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Controlling trawler waste discharge to reduce seabird mortality

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ABSTRACT

Responsible fisheries management requires the consideration of fishing effects on ecosystems including non-target species. Extensive distributional overlap between fisheries and seabirds, and the attractiveness of the catch and fishery waste to foraging birds, leads to fatal interactions between seabirds and fishing gear. In a series of experiments, we have investigated measures for managing trawl processing waste to reduce seabird mortalities. Different fisheries generate different volumes of processing waste, and vessel capacities for holding this waste can vary significantly both within and between trawl fleets. Here, we compare seabird responses to discharging trawl fisheries waste ad hoc, as and when waste became available, with responses to discharging waste after holding periods of 30 min and 2 h. Using abundance as a proxy for the risk of mortality, we show that compared to discharging ad hoc, holding waste for two specified periods prior to discharge significantly reduces vessel attendance by small seabirds, and both small and large seabirds, respectively. Drawing on this study and our past work, we provide best practice guidelines for trawler waste management to reduce seabird mortality due to interactions with trawl warps. If the ideal approach of discharging waste only when fishing gear is out of the water is impossible, then discharging waste rapidly in maximally large batches, as infrequently as possible is recommended. Holding periods of 30 min to 8 h may be required to reduce the abundance of small species of seabirds attending vessels. For large seabirds, holding periods of 2–4 h are required, and 8 h holding periods are still more effective. Discharging waste as it becomes available is not recommended. Mincing processing waste can reduce the attendance of some seabird species at vessels, especially large albatrosses. However, holding waste is preferred, due to relative simplicity in the mechanics of dealing with waste, lower cost, and greater reductions in seabird abundance. Though developed on trawl fisheries, principles of these guidelines are applicable to any fishery discharging waste attractive to seabirds. While holding fisheries waste can minimise seabird captures on trawl warps worldwide, evidence-based management measures are still required to reduce seabird mortalities in trawl nets.

1. Introduction

In addition to providing for precautionary utilization of fish stocks, responsible fisheries management requires consideration of the ecosystems in which fisheries occur (FAO, 1995, 2007). Further, independent global assessments of fisheries sustainability include examining the effects of fishing on ecosystem components, such as non-target fish species, marine invertebrates, seabirds, and marine mammals (e.g. Monterey Bay Aquarium, 2011; MSC, 2011). As key components of marine ecosystems, seabirds often overlap in distribution with fisheries (Birdlife International, 2004).

As well as overlapping spatially, many species of seabirds forage on fish catch and the processing waste that is discharged as part of fishing operations. These foraging opportunities can appear beneficial to seabirds, as fishery discards may comprise a substantial part of their diet (e.g. Freeman and Wilson, 2002; Wagner and Boersma, 2011). However, there can also be negative consequences to this behaviour, e.g. reduced chick survival and increased depredation (Votier et al., 2004; Grémillet et al., 2008). Further, in the course of foraging on fish catch and fish processing waste, seabirds can be injured or killed by fishing gear. Consequently, there is global concern that incidental mortality in fisheries is adversely affecting the population status of seabirds (Butchart et al., 2004).

Although seabird mortality in trawl fisheries has been recognized for some time (Bartle, 1991), longline fisheries have been the primary focus of management measures (FAO, 1999). However, seabird bycatch has now been widely reported from trawl fisheries, including in Alaska, Argentina, Australia, the Falkland

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Islands, New Zealand, and South Africa (Baird, 2001; Wienecke and Robertson, 2002; Gonzalez-Zevallos and Yorio, 2006; Sullivan et al., 2006; Watkins et al., 2008; Melvin et al., 2010). Trawling accounts for approximately 40% of worldwide fish catch per annum (Watson et al., 2006). Due to the global importance and scale of trawl fisheries and the extent of documented interactions with seabirds, including threatened species (IUCN, 2010), this fishing method has been highlighted as a source of conservation concern (Croxall, 2008).

In trawl fisheries, birds can be caught in nets. They can also be injured or killed in flight when they collide with the cables used in trawl instrumentation and the cables (warps) used to tow trawl nets. Further, trawl warps can push birds under the water, where they may drown (Bartle, 1991; Bull, 2007, 2009; Abraham and Thompson, 2009a; Favero et al., 2010). Quantification of seabird mortality from warp interactions is difficult as dead birds typically do not come aboard at haul unless they are wrapped around the warp or caught on a splice (Sullivan et al., 2006). Data from New Zealand trawl fisheries have demonstrated that warp strikes are considerably more common than carcass recoveries (Abraham and Thompson, 2009a): for each dead albatross or giant petrel recovered from the trawl warps, 208 (150–290, 95% confidence interval) may have struck the warps. For other petrels and shearwaters, this figure is 7610 (3800–36,000, 95% confidence interval). While exact injury and mortality rates are unknown, there is no question that strikes can be fatal to both larger albatrosses and smaller petrels and shearwaters.

