CSIRO PUBLISHING

Emu, 2012, **112**, 244–254
http://dx.doi.org/10.1071/MU12002

Reducing effects of trawl fishing on seabirds by limiting foraging opportunities provided by fishery waste

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Abstract. By-catch of seabirds on trawl-fishing gear has been reported worldwide, and is exacerbated by the discharge of fisheries waste. We compared the attraction of seabirds to three forms of fishery waste – unprocessed discharge (offal, fish discards), hashed discharge (smaller chunks passed through a hasher pump) and cutter pump discharge (waste passed through the hasher and a cutter pump to further reduce particle size) – to identify the discharge form that most effectively reduced the risk of seabird by-catch. Seabird responses measured within specified areas astern of the vessel were the abundance of: large albatrosses (*Diomedea* spp.), small albatrosses and giant-petrels (*Thalassarche* spp.; Southern Giant-Petrels, *Macronectes giganteus*; and Northern Giant-Petrels, *M. halli*), Cape Petrels (*Daption capense*) and all other procellariid species. Seabirds on the water were less numerous during cutter pump and hashed discharge relative to unprocessed discharge (except small albatrosses – cutter treatment). Also, in some cases, the total number of birds decreased, relative to unprocessed discharge treatments (but not small and large albatrosses – cutter treatment). Particle size may be less important for reducing abundances than temporal discharge patterns, which affected how birds tracked the discharge stream. Manipulating discharge characteristics can reduce seabird attraction to fishing vessels. However, the risk of by-catch remained lowest when no discharging occurred.

Additional keywords: albatross, by-catch, offal discharge, petrel, procellariid, Procellariiformes.

Received 6 January 2012, accepted 16 May 2012, published online 21 August 2012

Introduction

For decades, scientists have documented the attraction of seabirds to fishing vessels at sea (e.g. Griffiths 1982). Many species of seabirds are attracted to the foraging opportunities provided by fishing vessels, which typically discharge fish waste as a normal part of fishing operations. Feeding on fisheries waste may appear beneficial to seabirds, but the direct and indirect consequences of this behaviour can be negative and far-reaching, including at the ecosystem level. Indirect effects include reduced chick survival when discards replace natural diets, increased depredation by seabird predators when the availability of discards decreases and changes in distribution at sea (Furness 2002; Votier *et al*. 2004; Grémillet *et al*. 2008; Bartumeus *et al*. 2010). Direct effects can include increased risk of injury and death, owing to birds interacting with fishing gear.

In trawl-fishing operations, seabirds can be killed and injured by the cables that connect trawl nets to vessels (trawl warps) as well as by the nets themselves (Bull 2009). Such interactions have been reported from trawl fisheries of both the northern and southern hemispheres, including in New Zealand, Australia, South Africa, Argentina, the Falkland Islands and Alaska (González-Zevallos and Yorio 2006; Croxall 2008; Watkins *et al*. 2008; Melvin *et al*. 2010). For example, government fisheries observers have collected more than 30 species of seabirds dead from New Zealand deep-water trawling operations (Department of Conservation 2008; Thompson 2009), including nine globally threatened species (IUCN 2012). Seabird by-catch in trawl fisheries is exacerbated by discharging fish waste when fishing gear is deployed (Abraham and Kennedy 2008; Abraham and Thompson 2009*a*; Bull 2009; Favero *et al*. 2011).

The foraging opportunities presented to seabirds by discharged trawler fish-waste are characterised by many factors, including the size and type of discharge, and the horizontal and vertical distribution of waste in the water column (Garthe and Scherp 2003; Furness *et al*. 2007). Seabird foraging patterns are also driven by the birds themselves. For example, gape-size and diving ability are keys to realising foraging opportunities, and breeding status, age and prey preferences can affect foraging intensity (Hulsman 1981; Xavier and Croxall 2007; Ronconi and Burger 2008; Lecomte *et al*. 2010; Zimmer *et al*. 2011). The distribution of seabirds around vessels during and after discharge of waste is the product of these factors, which, consequently also influence the exposure of seabirds to fishing gear.

Removing foraging opportunities by holding waste onboard consistently reduces seabird attendance at vessels, and consequently, reduces by-catch (Bull 2009). However, under current fishing patterns, the holding capacity of fishing vessels is often not sufficient to retain waste for the duration of a trawling tow, which is the time during which seabirds are at risk owing to exposure to fishing gear (Pierre *et al.* 2010). Some by-catch mitigation devices (see Bull 2009 for a detailed review) offer a partial solution to seabird interactions with trawling gear. However, the problem of discharge attracting seabirds to vessels still remains. When fisheries waste cannot be held for the duration of a trawl tow, reducing the attractiveness of trawler discharge to foraging seabirds should work to curtail harmful interactions between seabirds and fishing gear.

To date, investigations into waste management that reduces seabird foraging opportunities around trawlers and, consequently, seabird by-catch, have focussed on the effects of holding waste for specified periods (Pierre *et al.* 2010) and differences in the form of discharged waste (Abraham *et al.* 2009). Abraham *et al.* (2009) found that discharging minced trawl-fishing waste reduced the foraging activity of large albatrosses (*Diomedea* spp.) astern of the vessel, compared with discharge of large chunks of waste. However, discharging minced waste did not reduce the foraging activity of smaller albatrosses (mainly *Thalassarche* spp.) and other species of seabirds. Further research was necessary to clarify any effects of different particle sizes on the foraging opportunities minced waste provided.

Here, we examine the effects of discharging three forms of trawl fish-waste on seabird abundance at a trawl-fishing vessel (we assume that seabirds are attracted to vessels to take advantage of foraging opportunities). The waste discharges were: unprocessed discharge and two forms of minced waste (hashed discharge and cutter pump discharge). Our objectives were:

- to compare the abundance of seabirds astern of the experimental vessel during discharge of the three forms of waste, with specific reference to the particle size of the discharge;
- to assess the distribution of seabirds astern of the experimental vessel, and to compare these distributions between the three forms of discharge; and
- to identify the form of discharge that most effectively reduced seabird abundance at the stern of the vessel, given that abundance is an effective proxy for risk of by-catch.

