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EXECUTIVE SUMMARY

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In this report, the number of New Zealand sea lion (*Phocarctos hookeri*) captures in New Zealand's trawl fisheries are estimated for the 1995–96 to 2006–07 fishing years. Over this period, Ministry of Fisheries observers recorded the capture of between 5 and 39 sea lions within the New Zealand Exclusive Economic Zone, within each fishing year. During the 2006–07 fishing year, 15 sea lions were observed killed on trawls. For the purposes of this report, three captures were included in this total that were observed on the first day of the 2007–08 fishing year, in the last days of the southern blue whiting fishery. All of the captured sea lions were retrieved dead. Of the 15 sea lion captures, 7 were observed caught in the squid fishery around the Auckland Islands. This was the lowest number of observed captures in this fishery since the 1998–99 fishing year. Six sea lion captures were observed in the southern blue whiting fishery east of Campbell Island, continuing a trend of increasing captures in that fishery since 2002. Two other captures occurred, one in the scampi fishery near the Auckland Islands, and one in the squid fishery south of The Snares.

From these observations, estimates of total captures were made for four different trawl fisheries: the squid fishery near the Auckland Islands; the southern blue whiting fishery east of Campbell Island; other (non-squid) fisheries near the Auckland Islands; and all trawl fisheries on the southern end of the Stewart-Snares shelf. Bayesian generalised linear models were fitted to data from the first two of these fisheries. A previous model, used for estimating sea lion captures in the 2004–05 fishing year, was re-implemented for the Auckland Islands squid fishery. A new model was developed for the southern blue whiting fishery. Ratio estimates were calculated for the other (non-squid) Auckland Islands trawl fishery, and for all trawl fisheries on the southern end of the Stewart-Snares shelf.

Over the 12 years of data, fishing effort in the squid fishery near the Auckland Islands was highest in the 1995–96 fishing year, with 4467 trawls being made. Effort then decreased to fewer than 2000 trawls in each year between 1997–98 and 2002–03. In each year between 2003–04 and 2005–06, over 2400 trawls were made. The trawl effort fell to 1320 trawls in 2006–07.

Since 2001, squid trawl nets in the Auckland Islands squid fishery have increasingly been fitted with sea lion exclusion devices (SLEDs) that allow animals to escape from the net. The estimated interactions (captures and escapes via SLEDs) follow the patterns in effort. In 1995–96 and 1996–97 there were an estimated 141 and 140 interactions, respectively. In each year between 1997–98 and 2002–03 there were fewer than 75 estimated interactions. For the three years 2003–04 to 2005–06 there were 140 or more interactions. In 2006–07, the model estimated that there were 74 (95% c.i.: 32 to 136) sea lion interactions.

The model estimated that the probability that a sea lion failed to escape from a net fitted with a SLED (i.e., the retention probability) was 0.24 (95% c.i,: 0.13 to 0.39). This was similar to previous estimates, and correspondingly the predicted strike rate in 2006–07 of 5.6 sea lions per 100 trawls (95% c.i.: 2.7 to 10) was similar to estimates of the strike rate made previously. As SLEDs have been used more widely, the number of captures has fallen relative to the number of interactions, and in 2006–07 there were an estimated 20 (95% c.i.: 11 to 33) sea lion captures in the Auckland Islands squid fishery. The number of attributed mortalities in this fishery in 2006–07 was 60 (95% c.i.: 26 to 110), assuming a discount rate of 20%, which is less than the limit of 93 mortalities set by the Ministry of Fisheries.

There were 518 trawls made east of Campbell Island in the 2007 southern blue whiting season, of which 33% were observed. The observed sea lion capture rate was 3.49 animals per 100 trawls, and has increased over the last four years, from an observed captures rate of 0.37 animals per 100 trawls in 2002. Our model estimated 14 captures for 2007 (95% c.i.: 7 to 27), an estimated strike rate of 2.39 captures per hundred trawls (95% c.i.: 1.5 to 24.6).

In 2006–07, the bootstrapped ratio method provided estimates of 12 captures (95% c.i.: 1 to 27) in other (non-squid) Auckland Islands trawl fisheries, and 5 captures (95% c.i.: 2 to 9) for all trawl fisheries on the southern Stewart-Snares shelf. Estimates were also made for the 2004–05 and 2005–06 fishing years, because of the small number of captures no clear trends were discernible.

The four estimates were combined for the three fishing years 2004–05 to 2006–07. The total estimates for 2006–07 were 51 sea lion captures (95% c.i.: 33 to 74), and 105 sea lion interactions (95% c.i.: 60 to 169). This compared with a total estimate for 2005–06 of 60 captures (95% c.i.: 39 to 87) and 170 interactions (95% c.i.: 92 to 286). The reduction between the two years was largely due to a decrease in effort in the Auckland Islands squid fishery.

1. INTRODUCTION

The New Zealand sea lion (*Phocarctos hookeri*) population consists of large colonies on the Auckland Islands (at Enderby Island, Dundas Island, and Figure of Eight Island) and smaller colonies on Campbell Island, The Snares, and the South Island near the Otago Peninsula (Chilvers 2008). An endemic species, New Zealand sea lions are considered to be threatened (range restricted) by the New Zealand threat management classification system (Hitchmough 2002). In October 2008, they were added to the International Union for the Conservation of Nature and Natural Resources Red List of endangered species (IUCN 2008). They are currently considered to be vulnerable due to a 31% decline in pup production between 1997–98 and 2005–06 (Chilvers et al. 2007).

Under the Marine Mammals Protection Act 1978, New Zealand's Ministry of Fisheries is required to manage the impact of commercial fishing operations on sea lions. The Ministry runs an observer programme that monitors the capture of New Zealand sea lions by commercial fishers. A summary of the observed captures of protected species by New Zealand fisheries was given by Abraham & Thompson (2009). Sea lions are caught by trawlers operating around New Zealand's sub-antarctic islands (Figure 1). Between 1 October 1995 and 31 December 2007, the two largest clusters of captures were to the north and to the southeast of the Auckland Islands. Squid trawlers in the Auckland Islands fishery accounted

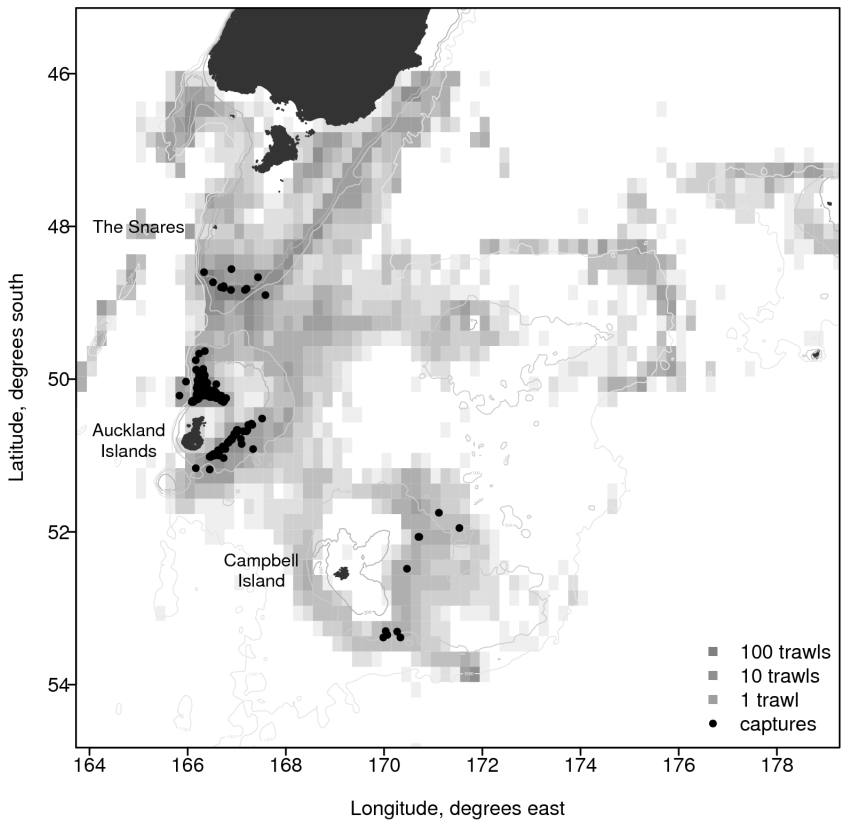


Figure 1: Sea lion captures in all trawl fisheries reported in the 12 year period from 1 October 1995 to 31 December 2007. Two sea lions captures are not included in this figure or in the analyses: one sea lion killed east of the Chatham Islands, and another caught west of The Snares and released from a charter surface longline vessel. The grey shading indicates the average annual trawl effort within each 0.2° × 0.2° cell.

for 83% of all observed sea lion captures over the 12 year period. Sea lions were also caught by trawlers targeting non-squid species in the Auckland Islands region, in the southern blue whiting trawl fishery east of Campbell Island, and in trawl fisheries on the southern end of the Stewart-Snares shelf. There were two other captures in the 12 years that are not shown in Figure 1. In May 1996, one sea lion was killed in a hoki trawl east of the Chatham Islands, and in April 2000 one sea lion was caught west of The Snares and released from a charter surface longline vessel. These two captures are not included in the analysis.

Since 2003, the Ministry of Fisheries has restricted the Auckland Islands squid fishery by setting a fishing-related mortality limit (FRML) on the number of sea lion deaths caused by the fishery. This limit is translated into a maximum number of trawls that can be made by the fishery by assuming a sea lion strike rate per trawl. In the 2006–07 fishing year, the FRML was set at 93 sea lion deaths. This was equivalent to a limit of 1755 trawls, assuming a strike rate of 5.3 sea lions per 100 trawls.

In 2001 a new bycatch mitigation method, the sea lion exclusion device (SLED), was introduced in the Auckland Islands squid fishery (Figure 2). The SLED is a grid fitted in the net before the codend, with the spacing between the bars designed to prevent sea lions passing through. The grid is angled so that the sea lions are directed upward towards a hole in the top of the net, and they are able to escape from the net. The Ministry of Fisheries certifies SLEDs that meet required specifications, and for approved SLEDs the assumed sea lion strike rate used for calculating the FRML is reduced. This reflects the assumption that fewer sea lions are killed during trawls with nets that have SLEDs fitted. Since 2004-05 almost all vessels operating in the SQU 6T fishery have used approved SLEDs. In the 2006–07 fishing year a discount rate of 20% was applied to trawls that used approved SLEDs. This increased the number of permitted trawls from 1755 to 2194.

