Estimation of fur seal bycatch in New Zealand trawl fisheries, 2002–03 to 2007–08

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EXECUTIVE SUMMARY

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New Zealand fur seals (*Arctocephalus forsteri*) have been caught in commercial trawl fisheries operating around New Zealand's EEZ. Ministry of Fisheries observers recorded 141 fur seal captures in trawl fisheries in 2007–08, and 72 in 2006–07. Fur seals were the most frequently observed non-fish bycatch species in 2007–08. Captures have been reported from trawlers operating throughout New Zealand's EEZ, with the exception of the north and east coasts of the North Island. Most captures have been observed in the hoki fishery, with 57 fur seals being observed caught in 2007–08. In contrast, few captures were reported from deepwater or scampi fisheries.

A Bayesian generalised linear model was developed using the observed trawl effort. The model was fitted to data from six fishing years, 1 October 2002 to 30 September 2008. The model was then used to estimate fur seal captures on unobserved tows. Trawl effort from the north and east of the North Island, and from the eastern end of the Chatham Rise, was excluded because there were no observed fur seal captures in those areas. Trawl effort from tows targeting inshore species was also excluded as observer coverage in inshore fisheries was very low, and no fur seals were observed caught. The model included covariates for fishing area, target species, day of the year, and distance to the shore. These covariates, which have been identified in previous work, were selected because they explained much of the variation in the capture rate.

In 2007–08, an estimated 714 (95% c.i.: 465 to 1130) fur seals were caught in trawl fisheries (with trawl fishing targeting inshore species not being included). The estimated capture rate was 1.55 (95% c.i.: 0.99 to 2.50) fur seals per 100 tows. The estimated capture rate for 2007–08 was contained within the confidence intervals of estimated rates for each of the six years, and there was no evidence of a trend in the fur seal capture rate. In 2006–07, 488 (95% c.i.: 288 to 826) fur seals were estimated to have been caught, and the capture rate was 0.98 (95% c.i.: 0.59 to 1.63) fur seals per 100 tows.

Fur seal captures followed a strong seasonal pattern, which was seen in all areas and targets. The estimated capture rate peaked to about five times the mean annual rate in the winter months of July, August, and September, and dropped to around one fifth the mean annual rate in the summer months of December, January, and February. The reduced capture rates in the summer coincided with the fur seal breeding season. Previous work identified the light condition as important, with more fur seals caught in the dark. It was found, however, that once a day of year effect was included, there was little evidence of a light condition effect. Distance to shore was also related to the fur seal capture rate. The capture rate was reduced when the fishing was more than 90 km from shore.

1. INTRODUCTION

Direct interactions between marine mammals and fisheries occur world-wide (Read et al. 2006, Lyle & Wilcox 2008). For many cetacean and pinniped species these interactions are frequently fatal and pose a significant threat to local populations (Lyle & Wilcox 2008). Globally, the annual bycatch of marine mammals is estimated to be more than 600 000 animals, about 53% of which are pinnipeds and 47% are cetaceans (Read et al. 2006).

In New Zealand, the marine mammal most frequently caught as bycatch in commercial fisheries is the New Zealand fur seal (*Arctocephalus forsteri*). The New Zealand fur seal occurs around most of the New Zealand coastline, its offshore islands, and southern Australia. Fur seals were an important source of food for early Polynesian settlers, and mainland populations were severely reduced by the time European settlers arrived in the late 1700s. European sealers further decimated populations on mainland New Zealand and its offshore islands (Lalas 2007). New Zealand fur seals were given partial protection in 1894, and in 1978 they were given total protection under the New Zealand Marine Mammals Protection Act. The size and dynamics of the current New Zealand population are poorly known and up-to-date counts and estimates are needed for many parts of New Zealand. The most recent census of New Zealand fur seals was in 1973, when the population was thought to be between 30 000 and 50 000. The consensus is that the population has increased since then (Lalas & Bradshaw 2001).

While gillnet fishing is responsible for most marine mammal bycatch globally (Read et al. 2006), New Zealand fur seals are predominantly caught in trawl fisheries, with smaller numbers of observed captures reported in surface longline fisheries (Abraham & Thompson 2009, Abraham et al. 2010). In the 2007–08 fishing year, the Ministry of Fisheries observer programme, charged with monitoring bycatch during commercial fishing operations, recorded 141 fur seal captures in trawl fisheries. Of these observed captures, 41% were in the hoki trawl fishery, 20% in the hake trawl fishery, and 17% in the southern blue whiting trawl fishery. Typically, fur seals caught in trawl nets are retrieved dead (77% of fur seals caught in trawl fisheries in the 2007–08 fishing year were reported by the observer as dead). In 2007–08, 10 fur seals were observed caught in surface longline fisheries, of which 9 were released alive. On rare occasions, fur seal captures are observed in bottom longline fisheries: there were 4 observed captures in the 10 year period 1998–99 to 2007–08, with no observed captures in 2006–07 or 2007–08.

In fisheries where there has been sufficient observer coverage, the observed fur seal capture data provides a basis for estimating bycatch on the unobserved portion of those fisheries. Previous authors have applied ratio estimation methods to estimate fur seal captures in trawl, surface longline and bottom longline fisheries in New Zealand's Exclusive Economic Zone (EEZ) for the fishing years 1990–91 to 1995–96 and 1998–99 to 2006–07 (Manly et al. 2002, Baird 2005a, 2005b, 2005c, Abraham & Thompson 2009, Abraham et al. 2010). The ratio estimation method has some limitations, however: it is reliable only when applied to fisheries in which there has been representative observer coverage, and it may be biased if the observer coverage is non-random with respect to factors that determine the rate at which fur seals are caught.

Recently, Smith & Baird (2009) used Bayesian models to estimate total fur seal captures and strike rates for the period 1994–95 to 2005–06 in five pre-defined areas within the EEZ (all south of 40°). The Bayesian modelling techniques permit estimations to be made on the total effort, and can be used to evaluate the influence of covariates, such as time of day or tow duration, on capture probabilities. They are also expected to give more reliable estimates of the uncertainties. Smith & Baird (2009) considered the covariates that might influence the likelihood of fur seal captures. Overall, the factors that consistently explained some of the fur seal captures for all of New Zealand were time of day and time of year. They found that fur seals were more likely to be caught during hours of low light (dawn, dusk, and nighttime) and during certain times of the year, most likely related to breeding seasons. Fur seals were less likely to be caught from January to March, possibly because they were feeding close to the rookeries, and more likely to be caught from July to September, possibly due to the weaning of pups and adults venturing further afield to forage. The findings of Smith & Baird (2009) were broadly similar to those of earlier studies by Manly et al. (2002), and Mormede et al. (2008), who also found that time of day, area, and day of year were correlated with likelihood of fur seal capture.

The intention of this report is to provide model-based estimates of the number of New Zealand fur seals caught as bycatch in New Zealand commercial trawl fisheries for each fishing year between 2002–03 to 2007–08. The methods used here build upon those already developed by Smith & Baird (2009) for estimating annual fur seal bycatch. The most significant difference in methodology is that we have used one model for the whole of New Zealand's EEZ, rather than modelling selected subregions. This work was completed as part of Ministry of Fisheries project PRO2007/02, which has the overall objective of describing the nature and extent of marine mammal captures in New Zealand commercial fisheries. The specific objective of the project was to estimate the total numbers, releases, and deaths of selected marine mammals, where possible by species, fishery, and fishing method, caught in commercial fisheries for the fishing years 2006–07, 2007–08, and 2008–09. Other reports have focussed on estimating the capture of sea lions (Thompson & Abraham 2009b) and dolphins (Thompson & Abraham 2009a), with the capture of all marine mammals being reported by Abraham & Thompson (2009) and Abraham et al. (2010). The data summaries (Abraham & Thompson 2009, Abraham et al. 2010) also included estimates of the number of fur seals captured in surface longline fisheries. Estimated captures of fur seals in the trawl fisheries during the 2008–09 fishing year will be presented in a subsequent report.

2. METHODS

2.1 Data sources and preparation

Commercial trawl vessels return a record of all fishing effort to the Ministry of Fisheries. Skippers complete either a Trawl Catch Effort Processing Return (TCEPR), a Trawl Catch Effort Return (TCER), or a Catch Effort Landing Return (CELR). Data from these forms are stored in databases administered by the Ministry of Fisheries (Ministry of Fisheries 2008). Information entered on these forms by the fisher includes date, time, location, target species, tow duration, and vessel size. This information is available from the *warehou* database.

Ministry of Fisheries observers on commercial fishing vessels record captures of protected species, including New Zealand fur seals. The capture events are recorded on paper forms by the observers and entered into a database maintained by the National Institute of Water and Atmospheric Research (NIWA) on behalf of the Ministry of Fisheries. Currently, data are housed in the Centralised Observer Database (COD).

Extracts from the *warehou* and COD databases were obtained, including all trawl effort within the outer boundary of New Zealand's Exclusive Economic Zone, spanning the period from 1 October 2002 to 30 September 2008. In New Zealand, the fishing year runs from 1 October to 30 September in the following year, so the data extract covered the period from the 2002–03 to the 2007–08 fishing years. A summary of the capture of all seabird and marine mammal species in this dataset, and for the period 1998–99 to 2001–02, was given by Abraham et al. (2010). The observer records were linked to corresponding fisher reported effort, using the same rules described by Thompson & Abraham (2009b). Model covariates were derived using fisher reported data from the linked records. This ensured consistency between the data used for building the model, and the data used for making the estimation.

During the 2007–08 fishing year, inshore trawl fisheries moved to reporting fishing effort on TCER forms, rather than CELR forms. The TCER form records the latitude and longitude of fishing effort, whereas the CELR forms gave only the statistical area. Consequently, in recent years there has been more accurate information available on where inshore fishing is occurring. In order to allow the modelling to include covariates that depended on information not available on CELR forms (latitude, longitude, and time of day), the missing data were either obtained from the observer record, if possible, or it was imputed. Imputed values were sampled at random from more recent fishing effort by the same vessel, in the same statistical area, targeting the same species, that had been reported on the TCER form. Imputation derived information was used for 16% of tows, most of which were targeting inshore species.

Fur seal captures have not been observed to the north or east of the North Island, or in the waters around the Chatham Islands. Trawl effort in these areas was excluded, under the assumption that there were not any captures in the unobserved effort in these regions. Inshore trawl fisheries accounted for more than 50% of the total trawl effort, when measured by number of tows. Coverage of inshore fisheries was very low, at 0.5% of tows or less, and no fur seals were observed caught in inshore trawl fisheries. Inshore trawl effort was excluded from the modelling and from the estimates, as it was expected that the characteristics of inshore trawl fisheries were different from the offshore fisheries. In order to determine how sensitive estimates of total captures were to excluding this effort, some estimation of captures by inshore trawl fisheries was made under the assumption that they have a similar catch rate to trawl effort targeting middle depths species. When making this extrapolation, effort targeting flatfish species was excluded, so no estimates have been made of fur seal captures in flatfish fisheries. This allowed comparison with Smith & Baird (2009) who also provided estimates of fur seal captures in trawl fisheries targeting all species, other than flatfish.

