001
				Var		
	Random	Sample:Trawl	0.54	1.06		
		Trawl	-0.87	1.43		
GP	Fixed	(Intercept)	-2.98	0.34	-8.78	< 0.001
(All contacts)		Ves. id Vessel B	3.31	0.50	6.65	< 0.001
Model: NB1		Treatment Batch	0.16	0.41	0.39	0.690
		Ves. id Ves. B: Treatm. Batch	-3.06	0.56	-5.47	< 0.001
				Var		

	Random	Sample:Trawl	0.67	0.44		
		Trawl	1.19	1.41		
GP	Fixed	(Intercept)	-5.31	0.53	-9.96	< 0.001
(Heavy contacts)		Ves. id Vessel B	3.27	0.74	4.44	< 0.001
Model: NB2		Treatment Batch	0.59	0.61	0.97	0.330
		Ves. id Ves. B: Treatm. Batch	-4.59	0.96	-4.79	<0.001
				Var		
	Random	Sample:Trawl	0.52	0.27		
		Trawl	1.59	2.53		

6.4. Appendix 4: GLMM outputs for models assessing the effect of discard rate and volume.

Table A8. Results of GLMM, with the selected response variable being **abundance** (a) and **contact rate** (log contacts/min) (b), and **discard level** and **discard rate** individually used as the primary variable of interest. Data were combined for black-browed albatross (BBA) and giant-petrel species (GP). NB1 = negative binomial distribution with a log-link function, where the variance increases linearly with the mean as σ 2 = μ(1 + α), with α > 0 (where α is the overdispersion parameter; Hardin and Hilbe, 2007; Magnusson et al., 2020).

a) Abundance

VESSEL A						
Model	Effects	Variable	Estimate	Std. Error	z value	Pr(>|z|)
BBA + GP	Fixed	(Intercept)	4.380	0.276	15.870	< 0.001
(40m air + water)		Disc_level Medium	-0.098	0.278	-0.350	0.730
Model: NB1		Disc_level Low	-0.221	0.277	-0.800	0.420
		Disc_level Negligible	-0.495	0.292	-1.700	0.090
		Disc_level Nil	-2.473	0.319	-7.760	< 0.001
				Var		
	Random	Sample:Trawl	0.24	0.06		
		Trawl	0.20	0.04		
			Estimate	Std. Error	z value	Pr(>|z|)
BBA + GP	Fixed	(Intercept)	4.392	0.157	28.060	< 0.001
(40m air + water)		Disc_rate Batch	-0.263	0.257	-1.020	0.306
Model: NB1		Disc_rate Intermittent	-0.227	0.166	-1.370	0.171
		Disc_rate Infrequent	-0.545	0.204	-2.670	0.008
		Disc_rate None	-2.496	0.231	-10.800	< 0.001
				Var		
	Random	Sample:Trawl	0.24	0.06		
		Trawl	0.23	0.05		
VESSEL B						
Model	Effects	Variable	Estimate	Std. Error	z value	Pr(>|z|)
BBA + GP	Fixed	(Intercept)	5.354	0.107	49.800	< 0.001
(40m air + water)		Disc_level Medium	-0.241	0.119	-2.000	0.043
Model: NB1		Disc_level Low	-0.151	0.095	-1.600	0.112
		Disc_level Negligible	-0.388	0.090	-4.300	< 0.001
		Disc_level Nil	-3.594	0.169	-21.200	< 0.001
				Var		
	Random	Sample:Trawl	0.21	0.04		
		Trawl	0.37	0.14		
	Fixed	(Intercept)	5.159	0.105	49.200	< 0.001
BBA + GP		Disc_rate Batch	-0.059	0.117	-0.500	0.615
(40m air + water)		Disc_rate Intermittent	-0.406	0.095	-4.300	< 0.001
Model: NB1		Disc_rate Infrequent	-0.808	0.241	-3.300	< 0.001
		Disc_rate None	-3.415	0.177	-19.300	< 0.001

				Var		
	Random	Sample:Trawl	0.19	0.04		
		Trawl	0.43	0.19		

b) Contacts

Vessel A						
Model	Effects	Variable	Estimate	Std. Error	z value	Pr(>|z|)
BBA + GP	Fixed	(Intercept)	0.007	0.162	0.040	0.970
(All)		Disc_level Medium	-1.271	0.132	-9.630	< 0.001
Model: NB1		Disc_level Low	-2.210	0.160	-13.820	< 0.001
		Disc_level Negligible	-3.895	0.437	-8.920	< 0.001
				Var		
	Random	Sample:Trawl	0.51	0.26		
		Trawl	0.92	0.84		
			Estimate	Std. Error	z value	Pr(>|z|)
BBA + GP	Fixed	(Intercept)	-0.389	0.212	-1.833	0.067
(All)		Disc_rate Batch	0.204	0.264	0.774	0.439
Model: NB1		Disc_rate Intermit.	-1.638	0.223	-7.332	< 0.001
		Disc_rate Infrequent	-3.460	0.593	-5.839	< 0.001
				Var		
	Random	Sample:Trawl	0.62	0.39		
		Trawl	1.01	1.03		
Vessel B						
Model	Effects	Variable	Estimate	Std. Error	z value	Pr(>|z|)
BBA + GP	Fixed	(Intercept)	1.453	0.201	7.21	< 0.001
(All)		Disc_level Medium	-1.169	0.28	-4.18	< 0.001
Model: NB1		Disc_level Low	-2.614	0.271	-9.64	< 0.001
		Disc_level Negligible	-3.448	0.199	-17.33	< 0.001
				Var		
	Random	Sample:Trawl	0.42	0.18		
		Trawl	0.73	0.53		
BBA + GP	Fixed	(Intercept)	-0.677	0.292	-2.315	0.021
(All)		Disc_rate Batch	2.772	0.189	14.641	< 0.001
Model: NB1		Disc_rate Intermit.	-1.027	0.452	-2.272	0.023
		Disc_rate Infrequent	-1.450	1.332	-1.088	0.277
				Var		
	Random	Sample:Trawl	0.76	0.58		
		Trawl	1.11	1.23		

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