Methods

Study area and experimental setup

We conducted experimental work during two voyages on a 40-m long deepwater factory trawler. The voyages ran 14–26 March and 17 April–1 May in 2008. The vessel was built in 1989, and flagged to New Zealand. During the experiment, fishing occurred in four main clusters of locations off the coast of the South Island of New Zealand, denoted northern, southern, western and eastern (Fig. 1). The targeted fish species during the voyages were Hoki (*Macruronus novaezelandiae*) in the northern, southern and western locations, Silver Warehou (*Seriolella punctata*), in the western location and Smooth Oreo (*Pseudocyttus maculatus*) in the eastern location. With the exception of the experimental discharge regimes, normal fishing practices were followed. This included the use of mitigation measures (paired streamer lines and bird bafflers) in accordance with New Zealand law (Department of Internal Affairs 2006). Streamer lines were deployed during fishing. Legal specifications for streamer lines were for two lines, ≥8 mm in diameter, entering the water ≥10 m astern of trawl warps. Lines were to be fixed at specified distances from the trawl blocks, and as close to the stern of the vessel as practicable. Bafflers were fixed in place throughout the voyages. Legal requirements for bafflers were for a minimum of two booms, each ≥4 m long, with at least one extending from each of the starboard stern quarter and the port stern quarter. Dropper lines were required to be attached to the booms at ≤2-m intervals, and to extend to ≤500 mm to the water surface in calm conditions. (For full details, see Department of Internal Affairs 2006). During the experimental voyages, a total of 11 seabirds were caught incidentally. Three were released alive (two Shy (White-capped) Albatrosses, *Diomedea cauta steadi*; one unidentified petrel), seven were killed in the trawl net on a single tow (five White-chinned Petrels, *Procellaria aequinoctialis*; two Sooty Shearwaters, *Ardenna grisea*; and one Shy (White-capped) Albatross was killed when it hit the bird baffler during fishing.

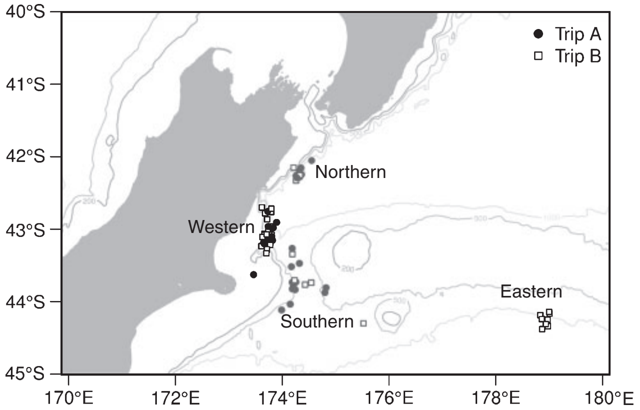

Fig. 1. Location of tows during which experimental observations were made. The positions of tows have been randomly jittered by ±0.1° to meet Ministry of Fisheries confidentiality requirements. Tows are grouped into four clusters (northern, southern, eastern and western) off the eastern coast of New Zealand. Depth contours are shown at 200 m (darkest grey), 500 m (middle grey) and 1000 m (light grey).

We implemented the three experimental discharge treatments during the voyages. These were: (1) unprocessed discharge, which comprised large chunks of offal, heads, guts and frames (skeletons) and whole fish discards, which represents typical trawler processing waste and discharge; and two forms of minced waste: (2) hashed discharge, which comprised large pieces of offal and whole fish discards chopped into chunks by passage through a hasher pump (see below) and (3) cutter pump discharge, which comprised the output from the hasher pump reduced to an even smaller particle size by recirculation through a cutter pump (see below). Waste was released in the specified form *ad hoc*, when available. Unprocessed waste left the vessel through the offal chute via a conveyor. Hashed waste was also discharged through the offal chute, after being cut into chunks by a hasher (Napier Engineering PB3-GC, processing capability of 3 t h^{-1}), modified at its outlet by the addition of a circular plate with 20-mm-diameter holes. Cutter pump waste passed through the hasher, and then into the sump, where a retro-fitted cutter pump (Grundfos SEG40.40.2.50B, flow capability of 312 L min^{-1}) recirculated the hashed waste with water to create a slurry. The rate of water flow in the slurry process created a steady, almost continuous, discharge through the vessel sump. There was some fish waste, specifically species of shark and heads of large Ling (*Genypterus blacodes*), which could not be processed by the hasher. This waste was retained for discharge between trawl tows. Normal operation of the sump pump continued throughout the experiment, including during sampling periods.

Experimental discharge treatments were each implemented for 24 h, according to a pre-determined randomised block design, and each treatment was deployed once every 3 days. Treatments changed at midnight. During the first voyage, we collected 1 kg of discharge from both the hasher and cutter pump systems and measured the particle size of these samples. Samples were of Smooth Oreo. Qualitative assessment determined that ~75% of the hashed sample was chunks and the other 25% was liquid slurry. The 20 largest chunks in the sample were 30–60 mm in diameter. Once the waste had passed through the cutter pump system, ~75% of the material was in slurry form. Of the remaining 25%, the 20 largest pieces were 10–40 mm in diameter.

In this experiment, we focussed on the area immediately astern of the vessel, which is where seabirds are risk due to trawl warps. Birds can strike warps both in the air (i.e. in-flight collisions) or in the water (i.e. warps push birds under the sea where they may drown). Although precise estimates of mortalities as a result of warp strike are not available, there is no doubt that some strikes are fatal (Bull 2009). Past studies have reported warp strike rates of 19–52 h^{-1} coincident with waste discharge and in the absence of mitigation measures (Watkins *et al*. 2006). We assessed the responses of seabirds to different discharge treatments by quantifying the abundance of seabirds within specified radii astern of the vessel. Abundance is an effective proxy for direct interactions. Increased numbers of seabirds attending vessels are associated with increased strikes on trawl warps (Middleton and Abraham 2007) and warp strikes result in mortalities (Bull 2009), although the form of the quantitative relationship is not precisely known as yet (Abraham and Thompson 2009*a*). As well as being unnecessary, owing to the existence of an effective proxy, levels of mortality required for a statistically robust lethal experiment were not prudent given the conservation status of the seabirds involved.