The intention of this report is to use the observer data to calculate metrics that are required by the Ministry of Fisheries for managing fisheries that capture sea lions. Observers are present on only some trawls, and so statistical methods are required to extrapolate from captures on observed trawls to captures on all trawls. The terminology used in this report generally follows that used by Smith & Baird (2007b) and key terms are detailed in Table 1. A schematic diagram showing the various reported quantities, for trawls with SLEDs, is given in Figure 3. On trawls with SLEDs, some sea lions escape from the nets. A key metric is an estimate of the total number of sea lions that would have been caught, on both observed and not observed trawls, if no SLEDs had been used. This is referred to as the interactions (Figure 3(f)). The number of interactions represents the maximum direct impact of the fishery on the sea lions. The number of sea lions excluded by SLEDs may be calculated as the difference between the interactions and the captures (Figure 3(c)). The interactions may be converted to strike rates (interactions per 100 trawls),

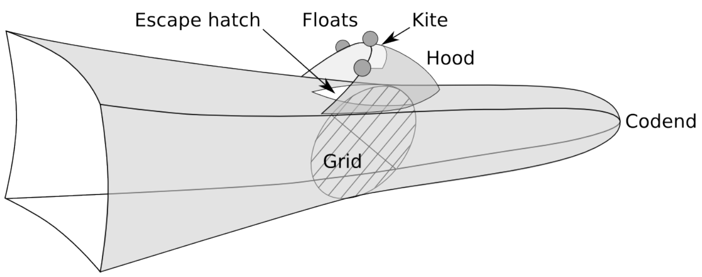


Figure 2: Schematic diagram of a sea lion exclusion device (SLED). The SLED consists of a grid fitted in the net, in front of the codend. Sea lions are unable to pass through the grid into the codend, but may escape through a hole above the grid. A forward facing hood fitted above the escape hatch is designed so that only actively swimming sea lions escape the net. The hood is held open by floats, and a strip of material known as a kite. A cover net may be fitted over the escape hatch to close the SLED.

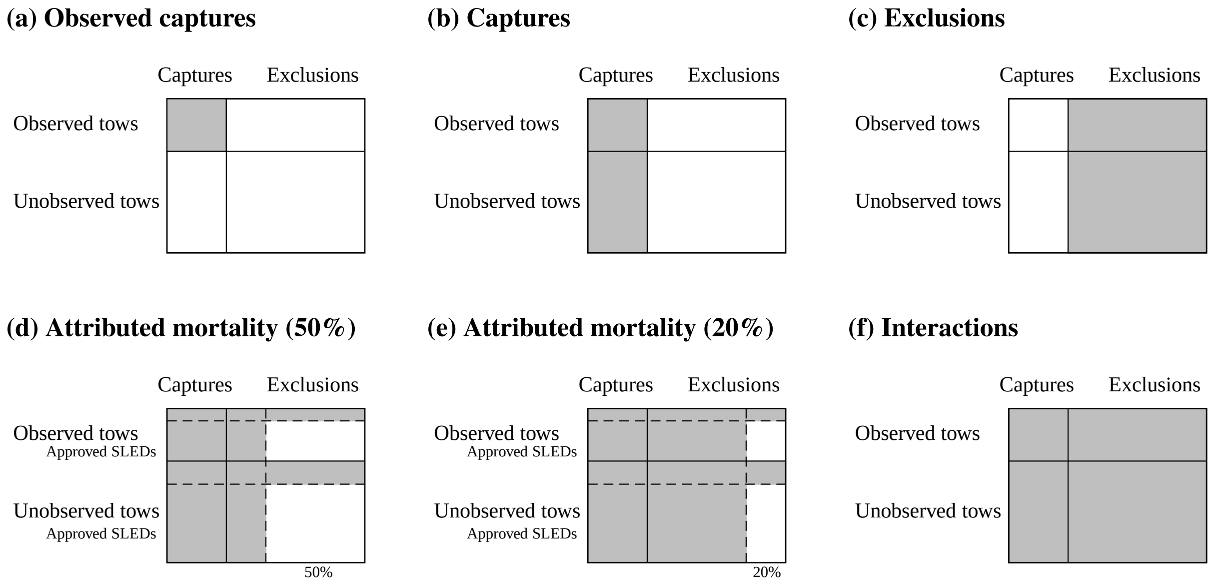


Figure 3: Quantities estimated for trawls that used SLEDs. Trawls are either observed or unobserved, and sea lions are either captured or are excluded (escaped through the SLED and would have been captured had a SLED not been used). The shaded grey areas are (a) Observed captures (b) Captures, the sum of observed captures and estimated captures on unobserved trawls (c) Exclusions, sea lions that escaped being captured because SLEDs were used (d) Attributed mortality at a 50% discount rate (e) Attributed mortality at a 20% discount rate (f) Interactions. In (d) and (e) the horizontal dotted line indicates the distinction between approved and unapproved SLEDs, and the vertical dotted line indicates the application of the discount rate.

allowing comparison between years and fisheries where there have been different numbers of trawls.

In the Auckland Islands squid fishery, the number of attributed mortalities is calculated. This is an estimate of the number of sea lions that would have been killed under the assumptions that no sea lions survived being excluded by a SLED unless the SLED had been approved by the Ministry of Fisheries, and that on trawls with an approved SLED, only a proportion of excluded sea lions survived. Attributed mortalities are calculated with the survival probability being the discount rate. They are illustrated in Figure 3(d) for a discount rate of 50%, and in Figure 3(e) for a discount rate of 20%.

Ratio estimates of sea lion strike rates, and of the total number of sea lion captures, in the Auckland Islands squid fishery have been published for the fishing years 1992–93 to 2002–03 (Baird & Doonan 2005, Baird 2005a, 2005b). Hierarchical general linear Bayesian models have previously been used to estimate the retention probability, strike rates, and captures of sea lions in the 2003–04, 2004–05, and 2005–06 fishing years (Smith & Baird 2005, 2007a, 2007b). In those previous analyses, observer data from 1992 were used to fit the models, including data from before the introduction of SLEDs (i.e., before 2001). Aside from a recent summary of protected species bycatch (Abraham & Thompson 2009), no previous estimates have been made of total captures in fisheries other than the Auckland Islands squid fishery.

In this report, estimates are provided for the four fisheries listed in Table 2. The model used to estimate captures in the Auckland Islands squid fishery is a re-implementation of the Smith & Baird (2007b) Bayesian model, originally used to estimate captures in the 2004–05 fishing year. A simpler model is used to estimate captures in the southern blue whiting fishery, and ratio estimates are presented for the remaining two trawl fisheries. In these other fisheries there are no SLEDs, captures are equivalent to interactions, and there is no need to calculate exclusions or attributed mortalities.

Table 1: Terminology used in this report, for sea lion captures in the Auckland Islands squid fishery. Further information can be found in Smith & Baird (2007b).

Term	Definition
Auckland Islands squid fishery	Trawlers targeting squid in the Auckland Islands part of the SQU 6T fishing area.
SLED	Sea lion exclusion device, a mitigation device used in the Auckland Islands squid fishery. SLEDs are fitted into the trawl net, providing a way for sea lions that are inside the net to escape. A cover net can be tied down over the exit when the SLED is not being used.
Approved SLED	A SLED that has been certified by the Ministry of Fisheries as meeting specifications.
Closed net	A trawl net that either does not have a SLED fitted, or that has a SLED fitted with the SLED exit covered so that sea lions are unable to escape.
Open net	A trawl net that has a SLED fitted with the SLED's exit being open.
Observed captures	The number of sea lions brought on deck both dead and alive, during observed trawls. Decomposed animals and any sea lions that climb on board the vessel are excluded (Figure 3(a)).
Captures	An estimate of the total number of sea lions captures, calculated as the sum of observed captures and the estimated captures that would have been recorded on unobserved trawls, had observers been present (Figure 3(b)). In Smith & Baird (2007b), captures were referred to as landed captures.
Interactions	An estimate of the number of sea lions that would have been caught if no SLEDs were used (Figure 3(f)).
Strike rate	Sea lion interactions per 100 trawls.
Exclusions	An estimate of the number of sea lions interacting with a net but not being brought on board the vessel. This is calculated as sea lion captures subtracted from interactions (Figure 3(c)).
FRML (Fisheries Related Mortality Limit)	The maximum number of sea lion mortalities permitted in the Auckland Island squid fishery. This is converted into a permitted number of trawls in this fishery by dividing by an assumed strike rate.
Discount rate	The discount rate is a percentage reduction in the assumed strike rate for trawls that use approved SLEDs, used when determining the amount of fishing effort permitted in the Auckland Islands squid fishery under the FRML.
Attributed mortality	The attributed mortality is the sum of interactions on trawls with unapproved SLEDs, and a percentage (100% less the discount rate) of interactions on trawls with approved SLEDs (Figure 3(d, e)). If the discount rate was 0%, the attributed mortalities would be the same as the interactions. Attributed mortality also includes any animals released alive.

Table 2: Summary of the estimates made for each fishery

Area	Fishery	Estimation method	Estimated quantities
Auckland Islands	Squid trawl	Bayesian model	Captures, Strike rate, Interactions, Attributed mortalities, Exclusions
Auckland Islands	Other trawl	Ratio	Captures, Strike rate
Campbell Island	Southern blue whiting	Bayesian model	Captures, Strike rate
Stewart-Snares shelf	Squid	Ratio	Captures, Strike rate

The data set used to fit the models, and make the ratio estimates, ranges over the 12 year period from 1 October 1995 to 30 September 2007. Although the primary focus of this report was to estimate sea lion captures in the 2006–07 fishing year, the methods used also provided estimates for every year during this 12 year period.

2. METHODS

2.1 Data Sources

All commercial trawler activity reported to the Ministry of Fisheries is entered into the *warehou* database (Ministry of Fisheries 2008). The database includes a record of trawl events in the New Zealand Exclusive Economic Zone (EEZ). Deepwater trawlers, like those operating around the subantarctic islands, record details of trawl events on Trawl Catch Effort Processing Return (TCEPR) forms, including the date, time, and position of the start and end of each trawl. The *warehou* data were assumed to be a complete record of trawl effort, and were used as the authoritative source for the trawl date, time, and location information required for the modelling.

The New Zealand fishing year runs from 1 October to 30 September in the following year. Data were used from the 1995–96 to the 2006–07 fishing years. In cases where the fishing year is indicated by a single year, such as in the figures, the second year is used. For example, 2007 or 07 refers to the 2006–07 fishing year.

The Ministry of Fisheries observer programme collects data on mammal and sea bird captures in New Zealand fisheries, including sea lion captures. The observers identify the species of any non-fish bycatch, recording the time and location of the captures. These data are keyed into the databases managed by the National Institute of Water and Atmospheric Research (NIWA) on behalf of the Ministry (Ministry of Fisheries 2008). Both the TCEPR effort and observer records were groomed, correcting for errors in date, time, and position fields. One trip, observed between 1 February and 3 March 1998, had no corresponding records in the TCEPR data. Effort data were inferred from the observer data on that trip, and were added to the effort record. All of the observer records were then linked to the effort data from TCEPR forms, by using the rules given in Table 3. This linking allowed the observed sea lion captures

Table 3: Linking between observed Auckland Island squid trawls and TCEPR effort records from *warehou*, for trawls made between 1 October 1995 and 30 September 2007. All linking was between trawls made by vessels with the same vessel key in both data sets. The table gives a description of the rules used, in the order that they were applied, and the number of trawls that could be matched between the observer and effort data using each rule.

