DRAGONFLY

Batching of waste to reduce seabird numbers behind trawl vessels

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EXECUTIVE SUMMARY

Seabirds are attracted to fishing vessels by the discard of waste from fishing. While this waste provides an available food source, seabirds foraging near vessels are at risk of either being caught or struck by the fishing gear. Within New Zealand waters, there were 212 seabirds observed killed by trawlers during the 2006–07 fishing year. Birds feeding on fishing waste behind trawlers may be struck by the trawl warps. The mortality from warp-strike can be reduced by using mitigation devices, such as tori lines, that deter birds from entering the region between the stern and the warps. While tori lines are partially effective, numbers of warp interactions are reduced to close to zero if no offal or discards are discharged. Strategies that reduce the discharge of fishing waste, such as converting it to fish meal and retaining it on board, or holding waste and discharging it while the vessel is not fishing, are expected to greatly reduce mortality. Many vessels hold waste in a container and discard it at intervals, a practice known as batching, in order to reduce interactions with seabirds.

In this study it is determined whether increasing the interval between batched discharges of offal reduces the numbers of albatrosses and petrels behind a squid trawl vessel. The experiment was carried out on a trawler fishing for arrow squid (*Nototodarus sloanii*) in the Stewart-Snares and Auckland Islands regions, between February 5 and March 14, 2008. All fishing waste was held in a 4.5 m^3 capacity container, and then dumped at prescribed intervals. Batches were discharged at either 30 minute, 2 hour, 4 hour or 8 hour intervals. Seabirds were counted in 40m and 10m radius sweep zones extending behind the stern of the vessel. Observations were made at 5 minute intervals before, during, and after discharge events. Separate counts were made of large birds (principally albatross species), small birds (principally petrels) and Cape petrel (*Daption capense*). Cape petrel moved away from the area during the trip, and these data are not considered. A statistical model is fitted to the count data from the 40m sweep zone, using Bayesian methods.

The experiment demonstrates a clear relationship between discharge and the number of birds close to the stern of the vessel. During discharge events, there was an increase in the total numbers of both large birds and small birds. There was also an increase in the proportion of birds on the water, compared to in the air. The response of the birds to the individual discharge events was rapid, and when discharge ceased the numbers of birds on the water fell back to the level associated with sump water faster than could be resolved by the five minute observation interval.

In each of the different bird groups there were, on average, fewer birds present during discharge when there was a four or eight hour interval between discharges, compared to when there was a thirty minute interval. During the four and eight hour treatments, the best estimate was that bird numbers were reduced to between 56% and 89% of the number present when there was a 30 minute interval between batches. In all categories, the median number of birds decreased when the interval between batches increased from two to four hours. The same consistent decrease was not seen between the four hour and eight hour batch intervals. While there is a reduction in numbers as the batch interval increases to four hours, there does not appear to be any further benefit achieved by increasing the batch interval from four to eight hours.

During the trip, over 94% of the tows were less than 8 hours long. The eight hour storage capacity used for the experiment could be used to hold waste until the end of the tow, and discharge it when the vessel is not fishing. There could then be no interaction between the birds and the warps during the discharge. Rather than using the batching to reduce the numbers of birds behind the vessel, it could be used to eliminate discharge of offal during fishing.

1. INTRODUCTION

Seabirds are attracted to fishing vessels by the discard of waste from fishing. While this waste provides an available food source (e.g. Thompson, 1992; Cherel et al., 2000; James & Stahl, 2000; Freeman & Wilson, 2002), seabirds foraging near vessels are at risk of either being caught or struck by the fishing gear. In Southern Ocean trawl fisheries, albatrosses and petrels feeding behind vessels are killed by being caught in the net when the net is hauled, and by being struck by the trawl warps or other cables during fishing (Bartle, 1991; Weimerskirch et al., 2000; Wienecke & Robertson, 2002; Sullivan et al., 2006b; González-Zevallos et al., 2007; Conservation Services Programme, 2008). In New Zealand waters, 212 birds were observed killed in New Zealand trawl fisheries in the 2006–07 fishing year (Abraham & Thompson, 2009a). The mortality from warp-strike is reduced by using mitigation devices, such as tori lines, that deter birds from entering the region between the stern and the warps (Sullivan et al., 2006a; Bull, 2007; Abraham & Thompson, 2009b). Trawlers over 28m in length are now legally required to use a mitigation device while fishing in New Zealand waters (Department of Internal Affairs, 2006).

While tori lines are partially effective, numbers of warp interactions are reduced to close to zero if no offal or discards are discharged (Sullivan et al., 2006b; Abraham & Kennedy, 2008; Watkins et al., 2008). Strategies that reduce the discharge of fishing waste, such as converting it to fish meal and retaining it on board, or holding waste and discharging it while the vessel is not fishing, are expected to greatly reduce mortality. In an experimental study, the numbers of albatross (*Thalassarche spp.*) feeding behind a trawler was reduced to less than five percent when waste was mealed and so discharge was reduced to sump water, compared to when all waste was discharged (Abraham et al., 2009).

For some vessels currently operating in New Zealand's deepwater trawl fleet, there are limited options for managing offal. Installing meal plants or large offal holding facilities on existing vessels may be expensive or technically difficult. Offal management solutions are needed that can be adapted for use on a variety of vessels and that can be implemented inexpensively. In this paper, we test the effect of discharging offal in batches on the numbers of albatross and petrels behind a squid trawl vessel. All fishing waste was held in a container, and dumped at prescribed intervals. We determine how the number of birds behind the vessel responds to the individual discharge events, and to the interval between batches. Our expectation was that the number of birds following the vessel would decrease as the interval between batches grew, and so the risk to seabirds of the offal discharge would be less. Simple counts of the seabird numbers within a given distance from the stern is used as the main metric. Seabird abundance behind trawl vessels is closely associated with warp strike and warp mortality (Abraham & Kennedy, 2008), and so reducing the numbers of birds behind the vessel is expected to reduce the warp mortality.

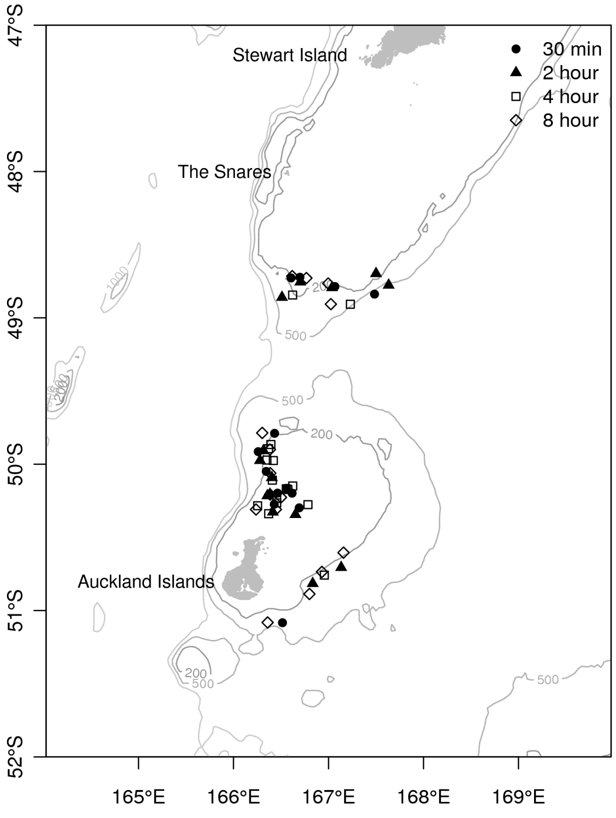
The experiment continues a series of work aimed at reducing the bycatch of seabirds in New Zealand fisheries, including studies of the efficacy of mitigation (Middleton & Abraham, 2007; Abraham et al., 2008) and previous trials of different offal management strategies (Abraham, 2006, 2008), that have been coordinated by the Mitigation Technical Advisory Group. This group has representation from the fishing industry, the Ministry of Fisheries, the Department of Conservation, WWF-New Zealand, and Birdlife International.