When seabirds are in attendance at trawl vessels, bycatch mitigation devices can reduce the risk of captures occurring (Bull, 2007, 2009). However, these are of varying efficacy, do not protect all risk areas (e.g. warps, net, paravane), and require ongoing monitoring and maintenance. Removing foraging opportunities when fishing gear is deployed provides a more direct and effective solution to bycatch. Holding fish waste onboard during fishing is an obvious way to achieve this. However, understanding the effects of holding periods on seabird attendance at vessels is important, as the volume of fish waste generated, and therefore holding capabilities, can vary significantly between vessels and fisheries. For example, a trawler operating in a fishery without significant non-target fish catch may easily be able to retain waste for 8 h. The same vessel operating in a bulk fishery with significant non-target fish catch may be unable to consistently maintain holding periods 2 h in duration.

Since 2005, we have experimentally investigated approaches to trawler waste management to reduce the risk of seabird mortality due to interactions with trawl gear. Work has included examining the effects of the form of discharge and the timing of discharge events on seabirds attending trawlers. With respect to the form of discharge, minced fish waste (compared to large chunks of waste) proves somewhat less attractive to seabirds, especially large albatrosses (*Diomedea* spp.). However, small albatrosses (*Thalassarche* spp.) and Cape petrels (*Daption capense*), are still attracted to forage on the minced discharge (Abraham et al., 2009; Pierre et al., in press). Temporal characteristics of discharge events also influence seabird attendance at trawlers. For example, Pierre et al. (2010) found that fewer seabirds attended discharge events four or more hours apart, compared to events 2 h or 30 min apart.

If management measures are to be effective in reducing fisheries impacts on seabirds, they must be practical, achievable, and able to be applied fleet-wide. Thus, while Pierre et al. (2010) confirmed the efficacy of longer (≥4 h) holding periods in reducing risks of seabird mortality, here we examine the efficacy of holding waste for periods of 2 h or less, to provide for evidence-based management in accordance with vessel-specific waste retention capabilities. We determine whether these shorter holding periods are an improvement, in terms of reduced risk of seabird mortality, on simply discharging waste ad hoc as it becomes available during fish processing in the vessel factory.

Given the injurious nature of warp strikes, the number of warp strikes (and consequent mortalities) required to test experimental effects, the required use of mitigation devices, and the conservation status of the species involved, we did not consider a lethal experiment to be prudent. However, previous work has shown that the number of birds astern vessels is a strong predictor of the warp strike rate (Middleton and Abraham, 2007; Abraham and Thompson, 2009a; Abraham et al., 2009). Therefore, this measure is an effective proxy for the risk of warp strike astern the experimental vessel, and consequent mortality. As such, it has been used here and in our more recent work (Pierre et al., 2010, in press).

In this paper, our objectives are:

(1) to assess whether holding periods of 2 h and 30 min reduced seabird attendance at the experimental vessel relative to an ad hoc discharge regime (i.e. discharging as and when waste is available, and including some periods of continuous discharge),
(2) to compare the effects of ad hoc discharge, and holding periods of 2 h and 30 min on seabird attendance at the vessel, with the longer holding periods (≥4 h) proven to reduce attendance in previous work (Pierre et al., 2010),
(3) to compare the efficacy of fish waste management regimes examined to date, and develop evidence-based best practice guidelines for management of fishery waste to reduce seabird mortality.

Our work has been conducted in trawl fisheries. However, the principles of best practice guidelines we develop are relevant not only to trawl fisheries, but also to other fishing methods that generate mortality risk for seabirds by discharging fish waste.

2. Methods

2.1. Experimental set-up

The experimental platform was a New Zealand-flagged deepwater factory trawler, 42.5 m in length and built in 1989. The vessel's discharge management system included a retrofitted storage tank and macerating equipment (Pierre et al., in press), although waste was not macerated in this experiment. The experimental voyage ran 11 February–13 March 2010 off New Zealand's east coast, in Fishery Management Areas 2–4 (Fig. 1, Clement and Associates Ltd., 2010). Target species were hoki (*Macruronus novaezelandiae*) and alfonsino (*Beryx splendens* and *Beryx decadactylus*). Normal vessel operations and fishing practices were implemented, with the exception of the three experimental discharge regimes. Seabird bycatch mitigation measures required by New Zealand law were deployed during fishing (streamer lines and bird bafflers, Department of Internal Affairs (2006)).

Three experimental discharge management regimes were applied: (1) ad hoc discharge (all material released as available, including whole fish discards, heads, guts, frames etc., and including periods of continuous discharge), (2) a 30 min holding period (all fish waste held onboard the vessel for 30 min, then discharged), and (3) a 2 h holding period (all fish waste held onboard the vessel for 2 h, then discharged). After storage in a holding tank for the required retention period, fish processing waste was discharged through an offal chute out the side of the vessel, via a conveyor. The timed holding periods ran between the start of one batch discharge event, and the start of the next batch discharge event, once fish processing was underway (i.e. waste became available). Each experimental discharge regime ran for 24 h changing at midnight. The three regimes were implemented following a randomised block

