Warp strike mitigation in large‑vessel trawl fisheries in New Zealand

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EXECUTIVE SUMMARY

Efforts to prevent seabird interactions with commercial fisheries include the use of bycatch mitigation devices during active fishing operations. In New Zealand, mandatory mitigation requirements for trawl fishing by large vessels (≥28 m length) include the use of at least one of three types of mitigation device, bird scaring (tori, streamer) lines, bird bafflers, or warp scarers (warp deflectors). During fishing operations, fisheries observers record information pertaining to the use of these mitigation devices, including seabird interactions, such as incidental captures. These data were used in the current study in an initial exploration aimed at characterising the use of mitigation devices in large-vessel trawl fisheries. This data exploration also included an assessment of seabird captures in relation to mitigation device type. The analysis was limited to warp captures, omitting records of net captures. The characterisation also considered the configuration of mitigation devices used across different large-vessel trawl fisheries.

The present assessment included statistical modelling to examine whether the use of mitigation devices influenced seabird capture rates. This part of the analysis used generalised linear mixed models to estimate capture rates from fisheries observer data. Covariates included in the models were fishing year, fishery, area and vessel as random effects, with mitigation gear included as a categorical fixed effect (at levels baffler-only, tori-line-only, baffler-and-tori-line).

The characterisation of warp mitigation devices showed that bird bafflers were the most prevalent mitigation gear used in large-vessel trawl fisheries. In addition, there was an increase in the use of this mitigation gear type over time. Bird bafflers in combination with tori lines were also used on a comparatively high number of tows, followed by the use of tori lines. There were only limited observer records of warp strike mitigation using warp scarers or other combinations of mitigation gear. These data were insufficient to be included in the statistical modelling.

Comparing the effectiveness of mitigation devices with bird bafflers as the reference indicated that tori lines were more effective than the former mitigation device type. The combination of bird bafflers and tori lines was slightly less effective than the use of bird bafflers only, but this finding was inconsistent across models. It may also be confounded by varying mitigation requirements; e.g., the use of multiple mitigation types required during "high risk" periods when there are more birds foraging such as during the peak squid trawl season. In addition, the modelling suggested that the effectiveness of bird bafflers has improved, especially after 2015. The inclusion of data that describes mitigation device gear changes (in both design and configuration) over time.

For the analysis of the configuration of mitigation gear, there was considerable variation in the amount of information available in the observer records. In addition, a high number of unique configurations of mitigation devices used during fishing prevented the analysis of particular configurations in relation to seabird captures.

Highlighting these limitations and challenges, recommendations from the present study include the exploration of different analysis techniques to assess the diversity of gear configurations. These techniques include clustering algorithms and dimensionality reduction, to group configurations of mitigation gear into consistent sets. The configuration groups can then be used to assess differences in bycatch rates, while taking into account the relative abundance of seabirds. The latter may also include the use of seabird count data that are regularly recorded at the back of fishing vessels. In addition, in-depth analysis of mitigation gear data may be augmented by including data on vessel waste management.

To provide context for the analysis, the current project also included a comparison of the three mitigation devices, based on existing information. Although there has been ongoing research into the use of different mitigation devices for a number of years, relatively few studies provide sufficient information to support formal analyses of their efficacy. Most research has focused on assessing the effectiveness of bird scaring lines, with findings consistently indicating a reduction in warp strike associated with their use across different trawl fisheries. Based on this evidence, and consistent with the model results in this study, bird scaring lines are the only mitigation device type included in the recommendations of best-practice mitigation measures by the Agreement on the Conservation of Albatrosses and Petrels.

1. INTRODUCTION

At-sea interactions with commercial fisheries can lead to the injury and incidental capture of seabirds, frequently resulting in bycatch mortality (e.g., Clay et al. 2019). On a global scale, bycatch has been identified as one of the main threats for a range of seabird species and populations, including endangered and threatened albatrosses and petrels (Phillips et al. 2016, Dias et al. 2019). At the same time, the recognition of bycatch impacts has led to increasing efforts to prevent or reduce interactions between seabirds and commercial fishing operations. Mitigation efforts have included operational changes in fishing practices and the development of techniques and measures that deter or prevent seabirds from interacting with fishing vessels and gear (Pierre et al. 2012, Favero & Seco Pon 2014, Goad & Williamson 2015).

In New Zealand, one of the main goals of the "National Plan of Action – Seabirds 2020" is the prevention of seabird bycatch through the use of effective mitigation (Fisheries New Zealand and Department of Conservation 2020). The latter includes non-regulatory "best practice" approaches and mitigation standards across different commercial fisheries (e.g., Plencner 2023), and also mandatory measures, such as for large-vessel trawl fisheries (defined as vessels that are at least 28 m in overall length; New Zealand Government 2010). Regulatory measures in these fisheries require the use of one of three types of seabird scaring device, with specific requirements for each device: bird scaring lines (i.e., paired streamer or tori lines), bird bafflers, or warp scarers (i.e., warp deflectors). All three devices are aimed at preventing seabird interactions with trawl cables (warps), as warp strike poses one of the main risks associated with seabird interactions in trawl fisheries.

Ongoing monitoring data pertaining to the use of mitigation devices are available from fisheries observers, who record information on protected species interactions and mitigation measures while onboard commercial vessels. These observer records have been used in previous analyses of mitigation measures in New Zealand trawl fisheries (Abraham & Kennedy 2008, Abraham & Thompson 2009). In addition, there have been qualitative and experimental studies focused on the use of mitigation techniques aimed at preventing warp strike in New Zealand waters (e.g., Middleton & Abraham 2007, Cleal & Pierre 2012b).

Since the introduction of mandatory warp mitigation devices in large-vessel trawl fisheries in 2006–07 and other mitigation measures, there have been some declines in estimated seabird captures and capture rates; however, bycatch estimates have remained variable overall, including in recent fishing years (Abraham & Richard 2020).

This variability in seabird bycatch provided the impetus of the present project "to assess the use and effectiveness of warp mitigation measures currently in use across New Zealand's commercial large-vessel trawl fisheries." The assessment was based on an initial exploration and analysis of observer data across vessels and target fisheries, and included a review of existing information regarding the effectiveness of warp strike mitigation measures.

2. METHODS

The initial data exploration and analysis focused on a characterisation of data recorded in the Centralised Observer Database (COD). The characterisation examined seabird capture rates across different large-vessel trawl fisheries in relation to observer effort. This part of the assessment was based on observer data for the period from 1992–93 to 2019–20. Prior to the introduction of mandatory mitigation measures in January 2006, the use of mitigation devices followed a voluntary code of practice, and early data may contain some inconsistencies; however, data from this period were included in the initial exploration.

The current assessment also included the configuration of mitigation devices used in large-vessel fisheries, and exploration of these data for the analysis of seabird captures. Further analysis focused on the assessment of seabird capture rates in relation to recorded warp mitigation device types. These analyses included data from the period following the mandatory introduction of mitigation measures in 2007 (i.e., from 2007–08 to 2019–20) onwards.

To provide context for the analysis, a review of existing information focused on studies that assessed the effectiveness of these warp mitigation devices in trawl fisheries.

Throughout this report, bird scaring lines and warp deflectors are also referred to as tori lines and warp scarers, respectively.

2.1 Review of existing information

The review of existing information was based on a systematic literature search of research and studies that assessed the efficacy of each of the three types of seabird mitigation device in trawl fisheries. The search for information was primarily based on published reviews and individual research publications (including cross-referencing), with a particular focus on recent publications (i.e., since 2015), building on earlier reviews (e.g., Bull 2007, Parker 2017, Sacchi 2021). The search focused on a number of databases and internet search engines: Aquatic Sciences and Fisheries Abstracts (including Biological Sciences, Biology Digest, BioOne.1, Conference Papers Index, Ocean Abstracts, Scopus Natural Sciences), Science Direct, Ornithological Worldwide Literature (includes coverage of grey literature), Searchable Ornithological Research Archive, Google, and Google Scholar.

Keywords for each mitigation device were searched individually or in combination; e.g., search terms for tori lines included *seabird, trawl*, mitigat*, tori, streamer, bycatch, warp, strike, bird, scar*, BSL; the initial search was narrowed using key words such as effective*, test, and trial.

2.2 Relative effectiveness of warp mitigation gear

The analysis of observer data was based on the development of existing models used for the estimation of seabird bycatch (see Abraham & Richard 2020). These models were initially developed to estimate seabird capture rates by fishery group and area based on observer data. Mitigation gear type was not previously included in these models. The models were, therefore, expanded to allow the inclusion of covariates for the three types of mitigation device—tori lines, bird bafflers, and warp scarers. Modelling examined whether the use of these mitigation devices affected seabird capture rates. The analysis was limited to warp captures, distinguishing their records from records of net captures.

The modelling was aimed at identifying the effectiveness of device combinations based on available data. Gear configuration data were considered too sparse and inconsistently recorded to allow more detailed modelling. For this reason, only the mitigation gear type recorded for each trip was used in the analysis. Data included records for the fishing years from 2008–09 to 2019–20. Records without information of warp mitigation gear and where mitigation gear was indicated as "none" were excluded from the analysis.

Capture rates were estimated from observer catch rates using generalised linear mixed models. The covariates included in the model were fishing year, fishery, area and vessel as random effects, with mitigation gear included as a categorical fixed effect (at levels baffler-only, tori-

line-only, baffler-and-tori-line). Interactions of gear type with year and vessel were used to assess the consistency of mitigation gear effectiveness over time and across vessels. Candidate models were developed to include a range of these factors, from simple models including only mitigation type, to more complex models that considered fishing year, area, fishery group, and the interactions of gear and vessels and fishing year (Table 1).

Models were estimated within the general Bayesian linear model framework "brms" (Bürkner 2018). A negative binomial model was used, which is preferred for highly skewed discrete distributions with considerable numbers of zeros. The models fit estimates of capture rates (captures per tow), with a negative parameter estimate indicating a reduction in capture rate.

Models were fitted with eight separate Markov Chain Monte Carlo (MCMC) chains with 3000 iterations, including a 1000 iteration burn-in period that was discarded from posterior samples. Convergence was assessed by marginal and multivariate scale reduction factors (MSRF) across the eight chains (at convergence of MCMC runs, the MSFR (or $\hat{R}$) is one). Model fit was evaluated by posterior predictive checks and Leave-One-Out information criterion (LOOIC; Vehtari et al. 2017) comparisons between models. The model with the best LOOIC was taken to be the model which best explained observed capture rates.

Table 1: Candidate models for seabird capture rate (captures per tow) in relation to mitigation gear type, fishery group, vessel, year and area, and their interaction effects.

Model	Formula
1	mitigation_type
2	(1|area) + mitigation_type
3	(1|Fishery Group) + (1|area) + mitigation_type
4	(1|vessel) + (1|Fishery Group) + (1|area) + mitigation_type
5	(1|fyear) + (1|Fishery Group) + (1|area) + mitigation_type
6	(1|fyear) + (1|vessel) + (1|Fishery Group) + (1|area) + mitigation_type
7	(1|fyear) + (1|vessel) + (1|Fishery Group) + (1|area) + mitigation_type + (1|vessel:mitigation_type)
8	(1|fyear) + (1|vessel) + (1|Fishery Group) + (1|area) + mitigation_type + (1|fyear:mitigation_type)
9	Model 8 + (1|vessel:mitigation_type)

2.3 Configuration of warp mitigation devices

Since 2007, fisheries observers have recorded the configuration of mitigation devices, including characteristics such as type, material, colour, and length. These records are stored in COD (Sanders & Fisher 2022).