Bayesian modelling is computationally expensive, and there were more observed trawl events than could be easily fitted by the model using an MCMC approach. Trawl events were aggregated together to reduce the computational load. While grouping the data reduced the fidelity of some covariates, it allows trawl data from the whole of New Zealand's EEZ to be fitted simultaneously. The grouping followed methods similar to those used by Manly et al. (2002). Tow groups were defined as trawls by the same vessel, in the same statistical area, targeting the same species, observed or not, occurring within five days of each other, and with no more than than 20 tows being included in each group. Tows within a group were consecutive. Covariates were calculated for each group, by aggregating the value for each trawl event in an appropriate way. The grouping had the additional advantage that it reduced the correlation between fur seal captures on subsequent data points.

2.2 Covariate exploration

A range of potential covariates was explored to determine whether there was a relationship between the covariates and the fur seal captures. Potential covariates included those identified by Smith & Baird (2009) and Mormede et al. (2008), aggregated appropriately to the grouped data. Covariates were restricted to quantities that could be defined from the fisher reported data. In order to explore the functional form of the relationship between each covariate and observed New Zealand fur seal captures, generalised additive models (GAMs) were fitted to the capture data (Wood 2004). The GAMs identified the semi-parametric splines that best described the relationship between the covariate and the seal captures. Fixed target species and fishing area effects were included in each of the GAM models to control for the influence of these factors on the fur seal capture rate. A negative binomial error relationship was used for the GAMs, with a logarithmic link function being used, as this is appropriate to count data (Hilbe 2007).

Having selected plausible covariates following an exploratory phase, a step analysis was performed to narrow the list of covariates explored in the full Bayesian models (Venables & Ripley 2002). Negative binomial general linear models were fitted using maximum likelihood methods, with covariates tried in turn. The covariate that reduced the AIC (Akaike 1974) the most at each stage was retained, and the process repeated. In this way, the covariates were ranked according to their explanatory power. From the step analysis, four candidate models were selected. Full Bayesian modelling was carried out on each candidate model, with the final model being selected by minimising the Deviance Information Criterion (DIC), as described by Gelman et al. (2004). The DIC was calculated as the sum of the deviance and an estimate of the effective number of parameters, derived from the variance of the MCMC samples of the deviance. The two step selection process was used, as full model selection within the Bayesian framework was computationally prohibitive.

2.3 Model structure

Captures, y_i, in a trawl group, i, were modelled as samples from a negative-binomial distribution:

$$y_i \sim \text{NegativeBinomial}(\text{mean} = \mu_i n_i, \text{shape} = \theta n_i), \tag{1}$$

where n_i is the number of tows in a trawl group. The shape parameter, θ, allows for extra dispersion in the number of captures, relative to a Poisson distribution. The shape was assumed to be the same for all trawl groups. The negative-binomial distribution has the property that the mean of n samples from a negative-binomial distribution (NegativeBinomial(μ, θ)) is itself negative-binomially distributed, with mean μn and shape θn. For this reason, while y_i is the number of captures per group, μ_i should be interpreted as the mean strike rate per tow.

The mean capture rate within each group was estimated as the product of a random year effect λ_{y_i}, a random vessel-year effect $\nu_{v_i y_i}$, and the exponential of a sum over covariates,

$$\begin{aligned}
\mu_i &= \lambda_{y_i} \nu_{v_i y_i} \exp\left(\sum_c \beta_c x_i^c\right) && (2)\\
\log(\lambda_{y_i}) &\sim \text{Normal}(\mu = \mu_\lambda,\ \sigma = \sigma_\lambda) && (3)\\
\nu_{v_i y_i} &\sim \text{Gamma}(\text{shape} = \theta_\nu,\ \text{rate} = \theta_\nu) && (4)
\end{aligned}$$

The random year effect λ_{y_i} on each tow was drawn from a log normal distribution with mean μ_λ and standard deviation σ_λ. The random vessel-year effect $\nu_{v_i y_i}$ for each observed vessel v_i and year y_i was included to account for the variation between vessels, and was drawn from a gamma distribution with shape and rate θ_ν. With this parameterisation, the gamma distribution has unit mean. The coefficient of a covariate c was denoted β_c, while the value of the covariate at tow i was denoted x_i^c.

Standard priors were used for the model (hyper-)parameters (e.g., Gelman et al. 2006). Diffuse normal priors were used for the covariate coefficients and for the logarithm of the mean year effect, μ_λ. The shape hyper-parameters were given uniform shrinkage priors, with the size parameter for the overdispersion equal to the mean number of captures, and the size parameter for the vessel-year effect equal to the mean number of captures per vessel:

$$\begin{aligned}
\log(\mu_\lambda) &\sim \text{Mean}(\mu = \bar{y}_i, \sigma = 100) && (5)\\
\sigma_\lambda &\sim \text{Half-Cauchy}(25) && (6)\\
\theta &\sim \text{Uniform-shrinkage}(\bar{y}_i) && (7)\\
\theta_\nu &\sim \text{Uniform-shrinkage}(\bar{y_{v_i}}) && (8)\\
\beta_c &\sim \text{Normal}(\mu = 0, \sigma = 100) && (9)
\end{aligned}$$

The models were coded in the BUGS language (Spiegelhalter et al. 2003), a domain specific language for describing Bayesian models. The model was fitted with the software package JAGS (Plummer 2005), using Markov chain Monte Carlo (MCMC) methods. To ensure that the model had converged, a burn-in of 10 000 iterations was made. From there, the model was run for another 100 000 iterations and every 20th iteration was kept. Two chains were fitted to the model, and the output included 5000 samples of the posterior distribution from each chain. Model convergence was checked using diagnostics provided by the CODA package for the R statistical system (Plummer et al. 2006). To test whether the model produced a suitable representation of the data, simulations of observed captures were made using randomly chosen samples from the Markov chains and visually compared with the actual observed captures (Gelman et al. 2006). Randomised quantile-quantile plots were used to compare the estimated captures on the observed tows with actual observed captures (Dunn & Smyth 1996). By calculating the quantile residuals for each sample from the chain, a distribution of residuals could be obtained. All uncertainties were calculated as the 95% percentiles of the posterior distributions, from the MCMC chains.

3. RESULTS

3.1 Data sources

Over the six year period, 159 758 tows were reported on 58 482 CELR forms, 341 662 tows on TCEPR forms, and 28 068 tows were reported on the newer TCER forms (all since 19 June 2006). Grooming of the data corrected the effort number (the number of tows) from 117 CELR forms, and position data were groomed from 59 TCER forms. Observer data sourced from the COD database did not require any grooming. Over 99% of all observed trawl events were linked to the fisher reported effort. There were 23 fur seal captures on observed tows that could not be linked to fisher reported effort. In 2007–08, 1 fur seal capture could not be linked, but in 2006–07 there were 11 captures that could not be associated with fisher reported effort. These captures were not included in the analysis. A summary of the model dataset is shown in Table 1. Grouping the tows reduced the dataset to around a sixth of its initial size, with a similar reduction in all years and in both observed and non-observed data.

Table 1: A summary of the model dataset. The columns are the number of tows, number of groups, and the number of groups as a percentage of the number of tows, for all fishing effort and the observed effort. Fur seal captures are also shown, both as a total and as a number of captures per 100 tows. All trawl effort from the 10 selected areas is shown, excluding tows targeting inshore species. Fur seal captures that could not be linked to fisher reported effort are not included.

	Effort			Observed			Fur seal captures	
	Tows	Groups	%	Tows	Groups	%	Number	Rate %
2007–08	31 977	6 106	19.1	7 021	1 168	16.6	140	1.99
2006–07	35 486	6 423	18.1	6 251	1 030	16.5	61	0.98
2005–06	38 887	6 635	17.1	5 539	819	14.8	143	2.58
2004–05	44 324	7 501	16.9	6 563	905	13.8	191	2.91
2003–04	48 379	8 147	16.8	5 679	737	13.0	83	1.46
2002–03	56 298	9 502	16.9	5 774	955	16.5	67	1.16
Total	255 351	44 314	17.4	36 827	5 614	15.2	685	1.86

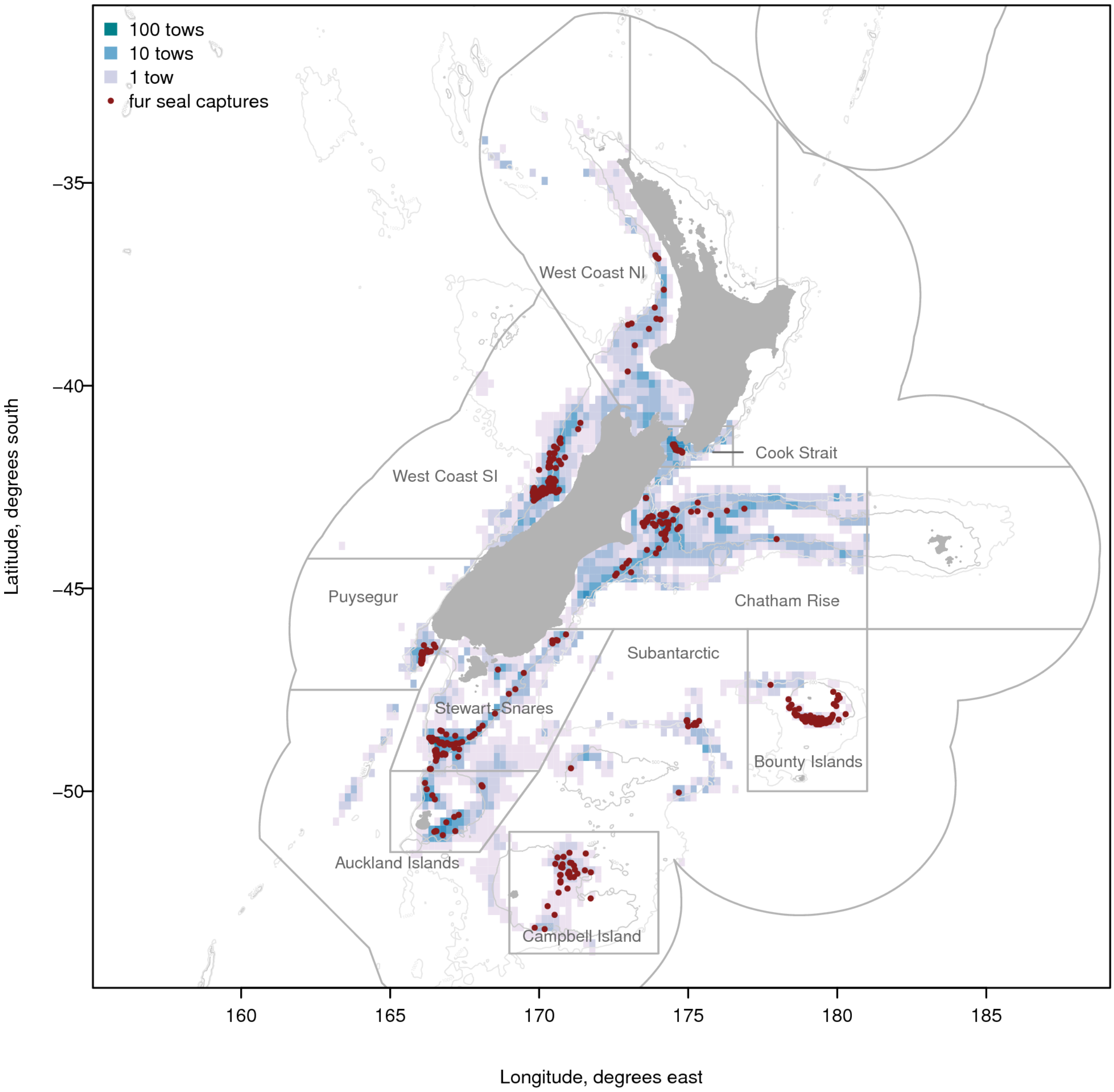


Figure 1: Map of trawl effort and fur seal captures from the model dataset, for the period 1 October 2002 to 30 September 2008. The colours of the heatmap indicate the average annual trawl effort within 0.2° × 0.2° squares. The 10 defined subareas are indicated, the areas without names are not included in models or tabulated results.