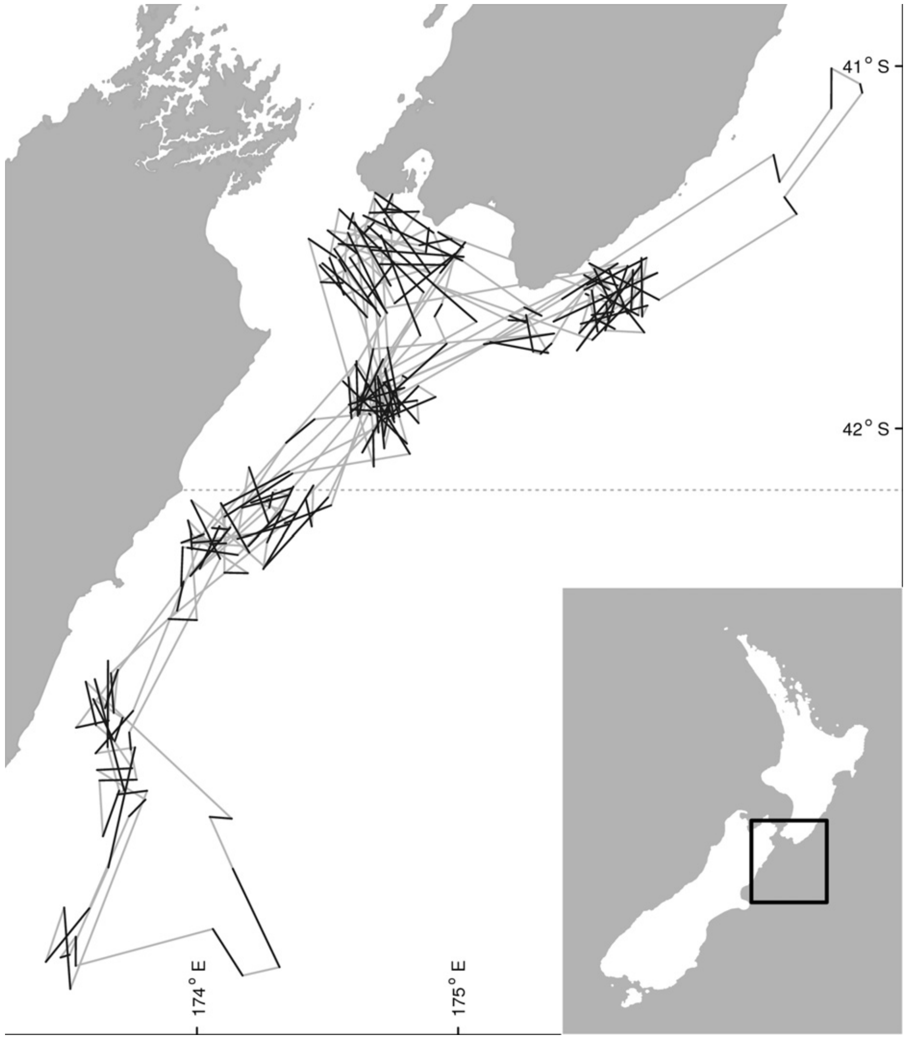

Fig. 1. Location of fishing activity during the experimental voyage off New Zealand. The black segments represent trawl tows within vessel tracks (in grey). The dotted line delimits Fishing Management Area boundaries. Points have been randomly moved by between ±0.1° of latitude and longitude to meet Ministry of Fisheries confidentiality requirements.

design; this ensured each regime was implemented once every three days. Sump discharge was automated for safety reasons, throughout the experiment.

2.2. Data collection

We focussed on the risk of seabird mortality due to interactions with trawl warps. Following data collection procedures described in Abraham et al. (2009), we quantified seabird responses to the experimental discharge regimes by assessing abundance within semi-circular areas of 10 m and 40 m radius, centered on the vessel stern. As described above, this measure is an effective proxy for interactions between seabirds and trawl warps (Middleton and Abraham, 2007; Abraham and Thompson, 2009a; Abraham et al., 2009) eliminating any need for a lethal experiment.

Seabird abundances were assessed by an experienced government fisheries observer, during observation periods of approximately 1 h with at least an hour gap in between. One to four observation periods were conducted daily during fishing (i.e. when the trawl net was deployed). For the 30 min and 2 h holding treatments, observations commenced around 10 min before a discharge event, and continued for 45 min after the discharge event. For ad hoc discharge treatments, observations commenced at a randomly selected interval after factory discharge started.

Assessing seabird abundances required the observer to repeatedly sweep their gaze around each of two semi-circles, of 10 m and 40 m radius, centered on the mid-point of the vessel stern. The 10 m-radius semi-circle included the trawl warps, and the point at which they entered the water. Counts within the 40 m area included those birds within 10 m of the stern. Seabirds were classified into three groups, and the abundance of each group was assessed both on the water and in the air. Thus, each ‘observation’ (i.e. set of counts) required 12 individual sweeps through the sampling area. Consecutive sweep counts in each observation period were conducted at most 60 s apart, and so were necessarily approximate when bird abundances were high. The seabird groups defined for the counts were “large seabirds” (comprising albatrosses (*Diomedea* spp. and *Thalassarche* spp.), and giant petrels (*Macronectes* spp.)), “small seabirds” (comprising all other procellarids except Cape petrels (*Daption capense*)), and Cape petrels. Seabirds were grouped as large, small, or Cape petrels due to differences in foraging styles, as well as vulnerability to warp strike and bycatch (Abraham and Thompson, 2009a,b) (cape petrels were subsequently excluded from the analysis, due to their low levels of abundance, and consequent lack of utility in investigating treatment effects).