Observers generally record the information about each device at the start of the fishing trip, and update it if necessary, e.g., when the device gets damaged. The characteristics recorded about a device depend on its type, and are stored in separate tables in COD, in tables *x_tori_line*, *x_bird_baffler*, and *x_warp_scarer*, for tori lines, bird bafflers, and warp scarers, respectively.

These data (from 2008–09 to 2019–20) were analysed as part of the current study, providing information of the characteristics across the different mitigation devices used.

3. RESULTS

3.1   Review of warp mitigation devices

Efforts to prevent seabirds from interacting with trawl (and other) fisheries have led to a range of studies focused on different mitigation approaches. Research has encompassed experimental studies and trials, anecdotal data collections, and analyses of fisheries observer data, including from New Zealand (Cleal & Pierre 2012a, Pierre 2018). Across studies, the most significant mitigation measure identified in bycatch research has been the management of fish waste, such as offal and discards, which attracts seabirds to the proximity of trawl gear at the stern of the vessel (e.g., see Abraham et al. 2009, Favero et al. 2011, Pierre et al. 2012, Kuepfer et al. 2022). Based on this research, the retention of waste has been highlighted as one of the most important best-practice mitigation measure, substantially reducing the attendance of seabirds during active fishing operations (Agreement on the Conservation of Albatrosses and Petrels 2023).

For specific studies of mitigation devices, qualitative and quantitative research has generally focused on particular trawl fisheries, assessing different types of mitigation device and their configurations and designs (e.g., see Melvin et al. 2011, Melvin et al. 2013, Sullivan et al. 2006). Although this research has been ongoing for a number of years, relatively few studies provide sufficient information to formally analyse the efficacy of different mitigation devices or to corroborate findings from at-sea trials and previous studies (but see for example Maree et al. 2014). In addition, there may be differences in trawl gear across studies so that the efficacy of mitigation devices may be specific to the fleet, fishing operations, or seabird species (e.g., see Løkkeborg 2011). These differences make it difficult to determine a universal mitigation device or design that is effective across all trawl fisheries. Similarly, the concomitant use of other mitigation measures (such as waste retention) in some studies means that observed decreases in seabird captures cannot always be attributed to a single device or measure. Nevertheless, existing research provides some overall distinction across the three device types included in the present study.

This aspect was also highlighted in a recent review of seabird bycatch mitigation measures for New Zealand commercial fisheries (Parker 2017). This review provides information across a range of mitigation approaches, including experimental studies and trials, with an appraisal of their efficacy. Across the three mitigation device types included in the present assessment, most studies have focused on bird scaring lines.

3.1.1   Bird scaring lines

There have been a number of quantitative studies assessing the effectiveness of bird scaring (tori) lines across different fisheries and regions. Most of this research documented marked reductions in seabird captures when tori lines were used, compared with fishing without mitigation device or with other device types (e.g., see reviews by Bull 2007, Bull 2009, Løkkeborg 2011, Parker 2017).

Statistical analyses of observer data have documented marked reductions in seabird collisions with warp cables when bird scaring lines were deployed (Tamini et al. 2015, Tamini et al. 2023). These analyses revealed significantly lower numbers of seabird captures overall (recorded as collisions per hour) when using this mitigation device compared with trawl fishing without bird scaring lines. Significant differences were also evident for each of the main seabird species observed in the collisions, namely black-browed albatross *Thalassarche melanophris*, southern

giant petrel *Macronectes giganteus*, northern giant petrel *Macronectes halli*, Cape petrel *Daption capense*, and white-chinned petrel *Procellaria aequinoctialis* (Tamini et al. 2015).

Studies quantifying reductions in seabird bycatch have reported declines between 70% and 95% in seabird mortalities across different trawl fisheries outside New Zealand waters (Melvin et al. 2011, Maree et al. 2014). An experimental trial comparing bird scaring lines with warp scarers and bird bafflers determined the former device type to offer the most effective mitigation (Sullivan et al. 2006).

In some of these studies, trawl fishing gear included a third cable, the sonde cable or net monitoring cable (e.g., see Melvin et al. 2011). Seabird mortality in trawl fisheries has been documented to be particularly high through contact with the sonde cable (Weimerskirch et al. 2000). For example, in Argentinean mid-water and bottom trawl fisheries, 85.7% of albatross and petrel bycatch was directly attributed to this gear component (Tamini et al. 2023). Nevertheless, the use of of bird scaring lines led to significant reductions in seabird bycatch in these fisheries, compared with fishing without the mitigation device. In New Zealand, the use of net sonde cables (or data transmission cables") has been prohibited since 1992, but a recent Fisheries New Zealand discussion paper proposes to revoke this prohibition (Fisheries New Zealand 2022).

Research from New Zealand is consistent with studies elsewhere, highlighting the efficacy of tori lines for preventing seabird bycatch in trawl fisheries (Middleton & Abraham 2007, Abraham & Thompson 2009). Experimental trials of different types of mitigation device in squid and hoki trawl fisheries indicated considerable reduction (80–95%) in the frequency of seabird interactions with fishing gear when tori lines were used (Middleton & Abraham 2007). Nevertheless, seabirds were also observed to interact with tori lines in these trials (and less so with bird bafflers and warp scarers), even though the severity of birds striking tori lines remained unknown. Similarly, an earlier analysis of fisheries observer data from primarily squid and also hoki fisheries reported considerably lower bird strike rates for the initial period following the introduction of tori lines between 2004–05 and 2006–07; however, there was some strike on bird scaring lines also (Abraham & Thompson 2009).

In addition, there have been at-sea trials of different specifications of tori lines, such as the material and configurations (Cleal et al. 2013). Results from the trials provided recommendations including the line attachment, and the size and weight of floats at the end of the lines (terminal objects), that were made available in a fact sheet.

Recognising their effectiveness, bird scaring lines are the only mitigation device type appraised as best practice for trawl fisheries by the Agreement on the Conservation of Albatrosses and Petrels (ACAP), with waste management and net cleaning reflecting other best-practice measures (Agreement on the Conservation of Albatrosses and Petrels 2023). Included in this advice by ACAP are recommended standards for the practical application of bird scaring lines, such as the maximum interval between streamer lines and terminal object drag weight.

3.1.2 Bird bafflers

Compared with tori lines, research into the effectiveness of bird bafflers had less distinct outcomes, although bird bafflers have been shown to reduce seabird captures (Parker 2017). Nevertheless, in a direct comparison that trialled bird bafflers, bird scaring lines and warp scarers, the former mitigation device (i.e., the Brady baffler) resulted in the smallest reduction in seabird mortality, although it was more effective than no mitigation (Sullivan et al. 2006). In addition, bird bafflers have undergone further development since these early studies.

Another comparison, an Australian study tested the efficacy of bafflers (and a water sprayer) on trawl vessels, revealing significant reductions (83.7%) in seabird interaction rates when compared with a warp deflector (Koopman et al. 2018). Based on this outcome, the Australian Fisheries Management Authority permitted the use of bird bafflers as part of the industry's requirements of seabird bycatch mitigation on trawl vessels.

In New Zealand trawl fisheries, statistical analysis of three years of fisheries observer data (2004–05 to 2006–07) indicated a lower strike rate when bird bafflers were used, but this reduction was not consistent nor significant across fishing years (Abraham & Thompson 2009). Nevertheless, although bird scaring lines had a markedly lower average strike rate than bird bafflers, there was a substantial further reduction when both mitigation device types were used in combination.

The New Zealand study of mitigation devices in squid and hoki trawler fisheries reported a significant reduction of 35–90% warp strike of large seabirds (defined as all albatrosses and giant petrels) compared with no mitigation; however, the reduction for small seabirds was not statistically significant (Middleton & Abraham 2007).

Overall, the efficacy of bird bafflers appears to be dependent on their design and configuration, and a number of trials have assessed different specifications and modifications, including in New Zealand fisheries (Cleal & Pierre 2012a). Nevertheless, there have been no clear standards or specifications of bird bafflers to date, and ACAP considered existing evidence insufficient to recommend bird bafflers as a mitigation measure in trawl fisheries (Agreement on the Conservation of Albatrosses and Petrels 2023).

3.1.3 Warp scarers

Similar to bird bafflers, limited research into the use of warp scarers documented some reductions in warp strike, but that they seem generally less effective than bird scaring lines (Bull 2007; and see review of trials in Parker 2017). For example, direct comparison of the three mitigation device types ranked warp scarers second after bird scaring lines, assessing them to be more effective for seabird bycatch mitigation than bird bafflers (Sullivan et al. 2006).
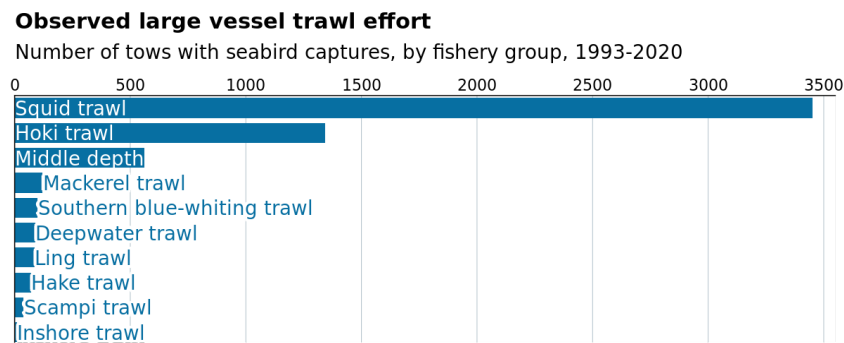
At the same time, at-sea trials of warp scarers (in comparison to warp deflectors) in Australia showed varied results of their efficacy, depending on the number of seabirds (i.e., "shy-type albatross" *Thalassarche*) and their behaviour around the stern of the vessel (Pierre et al. 2014). When bird numbers were high and birds were feeding aggressively, exploratory modelling suggested that warp scarers were effective in reducing warp interactions; however, they were less effective when birds were not aggressive during feeding or ended up submerged during interactions.

For New Zealand trawl fisheries, statistical modelling of observer data from the initial period of mitigation measures showed no significant reduction in warp strike rates associated with the use of warp scarers (Abraham & Thompson 2009). Subsequent at-sea trials of different mitigation devices indicated that warp scarers were effective in reducing warp strike compared with fishing without a mitigation device, but this reduction was more pronounced for large than small seabirds (Middleton & Abraham 2007).
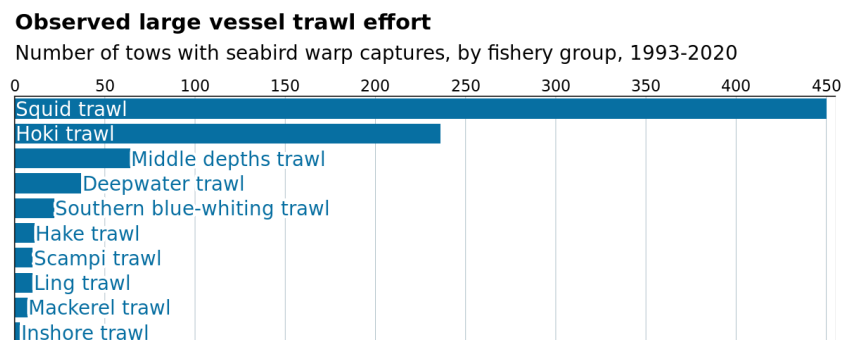
As for bird bafflers, ACAP does not recommend warp scarers as a best-practice mitigation device, as there is insufficient evidence to support this recommendation (Agreement on the Conservation of Albatrosses and Petrels 2023).