2. METHODS

2.1 Experimental treatments

The experiment was carried out on a trawler fishing for arrow squid (*Nototodarus sloanii*) in waters to the south of New Zealand, between February 5 and March 14, 2008. The vessel was a 65m long New Zealand flagged trawler, which carried out normal fishing operations during the experiment. The start

Figure 1: Start position of trawls where observations were made. The different symbols indicate the different batching intervals used as experimental treatments. The 200m, 500m and 100m depth contours are shown.



positions of tows where batching observations were made are shown in Figure 1. The displayed points have been randomly moved by between $\pm 0.1^\circ$ of latitude and longitude to meet Ministry of Fisheries data confidentiality requirements. Fishing was in the Stewart-Snares and Auckland Islands regions, with the vessel fishing on the Stewart-Snares shelf until February 14, and in the Auckland Islands region from February 15.

While the experiment was running, all waste other than factory sump water was stored temporarily in a tank, and then dumped according to a prearranged schedule through the normal discharge chute at the side of the vessel. The nominal tank volume, as estimated by vessel managers, was 4.5 m^3. During the experiment, the batch volume recorded by the observer was never more than 2 m^3. It is unclear whether the difference is because the tank was never filled to capacity, or due to differences in the way the volumes were estimated. The only difference between the experimental treatments was the time between discharges. Batches were discharged at either 30 minute, 2 hourly, 4 hourly or 8 hourly intervals. The same batching interval was used for a complete day, from 6 a.m. to 6 p.m.. A randomized-block design was used to assign experimental treatments to days before the trip, so each treatment was scheduled once within each block of four consecutive days. In addition to batching waste, the vessel also processed some of the waste stream through the meal plant. Observations were made either when the vessel was trawling, or not fishing, but no observations were made during shooting or hauling.

The observer liaised with the factory manager to determine when discharges would take place, and to keep records of discharge times and volumes. The observer recorded seabird abundance for up to an hour at a time, making observations of discharges and seabird abundance at five minute intervals. The intent was that the observer should make two or three observations before the start of each discharge event, and

Table 1: Discharge categories used in the analysis.

Category	Definition
None	Discharge rate of all categories none or negligible
Sump	Discharge rate of sump intermittent or continuous, discharge of all other categories none or negligible.
Batch	Discharge rate of either minced material, offal, or discards intermittent or continuous.

then continue recording bird counts during and following the discharge. This was to allow an abundance to be established before the start of the discharge, and then to determine the response of the seabirds to the discharge. On treatments with longer discharge intervals, the observer made intermediate sets of observations between discharge events.

During each observation, the observer recorded the discharge in each of four groups (sump water, minced or macerated material, offal, whole discards). The discharge rate of each type was categorised by whether there was no discharge, or whether the discharge was negligible, intermittent or continuous. The same discharge rate categorisation has previously been found to give a simple semi-quantitative measure that is associated with seabird abundance (Abraham et al., 2009), and with warp strike (Abraham & Kennedy, 2008). From the raw discharge data, a classification of the discharge into three categories was defined (Table 1) that was used for analysis of the data.

Birds were counted from the stern of the vessel within a 40m radius semi-circular sweep extending behind the vessel (Figure 2), following a protocol similar to one used previously (Abraham et al., 2009). A separate sub-total was also made of the number of birds within a smaller 10m zone, more tightly focussed on the region between the stern and the warps. Separate counts were made of birds in the air and on the water, in each of three species groups (Table 2). Cape petrels were separated from the other petrels into their own group, as there can be large numbers of Cape petrels attending vessels, but they are caught relatively infrequently (Abraham & Thompson, 2009a). During a single observation, a separate sweep count was made for each combination of species group and sweep radius, and for birds in the air and on the water. This resulted in a total of twelve sweep counts for each observation. The observer was instructed to spend no more than one minute on each individual sweep count. When birds were abundant the counts were necessarily approximate. Because separate counts were made of birds on the water and birds in the air, some individual birds may have landed on or taken off from the water between sweeps, and been either not counted or counted more than once.

In addition to the discharge and bird counts, the observer recorded the start time of each observation; the wind strength (on the Beaufort scale); the tow stage (shooting, fishing, hauling or not fishing); and the number of vessels visible. In addition, on each form (a group of up to twelve observations) the observer recorded the vessel speed (knots); swell height (metres); previous batch discharge finish time; previous batch volume (kilograms); batch start time; batch finish time; batch size (kilograms) and the main type of each discharge (whether it was squid, fish or crab).

As part of their other duties, the observer made a count of the birds within 50m of the vessel stern during the first daylight trawl of each day. The daily counts were made to species level, where possible, during the first fishing event of each day. They were intended to include all birds around the vessel, and were not restricted to the sweep zones.

Figure 2: Diagram of the sweep zones aft of the vessel. Birds were counted within 40m and 10m radius semi-circles, centered on the middle of the vessel's stern.

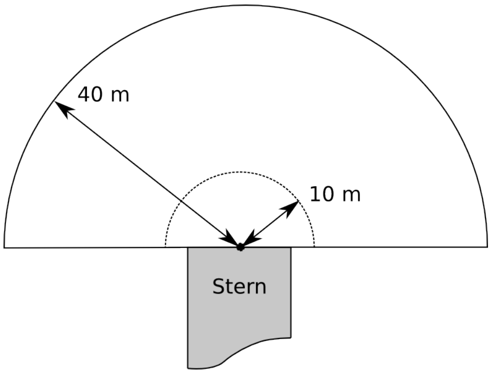


Table 2: Seabird groups used for sweep counts.

Seabird group	Definition
Large birds	Albatrosses (*Diomedea, Thalassarche, Phoebetria*) and giant petrels (*Macronectes*).
Small birds	All petrels, shearwaters and prions (except giant petrels and Cape petrels).
Cape petrel	Cape petrels (*Daption capense*), including the Snares Cape petrel supspecies (*Daption capense australe*).

2.2 Analysis

Data were double entered into a database, by two different people, with differences between the duplicates being resolved by comparison with the paper forms. An initial exploration of the data was carried out with box plots and other summaries being prepared for different groupings of the count data. The box plots give the median and quartiles of the counts within each group. The maximum extent of the whiskers is 1.5 times the inter-quartile range, with any outlying points marked by dots (R Development Core Team, 2008). Where box plots are used, the mean value of the data within each group is also given.

Following the exploratory analysis, four statistical models were built for large and small birds, in the air and on the water, within the 40m sweep zone, to determine the effect of the treatments on the bird counts. The models fit a time-dependent model to the data, and this allows for the non-random nature of the sampling to be accounted for. The data from the 10m zone were not modelled, as the counts were too low to allow stable models to be built. The model for each series of bird counts makes 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 time-scale representing how quickly birds leave the sweep region once discharge has ceased. This timescale is treatment independent.
4. There is no influence of batch discharge in one tow on seabird abundance 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.

The time variation in the mean counts is shown in schematic form in Figure 3. Expressing the model in formal terms, if the discharge is steady then the mean number of birds around the vessel, N, may be expressed as

$$\log(N_{ik}) = \log(\beta_{de}) + \sum_j \log(\beta_j) x_{ijk} + \epsilon_{id} \tag{1}$$

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}. 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:

$$\epsilon_{id} \sim \text{Normal}(0, \sigma) \quad . \tag{2}$$

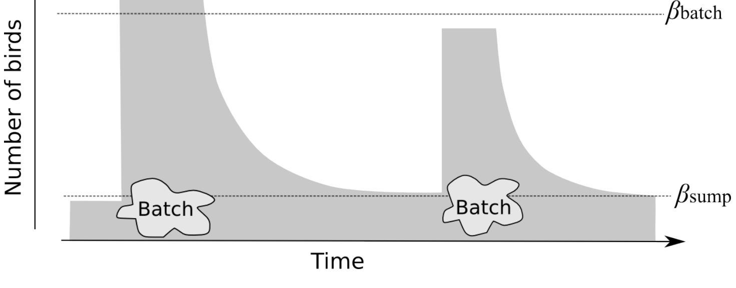
The full model allows for the mean count to return to the sump or no discharge levels with a time-scale T:

$$\mu_{ik} = \begin{cases} N_{ik}, & k = 1 \text{ or batch discharge} \\ N_{ik} + (\mu_{i,k-1} - N_{ik}) e^{-(t_{ik} - t_{i,k-1})/T}, & k > 1 \text{ and not batch discharge} \end{cases} \tag{3}$$

The value of the first observation on a tow is taken to be given directly by equation 1, and it does not depend on any discharges in the previous tow. After a batch discharge, the abundance returns to the non-discharge value at a steady rate, represented by an exponential function. The model includes three discharge categories, with the lowest level 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.