Data collection

Before the start of experimental sampling and during the first (daylight) trawl each day, the observer conducted a count of seabirds, by species, within 50 m of the vessel.

Experimental data collection procedures generally followed Abraham *et al*. (2009). Observation periods lasted ~1 h and 1–5 periods of observation were performed each day, with at least 1 h break between each. At the start of an observation period, the observer recorded the speed of the vessel, height of swell and the experimental treatment. The observation period consisted of a series of repeated counts of birds from the stern of the vessel during daylight hours. Observations were made by an experienced government fisheries observer, with a single observer conducting counts for the duration of each voyage. Before starting each count, the observer recorded the time, wind strength (Beaufort scale) and wind direction relative to the vessel, stage of the trawl tow (fishing, shooting (the deployment of the trawl net into the water, from when the net leaves the vessel to when it reaches fishing depth), hauling) and the number of vessels visible from the experimental vessel. Counts involved a sweeping count in a semicircle of 40-m radius, centred on the midpoint of the stern. A separate sweep count covered a semicircular area of 10-m radius, again centred on the midpoint of the stern of the vessel. This 10-m-radius semicircle included the point at which the trawl warps entered the water astern of the vessel, and so comprised a zone of heightened risk of by-catch. Separate sweeps were made to count each of four groups of seabirds, both in the air and then on the water, inside the 40-m and 10-m semicircles. Consequently, each observation period involved 16 separate sweep counts. Sequential counts were conducted at most 60 s apart and were, therefore, approximate when birds were especially numerous (owing to time constraints). Seabirds were counted in groups specified before the experiment. These groups were: (1) large albatrosses (*Diomedea* spp.), (2) small albatrosses and giant-petrels (*Thalassarche* spp.; Southern Giant-Petrels, *Macronectes giganteus*; and Northern Giant-Petrels, *M. halli*), (3) Cape Petrels (*Daption capense*) and (4) all other procellarid species (shearwaters, petrels other than those above, prions, fulmars, storm-petrels, diving-petrels). Cape Petrels were counted separately from other petrels and shearwaters owing to their unique foraging patterns and attendance at vessels in sometimes very high numbers (but with low rates of by-catch; Abraham and Thompson 2009*b*).

During each observation period, the observer also recorded the forms of discharge visible in the 10- and 40-m zones astern of the vessel. The observer classified visible discharge as: sump water, or one of the three treatment discharges: cutter or hasher discharge (i.e. minced discharges) or unprocessed discharge (i.e. offal and whole fish discards). Although not an experimental treatment *per se*, sump discharge may provide a visual stimulus to foraging seabirds (as sump discharge events also involve material being ejected from the vessel hull). However, sump discharge is predominantly water with minimal fish content. These categories (sump, hasher, cutter, unprocessed) carried through to the analysis. When visible, the location of discharge for each count was recorded in either or both of the 10- and 40-m-radius zones. Observation could start when the vessel was fishing, but not during shooting and hauling.

Statistical analyses

We estimated the effects of discharge on bird counts using generalised linear models (GLM). For each seabird group, bird location (in air, on water) and sweep radius (10 or 40 m), the mean count of birds was estimated as a linear function of several covariates, including the treatment. We allowed for the over-dispersion typical of count data by representing these data as samples from a negative binomial distribution (e.g. Hilbe 2007). The negative binomial was parameterised by a mean (μ) and an overdispersion (θ). The variance is then given by $\mu + \mu^2/\theta$. As the overdispersion increases to infinity, the variance goes to the mean and the negative binomial distribution converges to a Poisson distribution. As θ gets small relative to the mean, the negative binomial distribution becomes increasingly peaked at 0 and develops a long right-hand tail.

The negative binomial may be generated by a Poisson mixture distribution, with a gamma distributed mean. The count y_i made during the observation i may be modelled as:

$$y_i \sim \text{Poisson}(\mu_i \delta_i)$$

$$\delta_i \sim \text{gamma}(\theta, \theta)$$

where the gamma distribution has shape θ and a mean of 1. In this sense, the negative binomial is a natural choice for modelling bird counts, as the overdispersion may be taken to represent the effect of unknown processes on the variation of the mean count.

The logarithm of the mean count during a single observation (μ_i) was assumed to be a linear function of n covariates (x_{ij}) with:

$$\mu_i = \lambda \nu_{k_i} \exp\left(\sum_{j=1}^{N} \beta_j x_{ij} \right)$$

where β_j are the coefficients of the covariates (x_{ij}), λ is the average count and ν_{k_i} are random effects at the trawl-tow level. The covariates were all normalised before the model fitting, by subtracting the mean value and dividing by the standard deviation. After fitting, the regression coefficients (β_j) were converted back into standard units for presentation purposes.

The trawl-tow level random effects (ν_{k_i}) allow for the fact that bird numbers may change between trawl tows for reasons that are not captured by the other covariates. A trawl-tow level effect was chosen as this reflects the disruption to the seabirds attending the vessel that results from hauling and re-setting the net. The trawl-tow level random effects were drawn from a gamma distribution with unit mean and shape θ_ν,

$$\nu_{k_i} \sim \text{gamma}(\theta_\nu, \theta_\nu)$$

where k_i indicates the trawl tow associated with observation i.

During the model fitting, estimates were made for the parameters β_j, λ, θ and θ_ν. Prior distributions were required for these parameters. Diffuse normal prior distributions were used for the logarithm of the overall mean ($\log(\lambda)$) and regression coefficients (β_j). Uniform-shrinkage prior distributions were used for the overdispersion parameters θ and θ_ν (Gelman *et al.* 2006):

$$\log(\lambda) \sim \text{normal}(\mu = \log(\bar{y}_i, \sigma = 100)$$

$$\beta_j \sim \text{normal}(\mu = 0, \sigma = 100)$$

$$\theta \sim \text{uniform-shrinkage}(\mu = \bar{y}_i)$$

$$\theta_\nu \sim \text{uniform-shrinkage}(\mu = \bar{y}_k)$$

where $\bar{y}_i$ is the mean count per observation and $\bar{y}_k$ is the mean count per trawl tow.