Linking rule	Number of trawls
Trawls at same time, not in summer	1 848
Trawls at same time, in summer	671
Trawls at same time, adjusted to NZST, and same position, summer	3 403
Trawls at same time, adjusted to NZST, and same position, not summer	10
Trawls at similar time, trip already matched, summer	650
One unmatched event on each data set on the same day	249
One unmatched event on each data set, same day, over midnight	36
Gap of one event between matched trawls on both data sets	31
Gap of more than one event between matched trawls on both data sets	46
Unmatched trawls	65
Total number of observed trawls	7 009

to be associated with the trawl effort. The rules were applied in the order given in the table, with earlier rules assumed to imply a more certain linking. The observer and TCEPR records were considered to be at the same time if the start and end time were both within 10 minutes of each other, and at similar times if they were within 70 minutes of each other. They were considered to be at the same position if both the latitude and longitude of the trawl start position were within one sixth of a degree of each other. Observers record times in New Zealand Standard Time (NZST) and fishers record times in New Zealand Daylight Time (NZDT). Some rules were needed to allow the use of two different clocks to be corrected.

After the linking rules had been applied there were still 65 unmatched trawls (less than 1% of observations) in the Auckland Islands squid fishery. Two observed sea lion captures in the Auckland Islands squid fishery were excluded from the data used for the modelling because they were on observed trawls that were not recorded in the TCEPR data. These two captures, in 1998 and 2006, represented 1% of observed captures.

Three other sea lion captures were removed from the data set (from 1996, 1997, and 2002), because the observer recorded the animal as being long dead, or decomposing. Two sea lion captures (in 2001 and 2006) were added to the data set, as the animals were recorded by observers as fur seals but were determined to be sea lions during subsequent necropsies.

Records of SLED use in 2006–07 were collected by the Deepwater Group Limited. The SLED data set included a trawl by trawl record of whether a SLED was used, whether the SLEDs had been approved by the Ministry, and if the cover net was closed or open. Previously these data had been collected by the Seafood Industry Council. These industry data were linked to the TCEPR effort data. The SLED data from the Seafood Industry Council used a different vessel identifier from the vessel keys in the Ministry databases. The first step in linking the SLED data to the *warehou* data involved matching trips together to allow vessel identifiers to be matched. This was done in stages: 37 vessels had trips with exactly the same start and end dates, and the same number of trawls; 3 vessel matches were made by relaxing the condition on the number of trawls in a trip to allow it to be different by 3, and 5 vessel matches were made manually. Having matched the vessels together, individual trawl records could then be linked. In the fishing years since 2000–01, 95% of the squid trawl events near the Auckland Islands were able to be matched exactly with events given in the industry SLED data. For trawls that could not be matched between the TCEPR and SLED data, SLED use was inferred using a range of increasingly general criteria from other SLED usage by the same vessel in the same fishing year. A summary of the data linking is given in Table 4.

In Figure 4, SLED use on observed trawls is compared with the data used by Smith & Baird (2007b). There were some differences in SLED use resulting from the independent grooming of the data. In general, the grooming described here resulted in more observed closed net trawls than were assumed by Smith & Baird (2007b). The difference in 2000–01 was because the data provided by the Deepwater Group did not include that fishing year. This difference was not important for the modelling, as all nets during that fishing year were closed (i.e., all SLEDs had cover nets tied over their escape hatches). Some vessels reported using SLEDs in SQU 6T with closed cover nets in the 2006–07 fishing year. After discussion with the Ministry of Fisheries, it was assumed that this was a mistake in the form completion or data entry, and that all SLEDs in that year were used without cover nets. There remained 27 squid trawls within SQU 6T in 2006–07 that were made without SLEDs. These trawls were spread across six vessels.

Table 4: Linking between industry recorded SLED use and effort data, for trawls in the Auckland Islands squid fishery between 1 October 2000 and 30 September 2007. The summary gives a description of the linking rule, the number of trawls, and the number of observed trawls that are linked by each rule.

Linking rule	Trawls	Obs. trawls
SLED use, cover net, and approved flags (indicates which flag a vessel is flying) taken from a trawl record on the same day, with the same trawl number on that day, and by the same vessel.	12 154	4 123
SLED use, cover net, and approved flags consistent for the vessel through out the fishing year.	315	96
SLED use, cover net, and approved flags consistent for the vessel on that day.	81	42
SLED use, cover net, and approved flags taken from the most recent matched trawl for that vessel, in the same fishing year.	173	115
For unmatched trawls from before 1 October 2002, assume no SLED was used.	58	7
For remaining the unmatched trawl in 2004–05, assume that an unapproved open SLED was used.	1	0
Total number of trawls	12 782	4 383

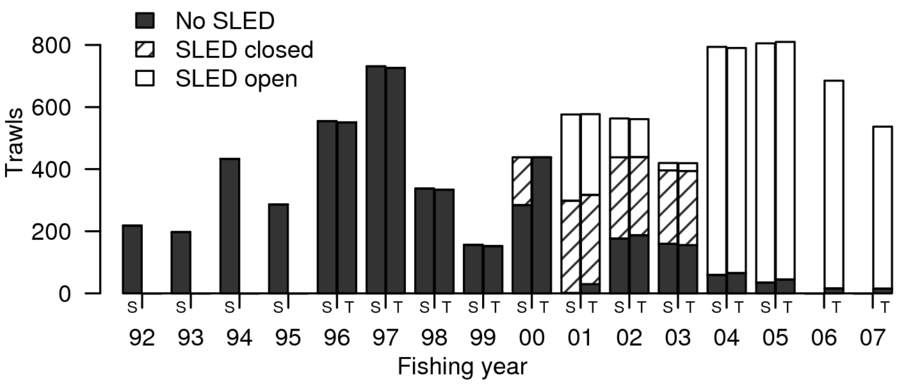


Figure 4: Time series of observed trawls, categorised into trawls using no SLED, a SLED with the cover on, and a SLED with no cover. The data from Smith & Baird (2007a) are included for comparison, and are marked with an 'S'. The data groomed for this report are marked with 'T'.

2.2 The squid fishery around the Auckland Islands

In this report we re-implemented the model published by Smith & Baird (2007b) to estimate sea lion captures in the Auckland Islands squid trawl fishery in the 2004–05 fishing year. Using the same model framework ensured consistency with previously published estimates. The model was completely rewritten using only the methods published by Smith & Baird (2007b). The basic unit of effort used in the model was a single trawl event. Observers recorded the number of sea lions caught per trawl, and the objective of the estimation was to predict the expected number of captured sea lions on the unobserved trawls. Trawls in fishing year y were indexed by vessel key, j, and number, k, and the number of sea lions captured on trawl jk in year y was denoted c^y_{jk}. The captures, c^y_{jk}, were assumed to follow a negative-binomial distribution with a mean, μ^y_{jk}, that varied from trawl to trawl, and with an over-dispersion, θ, that was the same for all trawls. The negative-binomial distribution was implemented using a Poisson distribution with a gamma distributed mean. This was achieved by multiplying the mean strike rate by a value randomly sampled from a gamma distribution with shape θ and unit mean. As $1/\theta$ decreases the model becomes less dispersed, with the limiting case, when $1/\theta = 0$, being a Poisson model. The model parameter θ was given the uniform shrinkage prior (Natarajan & Kass 2000, Gelman 2006) with mean equal to the mean number of sea lion captures per trawl, μ_θ:

$$c^y_{jk} \sim \text{Poisson}(\mu^y_{jk} g_\theta), \tag{1}$$
$$g_\theta \sim \text{Gamma}(\theta, \theta), \tag{2}$$
$$\theta \sim \text{Uniform-shrinkage}(\mu_\theta). \tag{3}$$

The mean strike rate μ^y_{jk} was composed of three components multiplied together: a random year effect λ_i, a random vessel-year effect v^y_j, and a linear regression component that depended on the value of covariates x^{yb}_{jk} and the regression coefficients β_b,

$$\mu^y_{jk} = \lambda^y v^y_j \exp\left(\sum_b x^{yb}_{jk}\beta_b\right) \quad . \tag{4}$$

The random year effects, λ^y, carried the mean strike rate for each year, and were drawn from a single log-normal distribution with mean μ_λ and standard deviation σ_λ. These hyper-parameters were given fixed prior distributions:

$$\log \lambda^y \sim \text{Normal}(\mu_\lambda, \sigma_\lambda), \tag{5}$$
$$\mu_\lambda \sim \text{Normal}(-4, 100), \tag{6}$$
$$\sigma_\lambda \sim \text{Half-Cauchy}(0, 25). \tag{7}$$

For each vessel and year combination there was a vessel-year random effect, v^y_j, that was drawn from a gamma distribution with mean one. This allowed the strike rate for each vessel in each year to have a mean different from the year effect λ^y. The shape of the gamma distribution was defined by the hyper-parameter, θ_v. The shape parameter was given the uniform shrinkage prior, with mean equal to the mean number of sea lions caught per vessel, μ_{vs}. For vessels that were not observed in a given year a value of the random effect v^y_j was drawn from the gamma distribution:

$$v^y_j \sim \text{Gamma}(\theta_v, \theta_v), \tag{8}$$
$$\theta_v \sim \text{Uniform-shrinkage}(\mu_{vs}). \tag{9}$$

The covariates used in the model were those selected by Smith & Baird (2007b) and are listed in Table 5. The choice of these covariates followed work specifically focussed on identifying the factors associated

Table 5: Covariates used in the Auckland Islands squid model.

Covariate	Definition
distance to colony	A continuous variable, the logarithm of distance to nearest sea lion breeding colony,
trawl duration	A continuous variable, the logarithm of trawl duration,
sub-area	A two level factor variable, indicating in which sub-area the start of the trawl is located. The Auckland Islands part of the SQU 6T area was divided into two sub-areas, NW (north of 50.45° south and west of 166.95° east), and S&E (the rest of the Auckland Islands part of SQU 6T),
open-net	A factor variable, indicating that the net had a SLED attached and that the cover net was open.

with sea lion captures (Smith & Baird 2005), and a subsequent estimation of sea lion captures in the 2003–04 fishing year (Smith & Baird 2007a). To improve model convergence, the covariates were normalised before model fitting by subtracting the mean value and dividing by the standard deviation. This normalisation was removed before presenting results from the model. The regression coefficients, β_b, were assumed to be the same for all years. The priors for the regression coefficients of the three covariates *distance to colony*, *trawl duration*, and *sub-area* were non-informative normal distributions,

$$\beta_b \sim \text{Normal}(0, 100). \tag{10}$$

The presence or absence of a SLED with the cover off was treated as a covariate along with the others. However, the regression coefficient $\beta_{open\text{-}net}$ was transformed into the SLED retention probability, $\pi = \exp\left(\beta_{open\text{-}net}\right)$, and was given a uniform prior,

$$\pi \sim \text{Uniform}(0, 1). \tag{11}$$

The model was coded in the BUGS language, a domain specific language for describing Bayesian models. The JAGS (Plummer 2005) software package provides tools for fitting models described in the BUGS language using Markov chain Monte Carlo (MCMC) methods. This system is similar to the WinBUGS (Spiegelhalter et al. 2003) models used by Smith & Baird (2007b).

To ensure that the model had converged, a burn-in of 100 000 iterations was made. From there the model was run for another 100 000 iterations and every 20$^{\text{th}}$ 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, version 1.0.3).