During each observation period, the observer typically conducted 12 observations at 5-min intervals. Prior to each observation, the observer recorded the time (New Zealand

Standard Time), wind strength (Beaufort scale) and the number of other fishing vessels that were visible (no other vessels were seen during the experiment, and this variable was subsequently ignored in the analysis). The observer also recorded the arrival rate (none, negligible, intermittent, or continuous) of each discharge type (sump, minced, offal, and whole discards) into the water astern the vessel during each observation. Finally, for each observation period, the observer recorded the vessel speed (in knots), the swell height (m), the characteristics of batch discharges occurring during the observation period (start and end time, and batch volume in kg), and the locations of fishing events. All data were recorded systematically by observers on a dedicated form. Locations were subsequently assigned to a Fishery Management Area to account for spatial variation in the seabird species present, and their abundance.

2.3. Statistical analyses

Statistical analysis of the data followed the methods used by Pierre et al. (2010).

We estimated the effects of discharge on bird counts using linear statistical models, with discharge being defined as occurring when minced waste, offal, or whole fish discards were discharged at least intermittently. The models fit a time-dependent model to the data, making the following assumptions:

- The mean value of the counts may be different for each experimental treatment and discharge level.
- When discharge begins, birds arrive faster than can be resolved by the data.
- There is a transition time-scale representing how quickly birds leave the sweep region once discharge has ceased. This timescale is treatment independent.
- There is no influence of batch discharge in one tow on seabird abundance in subsequent tows.
- There are other covariates which may influence the counts.
- The count values may differ from tow to tow for reasons that are not captured by the covariates.
- A negative binomial distribution may be used to generate the counts from the mean values.

Expressing these assumptions in formal terms, during periods when the discharge is steady then the mean number of birds around the vessel, N, may be written as

$$\log(N_{ik}) = \log(\beta_{de}) + \sum_j \log(\beta_j) x_{ijk} + \varepsilon_{id}$$

where the tows are indexed by i and the counts within a tow by k. The parameters β_{de} give the baseline count when there is discharge $d = d_{ik}$, during experimental treatment $e = e_i$. The covariates x_{ijk} are selected from the available data by fitting a simpler negative-binomial model which does not include tow-level random effects, and which assumes that the mean count on each tow is given by N_{ik}. Only the Fishery Management Area where the fishing was taken place is found to have an effect on the number of birds, and only this covariate was retained in the final analyses. The parameters β_j give the influence of each covariate on the mean count.

Tow-to-tow variation in the counts that is not related to either the discharge, the experimental treatment, or the covariates is captured through the random effect ε_{id}. The random effect is drawn independently from a normal distribution for each tow i and discharge category d.

Following cessation of discharge, the mean bird abundance returns to the no-discharge level with a time-scale T:

$$\mu_{ik} = \begin{cases} N_{ik}, & k = 1 \quad \text{or batch discharge} \\ N_{ik} + (\mu_{i,k-1} - N_{ik}) e^{-((t_{ik} - t_{i,k-1})/T)}, & k > 1 \quad \text{and no discharge} \end{cases}$$

The seabird counts respond to the beginning of a discharge event immediately. To fit this model to the data, the seabird counts are assumed to be drawn from a negative binomial distribution with mean μ_{ik}.

Bayesian methods were used to fit the model to the count data, using the software JAGS. Weakly informative normal priors, with zero mean and a standard deviation of ten, were chosen for each of the β parameters. The prior for the timescale T is a uniform distribution between zero and 24 h. The prior for the scale of the tow-level random effect is taken to be a half-Cauchy distribution, and the prior for the overdispersion of the negative binomial distribution is a uniform-shrinkage distribution (e.g., Gelman et al., 2006; Pierre et al., 2010).

In the longer treatments, the observations did not cover the full period between batch discharges. From each sample from the fitted model, the mean number of birds over the full period (a discharge event and the following interval) was calculated analytically from the estimated values of N and T:

$$\bar{N} = \frac{1}{P}(N_D t_D + N_S(P - P_D) + T(N_D - N_S)(1 - e^{-((P-P_D)/T)}))$$

with P being the treatment period (30 min or 2 h), P_D is the duration of discharge events, N_D is the estimated number of birds during offal discharge, and N_S is the steady-state number of birds when no offal is discharged. The mean number of birds for the continuous treatment was simply N_D The distribution of $\bar{N}$ was obtained by calculating a value of $\bar{N}$ for each value of the parameter samples, obtained from the Bayesian fitting, and by sampling at each iteration a value of t_D from the discharge lengths recorded by the observer. During this calculation, the covariates x and the random effect ε were taken to be zero. Samples of $\bar{N}$ were used to calculate the ratio of the number of birds present around the fishing vessel during the 30 min or 2 h treatments to the mean number of birds during continuous discharge.

3. Results

A total of 529 observations was made during the experiment: 199 were made during periods of ad hoc discharge, 150 during 30 min holding treatments, and 180 during 2 h holding treatments. Observations occurred within 18 periods of ad hoc discharge, eleven 30 min holding treatments, and sixteen 2 h holding treatments.

Seabirds observed in the areas fished included great albatrosses (*Diomedea* spp.), Buller's albatross (*Thalassarche bulleri*), Cape petrel (*Daption capense*), giant petrels (*Macronectes* spp.), Salvin's albatross (*Thalassarche salvini*), white-capped albatross (*Thalassarche steadi*), grey petrel (*Procellaria cinerea*), and Westland petrel (*Procellaria westlandica*). Four birds were killed during the experimental voyage, all in the trawl net: three Westland petrels and one Salvin's albatross. An additional northern royal albatross (*Diomedea sanfordi*) died after it struck the vessel deck during high winds.