To fit this model to the data, the seabird counts, n_{ik}, are assumed to be drawn from a negative binomial model with mean μ_{ik}. The negative binomial allows the count data to be over-dispersed compared to

Figure 3: Schematic diagram of the model used to represent the 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 timescale T. The actual model includes a third level corresponding to no processing and no discharge at all.



a Poisson distribution with the same mean. The negative binomial model may be parametrised as a Poisson-gamma mixture distribution, where the gamma distribution has mean one, and shape θ:

$$r_{ik} \sim \text{Gamma}(\theta, \theta) \tag{4}$$
$$n_{ik} \sim \text{Poisson}(r_{ik}\mu_{ik}) \tag{5}$$

With this parametrization, the variance of the negative binomial distribution is $\mu_{ik} + \mu_{ik}^2/\theta$.

Bayesian methods are used to fit the 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 ten, are chosen for each of the β parameters. The prior for the timescale T is a uniform distribution between zero and 24 hours. The prior for the scale, σ, of the tow level random effect is taken to be a half-Cauchy distribution. This prior is implemented as described by Gelman et al. (2006). The mean of the half-Cauchy prior is set to two, chosen to be higher than the standard deviation of the log of the average count per tow. The prior favours 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, is taken to be the uniform shrinkage distribution with mean value given by the mean count over all observations.

Models were fitted to data from the 40m sweep counts, for large birds on the water, large birds in the air, for small birds on the water, and small birds in the air. The count data was not analysed by form, but the whole time-series of counts was used. In many cases, the observer had made continuous observations for several hours, allowing good resolution of time-variation in the abundance. Treating the data as a time-series also allowed inclusion of information from observations made when there was no discharge.

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 chains were run, and convergence of the chains was checked using criteria formulated by Heidelberger & Welch (1983) and Raftery & 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 & Smyth, 1996) were compared with a normal distribution. To define the 95% confidence interval on the quantile residuals, the procedure was repeated 2,000 times for simulated count data with the median model predicted mean, μ_{ik}, and overdispersion, θ. The 2.5% and 97.5% percentiles of the resulting quantile-quantile curves were used to define the 95% confidence interval.

3. RESULTS

3.1 Experimental summary

Observations were made on a total of 39 days, with the experimental treatment being followed on all but three of those days (on two days the meal plant was broken and there was too much waste to be held for the full eight hours, and on one day the vessel sheltered at the Auckland Islands to avoid rough weather). On many days, however, the observer was restricted in the number of observations that could be made, either because of limited fishing, or because there was no processing being carried out and so the batching protocol was irrelevant.

During the trip 144 separate forms were completed. A total of 1,269 observations were made, with the observer recording 15,093 individual sweep counts over the course of the trip. There were 54 errors entering data from the forms into the database, a data-entry error rate of less than 0.2%. These were reconciled by comparison with the original forms. Many of these errors were caused by ambiguity in the wind direction. On many pages, the observer had drawn a diagram indicating the direction of the wind

Table 3: 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.

	30m	2h	4h	8h	Total
No batch	1	1	10	16	28
0-1 hour	45	0	0	0	45
1-3 hours	1	30	0	0	31
3-5 hours	0	0	21	2	23
5-7 hours	0	0	0	1	1
7-9 hours	0	0	1	14	15
Over 9 hours	1	0	0	0	1
Total	48	31	32	33	144

relative to the vessel. This was entered into the database as a number between 1 and 12, where the arrow indicating the wind is interpreted as the hour hand of a clock (in all the diagrams the vessel was drawn so that the bow was pointing to six o'clock). This wind direction information was, however, not used in the analysis as it was not available for all observations.

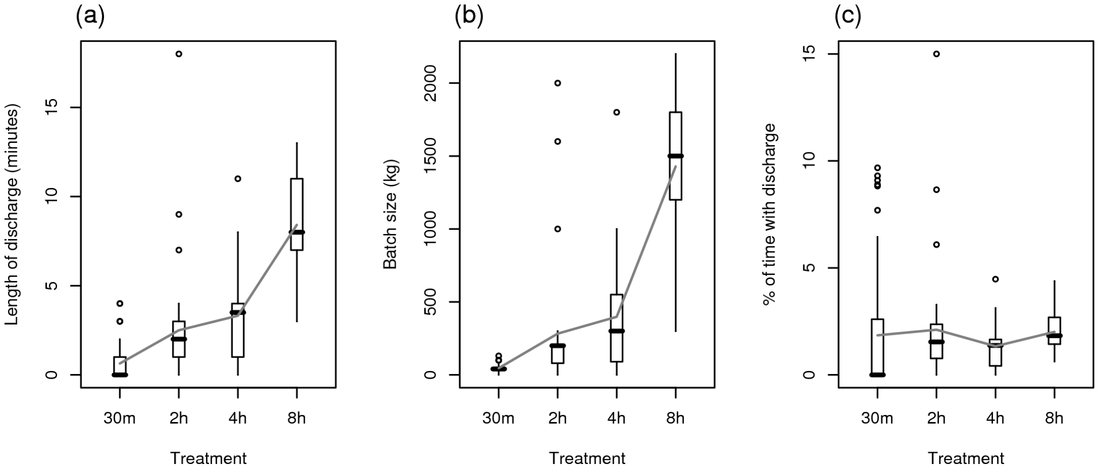
Out of the total of 1,269 observations, 1,002 were made when the vessel was fishing at a speed between four and five knots. There were 132 observations made when the vessel was not fishing, and all of these observations were made outside the normal range of fishing speeds (either less than three knots or more than five knots), these observations were not included in the analysis. There were no observations made when the net was being set or hauled.

As required by New Zealand law (Department of Internal Affairs, 2006), the vessel used mitigation devices (both tori lines and bird bafflers) throughout the experiment, with the exception of some tows where there were problems with the baffler. There was also 24 observations made on one day (March 2) when tori lines were not deployed, and there were eleven other observations made when the vessel had not deployed tori lines. As the tori lines strongly influence the number of birds within the sweep zones, these 35 observations were not included in the statistical modelling.

The relation between the experimental treatment and the batch interval recorded on the form is shown in Table 3. The time between batches is defined from the difference between the recorded batch start time and the recorded time of the previous batch. In general, the treatments are successfully followed. There was one observation recorded during the four hour treatment where the previous observation had been made eight hours earlier, and one observation during the thirty minute treatment where the previous discharge was twelve hours earlier. These were the first batches of the day. There were also three observations during the eight hour treatment where the recorded interval between discharge events is seven hours or less. Two of these were because the discharge was the first of the day, and there had been an early morning discharge when the vessel was not following the protocol, and one was due to an unscheduled discharge within the eight hour interval. During the 4h and 8h treatments, intermediate observations were made between discharge events, these appear in Table 3 as observations with no batch discharge.

The variation in the batch characteristics with the treatment are shown in Figure 4. The time taken to discharge the waste and the amount of material discharged with each batch increases approximately linearly with the nominal length of the batch interval. Although more material is held during the 8 hour treatment than the other treatments, it takes longer to discharge. As a consequence, the percentage of time during which there is batch discharge, as a percentage of the time between discharge events, is

Figure 4: 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 (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.



approximately constant. During all treatments, waste is discharged for approximately 2% of the time, with either no discharge or discharge of sump water at other times.