The models were run for 10 000 updates during burn-in, and then run for a further 50 000 updates, with every 20th sample being retained for analysis.

The model structure allowed for mean counts to depend on covariates. For each model, a step analysis was used to select the covariates (from those in Table 1) that had explanatory power (Venables and Ripley 2002), with discharge (none, sump water, cutter, hasher, unprocessed) always included. The covariates were transformed before being included. Although the range of wind speeds, swell heights or visible vessels was not large enough to necessitate the use of logarithmic transformation, the transformations were made for consistency of analysis with Abraham *et al.* (2009). Maximum likelihood methods were used to fit a negative binomial GLM to the count data. At each stage of the step analysis, the model was fitted repeatedly with each of the potential covariates included (or removed) in turn. The covariate selected was that that produced the greatest reduction in the Akaike Information Criterion (AIC). Steps continued until the deviance was not reduced by >2%. Placing a requirement on the deviance reduction prevented the inclusion of covariates that had little explanatory power. The selection was carried out separately for each model, and the appropriate covariates included in the full Bayesian fit. Convergence of the fitted Bayesian models was checked using a stationarity test (Heidelberger and Welch 1983), checking the chains for each of the discharge-related parameters.

Results

Species observed during daily counts conducted on the two voyages before the start of experimental sampling included large albatrosses, small albatrosses and petrels. Abundances ranged from a single individual of a species, to tens or hundreds

Table 1. A description of the covariates, and their values, used in the modelling

Covariate	Value	Description
Discharge	None, Sump water, Hashed, Cutter, Unprocessed	Discharge, the primary experimental covariate
Region	Northern, Eastern, Southern, Western	Location of the observation among the four groups (Fig. 1)
Swell	log(swell height + 1)	Swell height; the logarithm is taken to make the distribution less skewed
Wind	log(wind speed + 1)	Wind speed; the logarithm is taken to make the distribution less skewed
Vessels	log(vessels + 1)	The number of visible vessels; the logarithm is taken to make the distribution less skewed
Voyage	A numeric identifier for each of the two experimental voyages	Numeric identifier, included as a two-level factor

(Table 2). In addition to the species recorded in Table 2, White-chinned Petrels (*Procellaria aequinoctialis*) and Sooty Shearwaters (*Ardenna grisea*) were observed at times outside the daily counts.

In the raw count data, there is no consistent evidence for any effect of cutter or hashed discharge treatments on overall seabird attendance at the experimental trawler (Fig. 2). For some bird groups, the cutter or hasher treatments were associated with higher seabird numbers than the unprocessed treatment, whereas raw data for other seabird groups show the opposite result. However, there were consistently fewer birds attending the vessel during sump-water discharge, and when there was no discharge (although the number of observations in this category was low). In most cases, the ratios were similar for birds in the air and on the water. However, these results derived from the raw dataset do not allow the effects of covariates to be accounted for.

Covariates are summarised in Fig. 3. Similar numbers of observations were collected on each of the two experimental voyages, mostly in the western and southern fishing areas. Observations were most frequent between 1200 and 1600 hours New Zealand Standard Time, but were made throughout the day between 0600 and 1800 hours. The most frequently recorded discharge types observed during sampling periods were sump water and cutter pump discharge, followed by unprocessed discharge and hashed discharge. Typically there were no other vessels visible during sampling periods.

When we constructed models, covariate selection procedures consistently included discharge type (Table 3). Voyage and fishing location (region) were also typically selected for inclusion. The covariate 'Voyage' is expected to capture variation owing to different observers making seabird observations during each trip, as well as possible influences of fishing location (and noting that 'Region' was included as a specific covariate also). Whereas all covariates shown in Table 1 were included in Bayesian models, we focus here on reporting discharge effects. The other covariates were not consistently included in models, and in all but one case, they explained less deviance than the discharge covariate (Table 3).

The Bayesian models were successfully fitted in all cases, with the exception of large albatross in the air and on the water in the 10-m observation zone (Fig. 4, Table 4). These two large albatross models were unstable and did not complete model fitting, owing to the low absolute counts in these categories. In addition, when stationarity tests were used to check chain convergence, convergence was not achieved for the model of the total large albatross in the 10-m zone. The lack of convergence in this model manifested in chains for the no discharge factor, and one chain for the cutter pump factor. Consequently, results for the 'Total large albatross' model (Fig. 4*a*, Table 4) must be treated with caution.

Because they can account for covariates, models provide a more robust and clearer picture of experimental results than examination of the raw data. These results show that seabirds are less numerous on the water when sump water, hasher or cutter pump discharges are released, relative to the unprocessed discharge treatment (except small albatross, cutter pump treatment; Fig. 4*c, d*). In the 10-m observation zone, the abundances of seabird groups excluding large albatrosses (owing to convergence issues, as above) decreased by 31–63% (median). For large albatrosses in the 40-m observation zone, cutter and hasher discharge brought about decreases in abundance of 38 and 59%. Further, in all cases (i.e. bird groups, observation zones, discharge types) where models were successfully fitted, discharges other than unprocessed caused seabird abundances on the water to decrease more than abundances in the air. Finally, in many cases, the total number of birds attending vessels decreased, relative to the number present during unprocessed discharge. Exceptions were Cape Petrels during the hasher treatment, and small and large albatrosses during the cutter treatment.

Although cutter and hasher treatments delivered some reduction in numbers of birds on the water astern of vessels, further reductions resulted from the release of sump discharge only (except for Cape Petrels). Cutter and hasher discharges reduced the total number of birds within the 40-m zone to 41–99% of the number present during unprocessed discharge; the smallest reduction was for the small albatross group. In comparison, the discharge of sump water reduced the total number of birds within the 40-m zone to 32–68% of the number present during unprocessed discharge.

The structure of the experiment allows comparisons between the efficacy of each discharge processing method in reducing abundance of seabirds. When the cutter pump and hasher discharges are compared, hashed discharge was more effective in reducing the abundance of birds on the water, except for Cape Petrels.

Across the range of discharges (none, sump water, cutter, hasher, all relative to unprocessed discharge), there was a greater reduction in bird abundances in the 10-m zone compared with the 40-m zone (Table 4). The single exception to this was Cape Petrels in the air during cutter pump discharge.