The volume of waste discharged increased from 240 kg on average after 30 min holding periods, to 1440 kg following 2 h holding periods. Consequently, the duration of discharge events (i.e. the time period during which the vessel was actively discharging fish processing waste) also increased with holding interval (Table 1).

Raw seabird abundance (before consideration of covariates) was consistently higher during ad hoc discharge treatments compared to 30 min and 2 h holding treatments. Further, raw abundances

Table 1
Mean, minimum, and maximum discharge duration following 30 min and 2 h holding periods.

Holding period	Discharge duration (min)		
	Mean	Min	Max
30 min	3.1	2.0	5.0
2 h	9.4	5.0	26.0

during 30 min treatments were higher than during 2 h treatments (Fig. 2). These patterns held for large and small seabirds and for the 10 m and 40 m radius sampling areas.

Treatment effects were most pronounced at the first discharge event of each observation period. At this time, similar proportions of large seabirds occurred within 10 m of the vessel during ad hoc and 30 min treatments, compared to during 2 h treatments. However, a higher proportion of small birds occurred within 10 m during ad hoc treatments, compared to during 30 min and 2 h treatments (Fig. 3a). At the first discharge of ad hoc treatment observation periods, the smallest proportions of small and large birds were located on the water. For small seabirds, this proportion increased to a similar level at the first discharge following 30 min and 2 h holding periods. For large seabirds, proportions on the water increased for 30 min holding treatments, and again for 2 h treatments (Fig. 3b).

After model fitting and accounting for the only important covariate (Fishery Management Area), treatment effects are clear for observation periods in their entirety. In both the 10 m and 40 m sampling areas astern the vessel, large and small seabirds were significantly less abundant in the air, and on the water, during 2 h holding treatments compared to when ad hoc discharging occurred (Fig. 4). For small birds, this difference also held for 30 min holding treatments. However, for large birds, abundances astern the vessel did not differ significantly between ad hoc discharge treatments

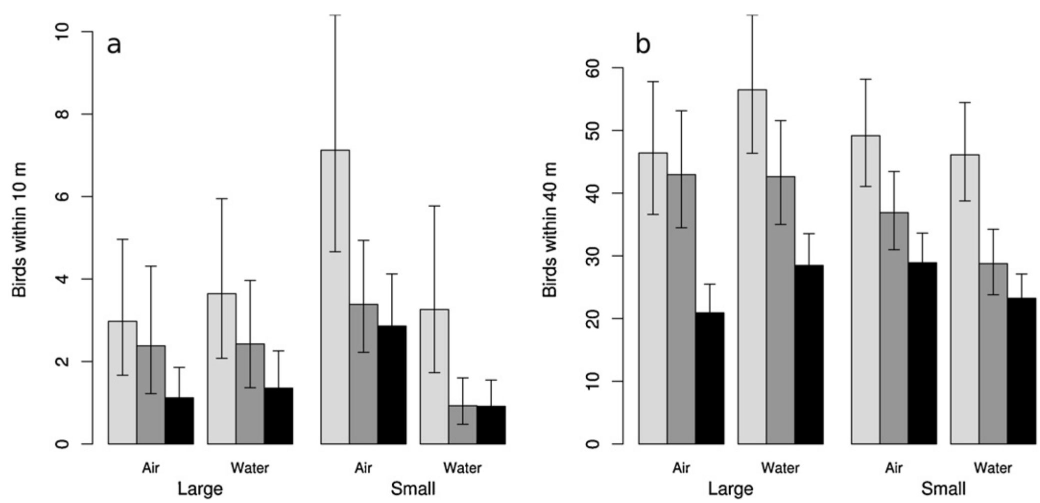

Fig. 2. Abundance (mean ± 95% CI) of seabirds (a) in a 10 m radius, and (b) in a 40 m radius, astern the experimental vessel during ad hoc discharge (light grey bars), after 30 min holding periods (mid-grey bars) and after 2 h holding periods (black bars).

