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EXECUTIVE SUMMARY

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In 2005–06, a total of 16 New Zealand sea lions (*Phocarctos hookeri*) were observed caught in New Zealand commercial trawl fisheries. In waters around the Auckland Islands, 11 were observed caught in squid trawl nets during February–March 2006; all were landed dead. Three dead male sea lions were caught from two observed southern blue whiting (*Micromesistius australis*) trawls east of the Campbell Rise during September 2006. One dead sea lion, of unknown sex, was caught in a scampi tow off the southeastern edge of the Auckland Islands Shelf during November 2005. The remaining observed sea lion capture was of unknown sex, released alive from a midwater trawl targeting squid off the southern edge of the Stewart-Snares shelf in March.

The primary purpose of this study was to provide estimates for the 2005–06 fishing year, and to provide time series back to the 1994–95 fishing year, of the strike rates and of various total captures for sea lions in the Auckland Islands SQU 6T squid trawl fishery, using model-based prediction methods. The fishery season is confined to February–June and the time series cover the 1995 to 2006 seasons. Use of Sea Lion Exclusion Devices (SLEDs) in the SQU 6T fishery from the 2001 season has made the prediction of the actual number of captures and mortality of sea lions impossible because very little is known about survival rate of sea lions that escape through open SLEDs (SLEDs without cover nets). Instead, the actual numbers of sea lions that are captured and landed on deck (landed captures) are predicted and the number of sea lions that escape through open SLEDs (exclusions) is also predicted for the 2001 to 2006 seasons. The number of sea lion interactions in a season is defined to be the number of landed captures plus the number of exclusions. Predictions of the numbers of interactions are made for each of the 1995 to 2006 seasons (in 1995 to 2000, no open SLEDs were used so the numbers of interactions equal the numbers of landed captures). Because the sea lion interaction rates vary among tows, the mean strike rate for a season is defined to be the average of the mean sea lion interaction rates over all the commercial tows.

The mean strike rate for the 2006 season was 6.0% with a c.v. of 34%. The mean strike rates in the first five seasons of the study (1995 to 2000) are lower than for all other seasons except for 2003, varying between 3.3% and 4.3%. The 2001 season stands out with the largest mean strike rate of 9.2%. This season was unusual in that almost all tows were observed and it was also the season when open SLEDs were first used. The 2004, 2005, and 2006 seasons had the largest estimated mean strike rates apart from the 2001 season, varying between 5.1% and 6.0%. These three seasons were also unusual, because almost all tows used open SLEDs.

The predicted number of interactions for the 2006 season was 147 with a c.v. of 35%. The seasons 1995 to 1997 and 2004 to 2006 were the seasons when most interactions occurred (using means of the predictive distributions as estimates) and the predicted numbers varied between 137 and 163 (with c.v.s between 14% and 36%). In the middle seasons, 1998 to 2003, when numbers of tows were generally less than for the other seasons, the interactions varied between 14 and 72 (with c.v.s between 14% and 34%), the low occurring in 1999 partly because of the low strike rate but mainly because there were very few tows that season.

The predicted number of exclusions for the 2006 season was 109 with a c.v. of 43%. Predicted numbers of exclusions varied between 15 and 27 (c.v.s between 40% and 47%) in 2001 to 2003 and between 99 and 110 (c.v.s between 41% and 44%) in 2004 to 2006.

The predicted number of landed captures for the 2006 season was 38 with a c.v. of 27%. Total landed captures for the six seasons 2001 to 2006 varied between 20 in 2003 (c.v. of 26%) and 45 in 2002 (c.v.

of 21%). The last three seasons had similar predicted numbers, varying between 37 and 44 (and similar c.v.s, between 22% and 28%).