Comparing seabird abundance between the 10- and 40-m-radius sampling areas shows the distribution of species groups during the different treatments. If birds were distributed evenly across the two zones, the ratio of the total number of birds within the 10-m zone, compared with the 40-m zone, would be 6%. If

Table 2. Summary of seabirds observed (ranges are numbers of each species counted during each voyage) within 50 m of the vessel, determined by counts conducted during the first daylight trawl each day of the experimental voyages

Species	Voyage 1	Voyage 2
Large albatrosses, including	1–23	1–10
Antipodean Albatross (*Diomedea antipodensis*)		
Northern Royal Albatross (*D. sanfordi*)		
Southern Royal Albatross (*D. epomophora*)		
Smaller albatrosses		
Buller's Albatross (*Thalassarche bulleri*)	1–20	
Campbell Albatross (*T. impavida*)	1–20	
Salvin's Albatross (*T. salvini*)	5–20	1–10
Shy (White-capped) Albatross (*T. cauta steadi*)	4–80	1–100
Petrels and shearwaters		
Cape Petrel (*Daption capense*)	23–295	1–10
Giant-petrels (*Macronectes* spp.)	1–15	1–20
Unidentified petrels or shearwaters	5–80	1–200

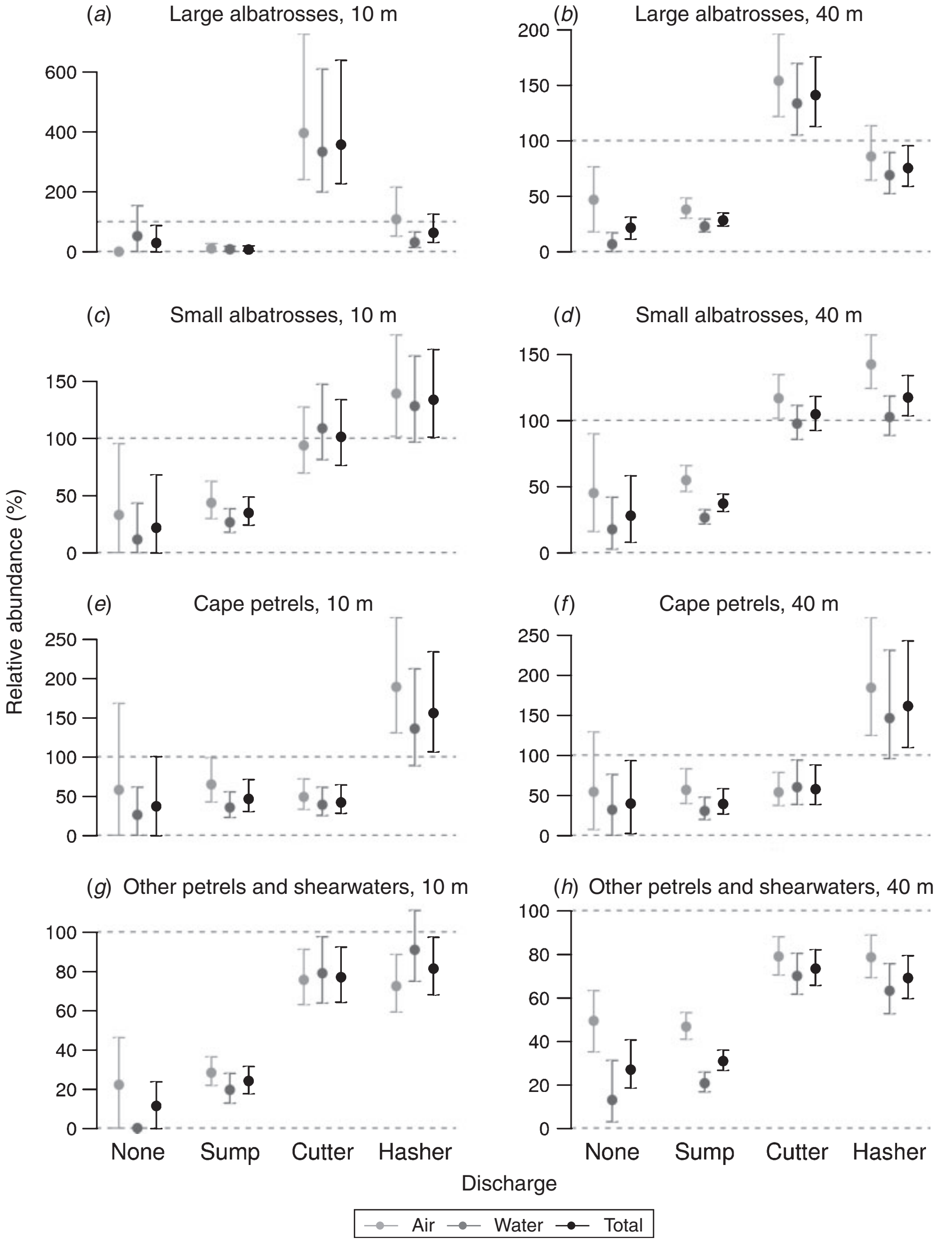

Fig. 2. Mean relative abundance of seabirds by seabird group, sampling area and discharge treatment compared with unprocessed discharge. Error bars are 95% confidence intervals of the ratio calculated from a simple bootstrap.

birds were spread in a linear fashion behind the vessel, this ratio would be 25%. Across treatments, Cape Petrels were consistently concentrated closer to the vessel than the other seabird groups (ratios of 33–48%), whereas smaller albatrosses were approximately linearly distributed through the 40-m zone (ratios of 19–23%). However, the distribution of large albatrosses varied with treatments: birds were approximately evenly distributed in the 10- and 40-m zones when there was no discharge or during hasher discharge. Cutter pump discharge brought large albatrosses closest to the stern. Unprocessed discharge brought them in to the 10-m zone in greater numbers than no discharge and hasher discharge.