3.2 Seabird abundance

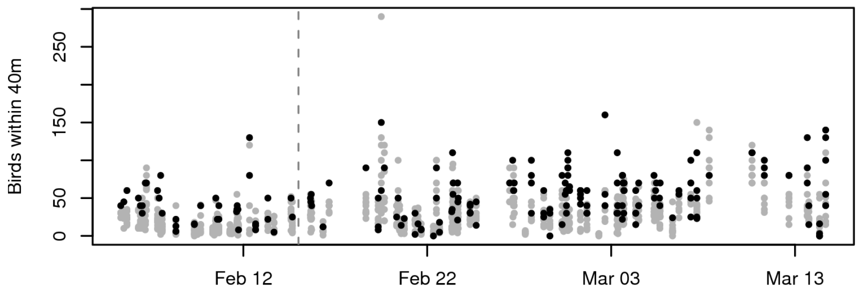
A summary of all the count data is shown in Figure 5, for each of the three species groups. Counts made during discharge events are marked. In the large bird and small bird groups there are no clear trends in abundance, whereas a pronounced decline is seen in the number of Cape petrel attending the vessel. The Snares subspecies of Cape petrel (*Daption capense australe*) breed on the Snares Islands. The decline seen in the abundance data is likely to be due to migration away from the subantarctic region at the end of the breeding season. In 1986 the mean fledging date was February 14 (Sagar et al., 1996), which coincides with the date when the vessel finished fishing in the Stewart-Snares region. Because of the low numbers of Cape petrel in the latter half of the trip, no analysis is made of these data.

A summary of the number of seabirds around the vessel obtained from the daily counts is shown in Table 4. These counts include birds beyond the sweep zone and so are larger than the numbers shown in Figure 5. Seabird abundance is higher in the Auckland Islands region with white-capped albatross, white-chinned petrel and sooty shearwater the most numerous species. The most abundant species in the Stewart-Snares region were Cape petrel, sooty shearwater and white-chinned petrel.

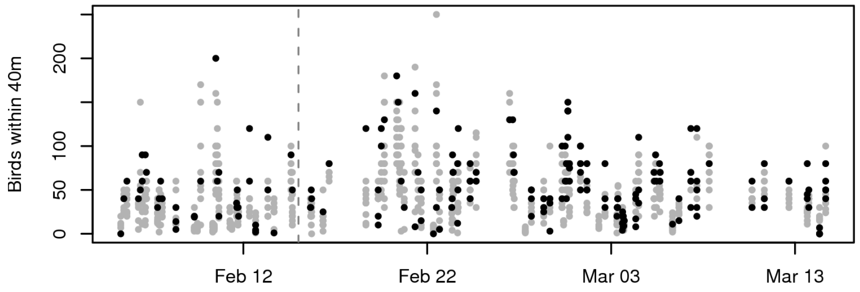
3.3 Relationship between discharge, treatment and abundance

The raw abundance data is grouped by the occurrence of discharge during the count, using the discharge categories defined in Table 1. The resulting box plots are shown in Figure 6, for large birds, and in Figure 7, for small birds. There are similar numbers of large and small birds within the 40m sweep, and there are similar numbers of birds in the air and on the water. As expected, there are fewer birds within the 10m sweep, with an average of less than three birds present in each of the categories.

(a) Large birds



(b) Small birds



(c) Cape petrel

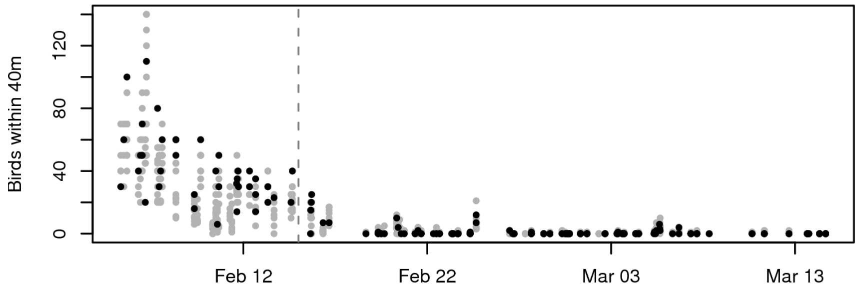


Figure 5: Time series of bird abundance counts for the three groups, summing the counts of birds in the air and on the water within the 40m sweep. The black dots mark observations where there was batch discharge. A single count of over 1000 Cape petrel has been ignored. The vertical line indicates the transition from the Stewart-Snares to the Auckland Islands region.

In all cases there is an increase in the numbers of birds when sump water is discharged, compared to when the factory is not processing and there is no discharge. While numbers of birds on the water increase further during batch discharge, the numbers of birds in the air are similar or are lower during batch discharge than during sump discharge. Total numbers of birds within the 40m sweep increase during batch discharge, but total numbers within the 10m sweep are lower during batch discharge than during sump discharge. The similar patterns seen in the responses of both large and small birds suggest that, at the scale resolved by the data, there is no evidence of one group of birds excluding the other from the sweep zone. Large and small birds respond together to changes in offal discharge.

The view of the data given in Figures 6 and 7 hides any time-dependent variation of abundance to changes in discharge. The response of the number of seabirds within the 40m sweep zone to individual batch events is shown in Figure 8. All discharge events were selected that were both preceded and followed by at least two observations with sump water discharge. For large and small birds, there was a rapid increase in the numbers on the water at the start of the discharge. The increase occurred within the 5min interval between successive counts. There was no evidence of an increase in number of birds on the water during the batch events. Following the finish of the batch, the numbers of birds decreased back to the original number within the 5 minute interval before the next batch. For birds in the air the response

Table 4: Seabird abundance by species, showing the mean and range of each daily abundance count for tows in the Auckland Islands region and Stewart-Snares regions.

Group	Common name	Scientific name	Auckland Islands		Stewart-Snares	
			Mean	Range	Mean	Range
Large	White-capped albatross	*Thalassarche steadi*	183.6	(20–400)	35	(15–60)
	Great albatross	*Diomedea spp.*	17.2	(5–30)	8.1	(2–15)
	Giant petrel	*Macronectes spp.*	14.5	(2–30)	2	(1–3)
	Buller's albatross	*Thalassarche bulleri*	2.8	(0–5)	5.6	(1–10)
	Black-browed albatross	*Thalassarche melanophrys*	1.4	(0–3)	0.9	(0–2)
	Salvin's albatross	*Thalassarche salvini*	0.5	(0–3)	1.9	(0–4)
	Light-mantled sooty alb.	*Phoebetria palpebrata*	0	(0–1)	0	(0–0)
Small	White-chinned petrel	*Procellaria aequinoctialis*	201.2	(40–400)	58.6	(10–120)
	Sooty shearwater	*Puffinus griseus*	132	(50–200)	135.7	(50–200)
	Storm petrel	*Oceanitidae*	27.3	(0–50)	0.4	(0–2)
	Prion	*Pachyptila spp.*	0.4	(0–2)	0	(0–0)
Cape petrel	Cape petrel	*Daption capense*	18.7	(0–100)	142.9	(50–200)

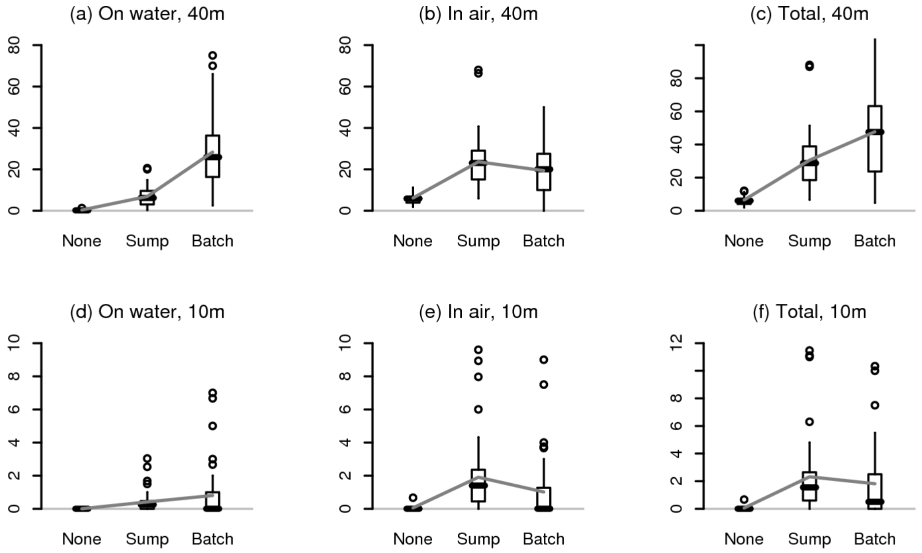


Figure 6: Summary of the raw observations of large bird abundance, giving box plots of the count data grouped by the three discharge categories. Summaries are shown for birds in the air and on the water, and the total number of birds, for birds within the 40m and the 10m sweeps. The gray line marks the mean value within each group.

was less marked, and there is more scatter in the data. There was a decrease in the number at the start of the batch, and an increase following the finish of the batch.