2.2.1 Model estimates of interactions, captures, and strike rate

From the fitted model, posterior distributions were calculated for the captures, interactions, strike rate, attributed mortalities, and exclusions. These quantities are defined in Table 1, and illustrated in Figure 3. For each sample from the Markov chain, the estimated number of sea lion interactions i_{jk} were calculated for each trawl (here, and in what follows, the year index y is assumed). The mean interaction rate was given by the linear predictor, μ_{jk} (Equation 4), but with the net assumed to be closed, irrespective of whether or not a SLED was used. This was enforced by setting the *open-net* covariate to the value corresponding to a closed net. The number of interactions on a trawl can be interpreted as the number of sea lions that would have been caught if a SLED had not been used. They were obtained from the mean interaction rate by sampling from a negative binomial distribution (following Equations 1, 2, and 3). From the interactions, the captures were calculated by sampling from a binomial distribution with probability given by the SLED retention probability and size given by the number of interactions,

$$c_{jk} \sim \begin{cases} \text{Binomial}(\pi, i_{jk}) & \text{(open net)}, \\ i_{jk} & \text{(closed net)}. \end{cases} \tag{12}$$

This procedure simulated the independent random capture of interacting sea lions, with probability π. It ensured that, on any trawl, the number of captures was less than or equal to the number of interactions. The number of sea lion exclusions on a trawl was calculated as the difference between the interactions and the captures, $e_{jk} = i_{jk} - c_{jk}$.

The estimated quantities were calculated as follows:

$$
\begin{aligned}
\text{Captures} \quad C &= \sum_u c_{jk} + C_o, & (13)\\
\text{Interactions} \quad I &= \sum_u i_{jk} + \sum_o e_{jk} + C_o, & (14)\\
\text{Strike rate} \quad \mu &= I/n, & (15)\\
\text{Exclusions} \quad E &= I - C, & (16)\\
\text{Attributed mortalities} \quad A &= \sum_{as} \text{Binomial}(1 - DR/100, i_{jk}) + \sum_{ns} i_{jk}, & (17)
\end{aligned}
$$

where C_o is the number of observed captures in the fishery, $\sum_u$ denotes a sum over unobserved trawls, $\sum_o$ denotes a sum over observed trawls, $\sum_{as}$ denotes a sum over trawls with approved SLEDs, $\sum_{ns}$ denotes a sum over trawls with no SLEDS or with unapproved SLEDs, the total number of trawls in the fishery is denoted by n, and DR is the percentage discount rate. The attributed mortalities were calculated for discount rates of 20%, 35%, and 50%. On tows with approved SLEDs, each interaction was counted as an attributed mortality with probability $1 - DR/100$. On tows without SLEDs, or with unapproved SLEDs, all interactions were counted as attributed mortalities.

Posterior distributions of these quantities were obtained by calculating them for every sample from the Markov chain. The posterior distributions were summarised by the median, mean, and 95% confidence interval (calculated from the 2.5% and 97.5% quantiles).

2.2.2 Comparisons with previous work

The model of sea lion captures in Auckland Islands squid fisheries published by Smith & Baird (2007b) was fitted to observer data from the fishing years 1991–92 to 2004–05, while the model presented in this report was fitted to the TCEPR data from 1995–96 to 2006–07. This was possible because the observer record had been linked to the TCEPR data for the whole period. The methods used to groom and link the data resulted in the number of observed captures in the fitted data being different by one for 5 of the 10 years when there was overlap between the two data sets. The data set used by Smith & Baird (2007b) included two decomposing animals that we excluded from the data, and excluded an animal that was found to be a sea lion during necropsy. One other difference was due to the exclusion in our data set of an animal that was captured on an observed trawl that could not be linked to a TCEPR record in 2005–06. We also had an additional record of a sea lion capture in 2002–03.

By fixing the values of the four covariates, and setting the random vessel-year effect to one, it was possible to interpret the random year effects, λ^y, as the mean interaction rate for each season. Smith & Baird (2007b) fixed the covariates at the mean values of the continuous covariates and the most common value of the two discrete covariates. To make a direct comparison with the estimated values of the year effects in their report, the values of the covariates were fixed to the same values: a trawl with no SLED, in the NW sub-area, at a distance of 48.3 km from the nearest sea lion colony, that took 3.26 hours. There were 10 years in the intersection of the two data periods where the mean interaction rate could be directly compared.

The data sets returned by Smith & Baird (2007b) as part of project ENV2005–02 were used to compare the two implementations of the model. The extracts included the observer programme data from 1992 to 2005, and TCEPR data for the 2004–05 fishing year. The data were already groomed, with derived covariates calculated. The re-implemented model was fitted to these data, and the estimated values of the various model parameters were compared with those published by Smith & Baird (2007b). Because the prepared TCEPR data were made available only for 2004–05, comparisons of predicted values were possible only for that one year. Following the original report, the model was run for a 100 000 iteration burn-in, and then for a further 100 000 iterations, keeping every 20th iteration to sample the posterior distribution.

2.3 Southern blue whiting fishery east of Campbell Island

There was a small, but increasing, number of sea lion captures in the southern blue whiting fishery east of Campbell Island. In the 2007 season, six sea lions were observed captured, compared to seven in the squid fishery around the Auckland Islands. A simple Bayesian model was used to estimate the captures in the southern blue whiting fishery. There were a total of only 13 observed sea lion captures in the data set, so the model was necessarily much simpler than the squid fishery model.

It was more natural to use calendar years rather than fishing years in the southern blue whiting fishery, as the season extended beyond the end of the fishing year (September 30). The fishery was focused in a short part of the year, with all the fishing effort between August and November. Figure 5 presents the temporal distribution of effort through the year. The dates of observed captures are indicated with vertical lines. Note that sea lion captures occurred throughout the period the fishery was operating, with the possible exception of fishing before the beginning of September. Despite observer coverage from earlier years, the first sea lion capture was observed in 2002. The capture data appear to be non-stationary, with the strike rate increasing with time. The data set used for modelling was restricted to the years 2002 to 2007; this restriction prevents the model being influenced by data from early years, when no captures were observed.

The southern blue whiting fishery operates on the Pukaki Rise, and on all sides of Campbell Island. However, all the sea lion captures have been observed on the shelf to the east of Campbell Island. The data set was restricted to the effort east of Campbell Island, and is plotted in Figure 6.

Nine derived variables were examined to see if a correlation could be found with sea lion captures (Table 6). By using the step function from the MASS R package (Venables & Ripley 2002), different combinations of the nine variables were tried to see which variables were potential covariates. This was the method used by Smith & Baird (2005) to find covariates associated with sea lion captures in the Auckland Islands squid fishery. The only variable with any predictive correlation was the latitude at the

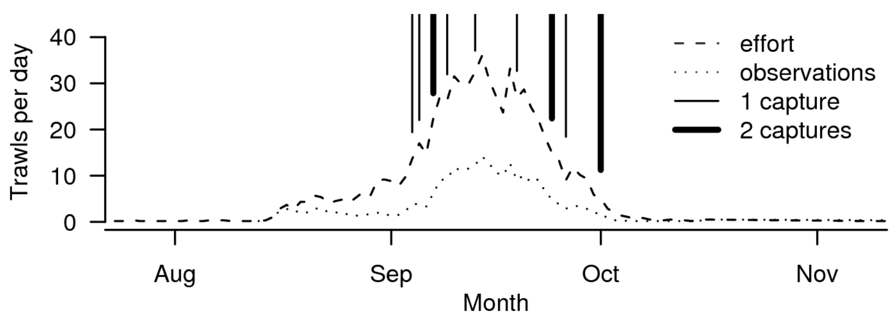


Figure 5: Average number of trawls per day for total effort and observed effort in the southern blue whiting fishery east of Campbell Island, for the years 2002 to 2007. Vertical lines indicate when capture events occurred.

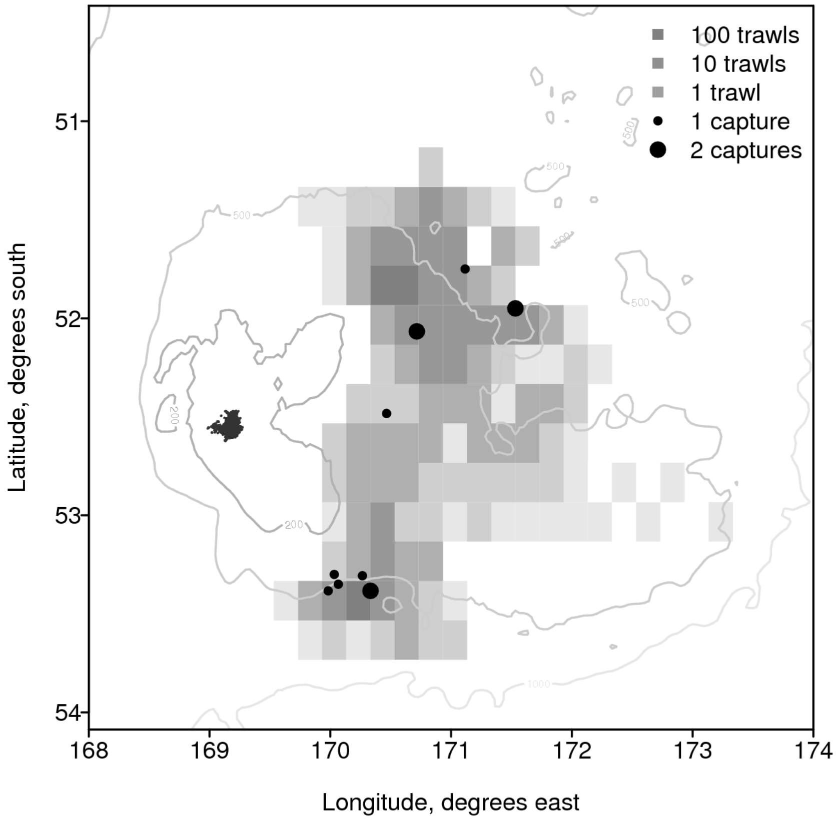


Figure 6: Map of average annual effort in the southern blue whiting fishery east of Campbell Island and location of captured sea lions, 2002 to 2007

start of the trawl, with more captures predicted in the southern part of the fishery. Because of the small number of captures, it was decided not to include latitude as a covariate. No variables were included as covariates in the final model.

The southern blue whiting model was a variation of the squid model described above. Simplifications were necessary, primarily due to the very small number of observed captures. Vessel-year random effects were not feasible due to the few vessels that had observed captures. Attempts to fit the data to the negative-binomial error model did not converge, either with uniform shrinkage prior on the overdispersion, or with fixed overdispersion. The model used a Poisson error model, and included only random year effects. The year effects allowed for a varying strike rate, without assuming any trend over the years.

2.4 Remaining fisheries

Ratio estimates of sea lion captures were calculated for the two remaining fisheries: the non-squid Auckland Islands trawl fisheries, and all the trawl fisheries at the south end of the Stewart-Snares shelf. The non-squid Auckland Islands trawl fisheries were defined as all trawls in the Auckland Islands part of the SQU 6T fishing area not targeting squid, and the southern end of the Stewart-Snares shelf was defined as the general statistical areas 028 and 602, but excluding SQU 6T.

Table 6: Potential covariates explored in the southern blue whiting fishery.

