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Reducing interactions between seabirds and trawl fisheries: Responses to foraging patches provided by fish waste batches

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ABSTRACT

Seabird bycatch in trawl fisheries is driven by the attraction of birds to foraging opportunities, i.e., the discharge of catch processing waste and the contents of trawl nets. The risk of seabird captures increases with seabird abundance and exposure to fishing gear. We investigated (1) how quickly seabirds responded to discharges of trawl catch processing waste and (2) whether decreasing numbers of seabirds attended trawlers during processing waste discharge events as the time interval between these events increased. Waste was retained onboard the vessel for four different holding periods (30 min, 2 h, 4 h, 8 h), one of which was applied each day using a randomised block design. We determined seabird responses to batch discharge events after the prescribed holding periods using the abundance of large (albatrossses and giant petrels *Macronectes* spp.) and small (all other petrels except cape petrels *Daption capense*, shearwaters and prions) seabirds in a semi-circle of 40 m radius, centred on the stern of the experimental trawler. Seabird responses reflected the type of discharge released: birds moved from the air to the water, as the amount of food available increased from no discharge, through sump discharge to batch discharge. When discharge occurred, seabird abundance increased faster than could be resolved with the 5 min sampling period. However, abundance decreased more slowly over a 10–15 min period after the discharge event. The number of large seabirds attending the vessel during discharge events decreased significantly when waste was held for 4 h. For small birds, significant decrease occurred after 8 h. Such holding periods emphasise the tenacity of foraging seabirds, although we have not evaluated any long-term habituation to a particular discharge regime. While holding waste for less than 4 h may not reduce seabird attendance during discharge events, holding for shorter intervals can still reduce bycatch risk, e.g., prior to and during net shooting and hauling.

1. Introduction

In recent years, the ecosystem model of fisheries management has attracted increasing attention in both conceptual and applied contexts (FAO, 2007). Within this paradigm of reducing the negative effects of fishing on ecosystem components, we have sought to identify effective measures to reduce seabird interactions with trawl fisheries (e.g., Abraham et al., 2009). Many seabird species are attracted to, and follow, vessels at sea (e.g., Griffiths, 1982; Hyrenbach, 2001). This behaviour increases the risk of seabird bycatch on fishing gear. In trawl fisheries, seabirds are killed and injured by trawl warps (the cables that connect nets and vessels) and trawl nets; such interactions have been reported widely from both the northern and southern hemispheres (Bull, 2007, 2009; Croxall, 2008). In New Zealand alone, approximately 30 species of seabirds, including nine species classified as threatened (IUCN, 2009), have been recorded bycaught by deepwater trawl fisheries (Department of Conservation, 2008; Thompson, 2009).

As in other locales where seabird bycatch by trawlers occurs (e.g., Alaska, the Falkland Islands, South Africa, and South America), the utilization of discharged fish waste by seabirds overlapping

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with trawl fisheries is a key determinant of bycatch rates, and holding waste onboard vessels consistently reduces seabird bycatch (Bull, 2007, 2009). While the augmentation of seabirds' natural diets with waste produced by trawl fisheries may appear beneficial in the first instance, implications of feeding on this waste are more complex (Grémillet et al., 2008), and can have significant consequences at the ecosystem level (e.g., Votier et al., 2004). We do not consider the indirect impacts of seabirds feeding on trawl waste further here. However, we note increased numbers of seabirds attending vessels are associated with increased strikes on trawl warps (Middleton and Abraham, 2007). Managing trawler operations such that seabird activity around fishing gear is minimized is important in reducing the direct impacts of fisheries on these birds, and the negative environmental effects of trawl fishing. Reducing the attraction of seabirds to trawlers should lessen the need to rely on mitigation devices to curtail harmful interactions between seabirds and fishing gear.

We expected that seabird responses to the foraging opportunities fishing vessels provide would coincide with their responses to natural foraging opportunities, e.g., in terms of foraging patch utilization and local enhancement (e.g., Hunt et al., 1999; Fritz et al., 2003; Grünbaum and Veit, 2003; Silverman et al., 2004). Consequently, we predicted that:

1. seabird numbers would increase during discharge events, and drop rapidly when discharge ceased;
2. decreasing numbers of seabirds would attend trawlers (including during discharge events) as the time interval between processing waste discharges increased;
3. decreasing the amount of time processing waste was around vessels would reduce vessel attendance by seabirds, including during discharge events;
4. as a consequence of (1)–(3), discharging processing waste in bigger batches, more rapidly and less frequently would reduce seabird attendance at trawl vessels, and, thus, the risk of bycatch.

The primary risk area our experiment was designed to consider was the stern of the vessel, around the trawl warps. Seabird strikes on trawl warps have been a particular focus of recent mitigation work (Bull, 2007, 2009). The fate of most birds struck by trawl warps is unknown. However, some are retrieved dead having been injured after striking a warp, or being pushed under the surface by the warp, where they drown. Some moribund or dead birds also fall into the water rather than being retrieved on board at the end of the trawl. Where estimates have been made, these show 208 (150–290, 95% confidence interval) warp strikes for every dead albatross or giant petrel landed from the trawl warps, and 7610 (3800–36,000, 95% confidence interval) for all other petrels or shearwaters (Abraham and Thompson, 2009a). These estimates have a range of possible explanations: at one extreme they could indicate a high level of cryptic mortality, while at the other extreme they could indicate that many strikes are harmless. Nevertheless, some strikes are fatal and a reduction in strikes would lead to fewer fatalities. In the presence of processing waste discharge, and in the absence of mitigation measures, interactions with warps have been recorded at rates as high as 19–52 per hour (Watkins et al., 2006).

2. Materials and methods

2.1. Study area and experimental set-up

We conducted experimental work south of New Zealand between 48.5°S–51.5°S and 166°S–168°E, on the Stewart-Snares shelf south of the Snares Islands, and on the Auckland Islands shelf. Both the Snares and Auckland archipelagos have abundant and diverse breeding seabird faunas, which include a number of albatross and petrel species (Taylor, 2000a,b). Waters in these areas are also actively fished by trawlers for a variety of target species including finfish, squid and crustaceans (Clement and Associates Ltd., 2008; Rowe, 2009).