The raw count data are shown in Figures 9 and 10, grouped by experimental treatment. While there is variation in the abundance, there is no clear trend in abundance with the interval between the batches, for any of the twelve groups shown. The raw data does not show any evidence of a treatment effect. This summary includes data from observations made during all discharge conditions. As most observations were made during sump discharge, the summary will not be sensitive to changes in abundance between treatments for observations made during batch discharge.

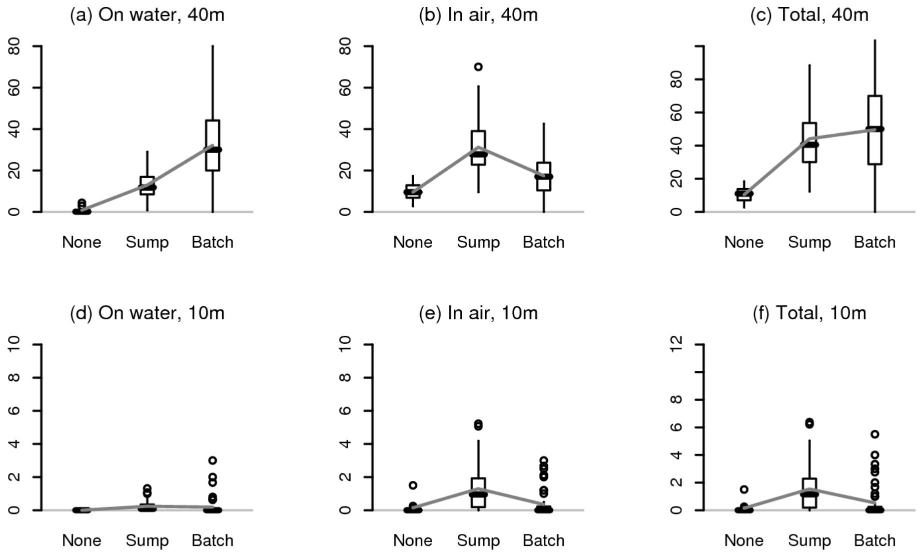


Figure 7: Summary of the raw observations of small bird abundance, giving box plots of the count data grouped by the three discharge categories. Summaries are shown for birds in the air and on the water, and the total number of birds, for birds within the 40m and the 10m sweeps. The gray line marks the mean value within each group.

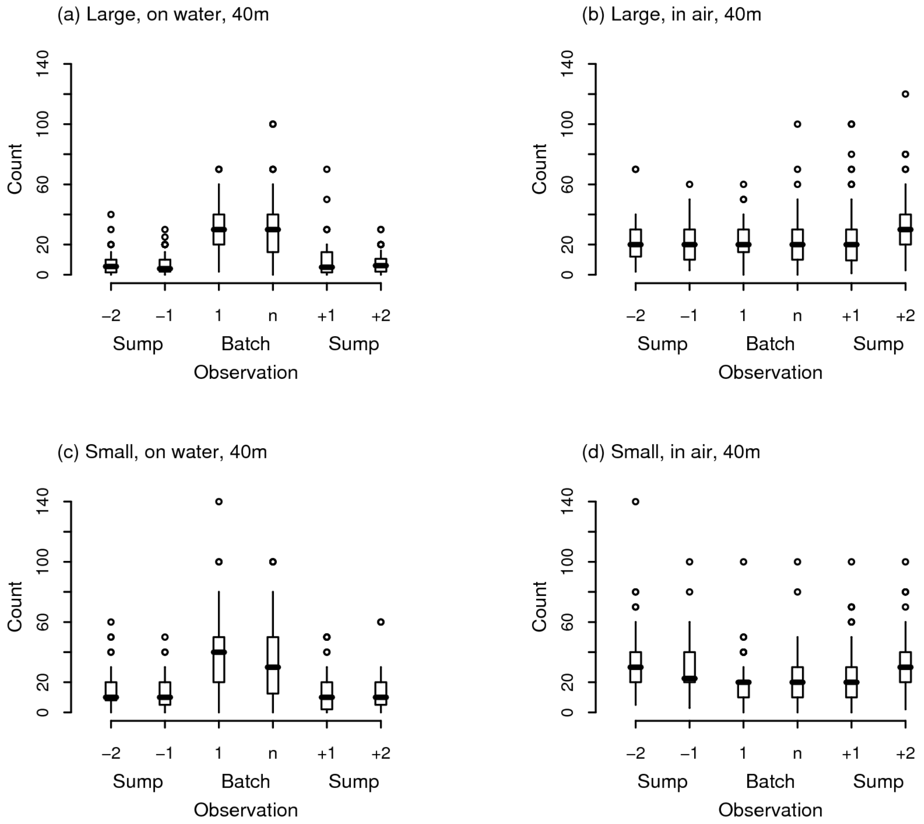


Figure 8: Change in abundance during batch events. The raw data is grouped by observation number, taken in relation to the start and finish of batch events. The data shows the observations before a batch event, the first and last observations during a batch discharge, and the two observations following the end of the discharge.

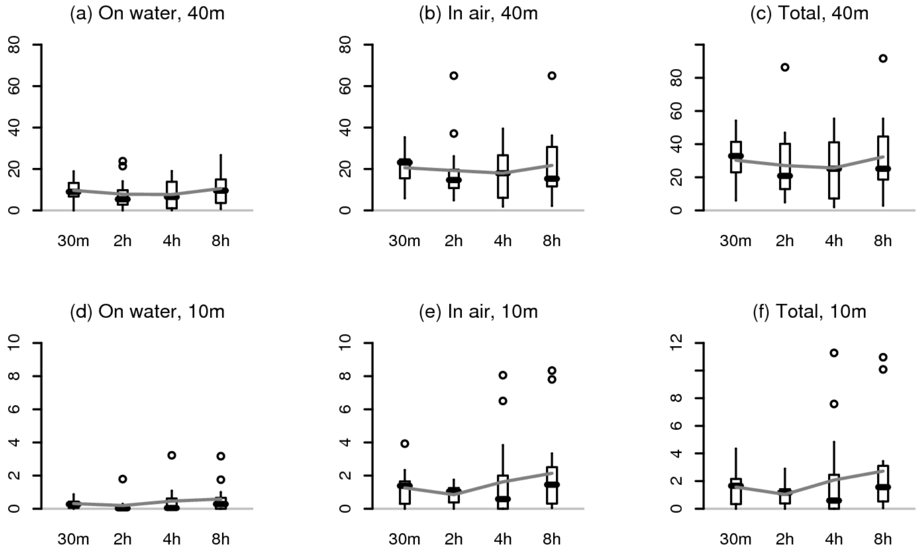


Figure 9: Summary of the raw observations of large bird abundance, giving box plots of the count data grouped by the four treatment categories. Summaries are shown for birds in the air and on the water, and the total number of birds, for birds within the 40m and the 10m sweeps. The gray line marks the mean value within each group.