For the 2004 to 2006 seasons, when the fishery related mortality limit (FRML) was used to manage the SQU 6T fishery, the predictive distributions of the numbers of captures, assuming a 20% discount of the strike rate for tows with approved SLEDs, were obtained. However, the strike rates produced by the model were used instead of the nominal 5.3% strike rate assumed in the management plan. The probabilities that the FRML was exceeded were 53% in 2004, 39% in 2005, and 22% in 2006.

If a value for the survival rate for sea lions excluded by open SLEDs were assumed, then it is possible to predict the actual total number of sea lions either captured by the net or dying after being excluded by a SLED. As an example, the predicted number of sea lion captures plus deaths assuming 50% survival, was 92 with a c.v. of 31% for the 2006 season. In the 2004 to 2006 seasons the numbers of captures assuming 50% survival were much larger than in the previous three seasons. They varied between 87 and 98, whereas in the earlier seasons they varied between 34 and 59. If the survival rate were 50%, then the use of open SLEDs represents an estimated total saving in sea lion mortality of nearly 200 over the seasons 2001 to 2006 (an estimated 416 captures compared with an estimated 610 total interactions).

During the latter years of the time series there were changes to the SLED design, aimed at minimising the likelihood that sea lions could fit between the bars. Because of the few observed captures during this period it was not possible to model any resultant effect and, therefore, this study assumed a constant exclusion probability for any sea lion interacting with an open SLED.

1. INTRODUCTION

The New Zealand (Hooker's) sea lion, *Phocarctos hookeri*, is the only endemic pinniped species in New Zealand, with 83% of the annual pup production occurring at Enderby Island and Dundas Island, two of the three breeding locations in the Auckland Islands group (Chilvers et al. 2007). The species also breeds at Campbell Island and on the Otago coast. New Zealand sea lions are gazetted as 'threatened' under the World Conservation Union (IUCN) and the New Zealand Department of Conservation (DoC) threat classification systems (Hitchmough et al. 2007). The species is protected under the Wildlife Act 1953 and the Marine Mammals Protection Act 1978. Statutory obligations require the Ministry of Fisheries (MFish) to monitor the bycatch of associated or dependent species during commercial fishing operations in New Zealand waters. The MFish Scientific Observer Programme collects data on the incidental catch of New Zealand sea lions as part of its monitoring programme. The work reported here is part of the MFish project PRO2006/05, Objective 1, which states: *To estimate and report the total numbers, releases and deaths of marine mammals where possible by species, fishery and fishing method, caught in commercial fisheries for the years 1990 to the end of the fishing year 2005/06.* For New Zealand sea lions, it was agreed with MFish that the estimates and reported numbers be made for the 1994–95 to 2005–06 fishing years.

Captures of sea lions have regularly been recorded by observers in trawl fisheries south of 46° S (for example, see Baird 2005a, 2005b) and carcasses of deceased sea lions returned for autopsy and verification of species and sex (for example, Duignan & Jones 2007). Most reported captures are in the SQU 6T squid trawl fishery and annual totals of sea lion captures have been estimated over the years. This work presents the data and results of model-based estimation of New Zealand sea lion strike rates and captures in the SQU 6T squid fishery for each of the seasons 1995 to 2006. Captures reported by observers in other trawl fisheries during the 2005–06 fishing year are documented at the end of the report.

2. NEW ZEALAND SEA LIONS AND THE SQU 6T SQUID TRAWL FISHERY

The foraging areas and depths used by New Zealand sea lions overlap with the concentration of the squid trawl fishery around the Auckland Islands during February to June, resulting in the incidental capture of sea lions. Since the 1996–97 fishing year, the fishery has had an allowable catch of 32 369 t of squid, but catches have fluctuated, with annual reported catches between 950 t (in 1997–98) and 34 635 t (in 2003–04) (Ministry of Fisheries Science Group 2007); the annual reported catch in 2005–06 was 17 425 t. In the fishing years covered by this study the effort in the fishery has been restricted by management policies, aimed at protecting New Zealand sea lions, that place a limit on the incidental mortality of sea lions for each season, known as the FRML (fishing related mortality limit). The FRML has been reached in 9 of the 11 seasons from 1996 to 2006.