3.2 Potential covariates

3.2.1 Areas

New Zealand fur seals were caught in trawl fisheries on the west coast of both North and South Islands, on the east coast south of Wairarapa, and around the subantarctic islands. In Figures 1 and 2, observed captures are plotted for the six years of data included in the model. The New Zealand region was divided into the areas shown on the maps. These areas are similar to those defined in previous work (Abraham & Thompson 2009, Abraham et al. 2010), with a few exceptions. The Chatham Rise was split into western and eastern parts, the Bounty Islands and Campbell Island areas were split off the surrounding subantarctic area, and the Cook Strait and Auckland Islands areas were increased, to give coverage of the areas where fur seals are caught. Fishing effort on the north and east sides of the North Island, and from around the Chatham Islands, were excluded from the analysis as no fur seal captures were reported

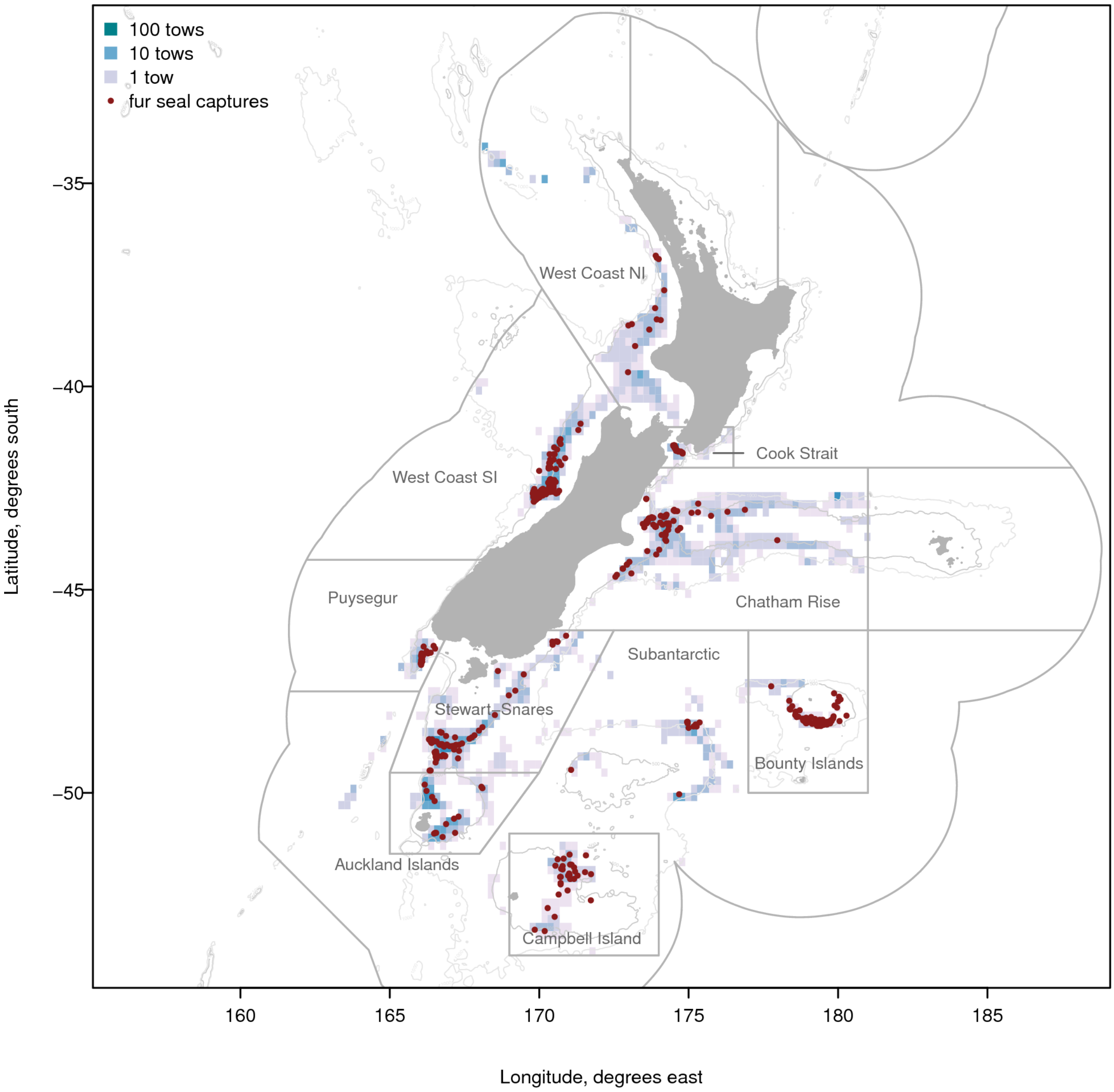


Figure 2: Map of observed tows and fur seal captures from the model dataset, for the period 1 October 2002 to 30 September 2008. The colours of the heatmap indicate the annual average number of observed tows within 0.2° × 0.2° squares.

in these areas in the six year period. Note that one fur seal was observed caught off the west coast of the Chatham Islands in May 2002, before the period reported here, by a trawler targeting jack mackerel.

The fishing effort, observer coverage, and observed captures for these areas are presented in Table 2. The capture rate varied considerably, with a capture rate of over 15 animals per 100 tows in the Bounty Islands area. The area with the next highest capture rate was Cook Strait, with an observed capture rate of 9.1 animals per 100 tows. This figure was based on low observer coverage of 3.5%. Of all observed captures, 30% occurred on the west coast of the South Island, with an observed capture rate of 3.3 fur seals per 100 tows.

Table 2: Summary of the model dataset by area. The columns show the trawl effort, observed trawl effort, observer coverage (%), observed fur seal captures, and observed fur seal capture rate (captures per 100 tows). The table includes all effort for the period 1 October 2002 to 30 September 2008, and is sorted in decreasing order of the capture rate.

	Effort	Observed tows		Observed fur seals	
	Tows	Tows	Coverage %	Captures	Rate
Bounty Islands	2 101	695	33.1	110	15.83
Cook Strait	24 598	867	3.5	79	9.11
Puysegur	5 650	762	13.5	31	4.07
West coast South Island	43 909	6 609	15.1	217	3.28
Campbell Island	4 030	1 354	33.6	42	3.10
Western Chatham Rise	74 580	6 853	9.2	86	1.25
Stewart-Snares	43 642	8 222	18.8	77	0.94
Other subantarctic islands	10 344	2 747	26.6	14	0.51
West coast North Island	23 295	3 965	17.0	13	0.33
Auckland Islands	23 240	4 753	20.5	14	0.29

Table 3: Summary of the model dataset by target species. The columns show the trawl effort, observed trawl effort, observer coverage (%), observed fur seal captures, and observed fur seal capture rate (captures per 100 tows). The table includes all effort for the period 1 October 2002 to 30 September 2008, and is sorted in decreasing order of the capture rate.

	Effort	Observed tows		Fur seals	
	Tows	Tows	Coverage	Captures	Rate %
Southern blue whiting	4 318	1 615	37.4	143	8.85
Middle depth species	56 286	3 521	6.3	101	2.87
Hoki	92 357	11 954	12.9	339	2.84
Jack mackerel	16 104	3 348	20.8	23	0.69
Squid	45 921	9 390	20.4	59	0.63
Deepwater species	23 116	5 414	23.4	14	0.26
Scampi	17 400	1 585	9.1	4	0.25

3.2.2 Target species

Target species were grouped to simplify the analysis, as reported by Abraham & Thompson (2009) and Abraham et al. (2010). Tows targeting hake and ling were further grouped with the middle depth targets. The effort and observations, by target species group, are shown in Table 3. The fur seal capture rate was over 8 captures per 100 tows for tows targeting southern blue whiting (Table 3). This was largely due to the high rates observed near the Bounty Islands, where southern blue whiting was the main target. Hoki and other middle depth species had observed capture rates of close to 2.5 captures per 100 tows.

3.2.3 Distance to shore

Distance to shore was identified in previous work as being correlated with fur seal captures in some areas (Mormede et al. 2008, Smith & Baird 2009). Distance to shore was calculated using functions from PostGIS (available from http://postgis.refractions.net), with the New Zealand coastline being obtained from the GSHHS database (Wessel & Smith 1996). Islands with an area of less than 25 hectares were excluded when calculating the distance to shore. In Figure 3(a) the distance to shore distribution of observer and fisher reported effort is compared. Observed effort was representative of all effort. The number of fishing events peaked between 40 km and 60 km from the shore, and the highest number of observed fur seal captures occurred in this range. Figure 3(b) shows the relationship been distance to shore and the fur seal capture rate, obtained from fitting a GAM. Target and area effects were accounted for in this fit. The relationship was positive between 25 km and 90 km, and errors were small. There was a reduction in fur seal capture rates until about 200 km from shore, beyond which there is no further consistent decrease in the capture rate. Before inclusion in the Bayesian model, distance to shore was converted into a four level factor. The chosen levels were closer than 25 km to shore, between 25 km and 90 km, between 90 km and 180 km, and further than 180 km. These distances are marked on Figure 3(b), and are shown in Figure 4.

(a) Distance to shore distribution

(b) Distance to shore effect

Figure 3: Relationship between fur seal captures and distance to shore. (a) The distributions of distance to shore for observed tows and all tows. The number of observed captures in each level on the distribution plots is displayed above the bars. (b) The relationship between seal capture rate and distance to shore derived from fitting a GAM. Target and area factors were also included in the GAM.