Covariate	Definition
depth	Depth of water at start of trawl
distance	Distance to the centre of Campbell Island in kilometres
month	Month of the year as a factor
day	Day of the year (a number between 1 and 366)
nation	Flag state of the vessel
daytime	Whether the start of the trawl is during the day
altitude	Solar altitude at start of trawl
duration	Duration of trawl in hours
latitude	Latitude at start of trawl

Ratio estimates were calculated using data from the fishing years 2004–05 to 2006–07, by assuming a constant capture rate over these years. The estimated number of captures in a year, y, was

$$C^y = C_o^y + C_u^y, \tag{18}$$

where C_o^y were the observed captures and C_u^y were the estimated captures during unobserved fishing. The unobserved captures were estimated by calculating an average rate from the observed data, and applying that to the unobserved effort. If the number of observed trawls in a year was o^y, then the average sea lion capture rate was

$$r = \sum_y C_o^y / \sum_y o^y, \tag{19}$$

where the sum was over all the fishing years that were included in the estimate. The unobserved captures in each year were then estimated as

$$C_u^y = r(n^y - o^y), \tag{20}$$

where n^y was the total number of trawls in year y. The uncertainty in the captures, C^y, was estimated using bootstrap re-sampling (e.g., Davison & Hinkley 1997). Data from the observed trawls were re-sampled 5000 times, and the total bycatch was recalculated for each sample from Equations 18, 19, and 20. The 95% confidence interval in the estimate was calculated from the 2.5% and 97.5% quantiles of the distribution of re-sampled captures.

3. RESULTS

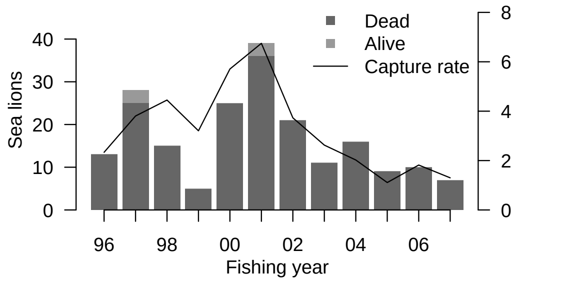
3.1 The Auckland Islands squid fishery

The 12 year time series of trawl effort, observed effort, and observed captures is presented in Figure 7 and Table 7. The 2000–01 fishing year stands out because it was almost completely observed, and had the highest capture rate of 6.7 sea lions per 100 trawls. The observed capture rate has been trending down since then, staying under 2 captures per 100 trawls for the last three fishing years. The 2006–07 fishing year saw trawl effort drop to 1320 trawls from 2465 trawls in the previous year. In the 2006–07 fishing year only seven sea lions were observed captured, the lowest number of captures since 1998–99. In 2006–07, there were six female sea lions and one male sea lion caught in the Auckland Islands squid fishery. In contrast, the eight animals caught in other fisheries during 2006–07 were all male.

In the 2006–07 fishing year, observers recorded the location of sea lion captures on trawls where SLEDs were used. This information is summarised in Table 8. The gap between the bars of the SLED grids was originally required to be 28 cm. With this spacing, some sea lions passed through the grid and were caught in the codend. Measurements of the girth of animals in the field suggested that a bar spacing of

(a) Observed sea lion captures and observed capture rate

(b) Trawl effort (observed and unobserved), and observer coverage



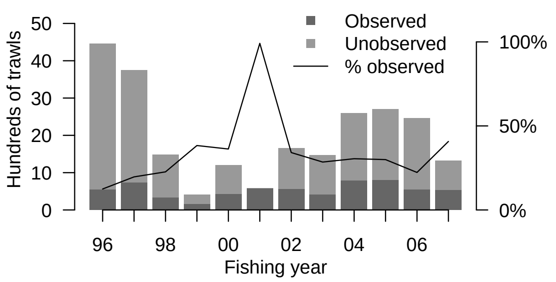


Figure 7: Annual time series of (a) observed captures and observer coverage, and (b) trawl effort, observed trawl effort, and percentage of effort observed, in the Auckland Islands squid fishery by fishing year

23 cm would prevent 95% of female sea lions from being able to pass through the grid into the codend (Chilvers 2005). This bar spacing was adopted as the standard from the 2005–06 fishing year onwards. Before the 2006–07 season, a detailed audit of the SLEDs was made, and any that differed from the specifications were altered to ensure consistency across the squid fleet (Clement & Associates 2007). Underwater video, from a camera attached to a trawl net, shows that the SLED hoods may sometimes collapse during deployment and cover the escape hole (Clement & Associates 2007). It is possible that this collapse was related to the failure of the sea lions to escape from the net.

In the 2006–07 year, no sea lions passed through the bars of a SLED into the cod end, but there were three animals that were coded by the observers as being "stuck in the SLED grid" (Code D; Table 8). While this coding may suggest that animals were stuck as a result of inadequate bar spacing, this may not be the case. Subsequent interviews with the Ministry of Fisheries observers who recorded the capture of these three animals indicated that in at least two of the cases it appeared that parts of the sea lions (e.g., the tail flippers) ended up protruding through the SLED grid bars as a result of the nets being hauled (Eric Mellina, Ministry of Fisheries, pers. comm.).

Table 7: Annual trawl effort (number of tows), observer coverage, observed numbers of sea lions captured and killed, and the observed capture rate (sea lions per 100 trawls), in the Auckland Islands squid fishery.

	Effort	% Obs.	Captured	Killed	Rate (%)
2006–07	1320	41	7	7	1.3
2005–06	2465	22	10	10	1.8
2004–05	2707	30	9	9	1.1
2003–04	2595	30	16	16	2
2002–03	1470	29	11	11	2.6
2001–02	1649	34	21	21	3.7
2000–01	583	99	39	36	6.7
1999–00	1208	36	25	25	5.7
1998–99	407	38	5	5	3.2
1997–98	1487	23	15	15	4.5
1996–97	3740	20	28	25	3.8
1995–96	4467	12	13	13	2.3

Table 8: Location of sea lion captures, for sea lions caught in the Auckland Islands squid fishery. The codes are entered by observers into the comments field of the non-fish bycatch form, and the descriptions are taken verbatim from the instructions to observers.

Description	Code	Number
At the grid, in the SLED lengthener (ahead of the grid)	B	1
Between the grid and the hood	B/C	1
In the SLED hood	C	2
Stuck in the SLED grid	D	3
Total		7

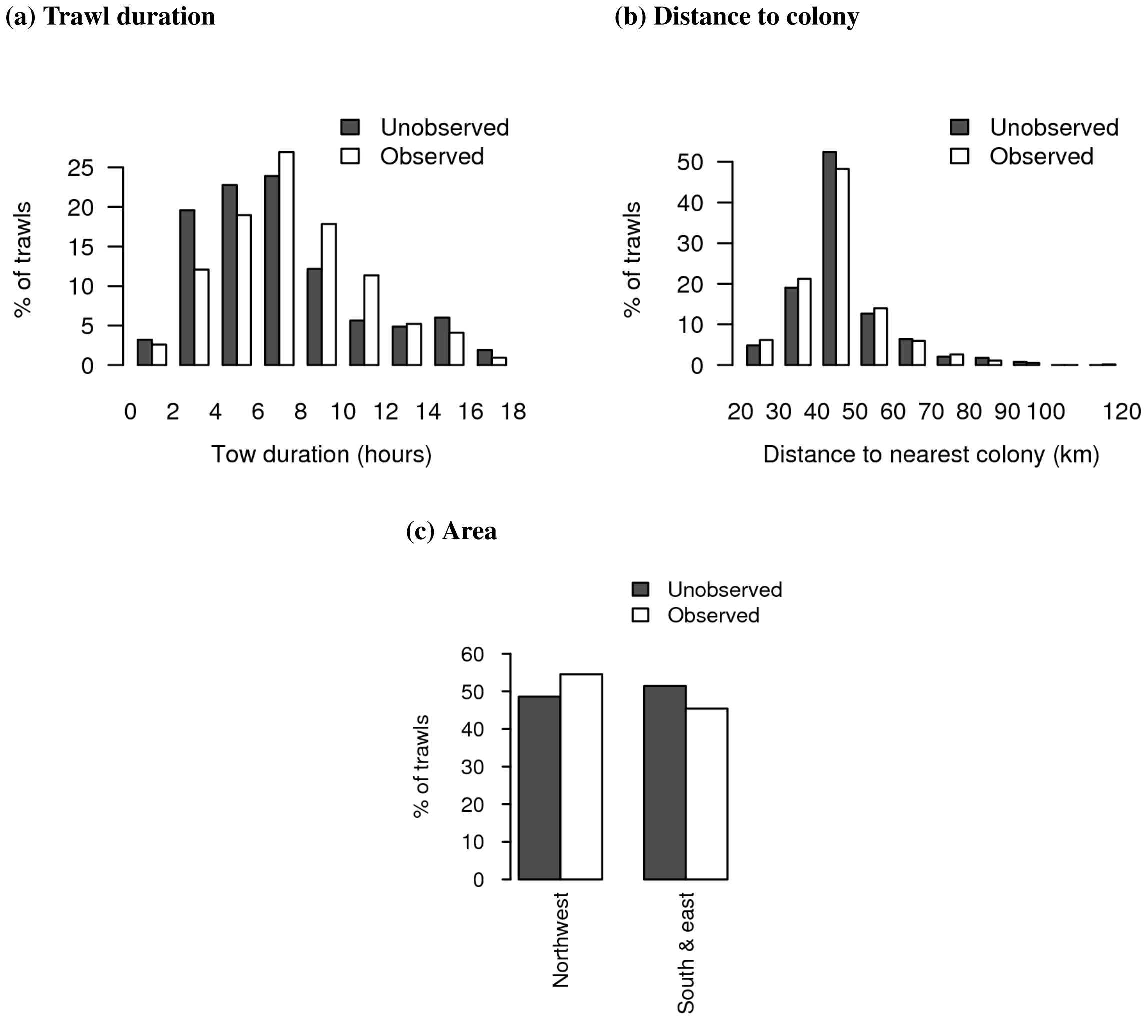


Figure 8: Distribution of covariates during observed and unobserved trawls in the Auckland Islands squid fishery for 2006–07 (a) Trawl duration (b) Distance to colony (c) Area

Table 9: Parameter estimates from the Auckland Islands squid fishery model.