3.2 Large-vessel trawl effort and observed capture rates

Considering trawl effort in relation to observed seabird captures across fisheries, a relatively small number of tows had records of seabird captures, which included net captures (Figure 1). Most of these records were associated with squid trawls, followed by hoki and middle-depth targets. A relatively small proportion of the former effort had capture records that were limited to warp captures (Figure 2).

Observed large vessel trawl effort

Number of tows with seabird captures, by fishery group, 1993-2020

Squid trawl
Hoki trawl
Middle depth
Mackerel trawl
Southern blue-whiting trawl
Deepwater trawl
Ling trawl
Hake trawl
Scampi trawl
Inshore trawl

Figure 1: Observed fishing effort (tows) by large trawl vessels with seabird captures (all capture methods), for the period between 1992–93 and 2019–20, by fishery group.

Observed large vessel trawl effort

Number of tows with seabird warp captures, by fishery group, 1993-2020

Squid trawl
Hoki trawl
Middle depths trawl
Deepwater trawl
Southern blue-whiting trawl
Hake trawl
Scampi trawl
Ling trawl
Mackerel trawl
Inshore trawl

Figure 2: Observed fishing effort (tows) by large trawl vessels with seabird warp captures, for the period between 1992–93 and 2019–20, by fishery group.

Over the study period, the proportion of observed trawl effort by large vessels increased across a number of target fisheries since the mid- to late 2000s (Figure 3). This increase has resulted in a number of large-vessel trawl fisheries having close to 100% observer coverage since 2013, such as southern blue whiting and squid trawl. The only large-vessel trawl fishery with substantial effort and persistently low observer coverage over this period was the scampi target fishery.

There was considerable variability in observed seabird captures across large-vessel fisheries (Figure 4). For example, observed captures were consistently low in deepwater and inshore large-vessel trawl fisheries, but were comparatively high in squid and scampi trawl. In addition, there were marked changes in recorded captures over time, following increases in observer effort in early 2000.

For warp captures, most records were in large-vessel squid and hoki trawl fisheries, but there was considerable variation in captures over time (Figure 5). In some target fisheries, such as

inshore, ling, middle-depth, and scampi trawl, there were distinct peaks among otherwise low warp captures over the study period.
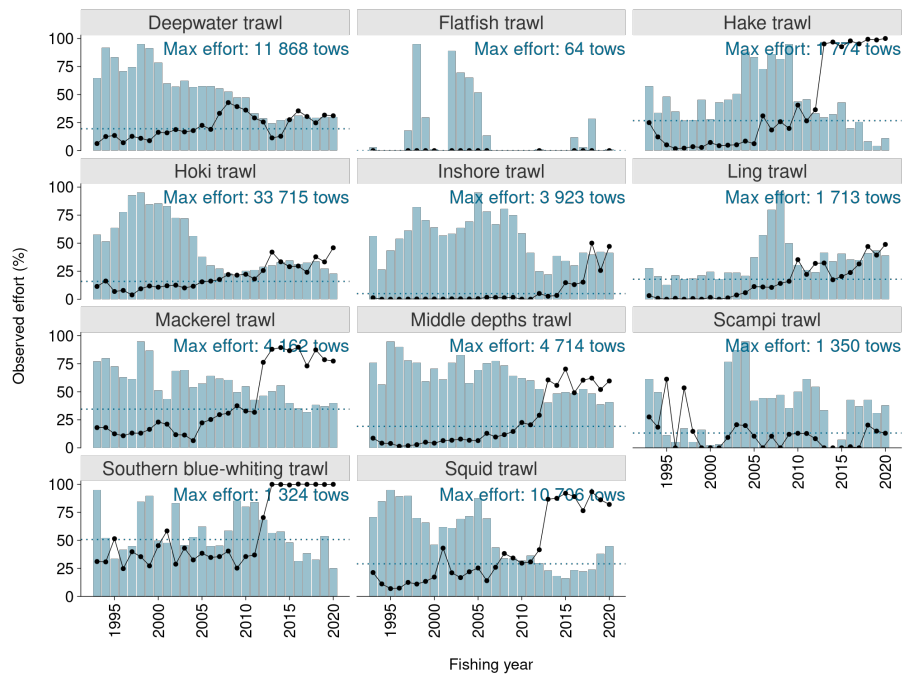
Figure 3: Observed (black dots) large vessel trawl effort (tows) as a percentage of total (bars) large vessel trawl effort, for the period between 1992–93 and 2019–20, by fishery group.
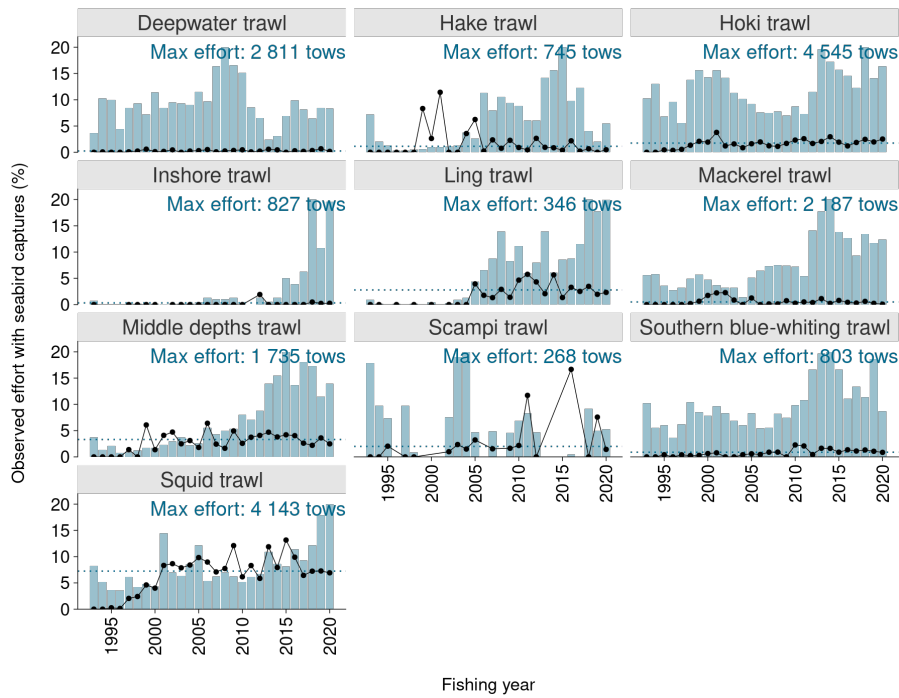
Figure 4: Observed (black dots) large vessel trawl effort (tows) with seabird captures from all capture methods, as a percentage of observed (bars) large vessel trawl effort, for the period between 1992–93 and 2019–20, by fishery group.
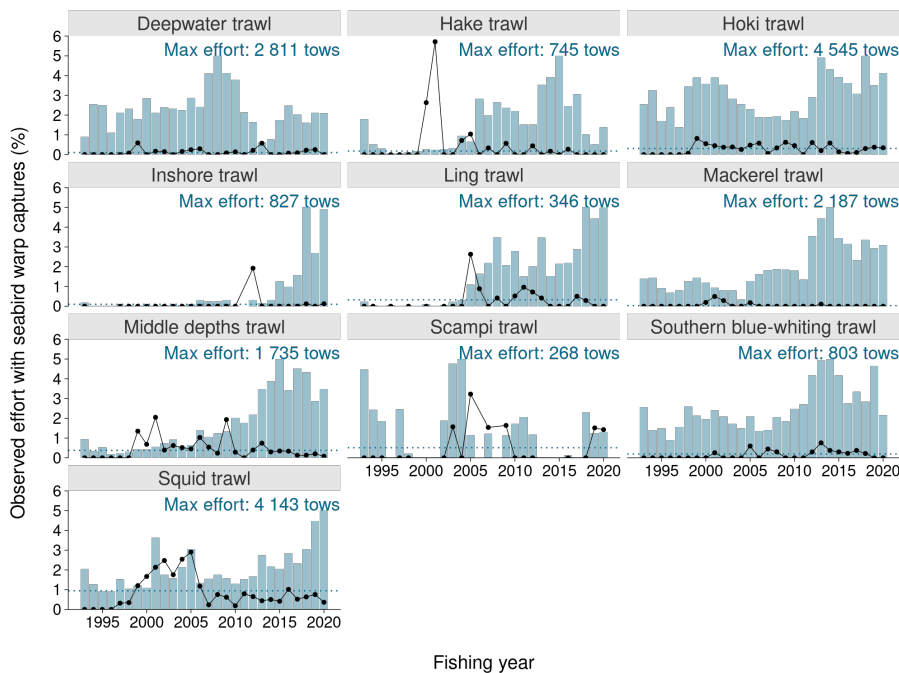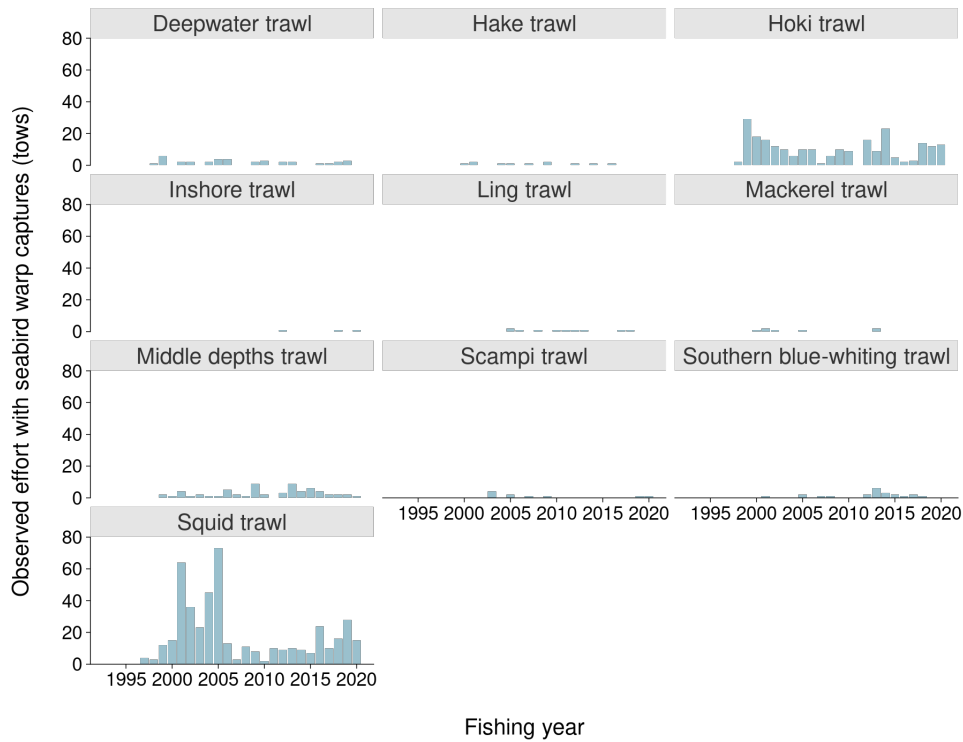

Figure 5: Observed (black dots) large vessel trawl effort (tows) with seabird warp captures, as a percentage of observed (bars) large vessel trawl effort, for the period between 1992–93 and 2019–20, by fishery group.

Considering warp captures in relation to observed effort, captures were particularly high prior to the introduction of mandatory mitigation measures in 2006 (Figure 6). This pattern was particularly evident in large-vessel squid trawl and to some extent in hoki trawl fisheries, which had sufficient effort to reveal discernible patterns.

Comparison of the number of observed warp captures and warp capture rates showed similar patterns (Figures 7 and 8). The observed number of warp captures was high in squid and hoki trawl fisheries, particularly before the introduction of mitigation measures. Similarly, observed warp capture rates were high in squid trawl in this earlier period, but also in middle-depth, hake, and scampi trawl.