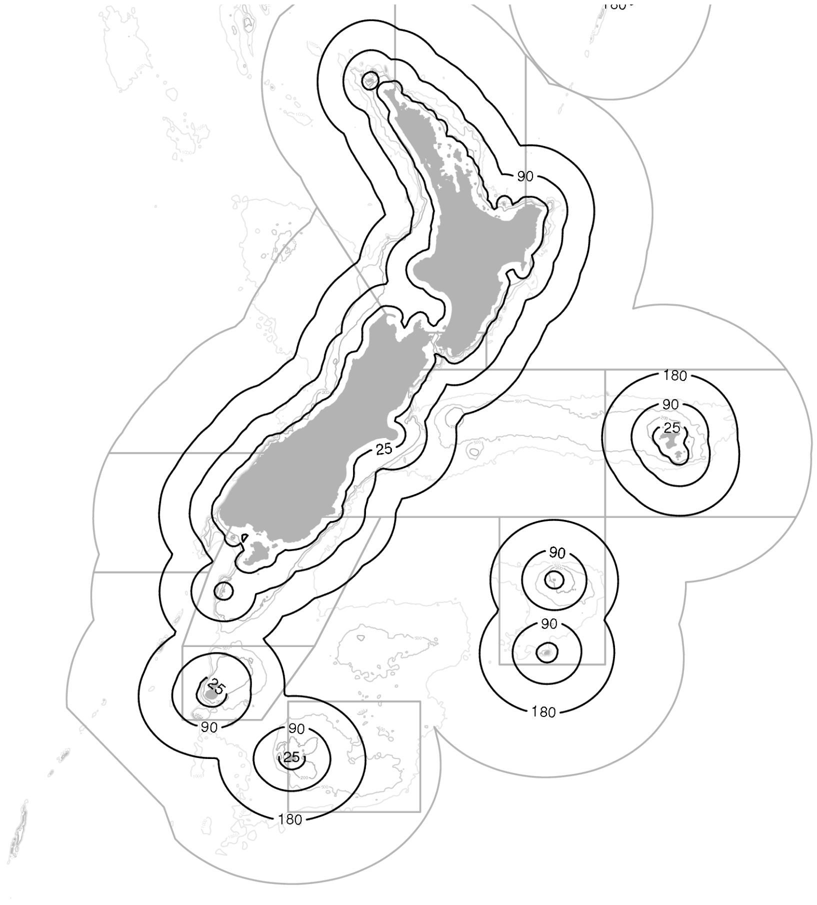


Figure 4: Map of the distance to shore factors. New Zealand's EEZ is divided into four regions according to the distance from shore: coastal ($\leq$ 25 km), near (25 to 90 km), far (90 to 180 km), and ocean ($>$ 180km).

3.2.4 Other covariates

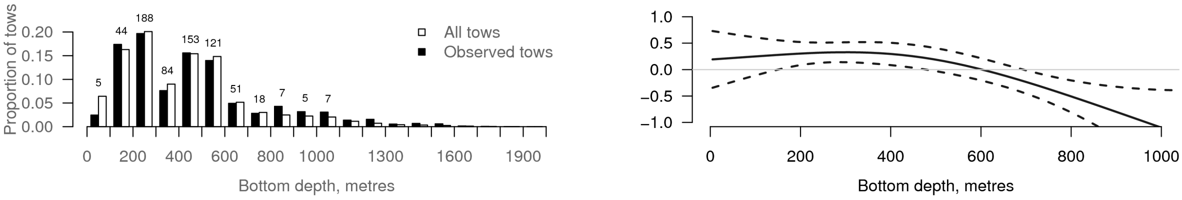
A range of other covariates was explored for a potential association with fur seal capture rates. These included bottom depth, tow duration, time of day effects, and day of year. In Figure 5 a selection of these covariates is shown. Definitions of all covariates taken through to the step analysis are given in Table 4. In general, the distributions of the covariates on observed tows were similar to the distribution on all tows. With respect to these variables, the observations appeared to be representative.

There was not a strong relationship between bottom depth and the fur seal capture rate in the depth range (0 to 1000 m) where most of the observations were concentrated (Figure 5a, b), although the fur seal capture rate appeared to decrease beyond 600 m depth. Tow duration was picked as a covariate for three of the six models by Smith & Baird (2009). A priori, it might be expected that more fur seals would be caught on longer tows. There was no evidence of this from the GAM fit (Figure 5d). In Figure 5(e, f) the proportion of tows within a group that started in the daytime is shown. For approximately one-third of groups, all tows within the group started during the day. There was a clear negative association with fur seal captures: the fur seal capture rate was lower for groups that had a higher proportion of tows starting during the day.

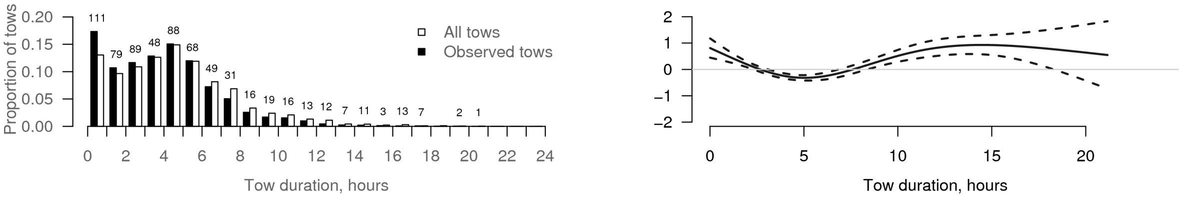
Although observations and effort were approximately evenly distributed through the year Figure 5(g), there was a clear relationship between season (time of year) and the fur seal capture rate. The seasonal effect is shown in Figure 5(h), with a peak in the winter months of July and August. A harmonic function of the day of year (the sum of a sine and a cosine term, both with annual periods) was also fitted to the fur capture data, and had a similar form to the GAM fit Figure 5(h). Three of the six models by Smith & Baird (2009) included a day of year effect, a sine and cosine with annual periods were included in the step analysis.

Another way of including light condition variable was the mean number of hours trawled at night. Over 60% of trawl groups had an average of less than 1 hour of fishing during the night, and there was no clear association between the average number of hours fished at night and the fur seal capture rate Figure 5(i, j).

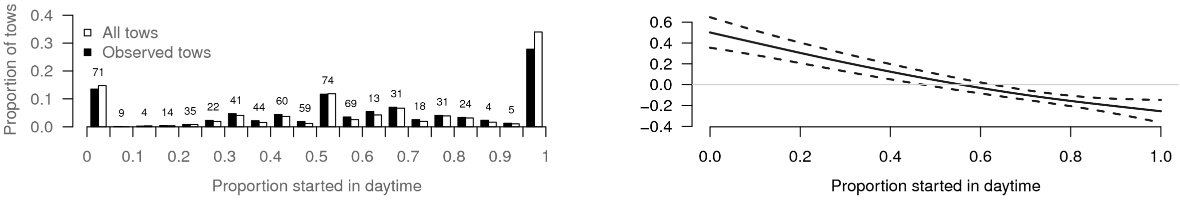
(a) Bottom depth distribution **(b) Bottom depth effect**



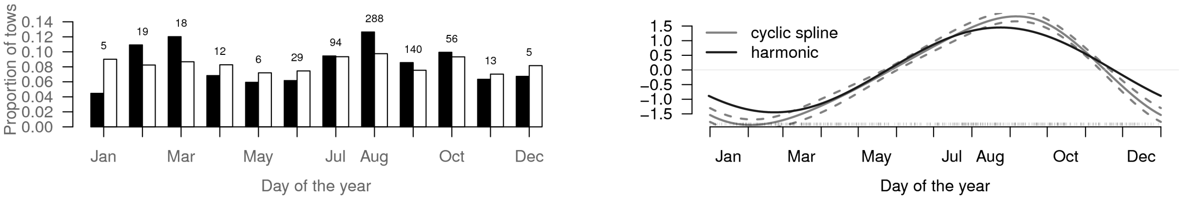
(c) Tow duration distribution **(d) Tow duration effect**



(e) Daytime at start distribution **(f) Daytime at start effect**



(g) Day of year distribution **(h) Day of year effect**



(i) Night hours distribution **(j) Night hours effect**

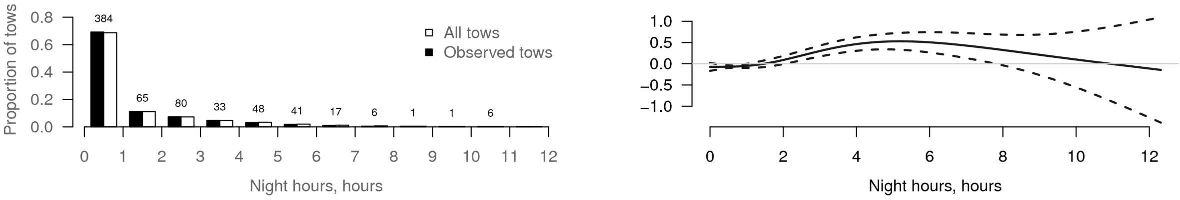


Figure 5: Detailed plots of various continuous covariates. On the left are distributions comparing observer and fisher reported effort. The number of observed captures in each level on the distribution plots is displayed above the bars. On the right are plots of the effect of covariates on the fur seal capture rate, derived from fitting GAMs. Note that target and area effects were included in the GAM structures.

Table 4: Covariates included in the step analysis

Fishing area	New Zealand's EEZ was divided into 13 fishing areas, corresponding to areas used in previous analysis and presented in Figure 1. The 10 areas where fur seal captures have been observed were included in the model data set.
Target species group	Target species were grouped together. The groups were the same as in (Abraham et al. 2010), with the difference that hake and ling tows were grouped with the middle depth species. The groups used were hoki, southern blue whiting, squid, jack (and blue) mackerel, scampi, middle depth species (ling, hake, barracouta, ribaldo, rubyfish, alfonsino, bluenose, frostfish, ghost shark, gemfish, spiny dogfish, sea perch, and warehou), deep water species (orange roughy, oreos, and cardinalfish). All inshore target species, excluding flatfish (9 species), were reported together as inshore trawl and included 89 species codes. The most frequently caught inshore fish were tarakihi, snapper, red cod, gurnard, trevally, John dory, and giant stargazer.
Tow duration	The mean tow duration of the tows in each group.
Day of year	The day of the year was used to capture any seasonal variation. Calculated from the mean day of the year of the tows in a group. Harmonic functions were used to ensure that the seasonal effects were truly periodic.
Moon illumination	The percentage of the moon illuminated was calculated from the date and location data (Meeus 1991). The average illumination was calculated over all the tows in the group.
Daytime at start (end) of the tow	The proportion of tows in a group that started (ended) in the daytime. Hours of daylight were calculated from civil dawn and dusk (Meeus 1991).
Night hours	Mean number of hours towed in the night-time. Calculated using the latitude, day of year, and start and end times of each tow. Night-time was calculated as between civil dawn and dusk (Meeus 1991).
Nation	The flag of the vessel, with five values: New Zealand, Russia, Korea, Japan, and Other.
Processor type	A three level factor covariate representing the type of processing on board, with values: meal plant, freezer, and fresher.
Gear type	A two level factor covariate describing what kind of gear was used on the tows, with values: bottom or midwater. The most frequently used gear within each group was used.
Vessel size	A four level factor covariate characterising the length of vessels, with values: small ($\leq$ 28 m), mid (between 28 m and 45 m), large (between 45 m and 85 m) and largest ($>$ 85 m).
Catch weight	The mean number of tonnes reported caught on the tows.
Bottom depth	The mean bottom depth calculated from the depth at the start of tows in each group.
Distance from shore	The mean distance from shore of the tows in each group.
Distance factor	A four level factor calculated using the distance from shore: coastal ($\leq$ 25 km), near (between 25 km and 90 km), far (between 90 km and 180 km), and ocean ($>$ 180 km), mapped in Figure 4.

3.3 Step analysis

The results of the step analysis are shown in Table 5. The area factor was identified as having the most explanatory power, accounting for over 24% of the residual deviance, while the target species factor accounted for a further 7% of the deviance. The strength of the area and target factors identified with the step analysis justified their inclusion in the final Bayesian models.

The sine and cosine of the day of year carried a strong seasonal effect, accounting for over 10% of the deviance. When these terms were included in the model, time of day effects were dropped. This is due to a relationship between season and hours of darkness: in the winter a larger proportion of tows start at night than in the summer, when daylight hours are longer.

The Bayesian model carried the mean in a random fishing year effect, and so fishing year was included in all the candidate models. For the purpose of selecting covariates using full Bayesian models, four models were tested. Combinations of the next two covariates from the step analysis, the distance factor and the vessel size, were tried in candidate Bayesian models.