However, the observer noted anecdotally that across all species, spatial dynamics of seabirds differed between treatments at a scale beyond what was captured by the 40-m-radius sampling area. The hasher pump discharged clouds of material in batches, and birds tracked these batches as they left the vessel and drifted astern. Over time, some birds returned to the vessel with the discharge of each new batch, to track that in the same way. Consequently, birds were not always concentrated at the vessel stern, instead following batch trajectories across the water. In contrast, the consistent emergence of waste during cutter pump treatment meant birds stayed in a single larger group astern of the vessel throughout periods of discharge.

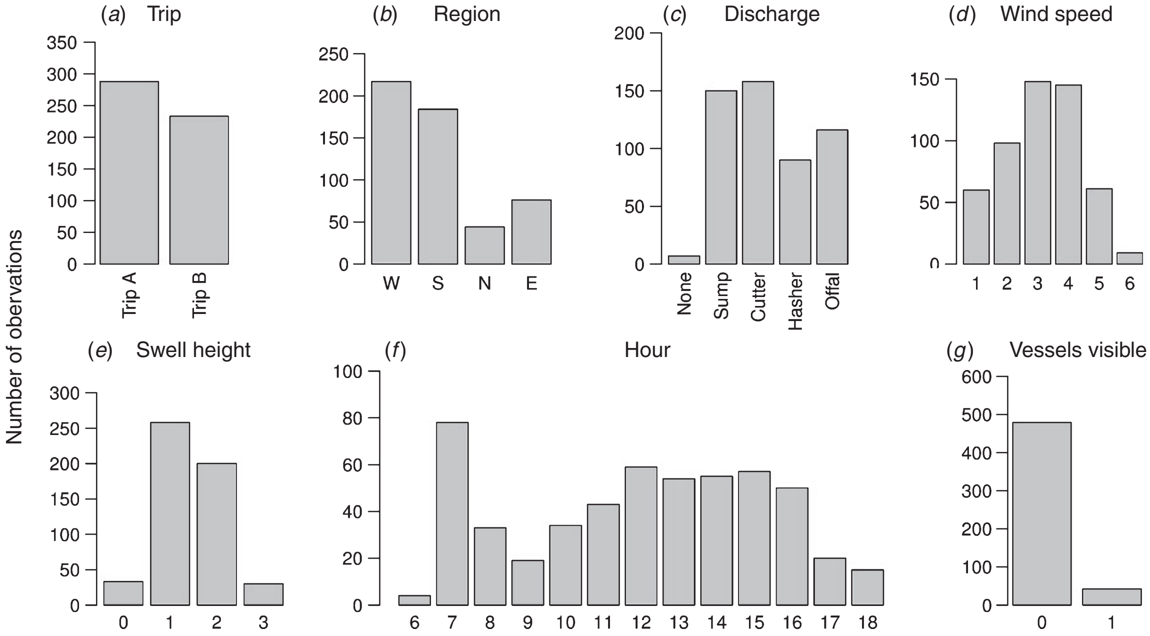

Fig. 3. Distribution of the potential covariates for observation data used in modelling: (*a*) experimental trip; (*b*) location (western, southern, northern, eastern); (*c*) discharge (no discharge, sump-water discharge, hasher pump discharge, cutter pump discharge, unprocessed offal discharge); (*d*) wind speed (Beaufort scale); (*e*) swell height (m); (*f*) hour of observation and (*g*) number of vessels visible during sampling.

Table 3. Summary of the model selection, from an analysis of variance, giving the percentage of the remaining deviance explained by the addition of each term to the model

Terms that explained <2% of the remaining deviance are not included

Birds	Observation zone (m)	Location	Covariates							
			Discharge	Voyage	Region	Swell	Wind	Vessels	Sin (h)	Cos (h)
Small albatross and giant-petrels	10	Air	9.3	70.7	16.9		5.8			4.4
		Water	16.2	47.9	7.8					4.1
		Total	11.4	60.1	9.8					3.1
	40	Air	25.7		8.0	3.7	17.2			
		Water	36.9	8.0	6.6		2.6			
		Total	38.5	7.2	9.4		12.4		2.5	
Large albatrosses	10	Air	28.9	53.1		6.6		4.1	2.7	12.8
		Water	33.8	46.4	5.2					8.1
		Total	33.5	53.9	7.2	2.6				8.8
	40	Air	19.4	32.0	7.5	13.6				
		Water	27.1	26.5	4.9					2.5
		Total	29.2	35.8	7.6		4.4		2.0	
Cape petrels	10	Air	10.6	82.9	43.9	3.1				
		Water	9.7	82.0						
		Total	9.7	84.9	43.3		3.0			
	40	Air	9.5	74.7	32.5				6.5	
		Water	8.1	67.7	24.8				6.4	
		Total	7.0	68.9	27.3				10.0	
Other petrels and shearwaters	10	Air	14.2	33.4	5.3	2.1				
		Water	20.3	24.6	7.6					2.3
		Total	16.7	31.5	5.1					
	40	Air	19.8	27.0	5.3	5.8			2.1	
		Water	32.7	7.2	12.9				3.4	
		Total	33.7	19.2	12.3	5.2			3.0	