	Mean	2.5%	50%	97.5%
Retention probability, π	0.242	0.138	0.234	0.393
Dist. to colony exponent	-0.897	-1.452	-0.896	-0.355
Duration exponent	0.685	0.349	0.683	1.035
Subarea S&E effect	0.508	0.340	0.498	0.730
Extra disperson, θ	2.726	1.144	2.603	4.894

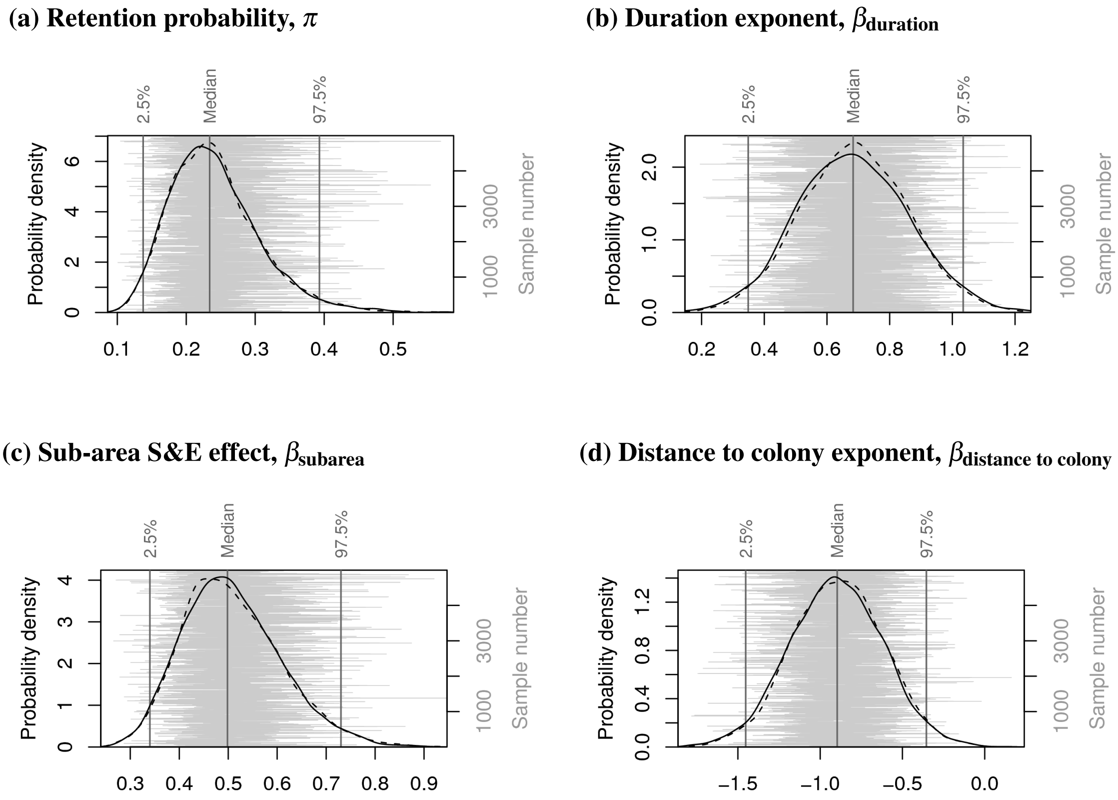


Figure 9: MCMC chain output, and the densities of the four covariant regression coefficients for (a) SLED retention probability (b) duration exponent (c) Sub-area S&E effect (d) distance to colony exponent.

3.1.1 Covariates

The distribution of the model covariates during trawls made in the Auckland Islands squid fishery in 2006–07 are shown in Figure 8. The observed trawls were broadly representative of the unobserved effort. Trawl duration in 2006–07 varied between half an hour and 18 hours (Figure 8(a)), with the most frequent trawl duration being between six and eight hours. There was some tendency for the unobserved trawls to be shorter in duration than the observed trawls. The distance to the nearest colony (Figure 8(b)) varied from 20 to 120 kilometres, with a strong peak between 40 and 50 kilometres. Trawls were evenly divided between the two sub-areas (Figure 8(c)), with a small bias towards the northwest sub-area in the observer data. The open-net data are not shown, as nearly all trawls in the 2006–07 Auckland Islands squid fishery used nets fitted with SLEDs.

The model converged successfully, passing the diagnostic criteria for the key parameters. The posterior densities of the four regression coefficients, β_b, are presented in Table 9 and Figure 9, together with traces of the two chains. The densities for the two chains were very similar, an indication of model convergence. The covariates enter the expression for the strike rate, μ^y_{jk} as the exponent of the product of the covariate and the corresponding regression coefficient, $\exp(x^{yb}_{jk}\beta_b)$ (Equation 4). In Figure 10 the mean annual value of this expression is plotted for each covariate. The product of the contribution from each covariate is also shown, giving the total contribution from all the covariates. The multiplicative contribution from the distance to colony and the sub-area covariates fluctuated around one, but did not exhibit any long-term trend. The strongest signal was the introduction of SLEDs in the 2000–01 fishing year, which caused a fall in the strike rate. The mean duration of trawls increased steadily since 2000–01,

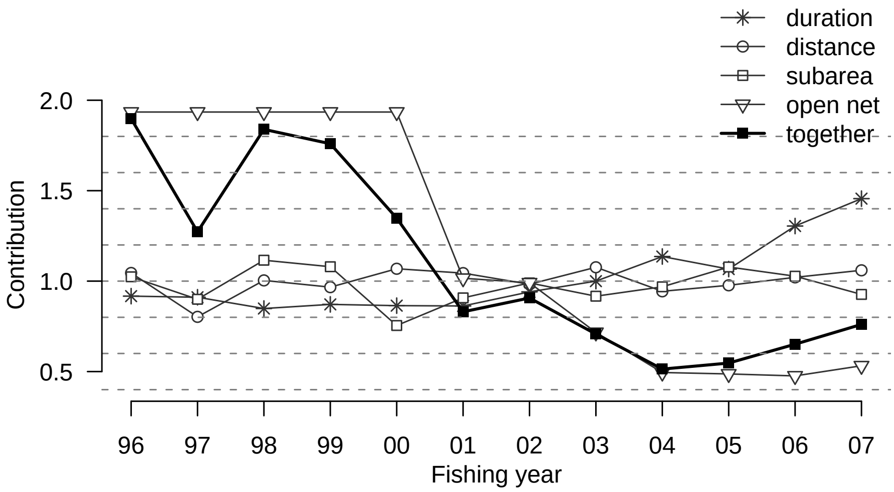


Figure 10: The multiplicative contributions of the annual mean values of covariates scaled by the regression coefficients for the Auckland Islands squid fishery: duration of trawl, distance to nearest colony, S&W sub-area factor, and open-net factor.

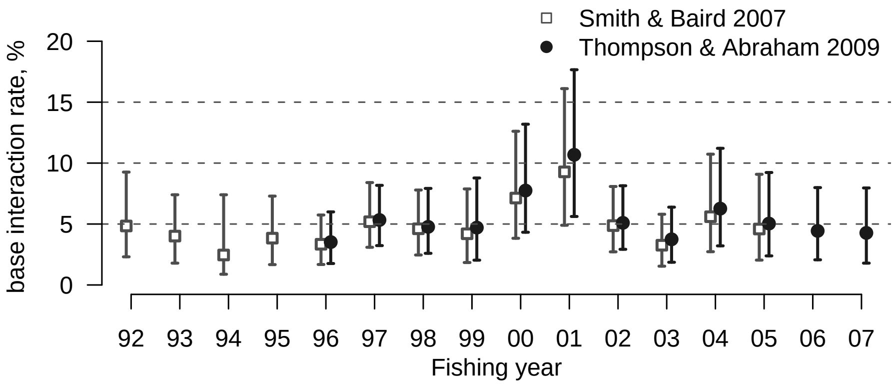


Figure 11: Annual time series of base interaction rates (captures per 100 trawls) for the Auckland Islands squid fishery, comparing the base rates published by Smith & Baird (2007b) with the base rates predicted by the current model.

and the corresponding contribution to the strike rate also increased. However, the effect of introducing SLEDs masked the impact. The total mean covariate contribution increased since 2004–05, largely due to the increasing trawl duration.

Complementary to the covariate contributions were the base interaction rates, obtained from Equation 4 by setting the covariates to fixed values and the vessel-year effects to one. These give the variation in the typical catch rate that was not related to changes in the covariates. The base interaction rates are shown in Figure 11, and are compared with results from Smith & Baird (2007b). Aside from the peak in fishing years 1999-2000 and 2000–01, there was very little variation in this strike rate, with none of the base rates outside those two years being significantly different from five sea lion captures per 100

Table 10: A comparison of the distribution of number of sea lion captures per trawl for observed captures, and predicted captures on the observed data, for the 12 fishing years 1995–96 to 2006–07 for the Auckland Islands squid fishery.

Number	Observed	Predicted	
		Median	95% c.i.
0	6293	6400	(6362 - 6435)
1	166	163	(130 - 199)
2	13	14	(6 - 24)
3	1	2	(0 - 6)
4	1	0	(0 - 3)

trawls. For the 10 years where there was overlap, there was good agreement between the two model implementations, both in the mean values and the 95% confidence intervals.

The distribution of the number of predicted captures per trawl is compared with the observed data (Table 10). The close similarity indicates that the negative-binomial model was an appropriate description of the capture data.

The model predictions of total interactions, captures and strike-rate for the 12 years of data are plotted in Figure 12, and given in Table 11. The predicted total interactions diverged from the predicted captures following the introduction of SLEDs in 2000–01. The confidence intervals around the mean strike rate estimate increased since 2003–04, as can be seen in Figure 12(b). This was also due to the increase in SLED use, as more uncertainty came from the estimated retention probability. The annual fluctuations of the mean strike rate were not significant with respect to these uncertainty intervals, and the estimated strike rate appeared to have been stable over the last four years at between 5.3 and 6.4 sea lions per 100 trawls. Similarly the strike rate was estimated as being close to 4 sea lions per 100 trawls over the period from 1995–96 to 2001–02, with the exception of the 1999–2000 and 2000–01 fishing years. The large increase in the total number of interactions between 2003–04 and 2005–06 was due to an increase in effort in those years, visible in Figure 7(b). In 2006–07 the fishing effort fell, and there was a corresponding decrease in the mean of the posterior distribution of total interactions, from 144 predicted interactions in 2005–06 to 74 interactions in 2006–07.

A more detailed breakdown of the predictions for the 2006–07 fishing year is given in Table 12. Because the total number of interactions was lower in 2006–07, there was a smaller difference between the attributed mortalities associated with the different discounts applied to trawls using SLEDs. Even for a 35% discount, the confidence interval of the attributed mortalities included the mean value of the total interactions.

3.1.2 Comparison with previous modelling

The model of sea lion captures was also fitted to the same data set that was used for the most recently published other sea lion estimation model (Smith & Baird 2007b), for the 2004–05 fishing year. In Table 13 the covariate regression coefficients and predicted captures from the re-implemented model are compared with those published in Smith & Baird (2007b). The largest difference was the retention probability, with the predicted mean of 0.26 being lower than the mean of 0.28 reported by Smith & Baird (2007b). In Figure 13 the posterior density of the retention probability is shown, and the median retention probability reported by Smith & Baird (2007b) is indicated for comparison. Although the median values were different, the difference was small compared with the width of the distribution. The values of the other covariates were very similar in the two models. The estimated captures for 2004–05

(a) Predicted total interactions and captures, giving the mean and 95% c.i.

(b) Predicted mean strike rate, giving the mean and 95% c.i.