Table 5: Analysis of deviance returned from the model selection algorithm. The columns are respectively the degrees of freedom, deviance, residual degrees of freedom, residual deviance, percentage of deviance explained by the addition of each term, and the AIC.

	Df	Dev.	Resid. Df	Resid. Dev.	% dev.	AIC
Intercept			5673	2216.73		3450.74
Area	9	540.05	5664	1676.68	24.4	3131.14
Target	7	119.65	5657	1557.03	7.1	3058.15
Sine of day of the year	1	84.94	5656	1472.09	5.5	2987.31
Cosine of day of the year	1	77.40	5655	1394.69	5.3	2917.64
Fishing year	5	37.79	5650	1356.90	2.7	2892.99
Distance to shore factor	3	27.71	5647	1329.19	2.0	2871.86
Vessel size	3	13.86	5644	1315.33	1.0	2863.98
Vessel flag	5	14.85	5639	1300.48	1.1	2859.37
Phase of the moon	1	4.64	5638	1295.84	0.4	2856.77
Log of night hours	1	4.59	5637	1291.25	0.4	2854.19
Processor type	2	5.32	5635	1285.93	0.4	2852.87

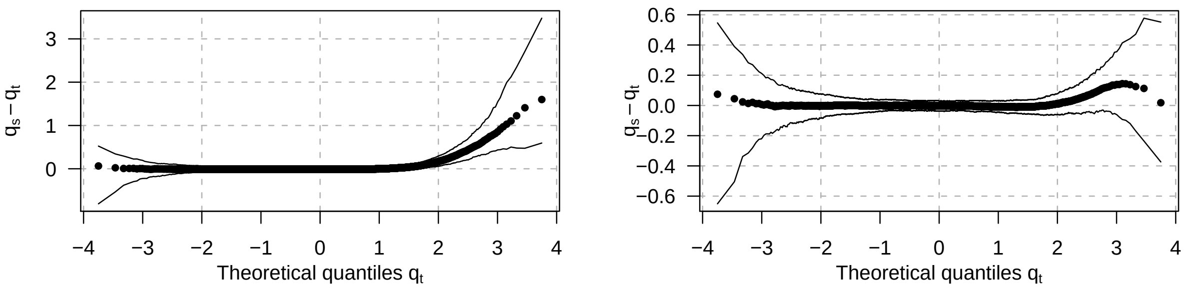
3.4 Model selection

Four models were selected as candidates for the final predictive model. The fishing areas, target species, and day of the year covariates were identified as as being strongly correlated with captures, and were included in all four models. The two covariates, distance to shore and vessel size, were included or dropped. The four models were: doy (day of year); doy and distance to shore; doy and vessel size; and doy, distance to shore, and vessel size.

Various model diagnostics are presented in Table 6. The model with the lowest DIC was chosen as the final model. Note that this model also had the lowest extra-dispersion. Quantile-quantile plots for the four models are presented in Figure 6. These compare the difference between the observed captures and the estimated mean capture rate with the theoretically expected residuals. If the model described the data accurately, the observed distribution of residuals, q_s, would be the same as the distribution predicted by the model q_t, and the difference $q_s - q_t$ would be zero. The model with the area, target species, and day of year covariates only did not account for the large capture events very well, as is visible in the quantile-quantile plot (Figure 6a). The other three models had similar residual distributions.

Table 6: Model diagnostics for the four tested models, the mean deviance, $\bar{D}$, the deviance information criteria, DIC, and the extra dispersion, $1/\theta$. The terms in the best model are in bold.

Model	$\bar{D}$	DIC	$1/\theta$	
			Median	95% c.i.
doy and size	2065	3487	13.60	9.82 - 18.35
doy, distance, and size	2060	3491	13.60	9.87 - 18.69
doy	2067	3505	13.43	9.59 - 18.23
doy and distance	2064	3476	13.34	9.60 - 18.08



(a) doy

(b) doy and size

(c) doy and distance

(d) doy, distance, and size

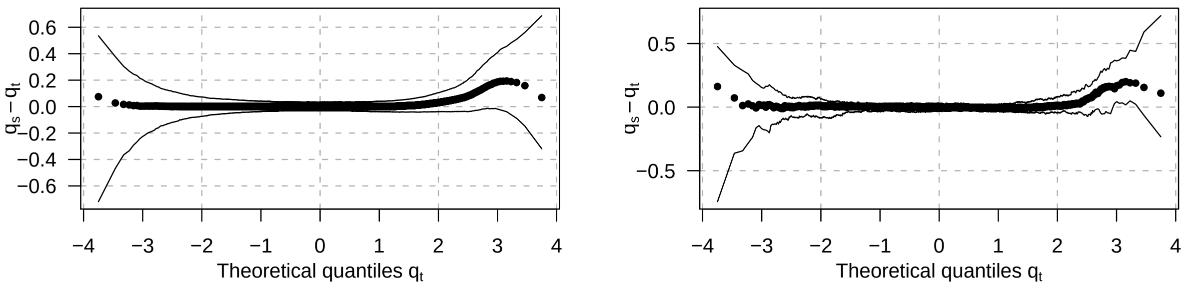


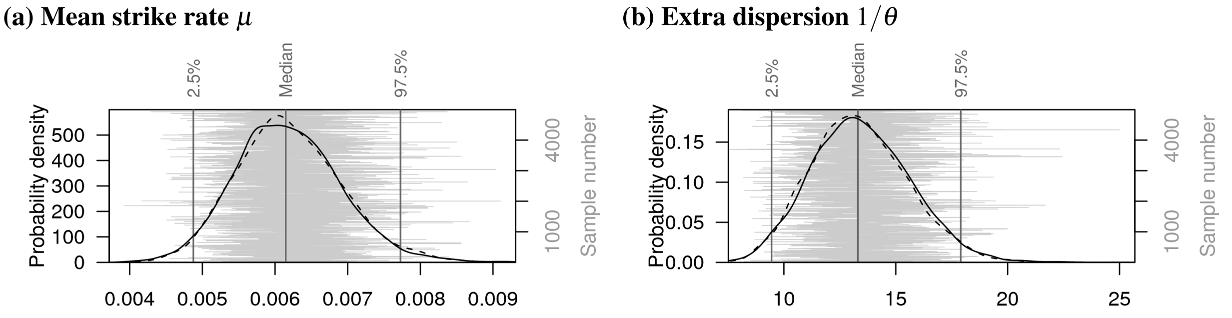
Figure 6: Quantile-quantile plots for each of the four Bayesian models.

3.5 Model diagnostics

The model with day of year and distance from shore terms was selected as the final model used for estimating fur seal captures. The posterior distributions of the parameters of the negative binomial distribution are presented in Figure 7. The chains converged well, and showed good mixing. Note that $\mu/\theta << 1$, and so the fur seal captures were close to being Poisson distributed.

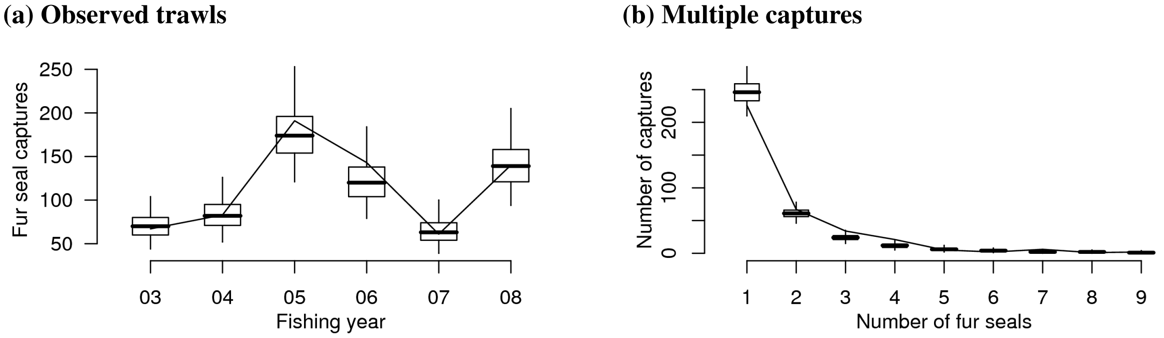
As a check, the fitted model was used to estimate the captures on the observed tows. The total annual observed captures are compared with estimated annual captures on the observed tows in Figure 8(a). The observed captures all fell within the 50% confidence interval, with the exception of 2005–06, where the observed captures were slightly higher. In Figure 8(b) the observed distribution of the number of captures in each trawl group is compared with the estimated distribution, giving a measure of how successfully the negative-binomial model fitted the data. The distribution of observed captures was consistent with the estimates.

The model was checked by comparing maps of simulated captures on observed tows (Figure 9c, d), with the observed captures (Figure 9a). The simulations were generated using the parameters from two different samples of the MCMC chains. For comparison a map is shown with randomly generated capture


(a) Mean strike rate μ

(b) Extra dispersion $1/\theta$

Figure 7: Posterior distributions from the two MCMC chains of (a) the mean strike rate, and (b) the extra dispersion $1/\theta$. Samples from the two chains are displayed in grey in the background. The median and 95% confidence interval are also indicated


(a) Observed trawls

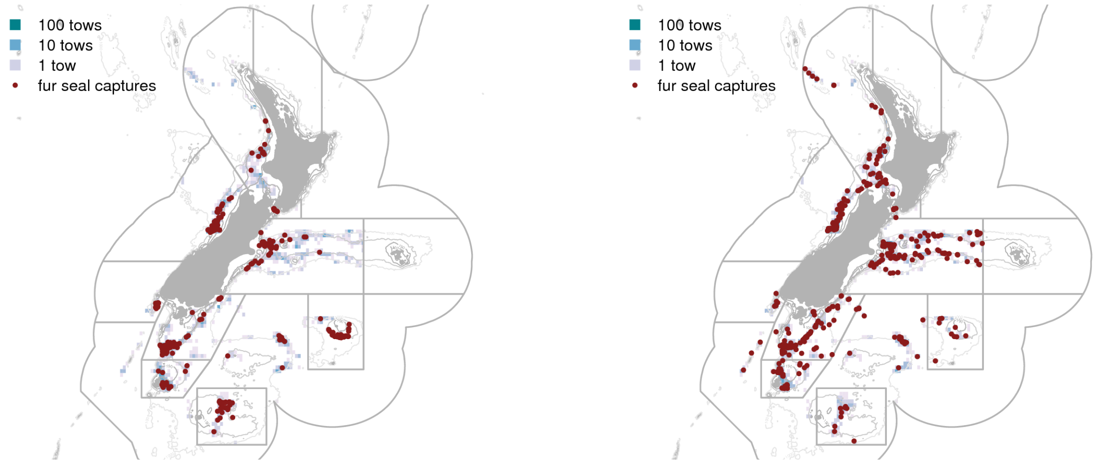
(b) Multiple captures

Figure 8: Predicted fur seal captures on observed tows (a) presented as a box plot with 50% confidence interval boxes and 95% confidence interval whiskers, and (b) comparing the observed (line) and estimated (box and whiskers) distributions of the number of fur seals caught within each trawl group.