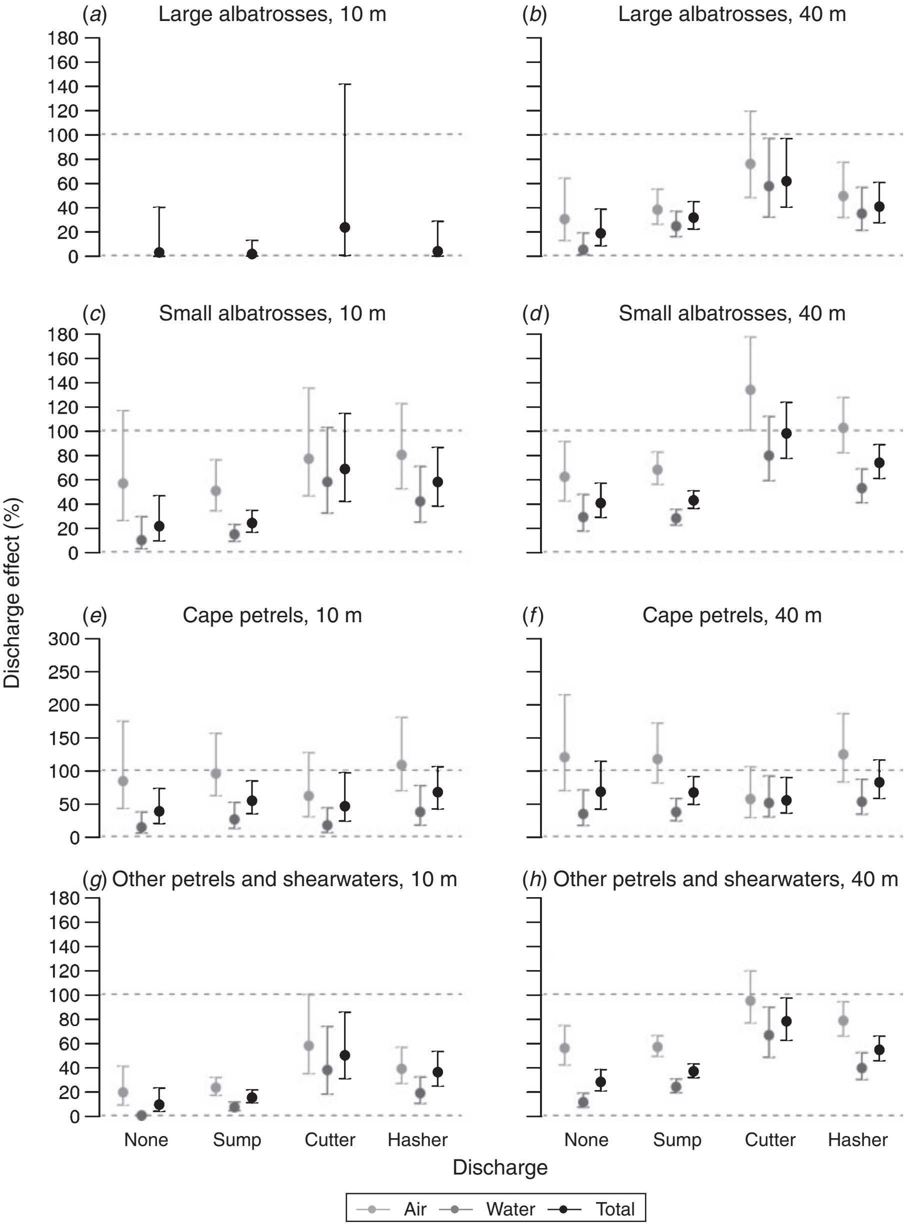

Fig. 4. Model results giving estimated effect of different discharge regimes relative to unprocessed discharge. Figures are medians and 95% confidence intervals of the posterior distribution of the model estimated coefficients of the discharge covariates.

Discussion

As expected, seabirds were attracted to foraging opportunities presented by the discharge of trawled fish waste from the experimental vessels. Investigation of the raw data did not reveal treatment effects owing to the particle size of discharged waste, because of the influences of covariates such as fishing location. However, despite any influence of covariates, seabird abundances still decreased during periods of only sump discharge, and when there was no discharge. Models incorporating covariates clearly demonstrated the effects of the different discharge treatments on seabird numbers. First, seabirds (except small albatrosses for the cutter pump treatment) were less abundant on the water astern of the vessel during discharge of all waste types (sump water, cutter, hasher), relative to unprocessed discharge. Further, discharges other than unprocessed discharge caused greater decreases in seabird abundances on the water than in the air (except for large albatrosses within 10 m of the vessel, when models could not be fitted successfully). Total abundance of birds was also lower during discharges other than unprocessed discharge (except Cape Petrels during the hashed treatment and small and large albatrosses during the cutter treatment). Reducing discharge to the sump pump further reduced seabird abundances, except for Cape Petrels.

Table 4. Summary of the model results, giving the effect of discharge on the abundance of birds relative to unprocessed discharge
The table summarises the posterior distributions of the discharge parameters from the Bayesian model, giving the median and 95% confidence intervals (CI)

Birds	Observation zone (m)	Location	Discharge							
			None		Sump water		Cutter		Hasher	
			Median	95% CI	Median	95% CI	Median	95% CI	Median	95% CI
Small albatrosses and giant-petrels	10	Air	0.56	0.26–1.16	0.5	0.34–0.76	0.77	0.46–1.35	0.8	0.52–1.22
		Water	0.1	0.03–0.29	0.14	0.09–0.22	0.58	0.32–1.02	0.42	0.24–0.7
		Total	0.22	0.1–0.47	0.25	0.17–0.35	0.69	0.42–1.15	0.58	0.38–0.87
	40	Air	0.62	0.42–0.91	0.68	0.56–0.82	1.34	1–1.77	1.02	0.82–1.27
		Water	0.29	0.17–0.47	0.28	0.22–0.35	0.79	0.59–1.11	0.52	0.41–0.68
		Total	0.41	0.29–0.57	0.43	0.37–0.51	0.99	0.78–1.24	0.74	0.61–0.89
Large albatrosses	10	Total	0.03	0–0.4	0.02	0–0.13	0.24	0.01–1.42	0.04	0–0.29
	40	Air	0.3	0.12–0.64	0.38	0.26–0.55	0.75	0.48–1.19	0.49	0.31–0.77
		Water	0.05	0.01–0.18	0.24	0.16–0.36	0.57	0.32–0.96	0.35	0.21–0.56
		Total	0.19	0.09–0.39	0.32	0.23–0.45	0.62	0.41–0.97	0.41	0.28–0.61
Cape petrels	10	Air	0.84	0.42–1.74	0.95	0.62–1.55	0.61	0.3–1.26	1.08	0.69–1.8
		Water	0.14	0.05–0.37	0.26	0.12–0.51	0.17	0.06–0.43	0.37	0.17–0.77
		Total	0.39	0.21–0.74	0.55	0.36–0.85	0.47	0.25–0.97	0.68	0.43–1.07
	40	Air	1.2	0.69–2.14	1.17	0.81–1.71	0.57	0.29–1.05	1.24	0.82–1.85
		Water	0.34	0.17–0.7	0.37	0.24–0.57	0.5	0.3–0.91	0.53	0.34–0.86
		Total	0.69	0.42–1.15	0.68	0.5–0.92	0.56	0.37–0.9	0.83	0.59–1.17
Other petrels and shearwaters	10	Air	0.19	0.09–0.4	0.23	0.17–0.31	0.57	0.34–1	0.39	0.26–0.56
		Water	0	0–0	0.07	0.04–0.11	0.38	0.18–0.73	0.19	0.1–0.32
		Total	0.1	0.04–0.23	0.16	0.11–0.22	0.5	0.31–0.86	0.37	0.25–0.53
	40	Air	0.56	0.42–0.74	0.57	0.49–0.66	0.95	0.76–1.19	0.78	0.66–0.94
		Water	0.11	0.07–0.18	0.24	0.19–0.3	0.66	0.48–0.89	0.39	0.3–0.52
		Total	0.28	0.21–0.38	0.37	0.32–0.43	0.79	0.63–0.98	0.55	0.46–0.66