Figure 6: Observed large vessel trawl effort (tows) with seabird warp captures, for the period between 1992–93 and 2019–20, by fishery group.
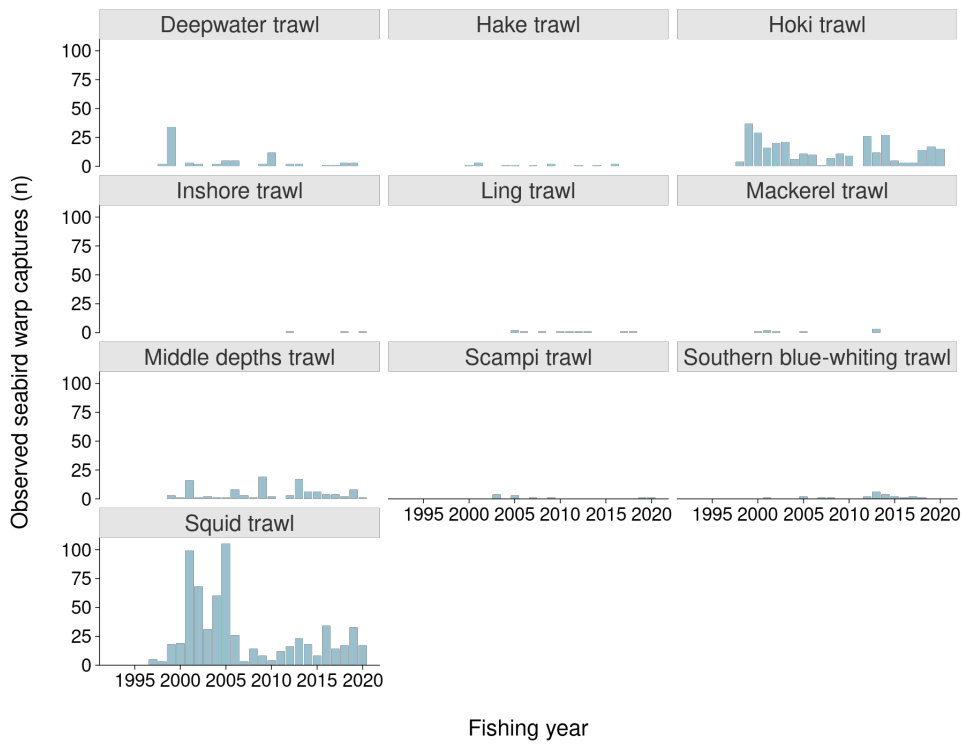
Figure 7: Observed large vessel trawl seabird warp captures, for the period between 1992–93 and 2019–20, by fishery group.
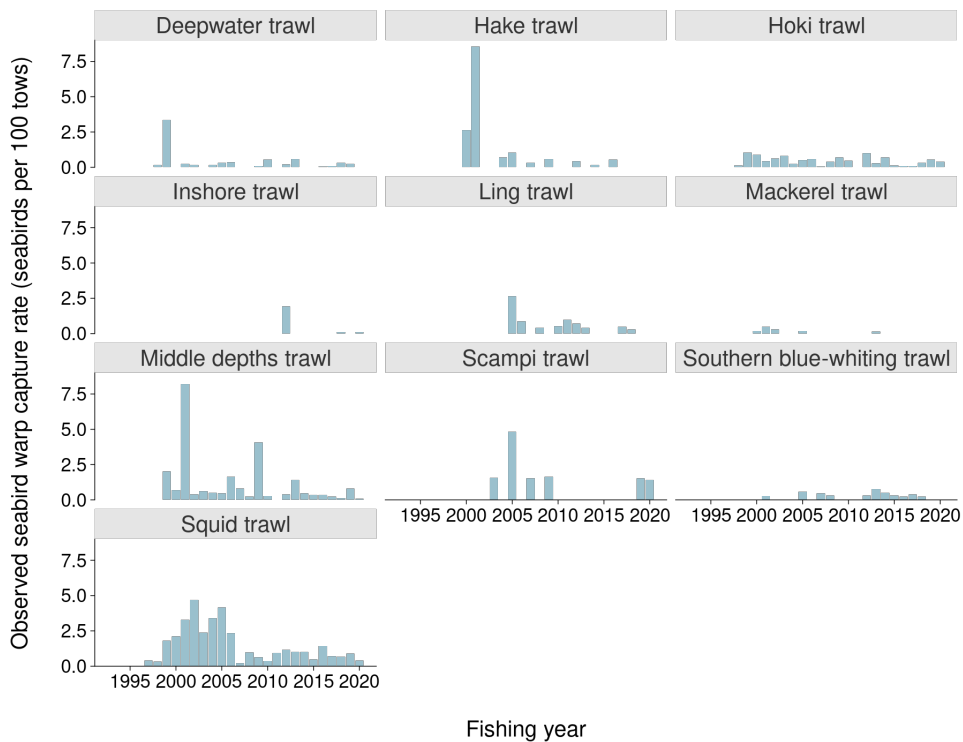
Figure 8: Observed large vessel trawl seabird warp capture rates, for the period between 1992–93 and 2019–20, by fishery group.

3.3 Configuration of mitigation devices

There were differences in the amount of information available in the database considering the configuration of devices (Tables 2 to 4). For tori lines, there was a total of 54 fields related to their configuration, but less than half of these fields contained values. In comparison, there were 14 fields for bird bafflers (generally all with values), and 21 fields for warp scarers (with most values filled in). Across all three types of mitigation device, there was a considerable number of different characteristics and unique configurations. This aspect was particularly prominent for tori lines, but also evident for the other two types of mitigation device.

Multiple mitigation devices may be used at the same time during a single fishing event, and their combination is stored in COD, in the field *mitigation_equipment* of table *x_fishing_event*. For example, a value of "B1T1T2" indicates the use of a bird baffler and two different tori lines. Each component of this value may be extracted and linked to the device characteristics for each fishing event using the trip number.

In the version of COD used in this project, the linking between the use of mitigation devices and the device characteristics was incomplete (Table 5). For example, there were 1187 fishing trips with some record relating to the use of tori lines, but only 837 trips had all records of the tori lines being deployed with a corresponding record of their characteristics. There were 227 trips with records of the tori lines characteristics, but without any record of them being used while fishing. Conversely, there were 120 trips with tori lines being used while fishing, but without data of their characteristics.

The linking was also incomplete for bird bafflers and warp scarers (Table 5). It is possible that some mitigation devices get characterised by observers when the devices are present on board the fishing vessels, though these devices may have not been used while fishing. Nevertheless, the presence of data confirming the use of devices while fishing but without corresponding information of their characteristics suggests that the latter were missed in the recording and management of this information.

For fishing events where the use of mitigation devices can be linked to the device characteristics, the configuration of the mitigation devices can potentially be related to the number of incidental captures of seabirds while fishing. These records were summarised separately for each mitigation device type, but without considering the potential simultaneous use of multiple device types (Table 6).

When calculating the "naive" capture rate, i.e., the ratio of the total number of seabird captures to the number of fishing events where the mitigation device type was used, the highest capture rate was when using tori lines at 6.4 birds per 100 fishing events. The capture rates for trawl fishing with bird bafflers and warp scarers was 3.4 birds per 100 fishing events and 2.3 birds per 100 fishing events, respectively. The lowest capture rate was for fishing events where none of these three mitigation device types were recorded, at 2 birds per 100 fishing events.

Nevertheless, the considerable number of unique configurations of mitigation devices deployed during fishing prevented the analysis of particular configurations in relation to seabird captures. For example, a total of 1 834 unique configurations of tori lines was recorded among the 45 938 fishing events observed using this mitigation device. Similarly, the simultaneous use of multiple mitigation types and the influence of other factors affecting seabird captures mean that further analysis through the development of multi-variate analysis of mitigation characteristics would be required in conjunction with a statistical model of effectiveness to ascertain which gear configurations are most effective at minimising the number of seabird warp-captures in large-vessel trawl fisheries.

Table 2: Description of the fields in the Centralised Observer Database（COD）related to the configuration of tori lines used on large (≥28 m length) trawl vessels. Shown are the number of fishing trips with some values, the number of unique values, and the percentage of values missing.

Field name	Description	Trips with values	Unique values	Missing (%)
line_diameter	Diameter of the line used	951	27	1.70
line_length	Length of the line	951	77	1.70
aerial_extent	Aerial extent of tori line	132	26	87.10
recovery_rope_yn	Presence of tori line recovery rope	176	2	83.10
reference_point	Location of the point of attachment (trawl block, bait entry, other)	737	5	23.20
reference_location	Location of the reference point (port, startboard, central)	718	3	25.20
distance_side	Distance from the reference point to the attachment in the port/starboard direction	764	49	19.40
side_code	Whether the attachment point is to port or to starboard of the reference point	959	3	0.00
distance_along	Distance from the reference point to the attachment in the forward/aft direction	735	39	22.30
along_code	Whether the attachment point is to forward or aft of the reference point	959	3	0.00
distance_vertical	Distance from the reference point to the attachment point in the vertical direction	752	37	20.40
vertical_code	Attachment point is above or below the reference point	959	3	0.00
attach1_tension_release_yn	Presence of a tension release for the attachment point	119	2	90.10
attach1_height	Height of attachment point above water	178	12	82.70
attach1_distance	Lateral distance from centre of stern to attachment point	179	32	82.50
attach1_port_stbd	Port or Starboard lateral distance for attachment point measurement	174	2	83.20
attach1_dist_stern	Distance from stern to the attachment point	176	26	83.00
attach1_adjustable_yn	Whether attachment point is adjustable	179	2	82.80
attach2_tension_release_yn	Whether dual attachment point has a tension release	110	1	90.00
attach2_height	Height above water for dual attachment point	9	6	99.20
attach2_distance	Lateral distance from centre of stern to dual attach point	7	6	99.50
attach2_port_stbd	Port or Starboard lateral distance for dual attachment point measurement	9	2	99.30
attach2_dist_join_stern	Distance from join to stern	1	1	99.90
attach2_dist_join_point	Distance from join to attachment point	2	2	99.80
attach2_streamer_join_yn	Presence of streamers between second attachment point and join	5	2	99.70
long_streamer_yn	Presence of long streamers	181	2	82.10
long_streamer_material	All long streamer material types	901	17	6.60
long_streamer_distance	Maximum distance between any long streamers	932	78	2.60
long_streamer_pair_single	Whether streamers are single or paired	173	2	83.10
long_streamer_number	Number of long streamers, or pairs, along the entire tori line	938	27	2.30
long_streamer_max_length	Maximum length of any long streamer attached to the tori line	935	99	2.50
long_streamer_min_length	Minimum length of any long streamer attached to the tori line	935	52	2.40
long_streamer_diameter	Minimum diameter of any long streamer on the line	916	25	5.40
long_streamer_colour_code	All the streamer colours observed for long streamers	932	66	3.20
long_streamer_dist_first	Distance to first long streamer that reaches water	164	21	84.00
long_streamer_aerial_yn	Whether long streamers cover aerial extent	165	2	83.80
long_streamer_touch_water_yn	Whether all long streamers touch water surface	0	0	100.00
long_streamer_height_water	Maximum height of long streamers above the water surface	0	0	100.00
long_streamer_num_touch_water	Number of long streamers that touch water	163	12	84.10
light_streamer_yn	Presence of light streamers	181	2	82.20
light_streamer_material	All light streamer material types	20	3	98.10
light_streamer_distance	Distance between light streamers	22	5	97.90
light_streamer_pair_single	Whether light streamers are single or paired	22	2	97.90
light_streamer_number	Number of light streamers, or pairs, along the entire tori line	22	10	97.90
light_streamer_max_length	Maximum length of any light streamer attached to the tori line	22	15	97.90
light_streamer_min_length	Minimum length of any light streamer attached to the tori line	22	8	98.00
light_streamer_diameter	Minimum diameter of any light streamer on the line	773	22	19.60
light_streamer_colour_code	All the streamer colours observed for light streamers	23	5	97.90
tow_object_yn	Presence of towed object	183	1	82.10
tow_object_code	Type of towed object (inverted funnel, buoy, etc.)	959	12	0.00
tow_object_size	Size of the towed object	885	75	7.70
minimum_branches	Minimum number of branches on any streamer on the line	754	8	21.00
maximum_branches	Maximum number of branches on any streamer on the line	756	9	21.10
comments	Comments	575	855	42.90

Table 3: Description of the fields in the Centralised Observer Database (COD) related to the configuration of bird bafflers used on large (≥28 m length) trawl vessels. Shown are the number of fishing trips with some values, the number of unique values, and the percentage of values missing.