The experiment was conducted on a New Zealand-flagged factory trawler, 64 m in length. The vessel was fitted with a holding tank of approximately 3 m^3, for the temporary storage of fish waste produced by processing the trawled catch. Holding capacity was increased further by a fishmeal plant (Atlas Stord International Type T5WH) capable of processing 50 tons of wet fish matter every 24 h. During the experiment, conducted between 5 February and 14 March 2008, the target species for trawling was arrow squid (*Nototodarus sloanii*). During all experimental days analysed here, the vessel used streamer lines and bird bafflers, to reduce interactions between seabirds and the cables between the vessel and the trawl net (trawl warps) (Bull, 2007). It is a requirement of New Zealand law to use one of three specified mitigation devices, including streamer lines and bird bafflers, during trawl fishing from a vessel more than 28 m in length (but not when setting or hauling the net; Department of Internal Affairs, 2006).

We implemented four experimental treatments, which involved holding all solid processing waste for varying time intervals. Prior to starting the experiment, treatments were assigned to days according to a randomized block design; each treatment was scheduled on one of every four consecutive days and experimental treatments changed at midnight. Each experimental day, waste was held for either 30 min, 2 h, 4 h or 8 h. Then at the end of the holding interval, waste was discharged through a chute on the starboard side of the vessel as rapidly as possible. During the experiment, the automated factory sumps remained operational. These sump pumps discharge wash from the vessel's factory floor. This wash is predominantly liquid, but may include small pieces of fish waste which have fallen to the floor during processing. Sumps are fitted with cutting blades to reduce the size of solid waste passing through them.

Effects of the experimental treatments were measured using the abundance of seabirds, by species group, in attendance in defined zones at the vessel stern. Seabird captures are obviously the result of direct interactions between birds and fishing gear. However, the rate of these interactions is related to seabird abundance around vessels (Abraham et al., in preparation), and abundance can be an effective proxy for direct interactions (Abraham et al., 2009). Further, given the large number of direct interactions that would be required to resolve treatment effects (Abraham et al., in preparation), the fact that captures are a statistically rare event, that warp strikes are reduced by the use of effective mitigation, and due to sensitivities around conducting lethal experiments, we did not use a more direct measure of seabird interactions.

Experimental data were collected on the vessel by a government fisheries observer experienced in undertaking seabird observations and following a clearly specified protocol. The same observer conducted all observations. Observations were carried out between 06:00 h and 18:00 h, New Zealand Standard Time. Observations were made when the vessel was towing the trawl net but not during shooting and hauling. Seabird abundances were recorded before and after the discharge of a batch of fish waste. Observations were planned to commence approximately 10–15 min before the discharge of a batch of fish waste, and then continue for approximately 40–45 min afterwards. Actual discharge was also assessed independently of the scheduled discharge regime throughout the observation period, and this information was used in the analyses. When waste was held for 4 h and 8 h, additional observation periods of approximately 30 min in duration were completed between discharge events.

For each observation period, vessel speed, sea swell height and wind direction were recorded, as well as the volume of the previous batch of waste discharged, and the time the previous discharge ended. During observation periods, the following data were recorded every 5 min: time (New Zealand Standard Time), wind strength (Beaufort scale), tow stage, discharge type observed, discharge rate, number of seabirds (according to species groups) within semi-circles of 40 m diameter and 10 m diameter centred on the vessel stern, and the number of other vessels visible with the naked eye. Tow stage was divided into setting, fishing, hauling, or not fishing. Discharge types were fish or squid offal, whole discards, macerated fish waste, and sump discharge. Discharge rate was assessed as none, negligible, intermittent or continuous.

Counts of the numbers of seabirds in the air and on the water, in the 10 m- and 40 m-diameter semi-circles, were made using successive 'sweeps' (where the observer swept their view once through the observation area), and the abundances of large seabirds, small seabirds and cape petrels (*Daption capense*) were recorded. Large birds were albatrosses and giant petrels (*Macronectes* sp.). Small birds were all petrels, shearwaters and prions (except giant and cape petrels). Cape petrels were counted separately due to the relative abundance of this petrel species. Further, this species forages differently to other petrels and is rarely bycaught despite attending vessels in large numbers (Abraham and Thompson, 2009b). The 10 m diameter semi-circle was chosen because it encompassed the point at which the trawl warps enter the water, which is a zone of particular risk for seabird entanglements. The 40 m diameter zone was intended to quantify birds outside this risk zone, but immediately available and likely to move in towards the vessel as feeding opportunities arose. To complete one 5 min sample of seabird abundances, 12 successive sweep counts were required. The observer spent no more than 30 s on any one sweep.

For each observation period, the characteristics of the batch discharge event were recorded. These were the start time of the batch discharge, the end time of the discharge, the estimated volume of material discharged, and a qualitative assessment of the type of discharge released, i.e., whether it was predominantly made up of fish, squid or crab waste.

During the experimental period, seabirds observed within 50 m of the vessel during the first daylight trawl tow were quantified by species. This sampling is part of normal data collection on all deepwater trawl voyages monitored by observers.

2.2. Statistical analyses

After an initial exploration of the data, four statistical models of bird abundance in the 40 m sweep zone were built. These modelled treatment effects on the abundance of large birds on the water and in the air, and small birds on the water and in the air. Time-dependent models were fitted, which allowed for the non-random nature of the sampling to be accounted for. Abundances in the 10 m sweep zone were too low to allow the construction of stable models. The four models make the following assumptions:

1. The mean value of the counts may be different for each experimental treatment and discharge level.
2. Birds arrive quickly when discharge begins.
3. There is a transition timescale representing how quickly birds leave the sweep zone once discharge has ceased. This timescale is independent of treatment.
4. There is no influence of batch discharge in one tow on seabird numbers in subsequent tows.
5. There are other covariates which may influence the counts.
6. The count values may differ from tow to tow for reasons that are not captured by the covariates.
7. A negative binomial distribution may be used to generate the counts from the mean values.