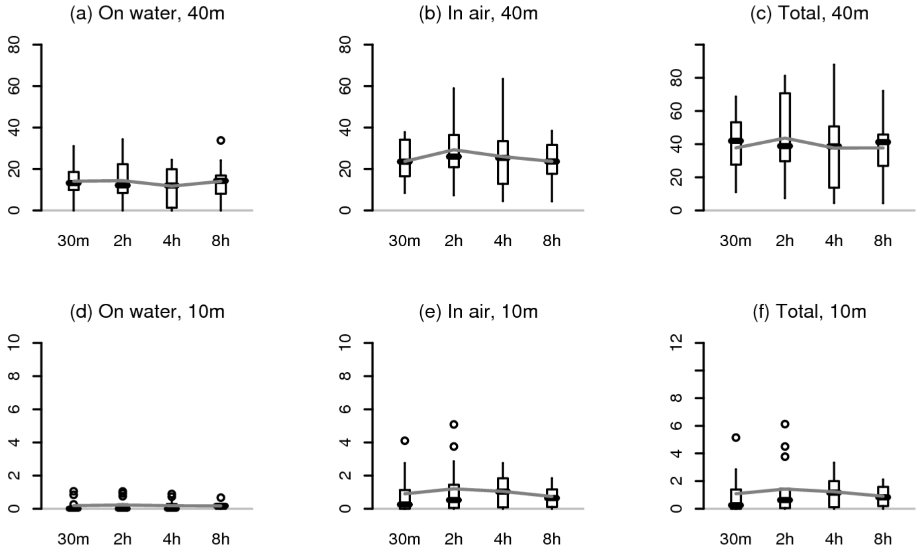


Figure 10: Summary of the raw observations of small bird abundance, giving box plots of the count data grouped by the four treatment categories. Summaries are shown for birds in the air and on the water, and the total number of birds, for birds within the 40m and the 10m sweeps. The gray line marks the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

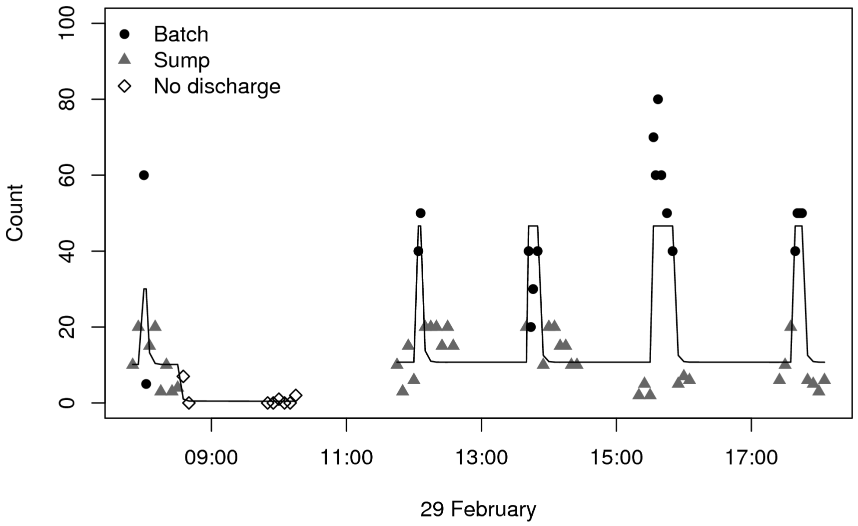


Figure 11: An example of the fit of the model to the count data, with points showing sweep counts of large birds on the water within 40m of the stern and the lines indicating the model fitted mean count. The data is from February 29, when there was a two hour interval between batches. The points are shaded to indicate the different discharge conditions recorded during the counts. The two separate lines interpolate estimated means from different tows.

3.4 Model results

After an initial exploration of the covariates, the region of the fishing (Stewart-Snares or Auckland Islands), the wind speed (the logarithm of the wind speed measured in the Beaufort scale), and the number of vessels visible (logarithm of visible vessels plus one) were chosen for inclusion in the model. The logarithm of the continuous variables (wind speed and visible vessels) was used, as the counts also enter the model through the logarithm link function. The wind speed had a median of force 4 (range: 2 – 8). The vessel was fishing in a fleet, with other vessels visible during 75% of observations. The median number of vessels visible was 2, with 13 vessels being visible during one observation. The vessel was fishing in the Stewart-Snares region during 28% of observations.

Convergence of the Bayesian models was successfully achieved, and was confirmed by the diagnostic criteria for the key parameters. An example of the fit of a model to the data is shown in Figure 11, which illustrates data from the model of large birds on the water within the 40m sweep, during a day when there was a two hour interval between batches. The median of the model estimated mean count, μ_{ik}, is shown by the lines. On that day, observations were made during two tows, and the two lines interpolate the predicted mean counts from each tow. The difference in the height of the peaks, and of the baseline abundance, between the tows is made possible by the random effects. There is a clear association in the data between the discharge events and higher bird numbers, and this is reflected by sharp peaks in the predicted mean abundance. Once the discharge finishes, there is a rapid return to the baseline level associated with the sump discharge. During the first tow, factory processing finished before 9 a.m., and the bird counts fell to a very low level. This decrease is successfully tracked by the model.

Further comparisons are shown for the same model in Figure 12. In Figure 12(a) the count data are compared with the predicted means, μ_{ik}, for each observation. In Figure 12(b) the randomized quantile residuals are given. The actual residuals largely fall within the 95% confidence interval, along the one-to-one line, and so support the use of a negative-binomial model to represent the data. Fits of the other models are not shown. The residuals of the model of small birds on the water shows some deviation from the expected one to one relationship, otherwise the models appear to fit the data well.

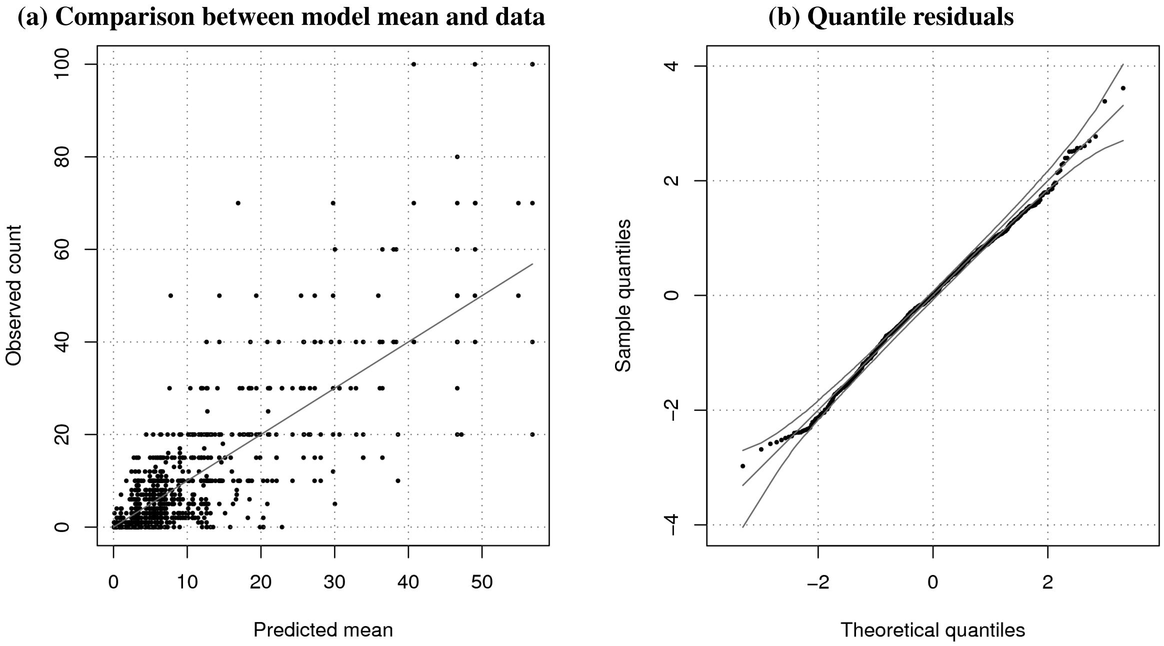


Figure 12: Comparison between the model of large birds on the water within the 40m sweep and the data. (a) direct comparison for all modelled observations. The one-to-one line is shown (b) randomized quantile residuals, with 95% confidence intervals. If the points lie within the confidence intervals they are consistent with the negative binomial distribution.