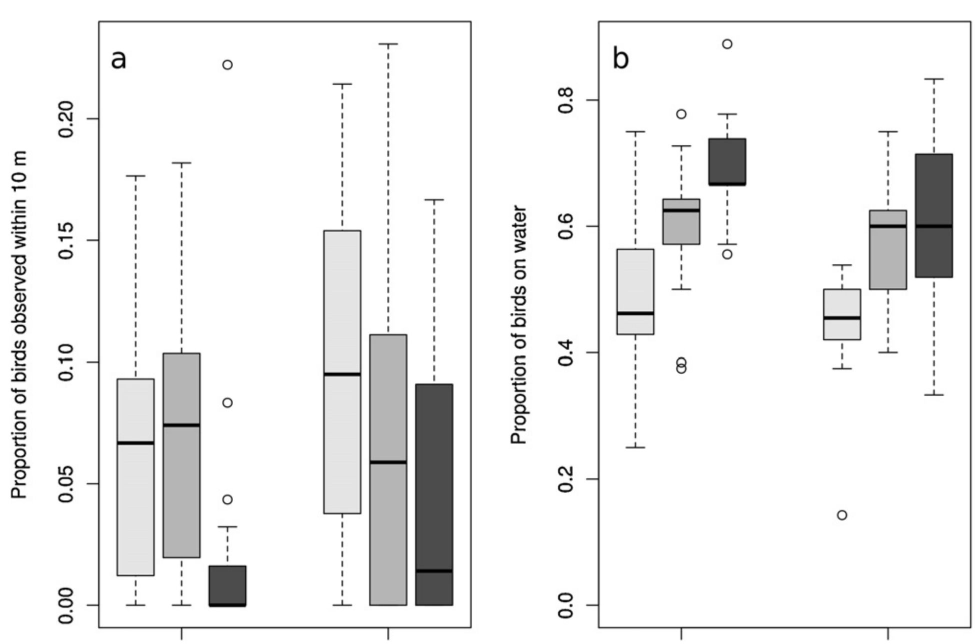

Fig. 3. Proportion (mean ± 95% CI) of seabirds at the first discharge of each observation period (a) within a 10 m radius centred on the vessel stern, and (b) on the water within a 40 m radius astern, for ad hoc discharge treatments (light grey bars), 30 min holding periods (mid-grey bars) and 2 h holding periods (black bars).

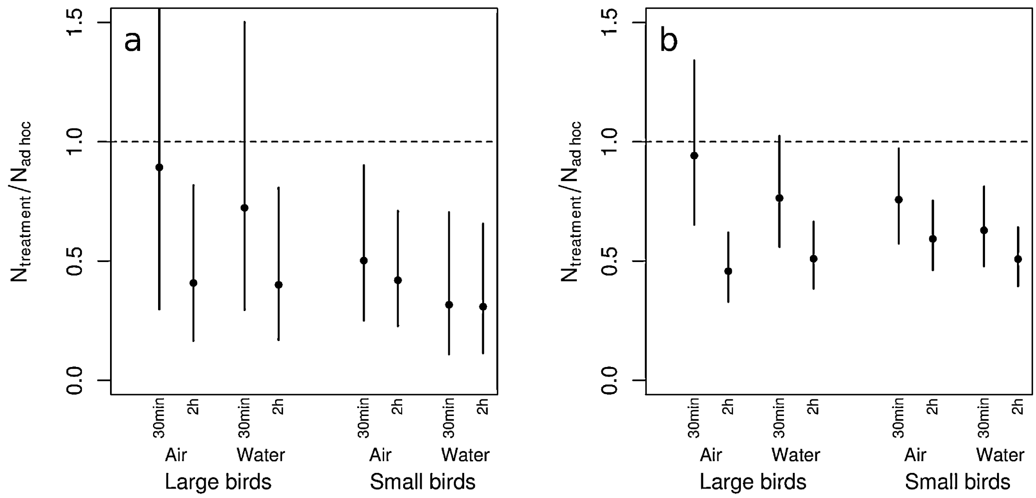

Fig. 4. Ratio of bird counts during the ad hoc discharge treatment to the corresponding counts during the 30 min and 2 h holding treatments, within (a) 10 m and (b) 40 m of the vessel stern. The ratio is calculated from the model estimated asymptotic counts during timed discharge treatments, divided by the ad hoc treatment. The points mark the median and the lines indicate the 5% and 95% quantiles of the posterior distribution of the ratio for each category.

and 30 min holding periods. Despite this, the median ratio was still consistently less than one (Fig. 4).

When modelled seabird abundances in the 40 m sampling area are examined through time, abundances peak when discharge events occur, then decrease rapidly, to a consistent level until the next discharge event for the 30 min and 2 h holding periods. The one exception was for small birds in the air, which show consistent abundance across time with no peak at discharge events (Fig. 5).

In the 10 m sampling area, discharge events taking place after 30 min holding periods invoke an increased abundance of large and small seabirds, both in the air and on the water. However, during discharge events following 2 h holding periods, seabird abundances show a slight decrease in the 10 m sampling area, after which abundances recover to a consistent level over time (Fig. 5). Further, within the 10 m sampling area, variability in abundances overlaps more between treatments than for the 40 m sampling area.

For ad hoc discharge, modelled abundances do not increase and decrease, but instead remain consistent across observation periods. During ad hoc discharge treatments, seabird abundances are maintained above the mean abundances occurring during 2 h holding treatments, with only one exception: large birds on the water within the 40 m sampling area, at the start of an actual discharge event. In this exceptional case, abundance spiked above the mean level of the ad hoc discharge treatments, before falling back to a level below ad hoc discharge within the next 10 min. Small birds on the water in the 40 m zone showed a similar pattern, but the increase in abundance was not as pronounced and so means for the two treatments did not overlap (Fig. 5).

Across the experimental results, confidence intervals used to describe variability in abundances showed some overlap. This is shown both over time (Fig. 5) and for observation periods as a whole (Fig. 2).