Time variation in the mean counts is shown in schematic form in Fig. 1. If the discharge is steady around the vessel, the model represents mean bird abundance (N) as follows (where trawl tows are indexed by i and counts within a tow by k, i.e., the first count in the first observation period of a tow is assigned $k = 1$, and sequential numbering is continued through other observation periods in the same tow).

$$\ln(N_{ik}) = \ln(\beta_{de}) + \sum_{j} \ln(\beta_j) x_{ijk} + \varepsilon_{id} \tag{1}$$

The parameters β_{de} give the baseline count when there is discharge $d = d_{ik}$ during experimental treatment $e = e_i$. The parameters β_j give the influence of each covariate on the mean count. Tow-to-tow variation in the counts that is not systematically related to discharge, experimental treatment, or 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: $\varepsilon_{id} \sim \text{Normal}(0, \sigma)$. The covariates x_{ijk} included in the final model were selected on the basis of a model selection process that fitted a simpler model which did not include random effects. The full model allows for the mean count to return to the sump or no discharge levels with a time-scale T:

$$\mu_{ik} = \begin{cases} N_{ik}, & k = 1 \text{ or batch disharge} \\ N_{ik} + (\mu_{i,k-1} - N_{ik}) e^{-(t_{ik} - t_{i,k-1})/T}, & k > 1 \text{ and not batch disharge} \end{cases} \tag{2}$$

The value of the first observation on a tow is taken to be given directly by Eq. (1), and it does not depend on any discharges in the previous tow. After a batch discharge, seabird abundance returns to the non-discharge value at a steady rate, represented by the exponential function. The model includes three discharge categories, with the lowest being when the factory is not operating and there is no discharge at all. The seabird counts respond at the rate T to changes in discharge, with the exception of transitions to batch discharge, which occur immediately. This choice was made after initial exploration of the data indicated that the increase in seabird numbers in response to a batch discharge occurred faster than could be resolved by the 5 min count interval.

To fit this model to the data, the seabird counts, n_{ik}, are assumed to be drawn from a negative binomial distribution with mean μ_{ik}. The negative binomial allows the count data to be overdispersed compared to a Poisson distribution with the same mean. The negative binomial distribution may be parameterized as a Poisson–Gamma mixture distribution, where the Gamma distribution has a mean of one and shape θ: $r_{ik} \sim \text{Gamma}(\theta, \theta)$, $n_{ik} \sim \text{Poisson}(r_{ik}\mu_{ik})$. With this parameterization, the variance of the negative binomial distribution is $\mu_{ik} + \mu_{ik}^2/\theta$.

Bayesian methods (Markov Chain Monte Carlo simulation) were used to fit the final model to the count data, using the software JAGS (Plummer, 2005). Fitting the model requires estimates of β_{de}, β_j, σ, θ and T. Prior distributions of these parameters must be specified. Weakly informative normal priors, with zero mean and a standard deviation of 10, were chosen for each of the β parameters. The prior for the time-scale T was a uniform distribution between zero and 24 h. The prior for the scale, σ, of the tow-level random effect was taken to be a half-Cauchy distribution. This prior was implemented as described by Gelman et al. (2006). The mean of the half-Cauchy prior was set to two, chosen to be higher than the standard deviation of the log of the average count per tow. The prior favors values of σ less than the mean, but allows higher values to be selected if there is strong evidence from the data. The prior for the overdispersion parameter θ was taken to be the

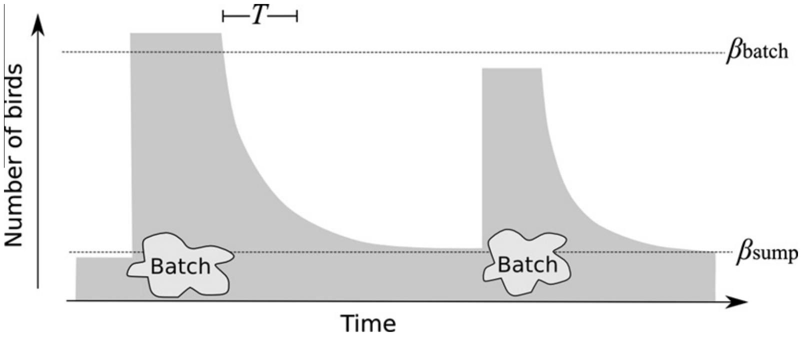

Fig. 1. Schematic diagram of the model used to represent seabird abundance, showing the changes in the mean abundance during a tow in response to batched discharge events. With each batch, mean abundance rises rapidly to the level β_{batch}. Other covariates, and random tow-to-tow variation, cause the peak abundance to differ from β_{batch}. Once the discharge finishes, the mean abundance falls back towards the level β_{sump} with a typical time-scale T. The actual model includes a third level corresponding to no processing and no discharge at all.

uniform shrinkage distribution with mean value given by the mean count over all observations (Gelman et al., 2006).

Models were fitted to data from the 40 m sweep counts, for large birds on the water, large birds in the air, small birds on the water, and small birds in the air. We also present model results from the totals of these, i.e., all birds in the air, and all birds on the water.

The models were burnt in for 10,000 samples, and were then run for a further 200,000 updates, with data from every 50th update being retained. Two independent MCMC chains were run, and convergence of the chains was checked using criteria formulated by Heidelberger and Welch (1983) and Raftery and Lewis (1992). It was also checked that the residuals were drawn from a negative binomial distribution, and so were consistent with the model. Randomized quantile residuals (Dunn and Smyth, 1996) were compared with a normal distribution.

To test whether bird numbers during discharge events decreased as the interval between batch discharges increased, the ratio of the expected number of birds during batch discharges at 2, 4, and 8 h was calculated relative to the 30 min treatment. The ratio was calculated from the asymptotic counts, $\beta_{\text{batch, treatment}}/\beta_{\text{batch, 30}}$, for each of the 8000 samples from the model posterior distributions. The proportion of samples that have a ratio of less than one can be directly interpreted as a probability that, given the data, the model and the priors, there were fewer birds present than during the 30 min treatment.