Field name	Description	Trips with values	Unique values	Missing (%)
boom_position	Boom position (port orstarboard and side or aft)	1 618	4	0.00
boom_present	Boom present or absent	1 618	1	0.00
boom_location	Distance to the appropriate reference point	1 595	39	2.80
boom_angle	Estimate of the angle of the boom from dead astern	1 613	38	1.50
inner_dropper	Distance from the edge of the vessel to the innermost dropper	1 616	43	1.80
outer_dropper	Total distance from the edge of the vessel to the outermost dropper	1 613	71	1.90
droppers_number	Number of droppers attached to the boom	1 610	18	2.00
webbing_type	Webbing Type connecting the droppers (rigid, flexible, or absent)	1 564	4	5.10
max_spacing	Maximum dropper spacing	1 616	28	1.40
line_length	Average dropper line length	1 615	87	1.80
object_length	Average dropper object length	1 576	43	5.80
surface_gap	Average gap between the bottom of a dropper object and the sea surface	1 608	45	2.20
material_types	All materials used to form the dropper lines and dropper object	1 584	198	4.30
material_colours	Colours on dropper	1 580	159	5.10

Table 4: Description of the fields in the Centralised Observer Database (COD) related to the configuration of warp scarers used on large (≥28 m length) trawl vessels. Shown are the number of fishing trips with some values, the number of unique values, and the percentage of values missing.

Field name	Description	Trips with values	Unique values	Missing (%)
attachment_point	Location of the point of attachment (port, starboard, central, or other)	18	3	2.80
mainline_diameter	Diameter of the mainline used	18	11	2.80
tow_object	Type of towed object	16	6	19.40
object_weight	Weight of the towed object	18	15	5.60
connector_type	Type of connector (clip, shackle, or hook)	16	3	8.30
connector_number	Number of connectors holding main line to warp	16	5	11.10
streamer_number	Number of streamers	14	7	27.80
streamer_max_gap	Largest gap from one streamer to the next	12	8	30.60
streamer_min_branches	Minimum number of branches on any streamer on the line	13	3	27.80
streamer_max_branches	Maximum number of branches on any streamer on the line	11	2	33.30
streamer_min_length	Minimum length of any branch of any streamer on the line	13	10	27.80
streamer_max_length	Maximum length of any branch of any streamer on the line	12	12	30.60
streamer_min_dia	Minimum diameter of any branch of any streamer on the line	12	7	30.60
streamer_max_dia	Maximum diameter of any branch of any streamer on the line	11	7	36.10
extent_distance	Estimate of the extent (distance) or coverage of the warp scarer	17	14	8.30
material_max_gap	Maximum gap visible in materials	14	12	25.00
mainline_visible_min_lgth	Minimum length of the main line visible material	16	14	13.90
mainline_visible_max_lgth	Maximum length of the main line visible material	16	16	16.70
colours	All the different streamer colours observed	19	15	0.00
materials	All the different streamer materials observed	17	10	5.60
comments	Comments	16	22	25.00

Table 5: Summary of the linking between data on the use and characteristics of mitigation devices on large (≥28 m length) trawl vessels recorded by fisheries observers. Data are shown by mitigation device type, including the number of fishing trips.

Mitigation	Recorded	Characterised	No. trips
Tori lines	Yes	Yes	837
	No	Yes	227
	Yes	No	120
	No	No	3
Bird bafflers	Yes	Yes	1 375
	Yes	No	313
	No	Yes	30
	No	No	2
Warp scarers	Yes	No	18
	Yes	Yes	18
	No	Yes	12

Table 6: Summary of data in the Centralised Observer Database with information of the configuration of mitigation devices that could be related to the number of incidental captures of seabirds in large-vessel (≥28 m length) trawl fisheries. For each type of mitigation device, shown are the number of trips and of fishing events with recorded use the mitigation device, the number of unique combinations of device characteristics, the observed number of seabird captures, and the capture rate (number of captures per 100 fishing events). Number of trips, of fishing events, and of seabird captures were not independent across mitigation device types, with some fishing events using multiple device types simultaneously.

Mitigation	Trips	Fishing events	Unique configurations	Seabird captures	Capture rate
Tori lines	958	45 938	1 834	2 957	6.44
Bird bafflers	1 612	124 628	3 557	4 221	3.39
Warp scarers	19	833	36	19	2.28
None	413	11 915		241	2.02

3.4 Relative effectiveness of warp mitigation gear

Mitigation device use has been consistently recorded across large-vessel trawl fisheries since 2008, following the introduction of mandatory measures in 2007 (Table 7). Nevertheless, missing records of the use of mitigation devices included empty fields for warp mitigation gear type ("Not recorded") and missing information recorded as "None" by observers in this field, leading to the lack of these data in COD. Following the mandatory nature of the use of mitigation devices after 2007, missing information of warp strike mitigation devices continued to be evident in the observer records over time across the large-vessel trawl fleet (Figure 9). These records were excluded from the present analysis.

Comparing observer records across different mitigation device types and combinations, bird bafflers were the most prevalent mitigation gear used each fishing year (Figure 10). In addition, there was a marked increase in the number of tows that used bird bafflers over time (i.e., since 2008). Bird bafflers in combination with tori lines were also used on a comparatively high number of tows over this period, followed by the use of tori lines only. Warp scarers and other combinations of mitigation gear were only used on a small number of tows.

The use of bird bafflers on a relatively high number of large-vessel trawl fishing trips was consistent over time, particularly since 2013 (Figure 11). This pattern was similar for the combination of bird bafflers and tori lines, with a considerable number of vessels using this mitigation gear combination (Figure 12). For the use of tori lines, there was an increase in the number of fishing trips with this mitigation gear in the middle of the reporting period, but there was a concomitant reduction of vessels using this combination (Figure 13).

There were only limited observer records of the use of warp scarers (Figure 14), preventing inclusion of these data in the modelling part of this study.

Table 7: Use of warp mitigation devices as recorded by fisheries observers in large‑vessel (≥28 m length) trawl fisheries for the period between 1992–93 and 2019–20. Shown are the number of tows by warp strike mitigation gear and by fishing year. Records shown as "Not recorded" indicate that the warp mitigation gear type fields were empty in the observer data form; "None" indicated lack of information of mitigation gear use recorded by observers.