4. Discussion

Consistent with previous work, the duration of discharge events increased with holding period as waste accumulated (Pierre et al., 2010), due to the conveyor mechanism used for waste discharge. Both raw data and modelled outputs show that more seabirds attended the vessel during ad hoc discharge compared to when trawl processing waste was discharged every 30 min or every 2 h. Further, more seabirds attended vessels when waste was discharged after 30 min intervals, compared to 2 h intervals. Significant reductions in the abundance of small seabirds occurred when waste was retained for only 30 min prior to discharge. While 30 min holding periods caused some reduction in large bird abundance, significant reductions in the abundance of both small and large seabirds were achieved when waste was held for 2 h.

Not only did ad hoc discharge result in the highest abundance of seabirds astern the vessel, but it also brought the greatest proportion of small seabirds within 10 m of the vessel and so at immediate risk of warp strike. For large birds, holding intervals of 30 min had similar effects. Proportionately more birds attended the vessel in the air during shorter holding periods, suggesting they were more actively following the vessel in order to forage when discharge became available. Thus, consistent with the effects of treatment on seabird abundance astern vessels, longer holding periods will also reduce the proportion of birds at risk of warp strike.

Examining seabird abundance over time reveals a consistent pattern of treatment effects between this and previous work. In the 40 m sampling area, seabird responses to discharges after 30 min and 2 h holding periods generally followed the model described by Pierre et al. (2010); that is, a steep increase in seabird abundance at discharge, followed by an exponential decline. The rate of decline is greater for seabirds on the water, compared to seabirds in the air. In the 10 m sampling area, seabird responses to discharges after 30 min holding periods follow similar patterns. However within this area, modelled responses to discharge events following 2-h holding periods suggest that seabirds were not closely attending the vessel, and so were not immediately available to feed on discharge released. Modelled seabird responses to ad hoc discharge treatments show that this approach to waste management generates consistently higher seabird attendance at the vessel throughout observation periods. Through time across observation periods, there is some overlap in confidence intervals capturing treatment effects. This illustrates the dynamism of seabird attendance at vessels, and how discharge will attract available seabirds to some degree, regardless of how often it is released.

While trends are consistent throughout work to date in that longer holding periods are more likely to reduce seabird attendances at vessels, the holding time required to significantly reduce abundances has varied between experiments. In this study, significant reductions in abundance occurred after 2-h holding periods. Pierre et al. (2010) noted non-significant reductions in seabird abundances at 2-h holding periods; significant reductions resulted