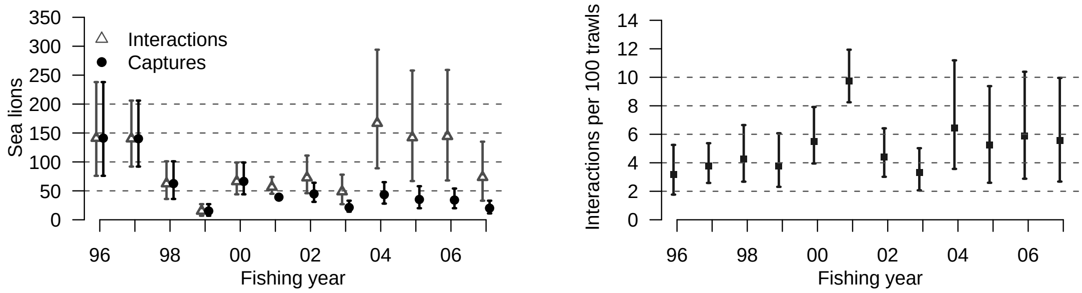


Figure 12: Annual time series from the 1995–96 fishing year to the 2006–07 fishing year of, (a) predicted total interactions and captures, and (b) the predicted mean strike rate as interactions per one hundred trawls for the Auckland Islands squid fishery.

Table 11: Summary of model results, giving estimated captures, interactions, and strike rate with 95% confidence intervals, in the Auckland Islands squid fishery.

	Captures		Interactions		Strike rate (%)	
	Mean	95% c.i.	Mean	95% c.i.	Mean	95% c.i.
2006–07	20	(11 - 33)	74	(32 - 136)	5.6	(2.7 - 10.0)
2005–06	34	(20 - 55)	144	(68 - 260)	5.9	(2.9 - 10.4)
2004–05	35	(20 - 57)	142	(67 - 260)	5.3	(2.6 - 9.4)
2003–04	43	(29 - 64)	167	(89 - 296)	6.4	(3.6 - 11.2)
2002–03	21	(14 - 33)	49	(25 - 80)	3.3	(2.1 - 5.0)
2001–02	45	(31 - 64)	73	(43 - 113)	4.4	(3.0 - 6.4)
2000–01	39	(39 - 40)	57	(37 - 80)	9.8	(8.2 - 11.9)
1999–00	66	(44 - 99)	66	(41 - 102)	5.5	(4.0 - 7.9)
1998–99	15	(7 - 27)	15	(5 - 29)	3.8	(2.3 - 6.1)
1997–98	62	(36 - 101)	63	(34 - 102)	4.3	(2.7 - 6.6)
1996–97	140	(92 - 206)	140	(91 - 207)	3.8	(2.6 - 5.4)
1995–96	141	(76 - 238)	141	(75 - 239)	3.2	(1.8 - 5.3)

Table 12: Predicted total interactions, attributed mortalities at discount rates (DR) of 20%, 35%, and 50%, captures, exclusions, and strike rate for the 2006–07 fishing year in the Auckland Islands squid fishery. Columns give the mean and selected percentiles of the posterior distribution.

	Mean	2.5%	50%	97.5%
Interactions	73.6	32	70	136
Attributed mortalities, 20% DR	59.6	26	57	110
Attributed mortalities, 35% DR	49.2	22	47	90
Attributed mortalities, 50% DR	38.8	18	37	72
Captures	20.0	11	19	33
Exclusions	53.5	19	50	109
Strike rate, %	5.58	2.68	5.31	9.96

Table 13: A comparison of the posterior distributions of regression covariates, and predicted totals for 2004–05 fishing year, as mean and percentiles, between the results published by Smith & Baird (2007b), and the reimplemented model fitted to the data released with ENV2005–02 for the Auckland Islands squid fishery.

	Smith & Baird (2007)				Thompson & Abraham (2009)			
Parameter	Mean	2.5%	50%	97.5%	Mean	2.5%	50%	97.5%
Retention probability, π	0.284	0.137	0.273	0.502	0.258	0.124	0.247	0.458
Dist. to colony exponent	-1.097	-1.671	-1.097	-0.543	-1.098	-1.665	-1.094	-0.534
Duration exponent	0.709	0.377	0.709	1.047	0.715	0.382	0.712	1.059
Subarea S&E effect	0.543	0.362	0.533	0.777	0.533	0.355	0.524	0.769
Extra disperson, θ	1.972	0.731	1.887	3.521	1.925	0.810	1.834	3.501
Interactions	132.0	61	123	257	141.9	63	131	280
Attributed mortalities, 20%	108.2	50	101	211	116.3	53	108	229
Captures	36.4	20	35	62	35.7	19	34	61
Exclusions	95.5	32	87	209	106.3	36	96	234
Strike rate, %	4.9	2.4	4.6	9.4	5.3	2.4	4.9	10.3

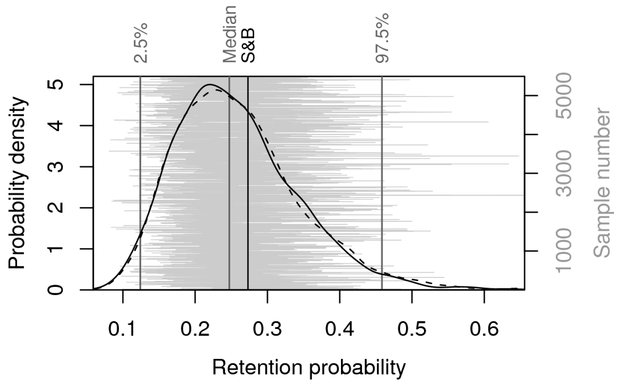


Figure 13: Markov chain output and density of the SLED retention probability, π, from the reimplemented model fitted to data used for Smith & Baird (2007b) for the Auckland Islands squid fishery. The published median value from Smith & Baird (2007b) has been added for comparison.

were tightly constrained by the data, and the two predictions were almost identical, with a mean of 35.7 compared with a mean of 36.4 in the original report. The other predictions for 2004–05 were higher in the reimplementation, reflecting the lower SLED retention probability. In particular, the mean strike rate was predicted to be 5.3 captures per 100 trawls, compared to 4.9 captures per 100 trawls in the original report.

3.2 Southern blue whiting fishery east of Campbell Island

A summary of the observed captures and effort in the southern blue whiting fishery is shown in Figure 14 and model predicted captures and strike rate are given in Table 14. The estimated number of captures and the strike rate have been steadily increasing since 2003, with an estimated total of 14 captures (95% c.i.: 7 to 27) in the 2007 fishing year. The estimated strike rate in 2007 was lower than the observed strike rate. This was because the model fits a mean strike rate across all the data (from 2002 to 2007) and represented the year-to-year variation as a random deviation from this mean. This had a tendency to pull the extreme values in towards the mean.

The model had a Poisson error structure, and Table 15 shows that the model over-estimated the number

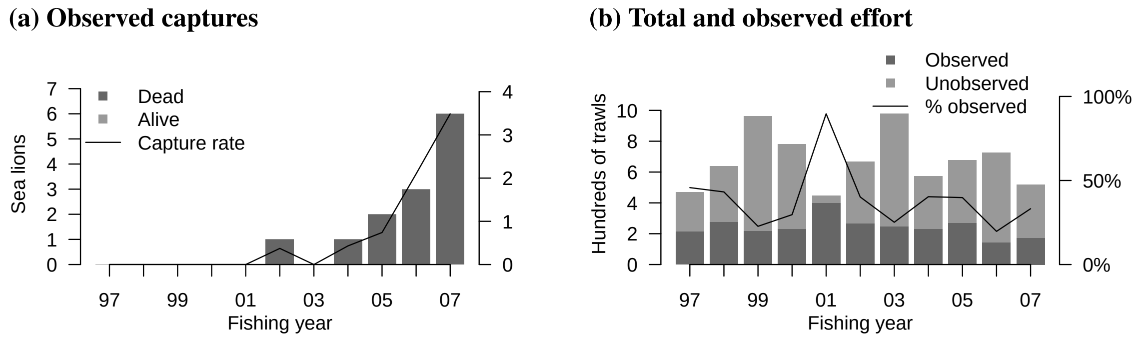


Figure 14: Annual time series of, (a) sea lion captures and the capture rate, and (b) trawl effort and observer coverage, in the southern blue whiting fishery east of Campbell Island from 1997 to 2007.

Table 14: Annual trawl effort, observer coverage, sea lions captured and killed, the observed capture rate, model estimated captures and strike rate in the southern blue whiting fishery east of Campbell Island. There were no captures observed before 2002.

		Observed				Est. captures		Est. strike rate (%)	
	Effort	% obs.	Capt.	Kill.	Rate (%)	Mean	95% c.i.	Mean	95% c.i.
2007	518	33	6	6	3.49	14	(7 - 27)	2.39	(1.46 - 24.64)
2006	725	20	3	3	2.1	7	(3 - 16)	1.13	(0.67 - 13.98)
2005	678	40	2	2	0.74	5	(2 - 12)	0.6	(0.31 - 10.38)
2004	575	40	1	1	0.43	3	(1 - 10)	0.45	(0.17 - 8.5)
2003	978	25	0	-	-	1	(0 - 5)	0.13	(0 - 3.98)
2002	667	40	1	1	0.37	4	(1 - 14)	0.41	(0.13 - 12.4)

Table 15: A comparison of the size distribution of capture events for observed captures, and predicted captures on the observed data, in the southern blue whiting fishery east of Campbell Island.

Number	Observed	Predicted	
		Median	95% c.i.
0	1517	1514	(1503 - 1522)
1	7	12	(4 - 24)
2	3	0	(0 - 1)

of single captures, and under-estimated the multiple captures. This suggested that the data were over-dispersed. Using a negative-binomial error structure was not possible as there were too few captures for the model to converge.

3.3 Other trawl fisheries around the Auckland Islands

The observed capture rate of sea lions in other trawl fisheries operating around the Auckland Islands had remained low, with only sporadic captures (Figure 15). There were only two observed sea lion captures in this fishery within the last three years. Most of the captures were by trawlers targeting scampi, although sea lions were also caught on hoki and deepwater species target trawls within this area.

The ratio estimated captures for the previous three years are given in Table 16. The estimated strike rate was fixed through this period and changes in the estimated captures reflected the small changes in the total fishing effort. In each year, the mean estimated catch was either 11 or 12, the 95% confidence

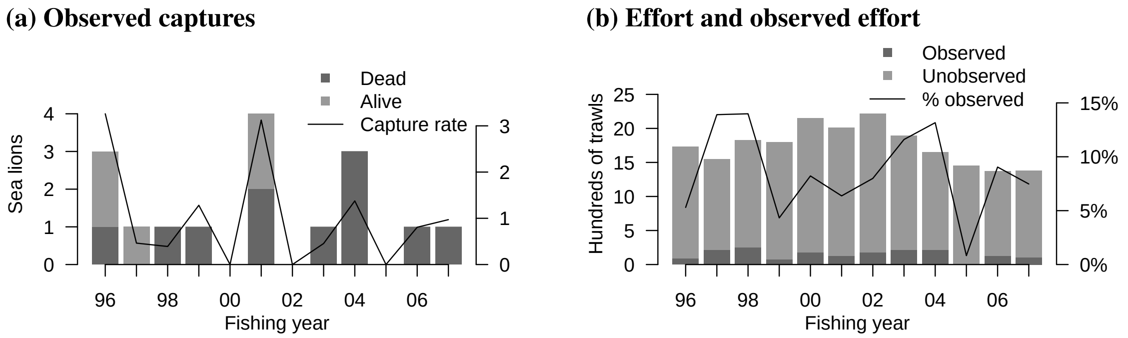


Figure 15: Annual time series of (a) observed captures and observer coverage, and (b) trawl effort, observed trawl effort, and percentage of effort observed, in other (non-squid) trawl fisheries around the Auckland Islands by fishing year

Table 16: Trawl effort, observer coverage, observed captures and ratio estimated captures, with bootstrapped confidence intervals, in other (non-squid) trawl fisheries operating around the Auckland Islands between 2004–05 and 2006–07.