A summary of the fitted model parameters from the four models is given in Table 5, with the median and 95% confidence interval of each parameter being presented. For the wind speed and the number of vessels visible, the numbers given are the logarithm of the parameter. The mean count is related to the wind speed and the number of visible vessels (plus one) 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, the abundance decreases as the number of vessels visible increases. If there was a closed pool of birds that were distributed between the visible 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. This may be because of the intermittent discharge, which allows birds to follow the discharge events from vessel to vessel. It may also be that the birds are distributed across the regional fleet, rather than just the visible vessels. Both these effects would lead to an exponent that was smaller than unity. The coefficient of the Stewart-Snares covariate 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.

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 timescale is presented graphically in Figure 15 and is discussed below.

The model predicted asymptotic counts, β_{de} are shown in Figure 13. Distributions of total counts are made by summing the number of birds in the air and on the water, for each sample from the posterior distribution. Mean counts vary with the discharge, and are similar between treatments. For both large and small birds the number of birds on the water within the sweep zone increases as the discharge increases

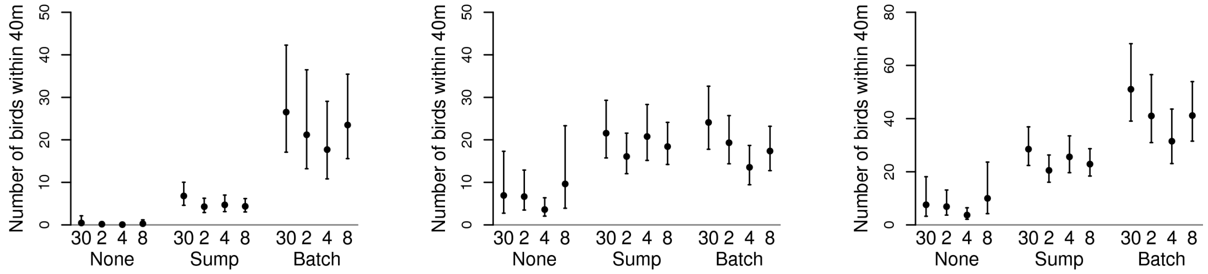
Table 5: Summary of the fitted parameters, for models of counts of (a) large birds and (b) small birds within the 40m sweep zone.

(a) Large birds within the 40m sweep

Parameter		On water			In air		
		Median	2.5%	97.5%	Median	2.5%	97.5%
β_{de}	None, 30m	0.459	0.0942	2.16	6.93	2.75	17.3
	None, 2h	0.169	0.0286	0.713	6.66	3.49	12.9
	None, 4h	0.0707	0.0215	0.201	3.61	2.06	6.38
	None, 8h	0.286	0.0572	1.19	9.63	3.92	23.3
	Sump, 30m	6.81	4.61	10	21.6	15.7	29.3
	Sump, 2h	4.29	2.91	6.28	16.1	12	21.6
	Sump, 4h	4.71	3.12	7.02	20.8	15.2	28.3
	Sump, 8h	4.36	3.03	6.21	18.4	14.2	24.1
	Batch, 30m	26.5	17.1	42.3	24.1	17.8	32.6
	Batch, 2h	21.2	13.2	36.5	19.3	14.4	25.7
	Batch, 4h	17.7	10.8	29.1	13.5	9.45	18.7
	Batch, 8h	23.5	15.6	35.4	17.4	12.8	23.2
$\log(\beta_j)$	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 40m sweep

Parameter		On water			In air		
		Median	2.5%	97.5%	Median	2.5%	97.5%
β_{de}	None, 30m	2.34	0.696	7.5	11.8	4.67	29.2
	None, 2h	0.466	0.165	1.2	9.76	5.03	18.8
	None, 4h	0.129	0.0495	0.299	4.75	2.69	8.14
	None, 8h	1.84	0.669	4.82	11.4	4.77	26.7
	Sump, 30m	12.1	8.78	16.8	28.2	20.3	38
	Sump, 2h	13.1	9.39	18	35.4	26.5	47.3
	Sump, 4h	10.5	7.38	14.8	32.8	24.2	44.6
	Sump, 8h	10.6	7.88	14.1	25.3	19.5	32.3
	Batch, 30m	30.8	21.2	45.4	19.9	14.4	27.6
	Batch, 2h	35.1	23.9	51.7	17.7	12.8	24.2
	Batch, 4h	24.1	15.6	36.3	12.6	8.8	18
	Batch, 8h	20.4	14.2	29	12.3	9	16.6
$\log(\beta_j)$	Log(wind speed)	0.0907	-0.248	0.423	0.449	0.179	0.708
	Log(vessels + 1)	-0.173	-0.325	-0.0181	-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


(a) Large, water (b) Large, air (c) Large, total

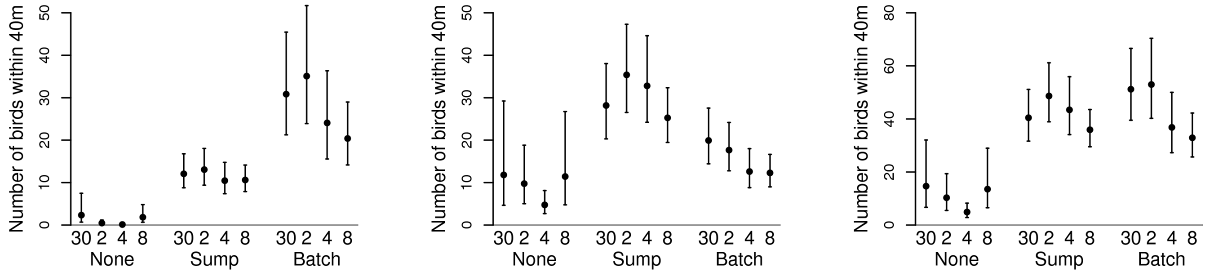

(d) Small, water (e) Small, air (f) Small, total

Figure 13: Median and 95% credible intervals for the model predicted asymptotic bird counts, β_{de}, for each combination of discharge and experimental treatment

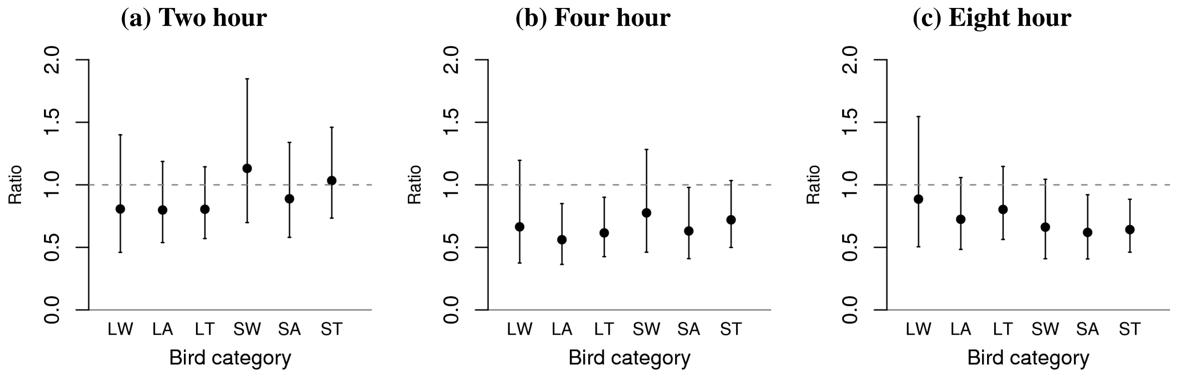


Figure 14: Ratio of bird counts to the corresponding counts during the thirty minute treatment during (a) the two hour treatment (b) the four hour treatment and (c) the eight hour treatment. The ratio is calculated from the model estimated asymptotic counts during batch discharge, $\beta_{\text{batch, treatment}}/\beta_{\text{batch, 30m}}$. 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).

from none, to sump water, to batch discharge. When there is no discharge the mean count is very low, less than one or two birds on the water within the sweep zone. For both large and small birds, the number of birds in the air increases when there is sump water discharge, compared to when there is no discharge. When there is discharge of sump water only, there are more birds in the air than on the water. 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. The total number of large birds is higher during batch discharge than sump discharge, but the total number of small birds is similar when there is sump or batch discharge. These patterns are similar the responses seen in the raw data (Figures 6 and 7).