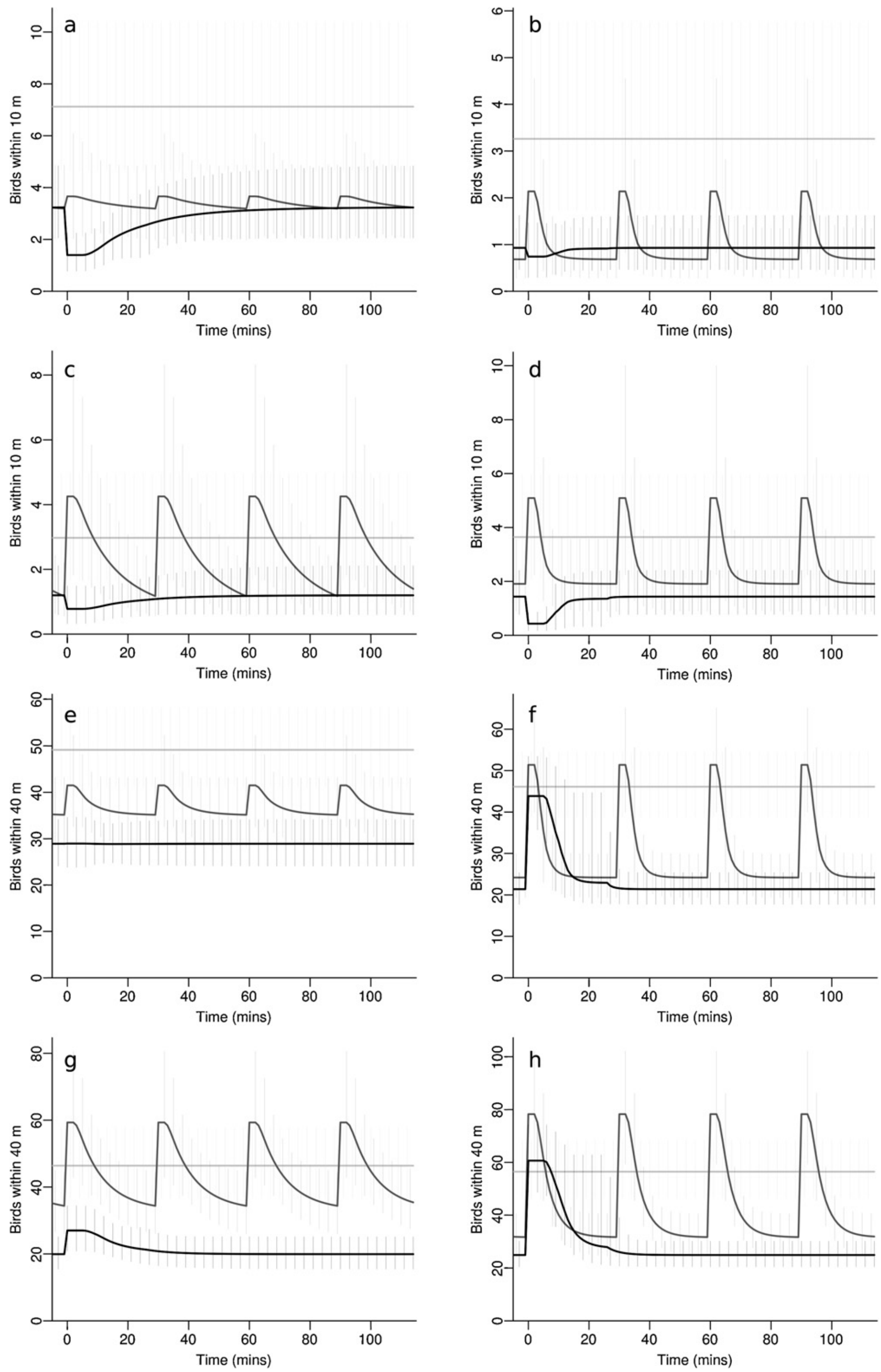

Fig. 5. Variation over time in the number of large and small seabirds from the model fitted to bird counts recorded while fishing waste was discharged either ad hoc (light grey lines), every 30 min (mid-grey lines), or every 2 h (black lines). Figures show the mean and the 95% confidence intervals of the variation of the mean, for (a) small birds, 10 m astern, in the air, (b) small birds, 10 m astern, on the water, (c) large birds, 10 m astern, in the air, (d) large birds, 10 m astern, on the water, (e) small birds, 40 m astern, in the air, (f) small birds, 40 m astern, on the water, (g) large birds, 40 m astern, in the air, and (h) large birds, 40 m astern, on the water.

for large seabirds when waste was held for 4 h. Similarly, where the current study detected significant reductions in the abundance of small seabirds when waste was discharged after 30 min, Pierre et al. (2010) found a near significant reduction after holding periods of 4 h, and a significant reduction after holding waste for 8 h. Differences may be due to a variety of factors, including weather conditions, seabird species attending, breeding status, other vessels present, type of discharge, etc.

The results of this study, alongside previous work (Abraham et al., 2009; Pierre et al., 2010), show that ad hoc discharge is the least desirable waste management strategy of those trialled to date for reducing risks of seabird mortality on trawl warps. Longer holding periods are more likely to reduce interactions between seabirds and trawl warps but shorter holding periods are still better than none. Given the threat classifications of many of the seabirds encountered during trawl fishing (IUCN, 2010), a precautionary approach is recommended.

5. Conclusions and recommendations

For management measures to reduce the effects of fishing on seabirds, practical and achievable measures must be developed and applied worldwide where seabirds are at risk. This paper concludes a six-year research programme using vessel-based experiments to test waste management techniques for seabird bycatch reduction. Based on this body of work (Abraham et al., 2009; Pierre et al., 2010, in press), we draw the following conclusions regarding the management of trawl waste to reduce seabird interactions with trawl warps.

(1) Holding all processing waste during fishing, for discharge when fishing gear is out of the water, remains the ideal waste management option for reducing interactions between seabirds and trawl warps.
(2) Discharging trawler processing waste ad hoc, as it becomes available, is the least desirable waste management option, due to heightened risk of seabird interactions with trawl warps.
(3) Second to holding waste for discharge when fishing gear is out of the water, discharging waste rapidly in maximally large batches, as infrequently as possible, is the recommended practice for reduction of seabird interactions with trawl warps.
(a) Holding waste for 30 min can reduce the abundance of small species of seabirds attending vessels. However, holding periods of up to 8 h may be required.
(b) Holding waste for 2 h can reduce the abundance of large seabird species at vessels. However, holding periods of 4 h may be required.
(c) Eight-hour holding periods are preferable to 4-h holding periods, to further reduce seabird abundance at vessels.
(4) Mincing processing waste can reduce seabird abundance at vessels, and consequently reduce interactions with trawl warps. Mincing is most effective in reducing vessel attendance by great albatrosses (*Diomedea* spp.). However, it is less effective in reducing attendance by smaller albatrosses (e.g. *Thalassarche* spp.), many species of which are of conservation concern.
(5) Further, limitations of mincing machinery mean that not all processing waste can be minced. Machinery is also expensive and can be difficult to retrofit to vessels. Consequently, compared to mincing trawl processing waste, holding waste for at least 2 h is simpler operationally and more cost effective, as well as more likely to reduce interactions between a greater diversity of seabird taxa and trawl gear.

The recommendations above describe current best practice for managing trawl fishery waste to minimise interactions between seabirds and trawl warps. However, while derived from a series of experiments conducted in trawl fisheries, principles underlying these recommendations are applicable to other fishing methods where fishery waste attracts seabirds to gear.

In trawl fisheries, seabird captures in nets are an unsolved cause of mortalities, requiring additional management. Holding waste prior to, and during, shooting and hauling trawl nets, shooting and hauling nets as rapidly as possible, and attempting to clear nets of fish scraps prior to shooting are currently best practice measures for reducing seabird captures in trawl nets (Bull, 2007, 2009). Preliminary work on net management measures, such as net weighting and binding, has been undertaken (e.g. Hooper et al., 2003; Clement and Associates, 2009). However, these measures still require further development and testing. Implementing effective management measures to minimize net captures and warp strikes will minimize the direct negative impacts of trawl fishing on seabirds, contributing to a reduction in the impacts of this fishing method on marine ecosystems.

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