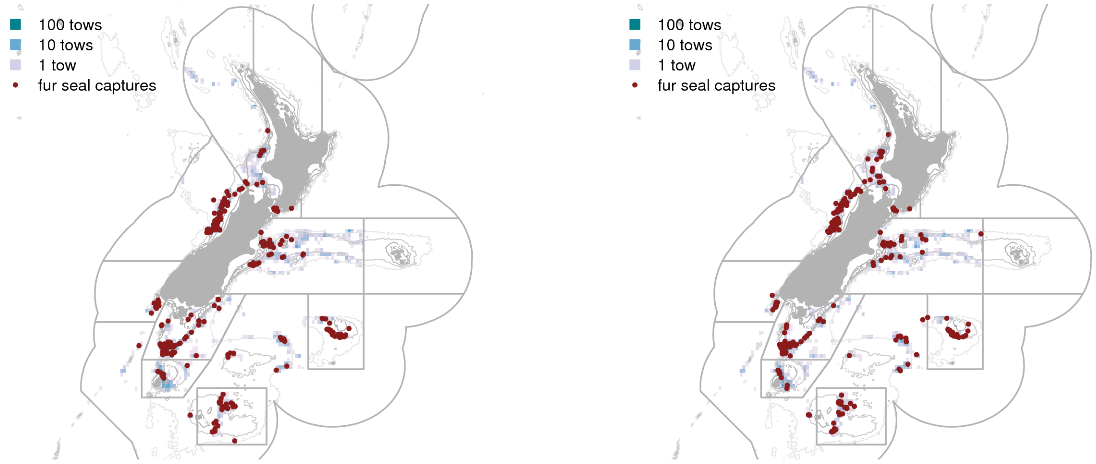
events, obtained by shuffling the observed captures between the observed trawl groups (Figure 9b). The model simulated captures better represented many of the geographical features of the observed captures than the randomly generated captures. For example, as with the observations, the simulations had few captures further out on the Chatham Rise or in the northwest of the North Island. The simulations also had a cluster of captures near the Bounty Islands that was not evident in the randomly generated captures. There were some areas where the maps suggested the model could be improved, in particular, on the west coast South Island the observed captures appeared to be more tightly focused on the Hokitika Canyon, toward the south of the observed effort, than was seen in the model simulations.

3.6 Model parameters

For reference purposes, a complete list of model parameters is given in Appendix A (Table A-1). The model base rates carried the year effects. The coefficients for each of the area, target, and distance effects were multipliers on the rate relative to the Stewart-Snares area, the hoki target species, and a distance to shore of between 45 km and 90 km. For example, the west coast of the North Island area had a model strike rate of about one-tenth that of the Stewart-Snares area, all other factors remaining equal. Similarly the squid fishery had a strike rate about three times that of the hoki fishery.



(a) Observed captures **(b) Random captures**



(c) Simulated captures **(d) Simulated captures**

Figure 9: Maps of captures on observed tows from all years, showing (a) all observed captures (b) randomly assigned captures, and (c, d) captures simulated from 2 of the 5000 samples of the Markov chains. The colours of the heatmap indicate the average number of observed tows per year in 0.2° × 0.2° cells.

3.7 Estimated fur seal captures

Estimates of fur seal captures on unobserved trawl effort were made by sampling the model, with parameters obtained by drawing from the posterior distributions. All trawl effort was used, excluding tows targeting inshore species and fishing in areas where fur seal captures were not observed. The estimates and uncertainty are presented in Table 7 and Figure 10 for each of the six fishing years.

The 2006–07 fishing year had the lowest fur seal capture estimate of 742 (95% c.i.: 355 to 1575) animals. This was an unusual year, with only 72 observed captures in trawl fisheries, around half the number of observed fur seal captures in 2005–06 or 2007–08. Of these captures, only 61 were on tows that could

Table 7: Estimated captures of New Zealand fur seals in trawl fisheries, excluding inshore targets, for the six fishing years from 2002–03 to 2007–08. Capture rates are expressed as animals caught per 100 tows. The effort and observations summarise the model dataset.

	Effort	Observations			Estimates			
	Tows	Tows	Captures	Rate	Mean	95% c.i.	Rate	95% c.i.
2007–08	32 045	7 021	140	1.99	714	465 - 1130	1.55	0.99 - 2.50
2006–07	35 479	6 251	61	0.98	488	288 - 826	0.98	0.59 - 1.63
2005–06	38 908	5 539	143	2.58	869	552 - 1378	1.60	1.00 - 2.55
2004–05	44 340	6 563	191	2.91	1314	839 - 2098	2.17	1.35 - 3.53
2003–04	48 378	5 679	83	1.46	935	553 - 1594	1.40	0.82 - 2.40
2002–03	56 300	5 774	67	1.16	786	468 - 1321	1.04	0.61 - 1.77

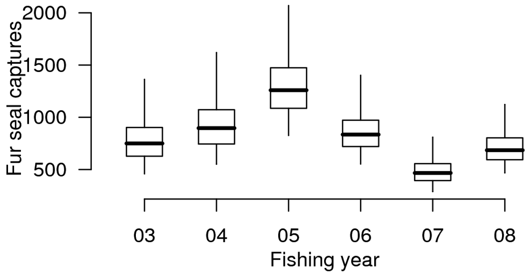


Figure 10: Estimated total fur seal captures by year, in all trawl fisheries other than inshore targets, for the six fishing years from 2002–03 to 2007–08.

be linked to fisher reported effort. In 2007–08, the estimated fur seal captures increased to 1028 (95% c.i.: 553 to 1993). The 2007–08 estimated capture rate of 2.37 (95% c.i.: 1.21 to 4.79) was similar to the 2005–06 rate. Trawl effort has decreased over the six year period, and the peak in estimated fur seal captures occurred in 2004–05, with an estimate of 1995 fur seal captures (95% c.i.: 1006 to 4108).

4. DISCUSSION

4.1 Comparison with previous work

In this report, a single model was defined that covered the region of the New Zealand EEZ where fur seal captures have been observed. To allow a single model to be fitted, the trawl events were grouped together, reducing the scale of the computation. Trawls targeting inshore species were not included in the estimates. Inshore fisheries were very poorly observed in most areas, with less than 1% of tows being observed. In 2007–08, no inshore trawl effort was observed in the Cook Strait or the Stewart-Snares areas, and trawls targeting flatfish species have never been observed. The inshore trawl effort accounted for over 50% of all effort in each year, when measured in numbers of tows (e.g., Abraham et al. 2010).

Smith & Baird (2009) estimated fur seal captures in commercial trawl fisheries for the fishing years from 1994–95 to 2005–06. They selected six areas, and fitted six separate Bayesian models. Two sets of estimates were presented, one including all trawl effort, and one including all trawl effort other than tows targeting flatfish species. The estimates were for six selected areas, and excluded some of the areas that were in the estimates presented here, in particular the west coast of the North Island, north of 40° S.

To make a comparison with previous work possible, we also estimated fur seal captures on all trawls, excluding flatfish targets. The inshore trawl effort was assumed to be similar to other middle depth effort.

Table 8: Comparison of estimated fur seal captures with (a) model estimates made by Smith & Baird (2009) including mean annual captures, coefficient of variation, and 95% confidence intervals, and (b) ratio estimates made by Abraham et al. (2010), also including percentage of non-inshore effort used in ratio estimate.

(a) Including non-flatfish inshore trawl effort

	Thompson et al.			Smith & Baird (2009)		
Year	Captures	c.v.	95% c.i.	Captures	c.v.	95% c.i. [a]
2007–08	1 028	37	553 - 1993			
2006–07	742	43	355 - 1575			
2005–06	1 327	40	672 - 2654	1 110	23	610 - 1610
2004–05	1 995	40	1006 - 4108	1 460	19	916 - 2004
2003–04	1 282	40	642 - 2629	937	20	570 - 1304
2002–03	1 064	40	535 - 2153	1 024	21	603 - 1445

(b) Excluding inshore trawl effort

	Thompson et al.		Abraham et al. (2009)		
Year	Captures	95% c.i.	Captures	95% c.i.	% eff. in est.
2007–08	714	465 - 1130	622	522 - 730	91.42
2006–07	488	288 - 826	513	412 - 626	92.61
2005–06	869	552 - 1378	560	461 - 675	89.14
2004–05	1 314	839 - 2098	1325	1039 - 1656	90.43
2003–04	935	553 - 1594	617	487 - 764	91.45
2002–03	786	468 - 1321	666	487 - 874	91.41

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[a] Calculated from published c.v., assuming normality.

These estimates are compared with the second set of estimates presented by Smith & Baird (2009) in Table 8(a). The mean values of both sets of estimates were within the corresponding confidence intervals, so the estimates were not significantly different. The uncertainty in our estimates was twice as large as those presented by Smith & Baird (2009). Much of the uncertainty in our estimates in Table 8(a) came from the inclusion of tows targeting inshore species, which were not part of the main scope of our modelling.

Stratified ratio estimates of fur seal captures were presented by Abraham et al. (2010). Trawl effort was stratified by fishing area, fishing year, and target species group. Bootstrap ratio estimates were made independently in each stratum, provided there were enough observations (more than 1% coverage, and at least 100 observed tows). None of the inshore trawl effort was included in these ratio estimates. In Table 8(b) these ratio estimates are compared to the model estimates in this report (with all inshore trawl effort excluded). The model estimates all lay within the ratio estimate confidence intervals. The confidence intervals for the model estimates were wider than confidence intervals around the ratio estimates. The ratio estimate ignores correlation between captures, but assumes that all observations are independent. For this reason, the ratio estimate is likely to overestimate the number of degrees of freedom, and so underestimate the uncertainty.

Manly et al. (2002) estimated fur seal captures in commercial trawl fisheries for the period 1990–91 to 1995–96. The estimates were calculated using a stratified ratio method, similar to the method used by Abraham et al. (2010). The estimated total fur seal captures ranged from 401 in 1990–91 to 2110 in 1995–96. Although there was no overlap in the years, these numbers were broadly similar in range to those reported in Table 7. In addition, Manly et al. (2002) looked at factors influencing the capture rate. They grouped data together to allow the inclusion of the whole data set in a step analysis, and used generalised linear models to estimate a strike rate, using a Poisson error model. The first four factors identified in the step analysis (area, target, year, and season), were the same as those identified in this report (Table 5). The seasonal effect was included as a four parameter factor and was included after the fishing year covariate, while we fitted the seasonal effect as a two parameter harmonic function which was included before the fishing year. Manly et al. (2002) did not consider distance to shore as a potential covariate.

4.2 Model parameters

The model estimated the coefficients of the area, target species, distance to shore, and day of year covariates. Random effects parameters were estimated for the fishing year and the vessel-year. A full list of the model parameters is given in the Appendix (Table A-1). Interactions between the covariates were not explored in this report, although these were likely to have been present. Some of the combinations of the covariates that were in the model were not represented in the observed effort, or in the total effort data. These issues make it difficult to directly interpret the various coefficients in Table A-1. For example, the coefficient for the other subantarctic area has a mean value of 10.8. This would mean that, everything else being equal, trawlers in the other subantarctic area would catch 10.8 times as many fur seals as those in the Stewart-Snares area. However, things are not all equal: 90% of observed effort in the other subantarctic area targeted deepwater species, and the observed capture rate was 0.52 fur seals per 100 tows, more than 15 times the capture rate of deepwater trawl effort in other areas. To compensate for this, the subantarctic area coefficient was elevated. The story was similar with other model parameters, and made it difficult to interpret the parameter values in isolation.