Vessels operate under a code of practice designed to minimise marine mammal capture and have been restricted to fishing outside a 12 nautical mile zone around the Auckland Islands since 1982. In the Auckland Islands part of the SQU 6T fishing area, mitigation devices known as Sea Lion Exclusion Devices (SLEDs) (Anon. 2002) have been trialled since the 2000 fishing season. The SLED provides a potential escape route for the animals. The escape route can be blocked by tying down a cover net, and initially observed tows with the cover net tied down were used to estimate the catch rate. Cover net use has varied since the 2000 season when SLEDs were first used. All observed tows with SLEDs in the 2000 season had the cover in place while in the 2004, 2005, and 2006 fishing seasons all observed tows with SLEDs had the escape cover open (Table 1). SLEDs have undergone development over recent years and their use is now universal in the SQU 6T squid trawl fishery. The seasons covered by the observer data summarised in Table 1 are from 1992 to 2006. Although the time series estimates cover only the 1995 to 2006 seasons, the earlier seasons were included in the observer data used for fitting the model from which predicted total captures and strike rate estimates were obtained.

The 2006 season was the third consecutive season managed using a predetermined official constant fishing related mortality rate per tow (strike rate) of 5.3%, with a 20% discount applied for tows using a SLED approved by MFish. Thus, the official strike rate for a tow using an approved SLED was 0.8 × 5.3% = 4.24%. (To gain approval by MFish, the spacing of the vertical bars in the SLED had to be less than a specified value and the vessel had to give 3 days warning of departure on a trip to allow for the inspection of any SLEDs carried and the possible placement of observers on the vessel.) The operational management rule then determined the number of tows permitted in each season through the official strike rate (including the discounted rate for tows with approved SLEDs). In the 2006 season, the FRML was originally set at 97 sea lions but then raised by the Minister of Fisheries to 150 sea lions later in the season (Ministry of Fisheries Science group 2007). In the 2005 season the FRML was 115 and the fishery closed on 20 April 2005. In 2004 the FRML was originally set at 62 and the fishery closed on 22 March 2004. A New Zealand Court of Appeal in April 2004 ruled that fishing could continue provided incidental sea lion captures did not exceed 124 and this effectively set the FRML at 124 for the season.

Table 1: Observed effort in the SQU 6T fishery including SLED use, sea lion capture numbers and observed strike rates. Tows in the closed net state are tows with either no SLED or a SLED with cover net tied down.

			Effort by SLED use			Captures		Obs. strike rate (%)	
				SLED		Net state		Net state	
Season	Vessels	Tows	No SLED	Covered	No cover	Closed	Open	Closed	Open
1992	7	218	218			8		3.7	
1993	9	197	197			5		2.5	
1994	7	433	433			4		0.9	
1995	7	286	286			8		2.8	
1996	9	555	555			13		2.3	
1997	14	731	731			29		4.0	
1998	10	337	337			15		4.5	
1999	11	156	156			5		3.2	
2000	11	438	284	154	0	25		5.7	
2001	23	576	1	297	278	33	5	11.1	1.8
2002	12	563	176	262	125	22	0	5.0	0.0
2003	11	420	159	237	24	10	0	2.5	0.0
2004	21	794	59	0	735	2	14	3.4	1.9
2005	23	805	35	0	770	1	8	2.9	1.0
2006	17	688	0	0	688		11		1.6
Total	74	7 197	3 627	950	2 620	180	38	3.9	1.5