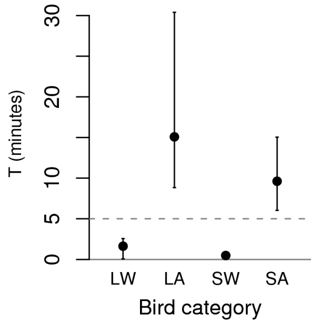


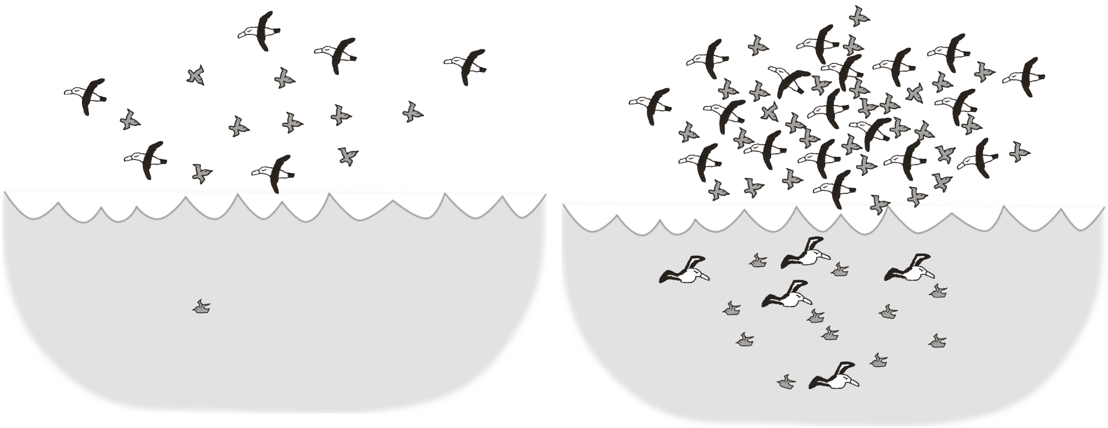
Figure 15: Median and 95% credible intervals for the transition time T, for each of the modelled bird count categories (LW = Large birds on water, LA = Large birds in air, SW = Small birds in water, SA = Small birds in air)

The initial motivation for this work was the idea that bird numbers during discharge events would decrease as the interval between batches increased. The model results are used to test whether this occurs. For each of the two hour, four hour and eight hour treatments, the ratio of the expected number of birds during batch discharge is calculated relative to the thirty minute treatment. The ratio is calculated from the asymptotic counts, $\beta_{\text{batch, treatment}}/\beta_{\text{batch, 30m}}$, for each of the 8,000 samples from the model posterior distributions. The proportional 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 are fewer birds present than during the 30 minute treatment. In all cases, with the exception of small birds on the water and the total number of small birds in the two hour treatment, the median of this ratio is less than one. During the four and eight hour treatments the median of the ratio ranges between 56% and 88%, depending on the bird categories. This supports the initial belief that increasing the batching interval would reduce the numbers of birds close to the stern of the vessel during discharge. The error bars are large, however, and during the two hour treatment the ratio is not significantly lower than one for any of the bird groups. During the four hour treatment, significant reductions occur for large birds in the air, the total number of large birds and small birds in the air. During the eight hour treatment, significant reductions occur for small birds in the air and the total number of small birds. The experiment does not demonstrate a significant reduction in the numbers of either small or large birds on the water for an increased interval between batch discharges.

The model includes a transition time-scale, T, parameterising how quickly the counts return to level associated with sump discharge once the batch discharge finishes. The estimated transition times are shown in Figure 15. For large and small birds, the transition time is faster than the five minute interval that was scheduled between observations. For both bird groups, there is a measurable transition time for changes in the number of birds in the air, of approximately 10 to 15 minutes. The estimated transition time is consistent with the raw data (Figure 8), which shows that after discharge events the numbers of birds on the water fall rapidly, but the number of birds in the air recovers more slowly.

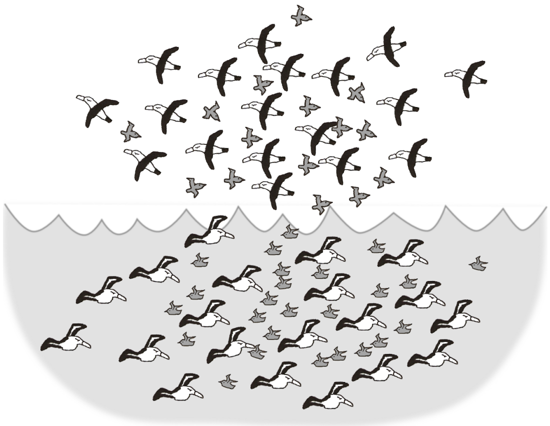
4. DISCUSSION

The experiment demonstrates a clear relationship between discharge and the number of birds close to the stern of the vessel. The increase in the total numbers, and the movement of birds from the air to the water, as the discharge increases is illustrated in Figure 16. This dependence of the abundance on the discharge is seen in both the raw data (Figures 6 and 7) and in the model results (Figure 13). The result confirms the importance of factory waste at attracting birds close to the stern of the vessel (Abraham et al., 2009).



(a) No discharge

(b) Sump discharge



(c) Batch discharge

Figure 16: Diagram showing the number of small and large birds in the air and on the water, within the 40m sweep zone. The numbers shown are from the model estimated parameters, β_{de}, given in Table 5, for (a) no discharge, (b) sump discharge, and (c) batch discharge.

The response of birds to changes in the discharge was rapid. Birds quickly moved into the sweep zone when there was discharge, and the number of birds on the water decreased within minutes of the discharge finishing. It took ten to fifteen minutes for the number of birds in the air to recover once the discharge finished. Presumably, this is the time taken for birds to finish feeding and return to the stern of the vessel. Video footage was taken during this trip, but has not yet been analysed. The video could be used to more precisely define the short-time dynamics of the number of birds behind the vessel and to help understand the behaviour behavioural responses associated with the abundance changes.

A key motivation for this work was the idea that increasing the interval between batches of discharge would result in fewer birds being present during discharges. In all categories, the median expected number of birds present during discharge was less when there was a four or eight hour interval between discharges than when there was a thirty minute interval. During the four and eight hour treatments, the best estimate of bird numbers were reduced to between 56% and 89% of the number present when there was a 30 minute interval between batches. Although the relationship between the abundance of birds in the air or on the water and the number of warp fatalities is not well known, it is likely that this reduction in bird numbers would lead to a reduction in the number of warp mortalities. While there is a reduction in the numbers as the batch interval increases, it does not match the reduction in warp strike that is seen when there is no discharge. For example, across all the warp strike observations that have been made in

New Zealand waters, the average large bird strike rate during discharge is 3.22 birds per hour (Abraham & Thompson, 2009b). This reduces to an average rate of 0.02 birds per hour when there is no discharge, less than 1% of the rate that occurs during discharge.

In all categories, the median number of birds decreased between the two hour and the four hour treatment, suggesting that there is a benefit of increasing the batch interval to four hours. The same consistent decrease was not seen between the four hour and eight hour batch intervals, so there does not appear to be any benefit achieved by further increasing the batch interval. On this vessel, the time taken to dump the offal was approximately proportional to the amount of material dumped. It may be that the utility of long batching intervals would be improved if the stored offal could be dumped more quickly, rather than fed through the discharge chute. This would reduce the proportion of time that offal is in the water during fishing, and so reduce the proportion of time when there were increased numbers of birds behind the vessel.

During this trip, the median tow duration was 6 hours, the maximum duration was 9 hours 44 minutes, and over 94% of the tows were less than 8 hours long. When the meal plant was in use, the container used for batching was generally able to hold material through an entire tow. Batching could be used to store waste until the end of the tow, and discharge it when the vessel is not fishing. There could then be no interaction between the birds and the warps during the discharge. Rather than using the batching to reduce the numbers of birds, it could be used to eliminate discharge of offal during fishing. The numbers of birds would then be reduced to the much lower number that are attracted to the sump discharge, and the warp interactions would be expected to be comparably reduced.

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