3. Results

3.1. Experimental implementation

Seabirds observed around the vessel during the experiment included royal and wandering albatrosses (*Diomedea* spp., 2–30 birds), white-capped albatross (*Thalassarche steadi*, 15–400 birds), Buller's albatross (*Thalassarche bulleri*, 0–10), black-browed/Campbell albatrosses (*Thalassarche impavida*/*Thalassarche melanophris*, 0–3), Salvin's albatross (*Thalassarche salvini*, 0–4), giant petrel (*Macronectes* spp., 2–30 birds), cape petrel (*D. capense*, 0–200), white-chinned petrel (*Procellaria aequinoctialis*, 10–400), storm petrel (Oceanitidae, 0–50), sooty shearwater (*Puffinus griseus*, 50–200), and prions (*Pachyptila* spp., 0–2). White-capped albatrosses and white-chinned petrels were observed in greater abundances around the Auckland Islands than on the Stewart-Snares shelf.

Observations were made on 39 days at sea, and the designated experimental treatment was implemented on 36 of these days. On 2 days, the meal plant broke down and sufficient waste could not be retained to implement the required holding period. On the third day, extreme weather caused the vessel to cease fishing and shelter at the Auckland Islands. In practice, the intervals between discharge events on the vessel generally conformed well to the treatments prescribed (Table 1). For days of the experiment assigned 30 min and 2 h holding treatments, 2–10 and 1–6 batch discharge events were observed, respectively. For days of the experiment assigned 4 h and 8 h holding treatments, 3–4 and 1–5 observation periods were undertaken. Fishing patterns affected the number of observation periods completed on different days.

Seabird abundance varied widely in the 10 m and 40 m sweep zones at the stern of the vessel. Cape petrels were only seen around the vessel in significant numbers in the Stewart-Snares shelf region, and their abundance decreased markedly (e.g., from more than 100 birds to near zero) when the vessel moved to the Auckland Islands. This is likely linked to their breeding cycle and location (Sagar et al., 1996; Taylor, 2000a,b). Consequently, count data on this species were excluded from analyses. Raw abundance data for other seabird categories enumerated do not show an obvious response to the experimental treatments (Fig. 2), hence the need for modelling analyses.

3.2. Treatment effects

After an initial exploration of the covariates, the following were chosen for inclusion in the model: fishing region (Stewart-Snares or Auckland Islands), wind speed (logarithm of the Beaufort scale wind speed), number of vessels visible (logarithm of the number of visible vessels +1). Logarithmic values were used to describe the continuous covariates (wind speed, number of vessels visible) because the counts also enter the model through the logarithmic link function. During observations, wind speed ranged from 2 to 8 on the Beaufort scale and 2–13 other fishing vessels were visible.

The MCMC simulations were judged to have converged, on the basis of convergence tests applied to key parameters (β_d, β_j, Σ, θ, and T) and the randomized quantile residuals. The models generally fitted the data well. The fitted model parameters are summarised in Table 2, for the main models constructed. The mean count is related to the wind speed and the number of visible vessels (+1) to the power of these values. For large birds, and for small birds in the air and on the water, the mean count increases as a positive power of the wind speed. In all the models, seabird abundance decreases as the number of other vessels increases. If there was a closed pool of birds that were evenly distributed between a group of vessels, then the number of birds would decrease as the number of visible vessels to the power of minus one. While the estimated exponent is negative, its magnitude is much smaller than one. The fitted coefficient relating to the Stewart-Snares area is less than one in all cases, indicating that there were fewer birds in all the four modelled categories when the vessel was fishing in the Stewart-Snares region.

Table 1
Numbers of observations grouped by the experimental treatment (nominal time between batches) and the recorded interval between the start of the batch discharge and the end of the previous batch.

Actual time between batch discharges (h)	Experimental treatment				Total
	30 min	2 h	4 h	8 h	
No batch	1	1	10	16	28
0–1	45	0	0	0	45
1–3	1	30	0	0	31
3–5	0	0	21	2	23
5–7	0	0	0	1	1
7–9	0	0	1	14	15
Over 9	1	0	0	0	1
Total	48	31	32	33	144

The negative binomial distribution converges to the Poisson in the limit that $\theta \to \infty$. In all models there is considerable overdispersion, as θ is less than the mean number of birds per observation. This justifies the inclusion of overdispersion in the modelling. The standard deviation of the random effects, σ, is tightly constrained in all models, and is less than the mean value of two specified in the prior. The response time-scale T is given in minutes. The time-scale is presented graphically in Fig. 3.

The model predicted asymptotic counts, β_{de} are shown in Fig. 4. Mean counts varied with the discharge, but were similar between treatments. For both large and small birds, the number of birds within the sweep zone increases as the discharge increases from none, to sump discharge, to batch discharge. When there is no discharge the mean count was very low, at less than one or two birds on the water within the sweep zone. This increases to 20–30 birds