	Effort	Observed				Est. captures	
		% obs.	Capt.	Kill.	Rate (%)	Mean	95% c.i.
2006–07	1378	7.5	1	1	0.97	12	(1 - 27)
2005–06	1371	9.0	1	1	0.81	11	(1 - 27)
2004–05	1455	0.8	0	-	-	12	(0 - 30)

intervals spanned the range from 0 to 30 sea lion captures.

3.4 All trawl fisheries on the Stewart-Snares shelf

Observed sea lion captures on the Stewart-Snares shelf were restricted to the southern end of the shelf, where the trawl effort was highest (Figure 1). Within the time span covered by these data, sea lions were first observed caught in this area in the 1999–2000 fishing year, and continued at a low rate since then (Figure 16), with less than one sea lion being caught for every 500 trawls. During the previous three years five sea lions were caught, based on observer coverage of between 17% and 24% of the fishery (Table 17). The effort in this region declined, and the ratio estimated captures similarly decreased, from 10 captures in 2004–05 to 5 captures during the 2006–07 fishing year.

Table 17: Trawl effort, observer coverage, observed captures, and ratio estimated captures, with bootstrapped confidence intervals, in trawl fisheries operating on the Stewart-Snares shelf between 1995–96 and 2006–07.

	Effort	Observed				Est. captures	
		% obs.	Capt.	Kill.	Rate (%)	Mean	95% c.i.
2006–07	3479	24	1	1	0.12	5	(2 - 9)
2005–06	4942	17	1	0	0.12	8	(2 - 14)
2004–05	6181	24	3	3	0.2	10	(4 - 18)

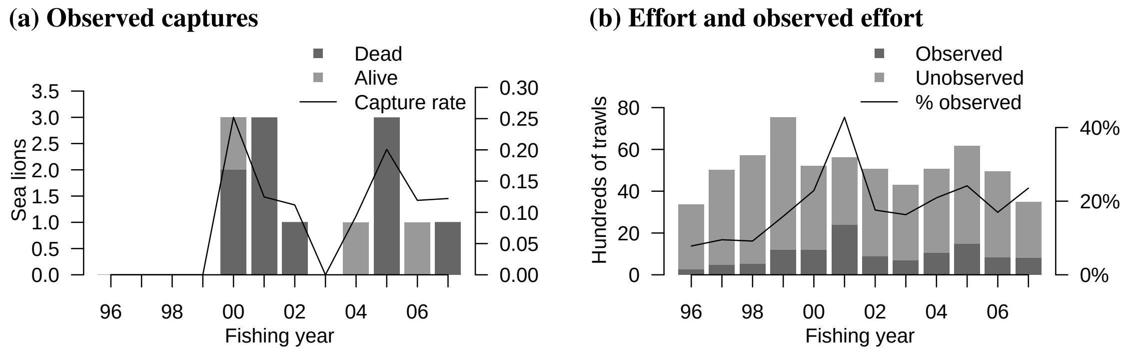


Figure 16: Annual time series of (a) observed captures and observer coverage, and (b) trawl effort, observed trawl effort, and percentage of effort observed, in trawl fisheries operating on the southern end of the Stewart-Snares shelf, by fishing year.

4. DISCUSSION

4.1 Model fitting and sea lion exclusion devices

In this report we re-implemented the model of Smith & Baird (2007b) and applied it to data from recent years. This included independently grooming all the source data, rewriting the Bayesian model code, and running the model against data from the 2005–06 and 2006–07 fishing years. We also developed estimates for sea lion captures in fisheries other than the Auckland Islands squid fishery. Our model implementation differed from the Smith & Baird (2007b) model in one important respect: their model was fitted to observer data and then applied to effort data, whereas the model developed here was fitted to the observed component of the effort data and then fitted to the unobserved component of the same data set. Our model was not influenced by any systematic differences between the observer and fisher collected data sets.

To test the model, it was fitted against final data from the Smith & Baird (2007b) project. In this case the model was fitted to the observer data and applied to the effort data, following the original methods. The estimated model covariates and the predictions of sea lion captures agreed closely between the two models. There was a difference in the strike rate, which was related to differences in the SLED retention probability. It was possible that the SLED retention probability was not parametrised in the same way as in the original model. Whatever the cause, the two estimates were well within each other's uncertainty.

Table 18: Comparison of the SLED retention probability estimates published by the model implemented in this report was fitted to two different data sets, the 1992–2005 data set prepared for the ENV2005–02 project, and the 1996–2007 data set prepared for this report. The results were obtained by fitting a generalised linear model using maximum likelihood methods.

		SLED retention probability, π			
Model	Data period	Mean	2.5%	50%	97.5%
Smith & Baird (2007a)	1992 – 2004	0.265	0.065	0.265	0.465
Smith & Baird (2007b)	1992 – 2005	0.284	0.137	0.273	0.502
Breen, Kim & Starr (2005)	2002 – 2005	-	0.166	0.305	0.564
Abraham (2008)	2000 – 2004	0.18	0.09	-	0.36
This report	1992 – 2005	0.258	0.124	0.247	0.458
This report	1996 – 2007	0.242	0.138	0.234	0.393

For comparison, the SLED retention probability from a range of previous models is given in Table 18. All of these models were generalised linear models (the model of Abraham (2008) was fitted by maximum likelihood methods, and the other models were all fitted by Bayesian methods). Although there was a broad range of estimated values, the confidence intervals of all estimates included the mean and median values from the other models, with the exception of the estimate of Abraham (2008) which was fitted to a restricted time period of the data.

The retention probability measures the impact of introducing SLEDs. All the models predict SLED retention probability to be significantly less than one, implying that the introduction of sleds has reduced the captures of sea lions. For example, the model developed in this report for the 1996–2007 fishing years calculated a retention probability with a mean of 0.242 (Table 18), ie., the likelihood of a sea lion capture on trawls with SLEDs was a quarter of the probability of capture on trawls without SLEDs. The maximum predicted median value for all models for the retention probability was 0.305 and the maximum 97.5% quantile of the posterior was 0.564.

The estimates were sensitive to the time period of the data used, as this affected the relative proportion of data in the model with and without SLEDs. There is a deeper problem here, however. Now that SLEDs are used on all trawls, there is no way for the model to obtain ongoing information relevant to the SLED retention probability. The model assumed that the SLED retention probability had remained constant. This assumption was not true, as there have been modifications made to the SLEDs that were explicitly aimed at making the SLEDs perform better. For example, before the 2004–05 season, the spacing between the bars was reduced to make female sea lions less likely to pass through the grid into the codend. There has also been little progress in establishing whether sea lions survive passage through a SLED. Without ongoing information on the SLED retention probability and on the mortality of sea lions after passage through a SLED, estimation of sea lion mortality in the Auckland Islands squid fishery will become increasingly difficult.

The estimation of the strike rate in the Auckland Islands squid fishery (the estimated number of interactions per 100 trawls) was closely related to the SLED retention probability. The mean 2006–07 strike rate was estimated as 5.6 interactions per 100 trawls. There was a high uncertainty in this figure however, with the 95% confidence interval ranging from a strike rate of 2.7 to 10.0 interactions per 100 trawls. The strike rate of 5.3 sea lions per 100 trawls that was assumed in setting the FRML was well within the range of this uncertainty.

4.2 Combined estimate of sea lion captures

In this report, sea lion captures in fisheries other than the Auckland Islands squid fishery were estimated. These estimates are combined in Table 19 for the three most recent fishing years. The combined estimate of 51 (95% c.i.: 33 to 74) captured sea lions in 2006–07 was slightly lower than estimates for the previous two years of 60 (95% c.i.: 39 to 87) captured sea lions in 2005–06, and 62 (95% c.i.: 39 to 93) captured sea lions in 2004–05. The total number of captures in the Auckland Islands squid fishery dropped after the introduction of SLEDs, and accounted for only 39% of all estimated captures in 2006–07 (down from 56% since 2004-05, the first year when comparisons with other fisheries can be made). Captures in the southern blue whiting fishery have been rising since 2003, accounting for 27% of predicted captures in 2006–07. Captures in other trawl fisheries, especially around the Auckland Islands, accounted for the remaining 34% of the predicted captures.

The combined estimate of the number of interactions (including sea lions that escape through SLEDs), was 105 (95% c.i.: 60 to 1169) sea lions in 2006–07. The fall from 170 interactions (95% c.i.: 92 to 286) in 2005–06 reflected the decrease of effort in the Auckland Islands squid fishery, which fell from 2465 trawls in 2005–06 to 1320 trawls in 2006–07, a decline of 46%. The total number of trawls in the

Table 19: Estimated sea lion captures and interactions, for the three fishing years 2004–05, 2005–06, and 2006–07. Estimates are given for each of the four fisheries, and in total.

	Estimated captures			Estimated interactions		
	Mean	Median	95% c.i.	Mean	Median	95% c.i.
2006–07						
Squid, Auckland Islands	20	19	(11 - 33)	74	70	(32 - 136)
Southern blue whiting, Campbell Is.	14	14	(7 - 27)	14	14	(7 - 27)
Other trawl, Auckland Islands	12	12	(1 - 27)	12	12	(1 - 27)
All trawl, Stewart-Snares shelf	5	5	(2 - 9)	5	5	(2 - 9)
Combined estimate	51	51	(33 - 74)	105	102	(60 - 169)
2005–06						
Squid, Auckland Islands	34	33	(20 - 55)	144	137	(68 - 260)
Southern blue whiting, Campbell Is.	7	7	(3 - 16)	7	7	(3 - 16)
Other trawl, Auckland Islands	11	11	(1 - 27)	11	11	(1 - 27)
All trawl, Stewart-Snares shelf	8	8	(2 - 14)	8	8	(2 - 14)
Combined estimate	60	60	(39 - 87)	170	164	(92 - 286)
2004–05						
Squid, Auckland Islands	35	34	(20 - 57)	142	136	(67 - 260)
Southern blue whiting, Campbell Is.	5	5	(2 - 12)	5	5	(2 - 12)
Other trawl, Auckland Islands	12	12	(0 - 30)	12	12	(0 - 30)
All trawl, Stewart-Snares shelf	10	10	(4 - 18)	10	10	(4 - 18)
Combined estimate	62	63	(39 - 93)	169	163	(93 - 286)

Auckland Islands squid fishery in in 2006–07 was less than the 1755 trawls imposed as an upper limit to protect the sea lions. Using the discount rate of 20% that was assumed for the 2006–07 year, the number of attributed sea lion mortalities in the Auckland Islands squid fishery fishery was 60 (95% c.i.: 26 to 110). The upper limit of the uncertainty range was more than the FRML of 93 mortalities set by the Ministry of Fisheries.

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