| Fishing year	Not recorded	None	Baffler	Tori	Scarer	Baffler & tori	Bafflers & scarer	Tori & scarer	Baffler & tori & scarer
1993	6 429								
1994	6 657								
1995	4 676								
1996	4 052								
1997	4 534								
1998	6 418								
1999	6 695								
2000	6 779								
2001	8 753								
2002	7 103								
2003	6 453								
2004	6 364								
2005	7 587								
2006	6 183								
2007	4 817	377	993	870	55	133			
2008	5	697	4 738	1 941	207	696		12	
2009		277	4 447	1 803	259	605		15	
2010		152	4 878	1 458	12	1 176			
2011		189	4 043	904		1 077			
2012	245	104	5 874	803		1 354			
2013		127	7 265	1 350	1	3 073	1		
2014	37	250	7 281	959		2 695			
2015	29	134	8 178	929		1 993			
2016		127	8 436	574		1 619			
2017	1	286	6 508	477		2 628			
2018	1	225	8 595	92		3 866	58		
2019		124	8 211	4		3 679			1
2020		137	8 720	25		4 406	90		2
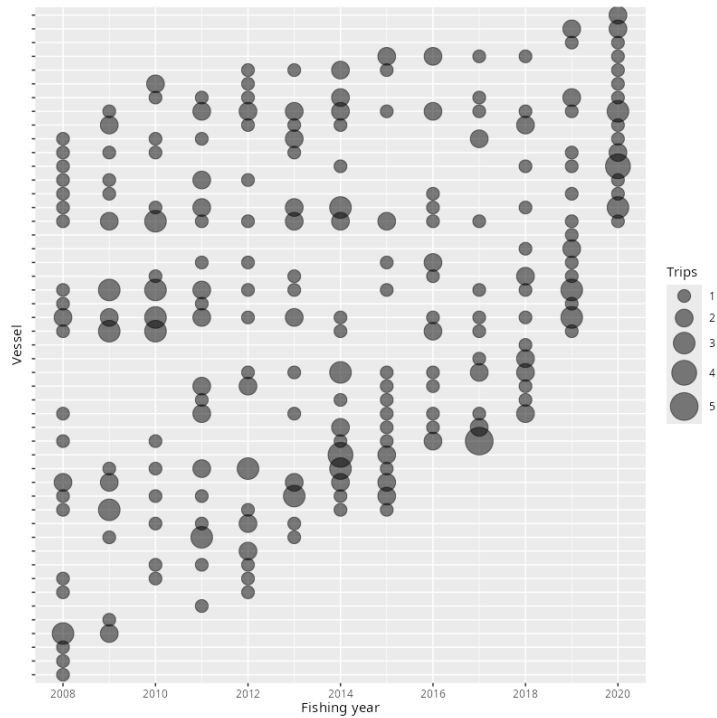
Figure 9: Number of large-vessel (≥28 m length) trawl fishing trips without data of the use of warp strike mitigation gear by vessel and fishing year, for the period between 2008–09 and 2019–20. These data were either not recorded or recorded as "none" in the mitigation device field by fisheries observers.
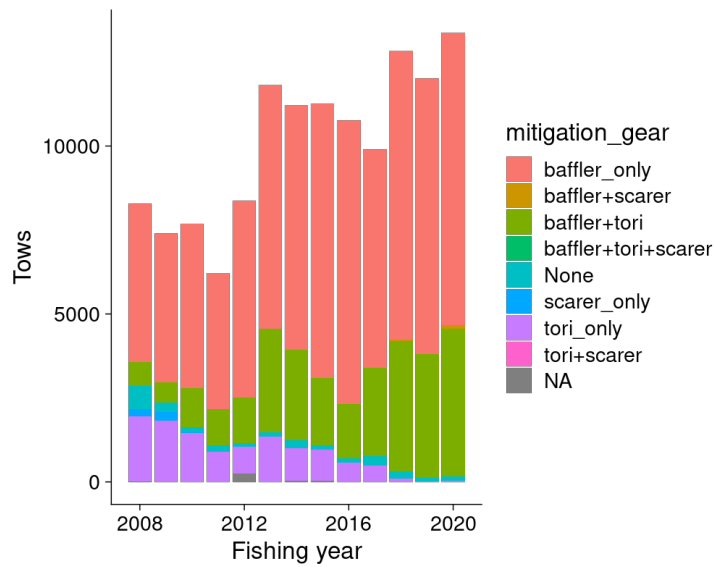
Figure 10: Number of tows with different warp strike mitigation gear as recorded by fisheries observer in large-vessel (≥28 m length) trawl fisheries for the period between 2008–09 and 2019–20. NA, no data available of the gear type used.
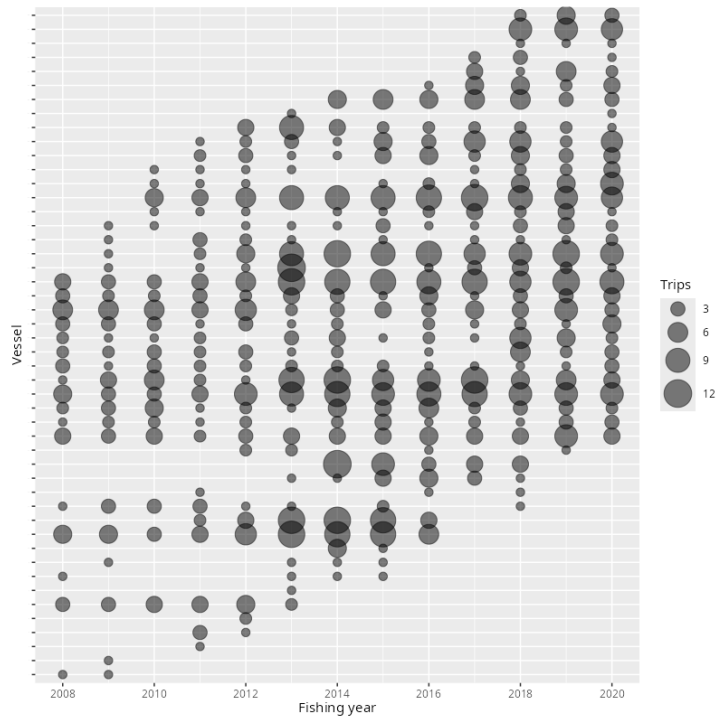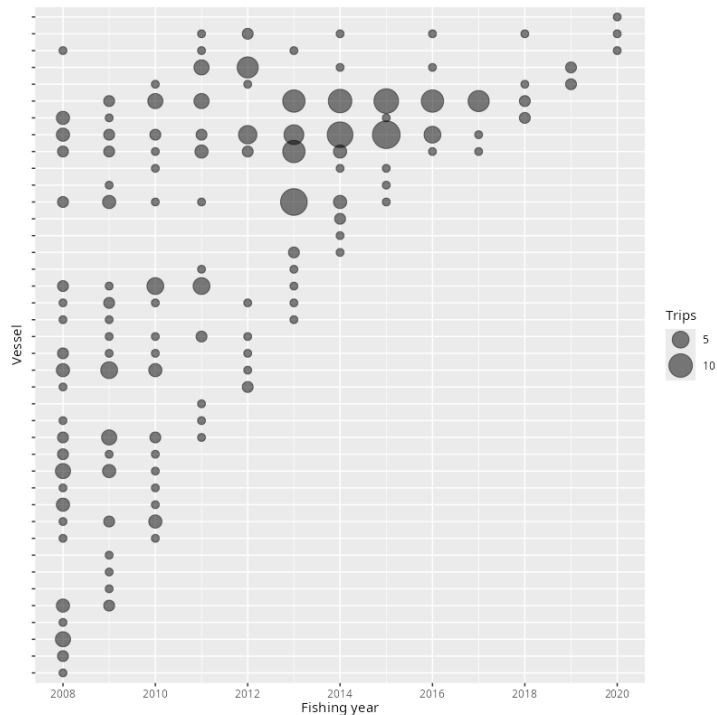
Figure 11: Number of fishing trips by large (≥28 m length) trawl vessels with warp strike mitigation use recorded as bird bafflers. Records are shown by vessel and fishing year, for the period between 2008–09 and 2019–20.
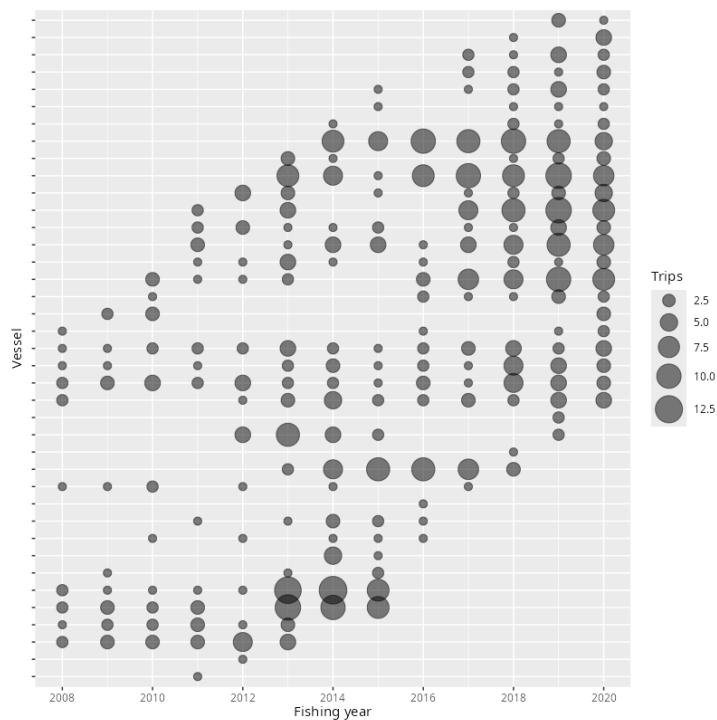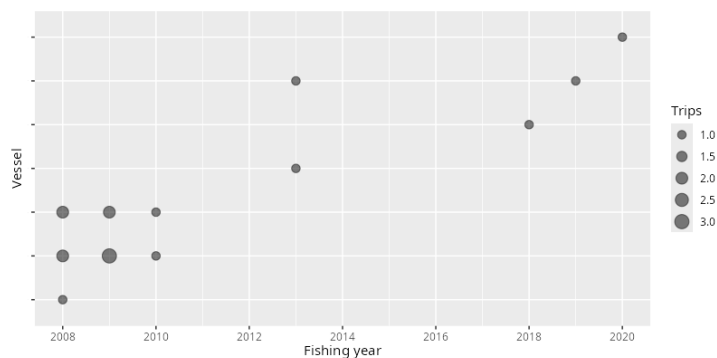

Figure 12: Number of fishing trips by large (≥28 m length) trawl vessels with warp strike mitigation use recorded as a combination of bird bafflers and tori lines. Records are shown by vessel and fishing year, for the period between 2008–09 and 2019–20.

Figure 13: Number of fishing trips by large (≥28 m length) trawl vessels with warp strike mitigation use recorded as tori lines. Records are shown by vessel and fishing year, for the period between 2008–09 and 2019–20.


Figure 14: Number of fishing trips by large (≥28 m length) trawl vessels with warp strike mitigation use recorded as warp scarers. Records are shown by vessel and fishing year, for the period between 2008–09 and 2019–20.

Assessing the performance of the different capture rate models, models 2 to 8 performed well, with SRF and MSRF values close to 1 for all variables, indicating convergence. In contrast, model 1 did not converge (see Appendix A, Figures A-1 and A-2 for model selection; Appendix B, Figures B-1 to B-3 for model diagnostics).

The best fit to the data was by models 8 and 9 (Figure A-1). These models included random effects for year and vessel, whereas the other models did not include these random effects. Distribution and trace plots of the estimated parameters showed reasonable mixing of MCMC chains for Model 8, and confirmed convergence (Figure B-1). Posterior predictive assessments for this model indicated that the model fit the data well for each of the mitigation gear categories (Figure B-3).

The best performing models (in order: models 8, 9, 7, and 6) had consistent results, and all models included an effect for vessel and for fishing year (Figure A-2). Compared with the use of bird bafflers, the model estimates indicated that tori lines were more effective (Figure 15). The combination of bafflers and tori lines was slightly less effective than the use of bird bafflers only; however, this result was inconsistent among models.
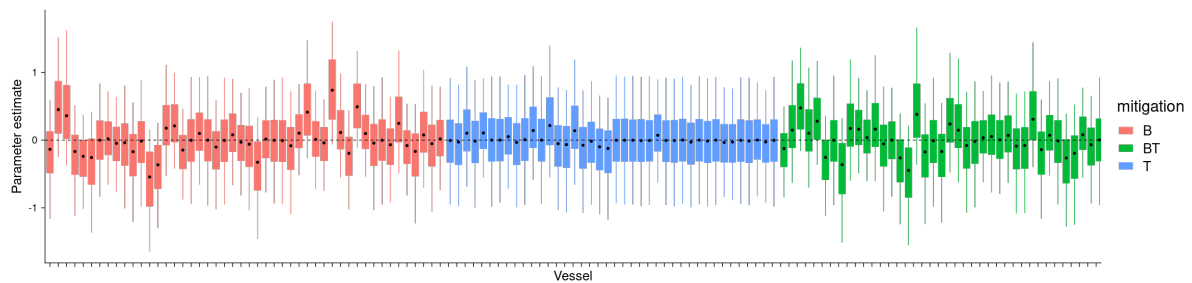
Model estimates and 95% credible intervals for the levels of mitigation gear by year suggested that the effectiveness of bird bafflers has improved, especially after 2015 (Figure 16). The effectiveness of tori lines (and tori lines used in combination with bird bafflers) was less variable than the effectiveness of bird bafflers only over time. Estimates and 95% credible intervals from Model 9 for the levels of mitigation gear by vessel suggested the effectiveness of tori lines was relatively consistent among vessels, whereas the effectiveness of bird bafflers was highly variable (Figure 17).
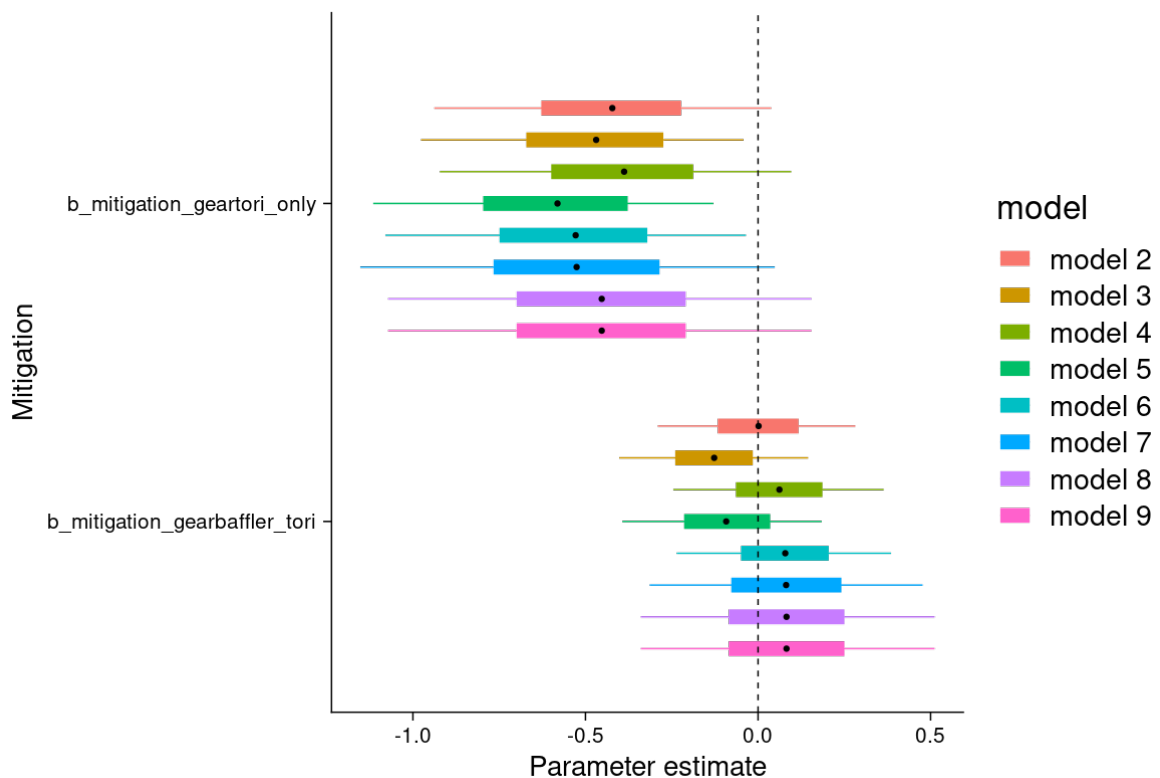
Figure 15: Model estimates and 95% credible intervals by model for the two types of warp strike mitigation gear, tori lines and the combination of bird bafflers and tori lines. For the modelling, bird bafflers only were the reference level at 0. A parameter estimate of less than 0 indicates a capture rate less than that for bird bafflers only, with the opposite indication for a parameter estimate great than 0.
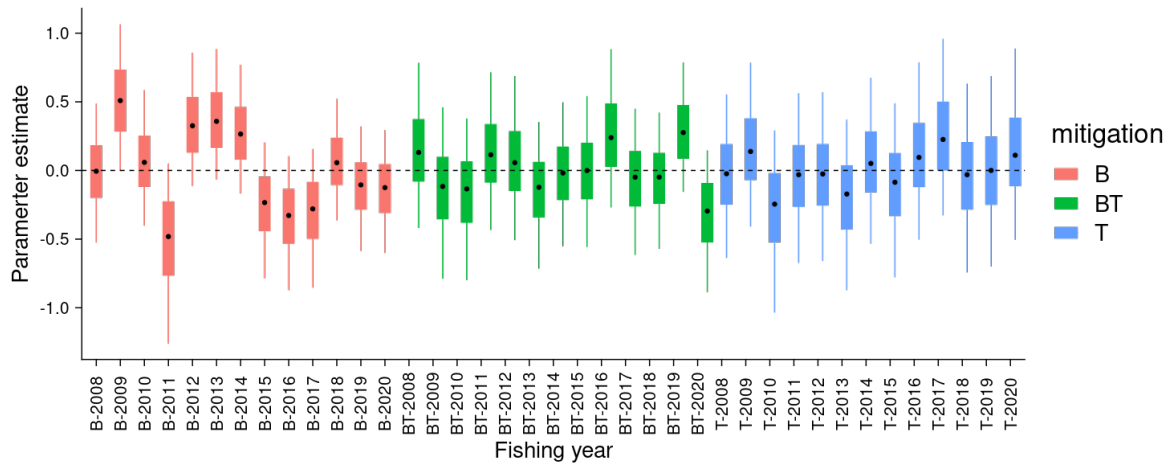
Figure 16: Model estimates and 95% credible intervals (Model 9) for the levels of the interaction effect combining fishing year and warp strike mitigation gear. Mitigation gear was: B, bird bafflers; BT, bird baffles and tori lines; T, tori lines. Reference level at 0 shows the average effect of each mitigation gear.