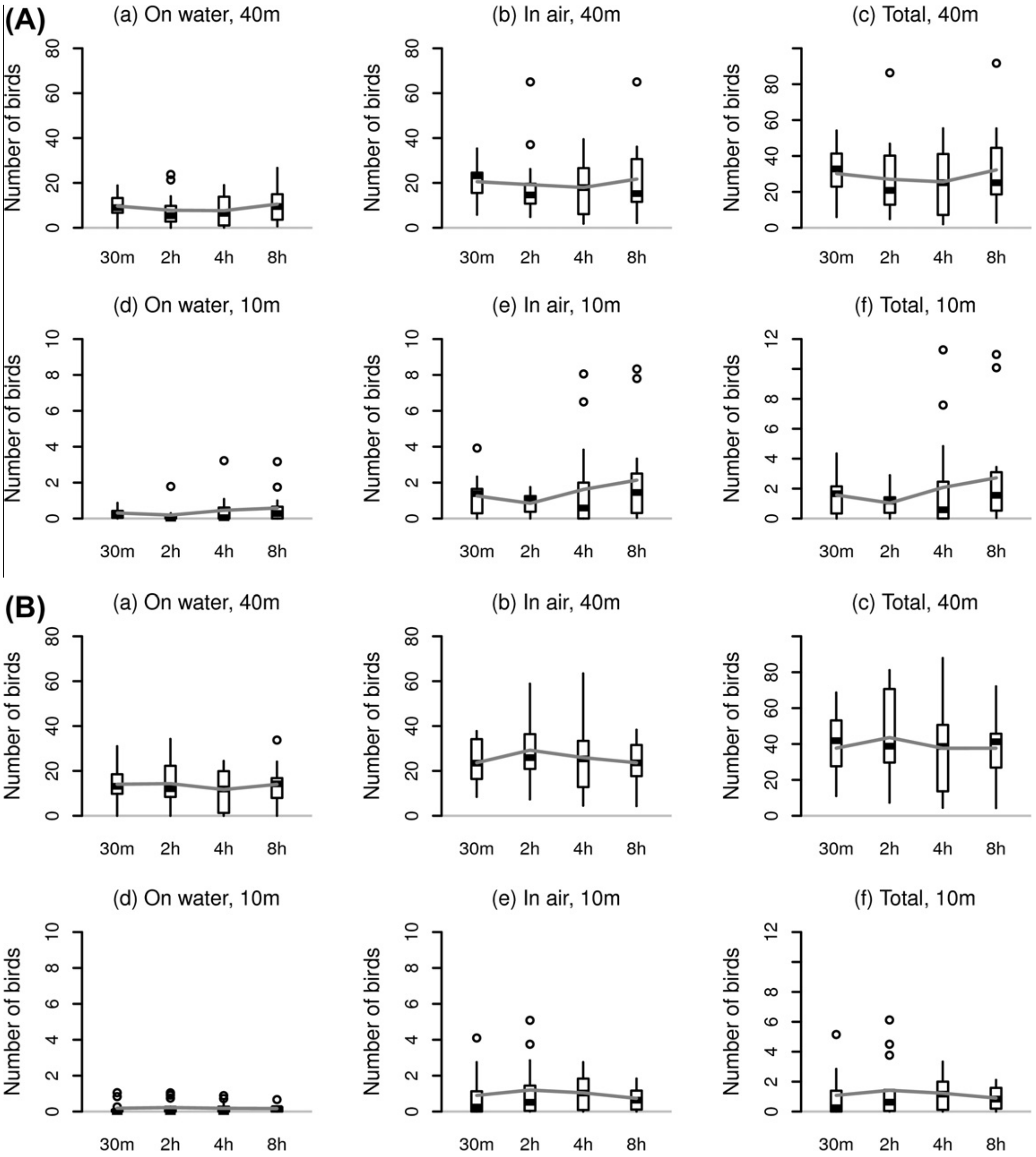

Fig. 2. Summary of the raw observations of (A) large bird abundance and (B) small bird abundance, giving box plots of the count data grouped by the four treatment categories. Summaries are shown for birds in the air and on the water, and the total number of birds, for birds within the 40 m and the 10 m sweeps. The gray line marks the mean value within each group.

Table 2
Summary of the fitted parameters, for models of counts of (a) large birds and (b) small birds, within the 40 m sweep zone.

Parameter		On water			In air		
		Median	2.5%	97.5%	Median	2.5%	97.5%
(a) Large birds within the 40 m sweep zone							
β_{de}	None, 30 min	0.459	0.0942	2.16	6.93	2.75	17.3
	None, 2 h	0.169	0.0286	0.713	6.66	3.49	12.9
	None, 4 h	0.0707	0.0215	0.201	3.61	2.06	6.38
	None, 8 h	0.286	0.0572	1.19	9.63	3.92	23.3
	Sump, 30 min	6.81	4.61	10	21.6	15.7	29.3
	Sump, 2 h	4.29	2.91	6.28	16.1	12	21.6
	Sump, 4 h	4.71	3.12	7.02	20.8	15.2	28.3
	Sump, 8 h	4.36	3.03	6.21	18.4	14.2	24.1
	Batch, 30 min	26.5	17.1	42.3	24.1	17.8	32.6
	Batch, 2 h	21.2	13.2	36.5	19.3	14.4	25.7
	Batch, 4 h	17.7	10.8	29.1	13.5	9.45	18.7
	Batch, 8 h	23.5	15.6	35.4	17.4	12.8	23.2
Log(β_j)	Log(wind speed)	0.665	0.262	1.08	0.754	0.474	1.03
	Log(vessels +1)	−0.345	−0.532	−0.157	−0.161	−0.281	−0.0418
β_j	Stewart-Snares	0.62	0.431	0.895	0.688	0.538	0.896
θ		1.6	1.41	1.83	5.42	4.81	6.11
T		1.63	0.0756	2.56	15.1	8.84	30.4
σ		0.66	0.525	0.825	0.532	0.446	0.644
(b) Small birds within the 40 m sweep zone							
β_{de}	None, 30 min	2.34	0.696	7.5	11.8	4.67	29.2
	None, 2 h	0.466	0.165	1.2	9.76	5.03	18.8
	None, 4 h	0.129	0.0495	0.299	4.75	2.69	8.14
	None, 8 h	1.84	0.669	4.82	11.4	4.77	26.7
	Sump, 30 min	12.1	8.78	16.8	28.2	20.3	38
	Sump, 2 h	13.1	9.39	18	35.4	26.5	47.3
	Sump, 4 h	10.5	7.38	14.8	32.8	24.2	44.6
	Sump, 8 h	10.6	7.88	14.1	25.3	19.5	32.3
	Batch, 30 min	30.8	21.2	45.4	19.9	14.4	27.6
	Batch, 2 h	35.1	23.9	51.7	17.7	12.8	24.2
	Batch, 4 h	24.1	15.6	36.3	12.6	8.8	18
	Batch, 8 h	20.4	14.2	29	12.3	9	16.6
Log(β_j)	Log(wind speed)	0.0907	−0.248	0.423	0.449	0.179	0.708
	Log(vessels +1)	−0.173	−0.325	−0.181	−0.198	−0.314	−0.0857
β_j	Stewart-Snares	0.678	0.49	0.922	0.76	0.583	0.981
θ		2.4	2.13	2.7	5.78	5.14	6.49
T		0.485	0.0145	0.91	9.62	6.04	15
σ		0.579	0.458	0.727	0.544	0.453	0.661

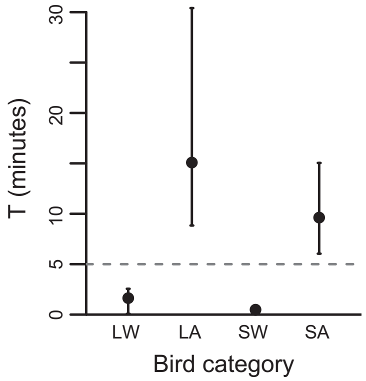

Fig. 3. Median and 95% credible intervals for the transition time T, for each of the modelled bird count categories (LW = large birds on water, LA = large birds in air, SW = small birds in water, SA = small birds in air). See Section 2 for further details.

within the sweep zone when there is batch discharge. For both large and small birds, the number of birds in the air is higher than on the water when there is no discharge (Fig. 5). The number of birds in the air increases when there is sump water being produced. The number of birds in the air does not increase any further during batch discharge, and for small birds the mean count decreases when there is batch discharge (Fig. 5). These patterns are similar to the responses seen in the raw data (Fig. 2).