The distance to shore factor was defined with four values. The model estimated that trawls in coastal regions (25 km or less) had a similar chance of catching fur seals as those in the near region (between 25 km and 90 km). The distance parameter in the far (between 90 km and 180 km) and ocean (over 180 km) regions were less than 1, indicating a reduction in the capture rate when fishing was more than 90 km from shore. These results were in broad agreement with results from the initial exploration of the data (see Figure 3b).

The day of year effect was modelled as a harmonic function with two parameters. The multiplicative effect of the day of year on fur seal captures is plotted in Figure 11. The confidence interval was small compared to the scale of the effect, indicating that the seasonal variation was significant. The peak in the day of year effect was at the end of August, in the middle of winter, when it was five times higher than the annual average. It then dropped to around a fifth of the average rate in the summer months. The shape of the seasonal pattern may be related to the fur seal breeding season. Pupping occurs at the same time around the whole region, with pups born in December and January (McKenzie 2006). Fur seal mating, pupping, and the first few months of the pups' lives coincide with the period of lowest capture rate.

4.3 New Zealand fur seal captures

In 2007–08, an estimated 714 (95% c.i.: 465 to 1130) fur seals were caught in trawl fisheries in New Zealand's EEZ. This estimate was over 20 times greater than the estimated 30 (95% c.i.: 18 to 44) fur seal captures in surface longline fisheries in 2007–08 (Abraham et al. 2010). The estimated captures in trawl fisheries in 2007–08 were higher than the 2006–07 estimate of 488 (95% c.i.: 288 to 826) fur seals, but within the range of previous years. The capture rate for 2007–08 was estimated at 1.55 (95% c.i.: 0.99 to 2.50) fur seals per 100 tows. Note that the annual capture rate confidence intervals included 1.5 fur seals per 100 tows for each of the six years estimated, and in this sense the 2007–08 year was typical. There was no evidence of a trend in the fur seal capture rate.

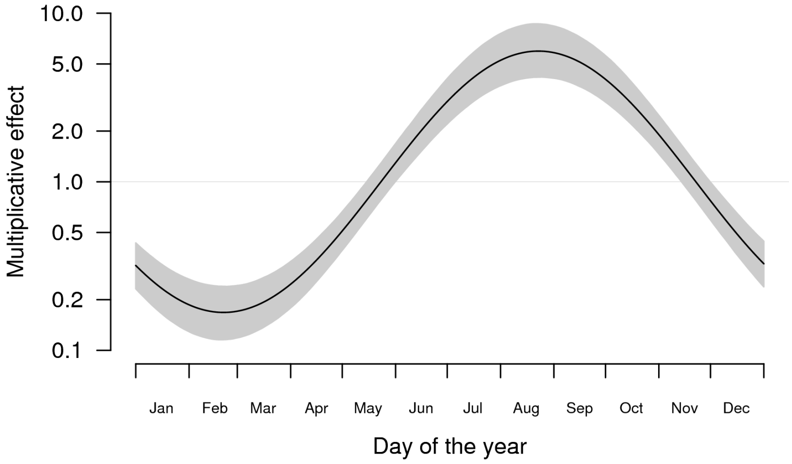

Figure 11: Day of year effect, with 95% confidence interval indicated with the shaded area, plotted with a logarithmic scale on the y-axis.

The lower number of captures in 2006–07 was partly due to an unresolved issue with the data. There were 11 observed captures on tows that could not be linked to fisher reported effort. This was 15% of the total number of observed captures in that year. The unlinked captures were on three trips that were targeting hoki in Cook Strait. At the time of the data extract, there did not appear to have been fisher reported effort corresponding to these trips in *warehou*. Across the whole six years, 3.2% of the observed captures were not included in the model dataset because of problems with the linking.

We assumed that no fur seals were caught in tows on the north and eastern sides of the North Island, where fur seal captures have never been recorded by observers. Trawl effort on the eastern end of the Chatham Rise was also excluded because fur seal captures were not observed there in the six year period. There are fur seal colonies on Chatham Island, but the observed effort included only 651 of the tows that targeted hoki or other middle depth species. If the capture rate was the same as on the western Chatham Rise, we would have expected about eight fur seal captures to have been observed. Because there were no observed captures, and few observations in middle depth fisheries in this region, it was simply assumed that there were no captures on the eastern end of the Chatham Rise.

Effort targeting inshore fisheries was also excluded from the estimates. Less than 1% of inshore trawl effort was observed, and no fur seal captures were observed in inshore fisheries. Trawls targeting inshore species accounted for more than half of the total trawl effort. Estimates are presented where the inshore effort (not targeting flatfish) was assumed to be equivalent to the other middle depth trawl effort (Table 8(a)). The estimates were about 50% higher than the estimates excluding inshore fisheries.

A summary of the observations and the model estimates grouped by target species is given in Appendix B (Table B-1). Fur seals were predominantly caught by tows targeting middle depth species such as hoki and barracouta. In 2007–08, an estimated 273 (95% c.i. 163 to 448) fur seals were caught in the hoki fishery. This was an increase on the estimate for 2006–07 of 196 (95% c.i.: 103 to 345) fur seal captures, but the estimates are not significantly different. The estimated capture rate of fur seals in the squid fishery was consistently greater than the observed rates. This was due to poor observer coverage of the squid fishery outside the Auckland Islands and Stewart-Snares areas. In particular, only 160 of the 7244 tows that targeted squid in the western Chatham Rise area were observed. In fisheries targeting scampi or deepwater species, the observed and estimated capture rates were generally less than 0.3 captures per 100 tows. In any of the years, there were fewer than 20 fur seals estimated to have been caught in either of the scampi or deepwater fisheries.

The fur seal captures by area are summarised in Appendix B (Table B-2). In 2007–08, an estimated 191 (95% c.i.: 75 to 380) fur seals were caught in the Cook Strait area, where 2651 tows targeting hoki and other middle depth species were reported. Low observer coverage of less than 10% in the Cook Strait area means that the uncertainties are high. Effort in the Cook Strait area was closer to shore than in any other area, with tows having a mean distance from shore of 18 km. The other two areas where it was estimated that more than 100 fur seals were caught in 2007–08 were the west coast South Island and western Chatham Rise areas. Both the observed and estimated fur seal capture rates were highest in the Bounty Islands area, with an estimated rate of 22 (95% c.i.: 13 to 41) fur seals per 100 tows. However, in 2007–08 there were only 300 tows targeting southern blue whiting in the Bounty Islands area.

There is little basis for interpreting fur seal captures in terms of their possible population effects. Obtaining population estimates of fur seals within the New Zealand region, and a better understanding of their demographic parameters, are essential to quantifying the impacts of fisheries on the New Zealand fur seal population. To date, there have been few observations made in inshore trawl fisheries. As inshore trawl fisheries account for over 50% of all trawl effort, measured by number of tows, assessing the capture rate of fur seals in inshore trawl fisheries is also an essential step towards a full estimate of how many fur seals are caught in New Zealand's commercial fisheries.

5. ACKNOWLEDGMENTS

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APPENDIX A: Model parameters

Table A-1: Mean, median, and 95% confidence intervals for final model parameters. Calculated from 5000 samples of the corresponding posterior distributions.

Parameter	Mean	Median	95% c.i.	
Extra dispersion, $1/\theta$	13.411	13.304	9.450	17.902
Mean rate, μ (captures per 100 tows)	0.619	0.615	0.488	0.773
Vessel/year effect standard deviation	0.753	0.749	0.575	0.955
2002–03 base rate (captures per 100 tows)	0.431	0.423	0.271	0.642
2003–04 base rate (captures per 100 tows)	0.562	0.552	0.363	0.817
2004–05 base rate (captures per 100 tows)	0.889	0.872	0.594	1.279
2005–06 base rate (captures per 100 tows)	0.669	0.655	0.444	0.967
2006–07 base rate (captures per 100 tows)	0.445	0.434	0.275	0.666
2007–08 base rate (captures per 100 tows)	0.717	0.701	0.488	1.041
Sine(doy) coefficient	-1.390	-1.389	-1.711	-1.081
Cosine(doy) coefficient	-1.119	-1.118	-1.434	-0.813
Area coefficients relative to Stewart-Snares shelf				
Western Chatham Rise	0.966	0.933	0.549	1.567
West Coast SI	0.465	0.446	0.247	0.800
Auckland Islands	0.327	0.310	0.150	0.603
West Coast NI	0.141	0.126	0.048	0.319
Other subantarctic	10.805	9.097	2.893	29.499
Campbell Island	1.521	1.242	0.355	4.441
Cook Strait	1.653	1.494	0.640	3.577
Puysegur	1.180	1.107	0.523	2.304
Bounty Islands	9.561	7.889	2.300	27.064
Target coefficients relative to Hoki				
Squid	3.069	2.881	1.495	5.630
Deepwater	0.054	0.047	0.015	0.137
Middle depth	1.447	1.417	0.975	2.097
Jack mackerel	1.567	1.470	0.701	2.997
Southern blue whiting	0.699	0.577	0.168	1.985
Scampi	0.340	0.292	0.074	0.895
Distance coefficients relative to Near (between 25 km and 90 km)				
Coastal (< 25 km)	1.106	1.066	0.602	1.842
Far (between 90 km and 180 km)	0.611	0.599	0.412	0.878
Ocean (> 180 km)	0.247	0.229	0.098	0.505

APPENDIX B: Estimate of New Zealand fur seal captures in trawl fisheries

Table B-1: Total effort, observed effort, observed captures, and estimated captures of New Zealand fur seals in trawl fisheries, organised by target group, for six fishing years from 2002–03 to 2007–08.