Figure 17: Model estimates and 95% credible intervals (Model 9) for the levels of the interaction effect combining vessel and warp strike mitigation gear. Mitigation gear was: B, bird bafflers; BT, bird baffles and tori lines; T, tori lines. Reference level at 0 shows the average effect of each mitigation gear.

4. DISCUSSION

The capture rate of seabirds depends on a number of factors, including the bird species, fishing location, target species, time of day, season, type of fishery, and waste management (Abraham & Richard 2019, Edwards & Dunn 2021, Pierre et al. 2012). Within this context, the current study aimed to elucidate the use of different mitigation gear in large-vessel trawl fisheries, and its potential influence on seabird captures (i.e., warp strike). Findings revealed a difference in effectiveness between the use of bird bafflers and tori lines. Nevertheless, trends were variable by year, particularly for the use of bird bafflers. The effectiveness of bird scaring or tori lines was estimated to be higher relative to bird bafflers alone, and their effect was also more consistent. This finding corresponds with other studies of seabird bycatch mitigation, which compared seabird captures across different mitigation devices in New Zealand trawl fisheries (Middleton & Abraham 2007, Abraham & Thompson 2009).

Nevertheless, the effectiveness of bird bafflers improved over time, suggesting potential improvements in their deployment in large-vessel trawl fisheries. Research in New Zealand has focused on updates and improvements to the design and at-sea trials of this mitigation device (Cleal & Pierre 2012a). Determining a potential relationship between these improvements and seabird capture rates requires further analysis, which could be part of a follow-up, in-depth analysis of the configuration of bird bafflers (and other mitigation devices).

This type of detailed analysis may focus on an overview of baffler configurations across large-vessel trawl fisheries, including the identification of updated and novel baffler configurations used. This analysis may also incorporate other sources of information, such as operational documents that may contain additional detail about the mitigation devices.

There was no evidence to suggest increased efficacy of the combination of tori lines and bird bafflers compared with the use of bird bafflers alone. This result is in contrast to earlier research, which showed reductions in seabird captures associated with the use of this combination of mitigation gear (Abraham & Thompson 2009). The current finding may be due to temporal aspects confounding improvements in the use of bird baffler use, and the use of bird scaring lines in combination with bird bafflers. Use of the latter combination increased markedly at the time when the efficacy of bird bafflers also increased. This finding may be related to the use of multiple mitigation device types during "high risk" periods, when high numbers of birds are foraging around vessels (e.g., during the peak squid trawl season). Further analysis may focus on elucidating this aspect including temporal patterns.

In contrast to the combination of tori lines and bird bafflers, the use of only bird scaring lines as a mitigation device declined to low level after 2017. For this reason, the documented difference between bird bafflers and tori lines as sole mitigation devices was largely based on data from a period when bird bafflers were estimated to be less effective. In comparison, the difference in efficacy between bird bafflers only and their combination with bird scaring lines was estimated from a period of overlap, dominated by years of data when bird bafflers were more effective. This potentially confounding factor may potentially be addressed in additional, more detailed data analyses.

Due to the lack of reporting of mitigation measures prior to their mandatory introduction, it was not possible to model the effectiveness of mitigation gear following its introduction. For this reason, the estimates here were relative between mitigation gear types. The considerable number of characteristics of mitigation devices and of unique configurations, the simultaneous use of multiple mitigation types, and the presence of other factors affecting seabird captures make it challenging to assess and derive an optimal configuration of mitigation gear. The preliminary analysis of gear characteristics suggested that this limitation is complex, preventing the inclusion of gear configurations in the modelling here. Using multivariate analysis, it may be possible to characterise "clusters" of gear configurations. These clusters would provide a potential way to incorporate a condensed form of these gear tables into models of gear efficiency. Although it is uncertain whether there will be sufficient statistical power to distinguish the effectiveness of different gear configurations given the relative rarity of warp strikes, this type of analysis is worth exploring in future efforts aimed at determining the efficacy of warp strike mitigation devices.

While the present study provided an initial exploration of the use of mitigation devices based on the three main device types, further analysis may focus on details of gear configurations, while also incorporating information from other sources. The latter may include operational documents and observer diaries that may provide further information of the use of mitigation devices and their configuration.

Further research may also include experimental studies that focus on the effectiveness of mitigation device types and their configurations. While an experimental approach may be able to assess the effectiveness of mitigation devices, these trials require considerable resources and would be limited to varying only some of the parameters of mitigation configurations. In contrast, existing data on seabird captures, fishing practices, and mitigation configurations are available and can be used to derive a more detailed estimate of the effectiveness of mitigation gear. These analyses are complex due to confounding factors and the lack of

independent variations in the configuration parameters that prevent the analysis of each parameter independently. Nevertheless, a more in-depth analysis of these data is likely to increase the understanding of the effectiveness of mitigation devices.

Recommendations from the present data exploration and analysis include:

- Exploration of different techniques to analyse the diversity of gear configuration, including clustering algorithms and dimensionality reduction. These techniques allow the grouping of mitigation device configurations into consistent sets. This approach addresses the limitation that configuration parameters cannot be analysed independently, and could be used to facilitate the comparison of capture rates between parameters.
- Use of these groupings to assess differences in bycatch rates, while taking into account the relative abundance of species. For example, seabird counts at the back of fishing vessels are carried out regularly, and these data could be linked to fishing events to control for the abundance of seabirds and normalise capture rates.
- Analysing the influence of waste management, which has varied over time and been shown to impact the abundance of birds around vessels (Pierre et al. 2012).

In addition, the collection of data on-board fishing vessels by fishery observers could be improved by:

- Ensuring that both the use of mitigation devices and their configuration are recorded in a consistent way.

- Clearly distinguishing between the lack of device use and the lack of a record of device use.

- Conduct a rapid assessment of the abundance and activity of seabirds around the fishing gear for inclusion in the analysis.

- Consistent recording of the discharge of fishing waste.

- Use of onboard cameras to record factors that facilitate an in-depth analysis of mitigation device use, such as the abundance of seabirds, the use of mitigation, and waste discharge.

5. ACKNOWLEDGEMENTS

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## APPENDIX A: Model selection and parameter estimates

Model	elpd_loo	se_elpd_loo	elpd_diff	se_diff	right side of formula
bmod8	-1,072.42	58.45	0.00	0.00	(1 | fyear) + (1 | vessel_key) + (1 | fisheryGroup) + (1 | area) + mitigation_gear + (1 | fyear:mitigation_gear)
bmod9	-1,072.86	58.44	-0.43	2.53	(1 | fyear) + (1 | vessel_key) + (1 | fisheryGroup) + (1 | area) + mitigation_gear + (1 | vessel_key:mitigation_gear) + (1 | fyear:mitigation_gear)
bmod7	-1,075.22	58.63	-2.80	3.94	(1 | fyear) + (1 | vessel_key) + (1 | fisheryGroup) + (1 | area) + mitigation_gear + (1 | vessel_key:mitigation_gear)
bmod6	-1,075.32	58.67	-2.90	2.75	(1 | fyear) + (1 | vessel_key) + (1 | fisheryGroup) + (1 | area) + mitigation_gear
bmod4	-1,078.68	58.83	-6.26	4.74	(1 | vessel_key) + (1 | fisheryGroup) + (1 | area) + mitigation_gear
bmod3	-1,106.11	60.11	-33.69	9.63	(1 | fisheryGroup) + (1 | area) + mitigation_gear
bmod5	-1,106.20	60.46	-33.78	9.73	(1 | fyear) + (1 | fisheryGroup) + (1 | area) + mitigation_gear
bmod2	-1,112.91	60.04	-40.49	11.02	(1 | area) + mitigation_gear
bmod1	-1,168.01	63.19	-95.59	15.74	mitigation_gear

Figure A-1: Models, ranked from the highest to the lowest performance in terms of expected log-posterior density (elpd) leave-one-out (loo) criterion, with associated standard error (SE), and elpd difference (diff) and associated standard error.