The experimental observations show that after discharge events, the number of birds attending the vessel on the water fell rapidly, but the number of birds in the air recovered more slowly. The modelling describes a measurable transition time of approximately 10–15 min for changes in the number of both large and small birds in the air. For large and small birds on the water, the transition time is faster than the 5 min interval that was scheduled between observations.

The total number of seabirds expected to attend the vessel decreased when the time between batch discharges increased from 30 min to 2 h, 4 h, and 8 h. However, this decrease was only significant ($P > 0.95$) for large birds at 4 h (driven by large birds in the air), and small birds at 8 h. No significant reduction was detected in the numbers of large birds on the water with increased intervals between batch discharges (Fig. 6).

Finally, despite our intention to have larger batches of waste discharged more rapidly (by volume) than smaller batches, the volume of waste collected and time taken to discharge the waste held increased approximately linearly with the length of time between batch discharges. Consequently, the percentage of time there is a batch discharge occurring, as a percentage of time between discharge events, is approximately constant across all treatments (around 2% of the time, Fig. 7).

4. Discussion

Our results are consistent with other work demonstrating that discharging processing waste from fishing vessels attracts seabirds

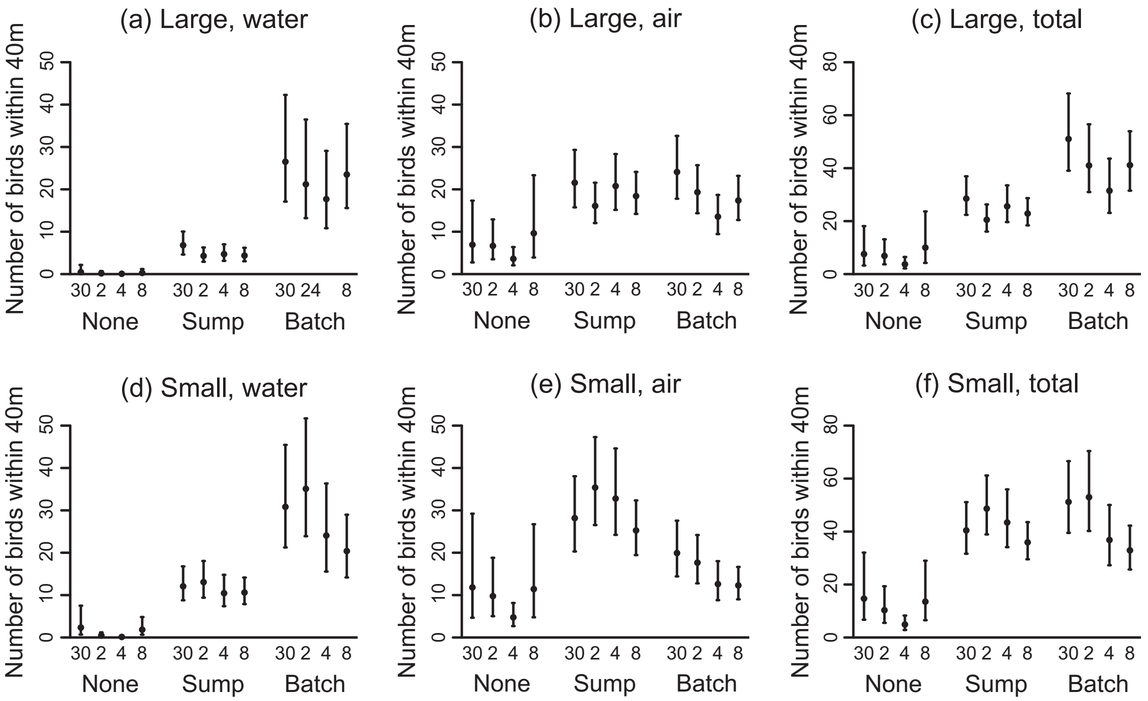

Fig. 4. Median and 95% credible intervals for the model predicted asymptotic bird counts, β_{de}, for each combination of discharge and experimental treatment. See Section 2 for further details.

(e.g., Bull, 2007; Abraham et al., 2009). However, we also show that rather than simply being attracted to the occurrence of discharge, seabird responses reflect the form in which discharge is released. Birds moved from the air, to the water, astern the vessel as the amount of food available increased from no discharge, through sump discharge to batch discharge. Also, the total abundance of birds increased between no discharge and sump discharge events. The abundance of large birds increased again between sump and batch discharges, however that of small birds did not.

We expect that these responses were driven by the cues (visual and olfactory) that different discharge types offer, as well as the differing volume of food made available. Sump discharge of factory floor wash (mostly water with some small pieces of fish waste) leaves the vessel as a liquid jet. Batch discharges exit the vessel as a series of various sized clumps and chunks (including whole fish discards), over a longer time period. These batches provide richer foraging opportunities, especially for larger seabirds, compared to the scraps that birds may find in sump discharges. For both sump and batch discharges, any chunks will be detectable in the water until they are consumed. Birds must be on the water to feed, but will identify foraging opportunities more easily from a vantage point in the air.

When batch discharges occurred, numbers of birds on the water increased faster than could be resolved with a 5 min observation period. Presumably, this was because a pool of birds was available close to the vessel and birds could readily drop from the air to feed. After discharge events, numbers of birds on the water decreased faster than birds in the air increased. This was because birds attended batch discharge patches for some time after batches were released from the vessel, i.e., as the vessel moved forward, the batches and birds drifted backward beyond the observation area. Bird numbers in the air increased again as birds abandoned batch patches, and returned to tracking the vessel.