It is well known, and intuitive, that eliminating the discharge of fish waste reduces seabird activity around fishing vessels to very low levels (Abraham *et al*. 2009; Bull 2009). This study shows that not only the presence of waste, but also how it is discharged, determines seabird abundance. Foraging opportunities provided by unprocessed discharge were generally more attractive than hasher and cutter discharge. Just as the attractiveness of natural foraging opportunities varies, so do those presented by discharged fish waste.

The cutter pump discharge was reduced to a finer particle size than the hasher pump discharge. Consequently, we expected that of these two discharge types, the cutter discharge would be less attractive to seabirds, especially those birds with larger gape size (e.g. following Xavier and Croxall 2007). In fact, the modelling revealed that the hasher discharge delivered a greater reduction in abundance among seabird groups than the cutter discharge. In practice, our assumption that particle size would drive seabird responses was confounded by the way hasher and cutter discharge left the vessel. The hasher pump exuded its waste in intermittent batches whereas the cutter pump discharged a more continuous stream. Birds would attend a batch of hasher waste on discharge and stay with that batch foraging as the batch drifted (away from the vessel, as the vessel moved forward). When foraging opportunities at that patch were exhausted, birds would move closer to the vessel again, to attend another batch of waste. In contrast, birds remained around the vessel during cutter pump treatments. This difference in the consistency of discharge was a result of the amount of liquid required to maintain waste movement through vessel piping during cutter pump treatments. To have both cutter and hasher pumps discharge continuously would require extensive changes to the set-up of equipment.

Previous work has compared both the effects of some forms of waste discharge, and the frequency of batch discharge events, on seabird abundance at trawl vessels. Our own work demonstrated that the form of waste discharged affects seabird foraging patterns. Abraham *et al*. (2009) found that mincing waste (maximum particle size 20-mm diameter), compared with discharging offal in larger chunks, reduced feeding activities of large albatross (*Diomedea* spp.) but had no detectable effects on foraging of other seabirds. Further, holding waste was more effective than discharging minced waste for reducing seabird abundance. That work did not investigate different particle sizes of mince.

Here, we show that reducing the particle size of discharged fish waste can reduce the abundance of seabirds as well as large albatrosses, at the experimental vessel. However, in accordance with Abraham *et al*.'s (2009) earlier mincing work, small albatrosses did not decrease in abundance in response to the cutter treatment. This group includes several species of conservation concern, and is a focus of by-catch reduction efforts. Consequently, the value of discharging waste through a cutter pump process in order to lessen the effects of fishing on seabirds is reduced. For this species group, the way waste is discharged (i.e. a discrete batch versus a more continuous stream) appears to be more important than particle size (at least within the range we tested). This requires further investigation.

Pierre *et al*. (2010) examined the effects of time between discharge events on seabird abundance at a trawl vessel. Batch discharges 4 h or more apart were attended by fewer seabirds than those <4 h apart. Although experimental regimes did not examine discharge intervals of <30 min, these results still clearly show the temporal effects of discharge streams on seabirds.

Percentage reductions in seabird abundance can be compared between this study involving processing waste of reduced particle size and unprocessed offal discharge, and experiments releasing batches of offal 4 and 8 h apart, relative to 30 min (Abraham *et al*. 2009; Pierre *et al*. 2010). Within the 10-m-radius semicircle astern of the vessel (excluding large albatrosses, owing to the lack of model convergence), processing waste with hasher or cutter pumps reduced median seabird abundance to 31–63% of abundances during unprocessed discharge. Holding waste for 4–8 h resulted in reductions of 11–44% of median abundance (including the small numbers of large albatrosses present), in the same 10-m-radius sampling area. However, reductions recorded are still not as substantial as when waste was retained onboard the trawl vessel, and sump pumps emitted the only discharge present for the duration of trawl tows (i.e. 95% reduction in small albatross abundance; Abraham *et al*. 2009).

In summary, our work to date shows that the attendance of seabirds at trawlers is still reduced most effectively by retaining fish waste. Although discharge in batches and mincing waste are at least somewhat effective in reducing the foraging opportunities trawl vessels provide to seabirds, these strategies are not without cost and limitations, and do not work on all species of conservation concern. To hold waste for the duration of a trawl tow requires space, but the installation (especially retrofitting operating vessels) of mincing equipment able to process all trawled waste is costly. To minimise seabird by-catch in trawl fisheries, the deployment of discharge management solutions is required across fleets operating in areas where seabirds occur. We recognise the efficacy of mitigation measures, such as streamer lines, in reducing seabird mortalities on trawl warps (Bull 2009) and consider that these devices offer a partial solution to seabird by-catch. However, reducing the attraction of seabirds to fishing vessels by manipulating the discharge of processing waste is a more fundamental solution to by-catch. Best-practice measures to minimise the risk of by-catch involve the deployment of streamer lines and effective management of the discharge of waste.

Acknowledgements

We are grateful to the manager, skipper, crew and onshore managers of the vessel used for their assistance with implementing the trial, and to the observers for their many hours of work counting seabirds. This work is the result of collaboration between the Deepwater Group Ltd, Sealord Ltd and the New Zealand Department of Conservation. Much of the experimental logistics, analyses and reporting were funded by Marine Conservation Services, New Zealand Department of Conservation. Observer placement was carried out by the New Zealand Ministry of Fisheries. We thank the reviewers for their constructive comments, which have improved the manuscript.

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