mods	baffler & tori	tori only	right side of forumla
bmod8	0.08 (-0.34 , 0.51)	-0.45 (-1.07 , 0.15)	(1 | fyear) + (1 | vessel_key) + (1 | fisheryGroup) + (1 | area) + mitigation_gear + (1 | fyear:mitigation_gear)
bmod9	0.09 (-0.41 , 0.59)	-0.47 (-1.17 , 0.2)	(1 | fyear) + (1 | vessel_key) + (1 | fisheryGroup) + (1 | area) + mitigation_gear + (1 | vessel_key:mitigation_gear) + (1 | fyear:mitigation_gear)
bmod7	0.08 (-0.31 , 0.48)	-0.53 (-1.15 , 0.05)	(1 | fyear) + (1 | vessel_key) + (1 | fisheryGroup) + (1 | area) + mitigation_gear + (1 | vessel_key:mitigation_gear)
bmod6	0.08 (-0.24 , 0.39)	-0.53 (-1.08 , -0.03)	(1 | fyear) + (1 | vessel_key) + (1 | fisheryGroup) + (1 | area) + mitigation_gear
bmod4	0.06 (-0.25 , 0.36)	-0.39 (-0.92 , 0.1)	(1 | vessel_key) + (1 | fisheryGroup) + (1 | area) + mitigation_gear
bmod3	-0.13 (-0.4 , 0.15)	-0.47 (-0.98 , -0.04)	(1 | fisheryGroup) + (1 | area) + mitigation_gear
bmod5	-0.09 (-0.39 , 0.18)	-0.58 (-1.12 , -0.13)	(1 | fyear) + (1 | fisheryGroup) + (1 | area) + mitigation_gear
bmod2	0 (-0.29 , 0.28)	-0.42 (-0.94 , 0.04)	(1 | area) + mitigation_gear
bmod1	0.36 (0.09 , 0.68)	-0.35 (-0.79 , 0.19)	mitigation_gear

Figure A-2: Model estimates and 95% credible interval (in parentheses) by model for the two levels of mitigation gear. The latter was the combination of baffler and tori lines and tori lines only; baffler only was used as the reference level at 0. Parameter estimates of less or greater than zero indicated a seabird capture rate less or greater than the rate for the baffler only, respectively.
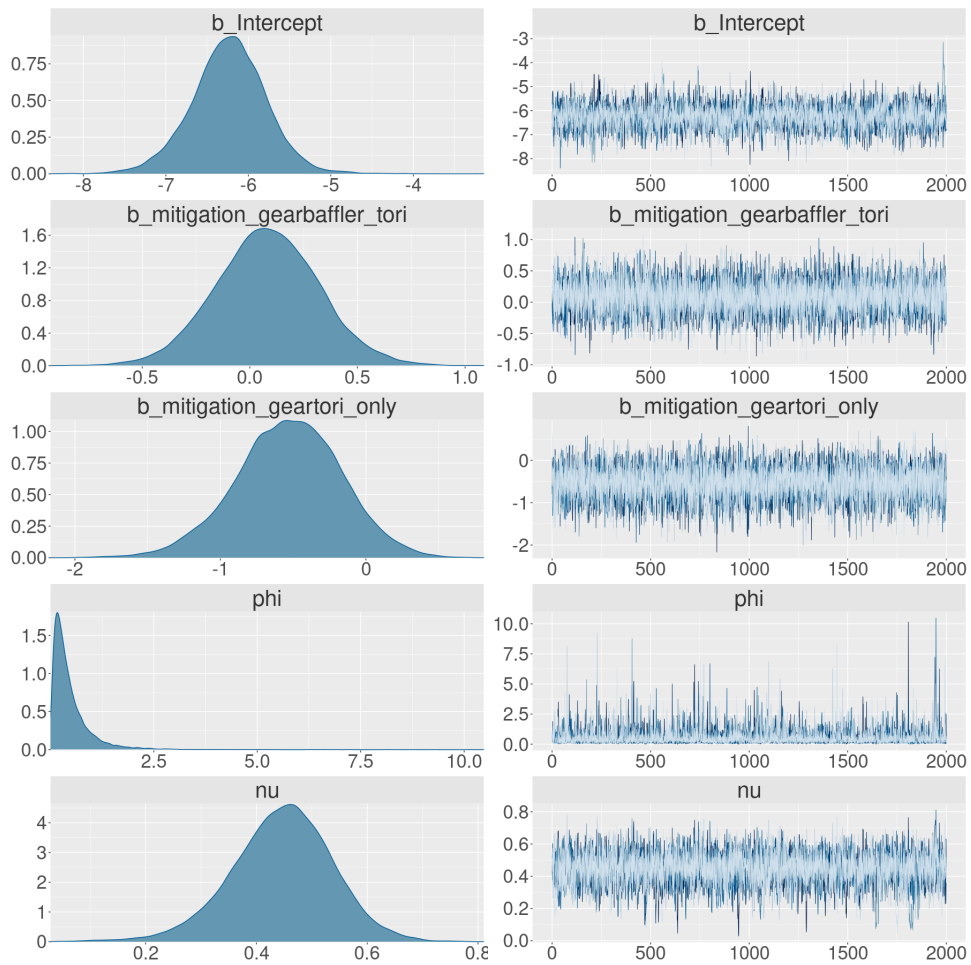
Figure B-1: Markov Chain Monte Carlo (MCMC) traces for 8 concurrent chains (right panels), with resulting posterior densities derived by combining all 8 chains (left panels), for key parameters in Model 8 for estimating the relative effectiveness of warp mitigation gear.
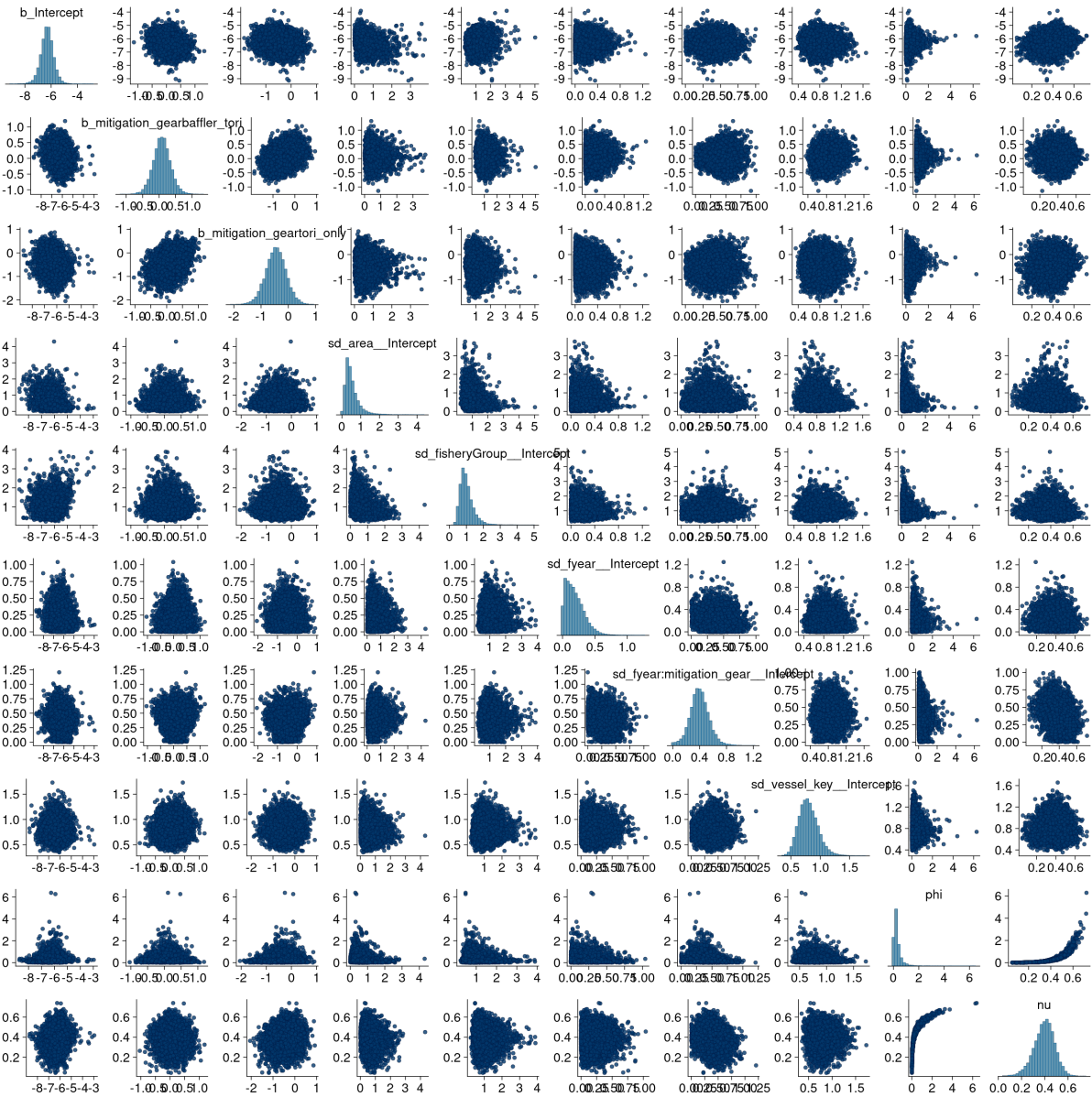
Figure B-2: Posterior distributions and correlation of Markov chain Monte Carlo (MCMC) draws across model parameters in Model 8 for estimating the relative effectiveness of warp mitigation gear. Strong correlation between the over-dispersion (phi) and scaling parameter of the over-dispersion (nu) are expected for this model.
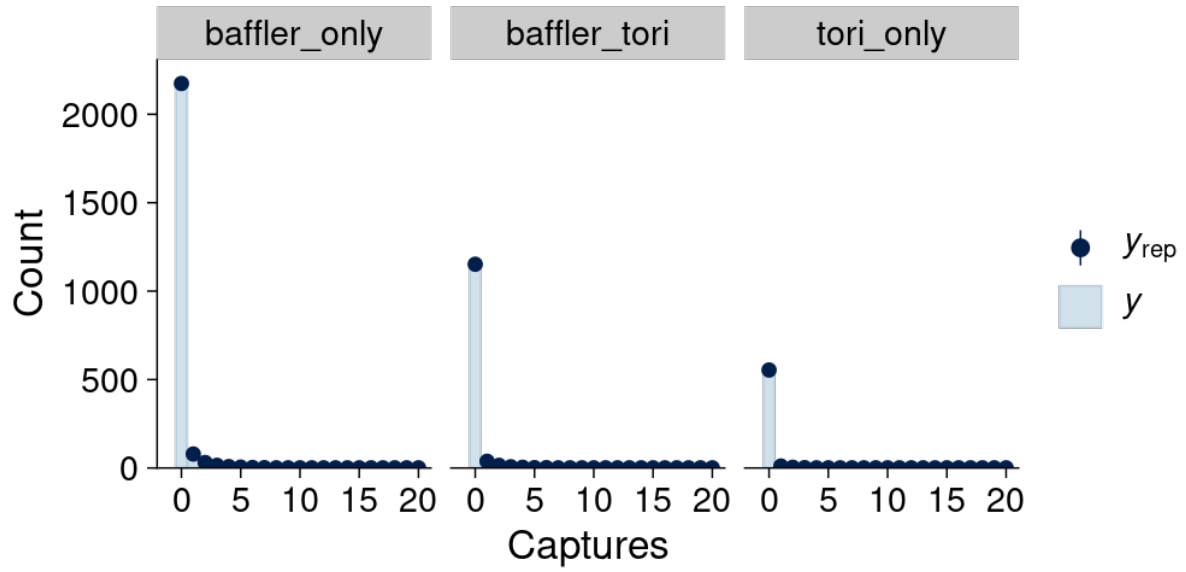
Figure B-3: Posterior predictive model diagnostic for Model 8 for estimating the relative effectiveness of warp mitigation gear. Shown are expected numbers of captures by mitigation device category in the model as predicted by the best model (black dots), compared with the data (blue bars). Mitigation device types were bafflers only, the combination of bafflers and tori lines, and tori lines only.