The number of birds decreased at the experimental vessel when more vessels were visible in the immediate area. However, the magnitude of decreases did not imply that a limited pool of birds was being shared between vessels in an area. Instead, this result may be due to the intermittent nature of discharge events which allows birds to track these events from vessel to vessel. It may also be that the birds are distributed across a wider regional fleet, rather than just the visible vessels. (Vessels do not attempt to coordinate discharge patterns or discharge management practices). Visual recruitment of seabirds to foraging flocks has been estimated to occur from distances of less than 10 km, although theoretical calculations of recruitment distances up to 20–30 km have been reported (Haney et al., 1992; Skov and Durinck, 2001).

We expected that the numbers of seabirds attending trawlers would decrease as time between discharge events increased. This prediction held true, but significant reductions only occurred during discharge events 4 or more hours apart, compared to shorter intervals. When significant, reductions were driven by the numbers of birds in the air, not on the water. Birds are at risk of warp strike when on the water, as well as in the air (e.g., Sullivan et al., 2006). Thus, the fact that batch discharge did not reduce seabird abundances in this area is significant in terms of the efficacy of the batching approach for reducing warp strikes and bycatch reduction.

An operational limitation of the batching method is the difficulty of discharging waste more rapidly. In our experiment, waste was discharged from a holding tank, onto a conveyor. The conveyor took waste to the discharge point in the vessel hull. We had expected that processing waste would be discharged more rapidly, per unit volume, with increasing volumes. However, this was not the case; because the amount of waste increased approximately linearly with holding time, so did the duration of discharge events, and the proportion of time that processing waste was entering the water. Therefore, we were unable to test the effects of more rapid discharge, per unit volume of waste. To achieve more rapid discharge would have required extensive changes to the layout of the vessel factory. While such modifications could be possible, avoiding the use of conveyors (or other motorised equipment) with a constant rate of movement for transporting waste may be operationally impractical for many factory trawlers.

While the production of processing waste is an inevitable consequence of factory trawling worldwide, management of waste is

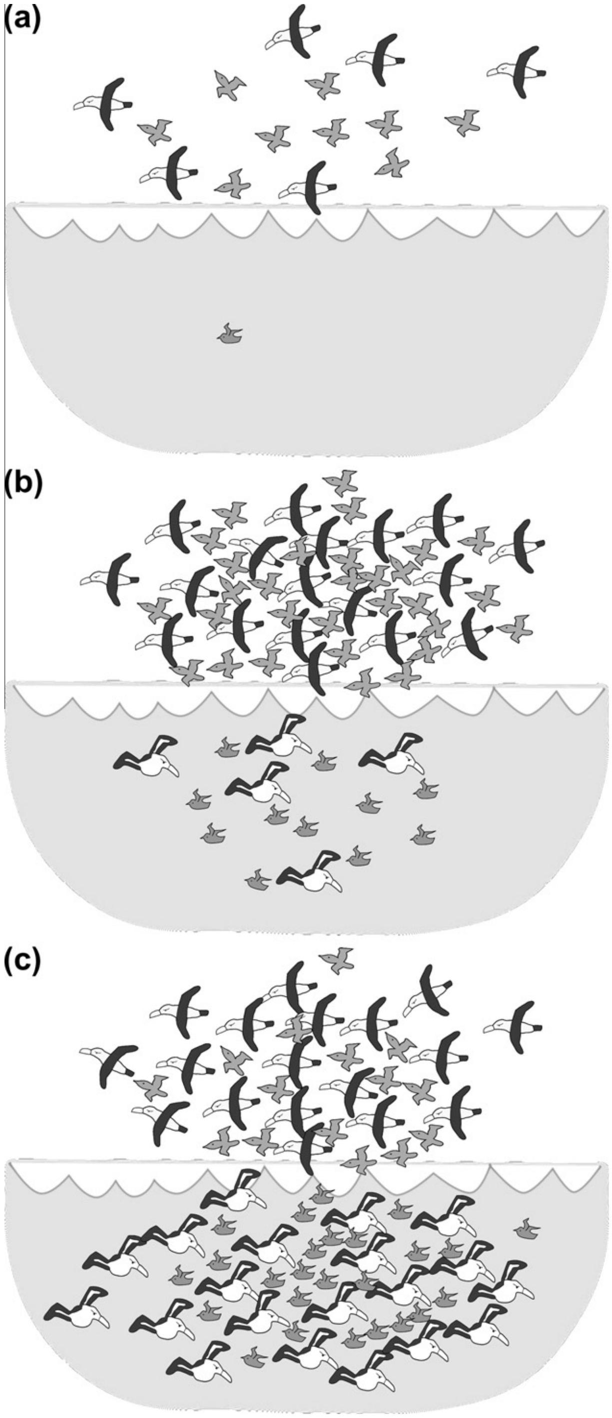

Fig. 5. Diagram showing the number of small and large birds in the air and on the water within the 40 m sweep zone. Numbers shown are from the model estimated parameters, β_{de}, (Table 2) for (a) no discharge, (b) sump discharge, and (c) batch discharge.