		Observed				Estimated			
	Tows	No. obs	% obs	Capt.	Rate	Est. captures		Est. rate	
2007–08									
Hoki	8 399	1 802	21.5	57	3.16	273	163 - 448	2.77	1.63 - 4.64
Hake	1 493	382	25.6	26	6.81	52	36 - 78	2.85	2.03 - 4.17
SBW	817	329	40.3	24	7.29	84	40 - 177	13.96	9.61 - 22.35
Middle depth	5 985	327	5.5	9	2.75	180	76 - 384	2.83	1.25 - 5.92
Squid	4 249	1 447	34.1	7	0.48	31	16 - 55	1.13	0.67 - 1.89
Ling	1 813	221	12.2	4	1.81	49	21 - 95	2.52	1.31 - 4.54
Jack mackerel	2 647	809	30.6	8	0.99	28	13 - 54	2.15	1.61 - 3.08
Scampi	3 279	297	9.1	1	0.34	10	2 - 29	0.31	0.08 - 0.85
Deepwater	3 363	1 407	41.8	4	0.28	7	4 - 15	0.15	0.07 - 0.33
2006–07									
Hoki	10 177	1 546	15.2	17	1.10	196	103 - 345	1.63	0.92 - 2.77
Hake	1 485	284	19.1	4	1.41	24	11 - 45	1.56	0.86 - 2.65
SBW	630	223	35.4	13	5.83	25	15 - 44	6.25	5.21 - 8.40
Middle depth	6 633	296	4.5	3	1.01	126	45 - 300	1.79	0.75 - 3.96
Squid	5 903	1 280	21.7	8	0.62	44	23 - 78	0.94	0.53 - 1.64
Ling	1 448	157	10.8	12	7.64	50	27 - 90	3.16	1.81 - 5.35
Jack mackerel	2 710	783	28.9	2	0.26	13	4 - 28	0.60	0.26 - 1.21
Scampi	3 415	219	6.4	0	0.00	6	0 - 20	0.19	0.04 - 0.53
Deepwater	3 078	1 463	47.5	2	0.14	4	2 - 8	0.10	0.06 - 0.19
2005–06									
Hoki	11 328	1 754	15.5	62	3.53	349	214 - 561	2.55	1.57 - 4.13
Hake	1 344	419	31.2	11	2.63	42	23 - 73	3.04	1.83 - 4.90
SBW	624	215	34.5	52	24.19	70	56 - 102	18.19	15.89 - 22.76
Middle depth	6 199	365	5.9	4	1.10	199	69 - 466	3.02	1.23 - 6.64
Squid	8 558	1 097	12.8	4	0.36	114	56 - 215	1.84	0.91 - 3.39
Ling	1 239	113	9.1	2	1.77	51	20 - 103	3.63	1.79 - 6.71
Jack mackerel	2 806	703	25.1	6	0.85	25	11 - 48	1.10	0.61 - 1.96
Scampi	2 951	214	7.3	0	0.00	7	0 - 21	0.38	0.08 - 1.07
Deepwater	3 859	659	17.1	2	0.30	11	3 - 29	0.21	0.08 - 0.49
2004–05									
Hoki	13 982	2 014	14.4	111	5.51	633	396 - 1008	3.68	2.29 - 5.94
Hake	1 239	94	7.6	2	2.13	39	17 - 71	2.65	1.36 - 4.73
SBW	869	335	38.6	33	9.85	78	44 - 157	10.78	7.72 - 16.75
Middle depth	7 231	182	2.5	10	5.49	268	103 - 609	3.89	1.55 - 8.75
Squid	10 491	2 500	23.8	16	0.64	178	95 - 319	2.74	1.42 - 5.04
Ling	958	76	7.9	10	13.16	65	28 - 138	6.36	3.47 - 11.32
Jack mackerel	2 509	557	22.2	5	0.90	20	8 - 40	1.02	0.52 - 1.94
Scampi	2 820	64	2.3	0	0.00	17	2 - 52	0.73	0.14 - 2.13
Deepwater	4 241	741	17.5	4	0.54	17	6 - 41	0.30	0.12 - 0.66
2003–04									
Hoki	21 503	2 288	10.6	48	2.10	581	333 - 996	2.38	1.32 - 4.17
Hake	1 529	140	9.2	0	0.00	19	7 - 39	1.25	0.61 - 2.28
SBW	740	238	32.2	13	5.46	34	18 - 69	7.96	6.24 - 11.39
Middle depth	7 120	130	1.8	0	0.00	150	46 - 380	2.17	0.77 - 5.32
Squid	8 330	1 762	21.2	17	0.96	104	57 - 181	1.66	0.88 - 3.01
Ling	521	22	4.2	0	0.00	20	5 - 51	2.99	1.29 - 6.15
Jack mackerel	2 381	152	6.4	2	1.32	13	4 - 30	0.84	0.43 - 1.54
Scampi	2 178	374	17.2	1	0.27	4	1 - 12	0.18	0.06 - 0.46
Deepwater	4 076	573	14.1	2	0.35	10	3 - 28	0.16	0.06 - 0.40
2002–03									
Hoki	26 968	2 550	9.5	44	1.73	509	300 - 851	1.61	0.93 - 2.72
Hake	804	44	5.5	3	6.82	16	7 - 31	1.74	1.03 - 2.86
SBW	638	275	43.1	8	2.91	21	10 - 43	3.18	1.87 - 5.52
Middle depth	8 671	253	2.9	1	0.40	131	42 - 319	1.61	0.57 - 3.88
Squid	8 390	1 304	15.5	8	0.61	70	34 - 128	1.24	0.72 - 2.12
Ling	534	16	3.0	0	0.00	12	2 - 34	2.08	0.79 - 4.66
Jack mackerel	3 051	344	11.3	1	0.29	15	4 - 34	0.76	0.29 - 1.63
Scampi	2 757	417	15.1	2	0.48	6	2 - 14	0.20	0.07 - 0.51
Deepwater	4 487	571	12.7	0	0.00	5	0 - 16	0.10	0.03 - 0.24

Table B-2: Total effort, observed effort, observed captures, and estimated captures of New Zealand fur seals in trawl fisheries, organised by area, for six fishing years from 2002–03 to 2007–08.

		Observed				Estimated			
	Tows	No. obs	% obs	Capt.	Rate	Est. captures		Est. rate	
2007–08									
Cook Strait	2 651	221	8.3	21	9.50	191	81 - 398	3.89	1.50 - 8.51
West coast South Island	4 415	915	20.7	58	6.34	161	107 - 256	2.43	1.67 - 3.80
Western Chatham Rise	10 238	1 361	13.3	15	1.10	154	81 - 277	1.19	0.64 - 2.12
Stewart-Snares	5 177	1 528	29.5	14	0.92	73	39 - 128	1.22	0.71 - 2.06
Bounty Islands	300	158	52.7	17	10.76	59	24 - 143	22.02	12.83 - 40.86
Campbell Island	559	230	41.1	7	3.04	18	9 - 34	7.09	6.12 - 8.78
West coast North Island	3 493	863	24.7	1	0.12	15	4 - 36	0.21	0.08 - 0.45
Other subantarctic islands	1 840	884	48.0	5	0.57	17	6 - 46	1.29	0.53 - 3.06
Auckland Islands	3 043	848	27.9	2	0.24	12	4 - 28	0.36	0.16 - 0.75
Puysegur	329	13	4.0	0	0.00	12	2 - 33	2.78	1.00 - 6.17
2006–07									
Cook Strait	3 154	202	6.4	11	5.45	138	58 - 294	2.35	0.95 - 5.19
West coast South Island	5 659	875	15.5	5	0.57	99	46 - 194	1.25	0.65 - 2.30
Western Chatham Rise	11 491	1 010	8.8	7	0.69	108	52 - 209	0.70	0.37 - 1.27
Stewart-Snares	6 423	1 350	21.0	21	1.56	86	50 - 141	1.14	0.68 - 1.87
Bounty Islands	260	145	55.8	8	5.52	11	8 - 21	5.21	4.63 - 6.59
Campbell Island	565	181	32.0	5	2.76	14	6 - 26	4.51	3.74 - 5.82
West coast North Island	3 253	945	29.1	1	0.11	7	2 - 17	0.10	0.04 - 0.22
Other subantarctic islands	1 448	854	59.0	2	0.23	9	2 - 28	1.31	0.44 - 3.26
Auckland Islands	2 870	646	22.5	0	0.00	6	1 - 16	0.24	0.09 - 0.52
Puysegur	356	43	12.1	1	2.33	11	2 - 30	2.34	0.85 - 5.19
2005–06									
Cook Strait	2 935	68	2.3	19	27.94	204	88 - 407	3.44	1.45 - 7.09
West coast South Island	6 522	1 168	17.9	31	2.65	182	109 - 299	1.94	1.15 - 3.21
Western Chatham Rise	11 801	1 162	9.8	15	1.29	171	82 - 337	1.00	0.50 - 1.87
Stewart-Snares	7 661	1 124	14.7	10	0.89	133	71 - 229	1.69	0.92 - 2.93
Bounty Islands	447	175	39.1	52	29.71	61	52 - 86	26.32	23.85 - 31.40
Campbell Island	519	137	26.4	1	0.73	13	4 - 29	2.48	1.11 - 4.83
West coast North Island	3 258	760	23.3	5	0.66	18	8 - 37	0.34	0.21 - 0.61
Other subantarctic islands	1 107	144	13.0	1	0.69	32	5 - 107	3.79	1.02 - 10.68
Auckland Islands	3 899	671	17.2	2	0.30	12	4 - 25	0.34	0.16 - 0.64
Puysegur	759	130	17.1	7	5.38	44	18 - 97	4.73	2.09 - 9.46
2004–05									
Cook Strait	4 419	108	2.4	23	21.30	365	155 - 769	5.37	2.17 - 12.03
West coast South Island	7 036	1 247	17.7	74	5.93	282	182 - 441	2.72	1.66 - 4.42
Western Chatham Rise	11 470	987	8.6	17	1.72	222	118 - 402	1.39	0.78 - 2.42
Stewart-Snares	8 646	1 857	21.5	13	0.70	162	90 - 273	2.07	1.13 - 3.55
Bounty Islands	449	135	30.1	24	17.78	52	27 - 123	13.27	9.35 - 21.87
Campbell Island	774	283	36.6	16	5.65	36	22 - 61	6.36	4.94 - 8.63
West coast North Island	4 381	637	14.5	6	0.94	30	12 - 65	0.29	0.12 - 0.69
Other subantarctic islands	1 578	343	21.7	4	1.17	66	17 - 192	5.76	1.73 - 14.97
Auckland Islands	4 450	824	18.5	1	0.12	17	5 - 36	0.45	0.20 - 0.89
Puysegur	1 137	142	12.5	13	9.15	83	36 - 169	6.12	3.22 - 11.11
2003–04									
Cook Strait	5 695	126	2.2	1	0.79	328	123 - 725	3.94	1.49 - 8.97
West coast South Island	9 354	1 400	15.0	29	2.07	217	130 - 366	1.83	1.12 - 3.09
Western Chatham Rise	12 381	886	7.2	16	1.81	143	77 - 256	0.79	0.42 - 1.43
Stewart-Snares	7 860	1 226	15.6	10	0.82	95	53 - 162	1.11	0.62 - 1.84
Bounty Islands	328	35	10.7	9	25.71	22	10 - 54	15.18	12.07 - 21.84
Campbell Island	797	232	29.1	4	1.72	18	7 - 36	1.74	0.93 - 3.13
West coast North Island	4 358	336	7.7	0	0.00	16	3 - 43	0.15	0.05 - 0.39
Other subantarctic islands	1 965	273	13.9	2	0.73	51	12 - 152	3.19	0.89 - 8.54
Auckland Islands	4 872	1 106	22.7	9	0.81	20	12 - 33	0.36	0.23 - 0.59
Puysegur	768	59	7.7	3	5.08	26	9 - 59	2.83	1.34 - 5.49
2002–03									
Cook Strait	5 736	142	2.5	4	2.82	236	90 - 516	2.88	1.08 - 6.48
West coast South Island	10 918	1 004	9.2	21	2.09	195	112 - 327	1.45	0.86 - 2.42
Western Chatham Rise	17 230	1 447	8.4	16	1.11	150	80 - 272	0.65	0.36 - 1.16
Stewart-Snares	7 891	1 137	14.4	10	0.88	66	36 - 114	0.82	0.48 - 1.34
Bounty Islands	317	47	14.8	0	0.00	9	0 - 31	3.78	1.23 - 8.72
Campbell Island	816	291	35.7	9	3.09	17	10 - 29	1.95	1.37 - 2.91
West coast North Island	4 575	424	9.3	0	0.00	12	2 - 33	0.11	0.03 - 0.32
Other subantarctic islands	2 414	249	10.3	0	0.00	51	10 - 160	2.07	0.56 - 5.46
Auckland Islands	4 106	658	16.0	0	0.00	4	0 - 11	0.11	0.05 - 0.22
Puysegur	2 297	375	16.3	7	1.87	47	21 - 92	2.26	1.30 - 3.93