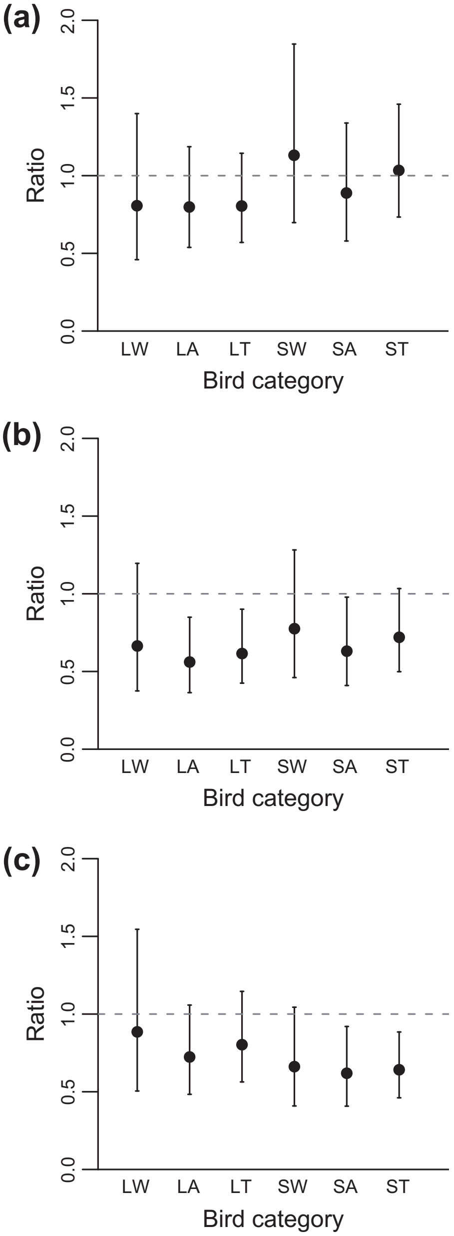

Fig. 6. Ratio of bird counts during the 30 min treatment to the corresponding counts during the (a) 2 h treatment, (b) 4 h treatment, and (c) 8 h treatment. The ratio is calculated from the model estimated asymptotic counts during batch discharge, $\beta_{\text{batch, treatment}}/\beta_{\text{batch, 30min}}$. The points mark the median and the lines indicate the 5% and 95% quantiles of the posterior distribution of the ratio for each category (LW = large birds on the water, LA = large birds in the air, LT = total large birds, SW = small birds on the water, SA = small birds in the air, ST = total small birds).

an important component of operational procedures to avoid seabird bycatch. While batch discharging is an appealing approach to the management of processing waste because it can be easily implemented on many vessels, our results showed that to have any effect on seabird abundance during discharge events, waste still had to be held for more than 2 h, and possibly not less than 4 h. However, we note that this is relative to a 30 min discharge interval, rather than discharging, for example, ad hoc, whenever waste was available. During the experimental trip, the median duration of trawl tows was 6 h. The longest tow was 9 h 44 min, and more than 94% of the tows were less than 8 h in duration. When the vessel's meal plant was in use, the factory's waste holding capacity was sufficient to avoid discharge for entire tows (i.e., the 8 h holding treatment). However, under current fishing operations, such holding periods are not possible for many trawlers operating in New Zealand waters.

The inability to hold waste for longer periods reduces some of the value of waste management strategies based on batch discharge. However, any ability to hold waste provides increased opportunities for management actions. Aside from the trawl warps, the other significant hazard for seabirds in trawl operations is the trawl net itself (Bull, 2007). Birds are caught inside the net or in its meshes when they seek to feed on the net contents. This can occur

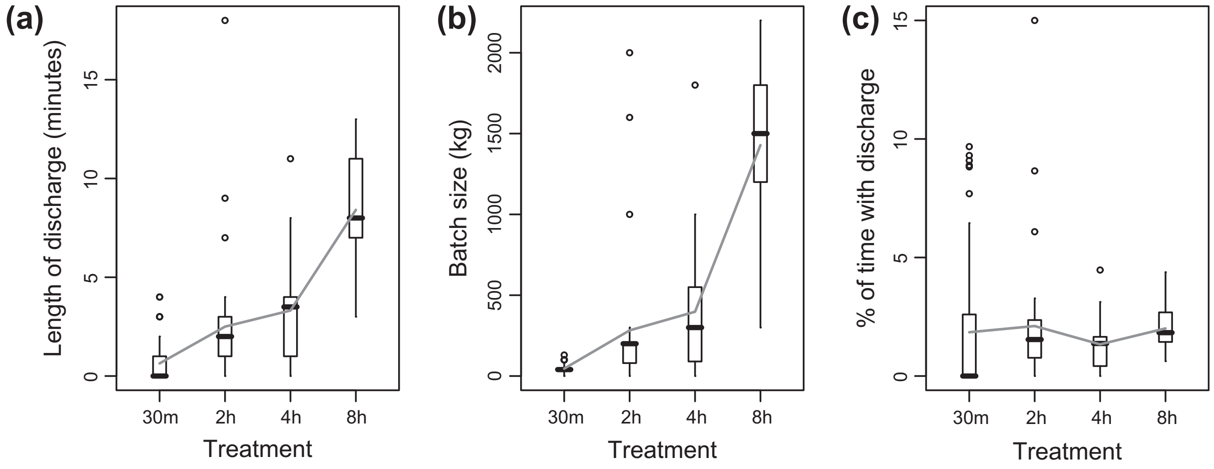

Fig. 7. Variation in the discharge characteristics with the batch interval, showing (a) the time taken for each batch to be discharged, (b) the amount of material discharged, and (c) the percentage of time that waste is being discharged, calculated as the duration of the batch over the recorded time since the previous batch. In each plot, the median, quartiles and range of the data are shown by the box and whiskers, and the mean values are indicated by the overlaid gray line. Data is presented from all sets of observations with a batch discharge.

at shooting, if birds attempt to feed on bits of fish adhering to the net ropes, and at hauling when birds are attracted to feed on the catch itself. Discharging processing waste before shooting or hauling exacerbates bycatch risk, by bringing birds into areas where the net will soon be exposed. Furthermore, some warp-strike mitigation devices cannot be operated during shooting and hauling. So, even if vessels cannot hold waste for sufficient periods to reduce the abundance of seabirds during the tow phase of the trawl, holding waste for the duration of shooting and hauling is likely to be a critical component of vessels' bycatch avoidance strategies.

With the global shift towards managing ecosystem impacts of fisheries, there has been an increasing focus on the sustainability of associated and dependent species. Managing the attraction of seabirds to fishing vessels is key to reducing bycatch, and this attraction is driven by the opportunity to feed on fish waste. If trawl processing waste cannot be held onboard vessels for the duration of tows, for discharge when fishing gear is out of the water, holding waste for at least around 4 h, as well as at key periods during the fishing cycle (shooting, hauling), will reduce some of the risk fishing gear represents to seabirds, and hence the impact of fishing on marine ecosystems.

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