Before Smith & Baird (2007a) introduced the fully Bayesian model-based method for predicting sea lion captures in SQU 6T for the 2004 squid season, the simple ratio estimate had mostly been used to obtain the estimates of the total sea lion captures in a season, see for example, Baird (2005a, 2005b). Doonan (2001) used a ratio estimate based method for the estimation of sea lion captures in-season in SQU 6T. Breen et al. (2005) used an approach that made the same assumption that is made in the ratio estimator approach, namely that the mean interaction rate was the same for all tows within the same season. However, they used a model which enabled the retention probability to be estimated and fitted their model to data from both SQU 6T and SQU 1T for the 2002–2005 seasons. Their method used industry reported sea lion captures. They were able to give estimates of the means of the total interactions, total landed captures, and total attributed captures for the seasons 2002–2005. Abraham (2007) and Smith & Baird (2007a, 2007b) provide further discussion about methods and their relative merits. Model-based prediction is the most appropriate method, especially for recent years when few tows are able to be used to calculate the strike rate directly, because most if not all observed tows used open SLEDs.

Briefly, in the model-based approach, a statistical model that incorporates covariates associated with variation in capture rates is fitted to observer capture data. The parameters of the model are then used to estimate the mean captures for all tows in the season and these in turn are used to predict the unobserved captures of sea lions for all the tows in SQU 6T in the 2005 season. The procedure adjusts for differences in capture rates between observed and unobserved tows using the estimated covariate coefficients. It also adjusts the capture rates for individual unobserved tows using estimated individual vessel effects for vessels observed during the season. Uncertainty about vessel effects for vessels not observed during the season is included as variation by using simulation from the probability distribution of the vessel-season random effects.

We use the method for predicting the total number of New Zealand sea lion captures in the SQU 6T squid trawl fishery during January to June. In recent years the official start of the fishery has been 1 February but we have included the tows in January that targeted squid in earlier years. Observer data from the 1992 to the 2006 seasons were used to fit the model.

2.1 Terminology and data

The number of sea lion deaths from commercial fishing operations cannot be positively quantified because little is known about what, if any, fatal injuries are suffered by sea lions that interact with fishing nets but are not captured. It has, therefore, been customary to consider only the numbers of sea lions captured and landed (whether dead or alive) as the measure of fishing interaction. However, the use of SLEDs with open covers in the SQU 6T fishery after 2000 has added the extra complication of the survival of sea lions that have escaped through the open covers of SLEDs. The model we use allows us to estimate the rate that sea lions escape from open SLEDs and hence predict the number of sea lions that escape from any SLEDs used (as does the model of Breen et al. (2005)). Unfortunately, no information is available to estimate the survival rate of sea lions that escape from open-net SLEDs with an open cover net and, consequently, we cannot directly estimate the total mortality of sea lions in recent seasons.

Instead we define quantities that can be used to bound the total number of sea lions that are either retained in the net or escape but do not survive. These and other terms are defined below. In keeping with the fact that the E in the SLED acronym is the first letter of “exclusion” we have chosen to describe a sea lion that has escaped through the open cover net of a SLED as a sea lion *excluded* by the open SLED and to count the event as one *exclusion*.

2.1.1 Definitions

Some definitions and terminology used in this report are:

SQU6T	the fishery comprising the Auckland Islands part of the squid trawl fishery in SQU 6T for January to June (the main squid trawl season is February to June but there has been a small amount of fishing effort in January in most years). Note that there is no space between U and 6 in this term, to distinguish it from area.
Season	the calendar year of the main fishing season in the SQU6T fishery.
SLED	sea lion exclusion device.
Closed tow	a tow that either has no SLED or the SLED is present with the cover net closed.
Open tow	a tow that has a SLED present with the cover net open.
Landed captures	sea lion captures, whether dead or alive, that are landed on the deck.
Observed captures	landed captures recorded by an MFish observer.
Exclusions	sea lions that escape from open tows.

Interactions	landed captures plus exclusions. The number of interactions equals the number of landed captures plus the number of sea lion exclusions from open tows.
Mean interaction rate	for each tow, a parameter that is the expected number of sea lion interactions.
Retention probability	a parameter that is the probability that a sea lion is retained and landed (not excluded) in an open tow.
Approved-SLED tow	an open tow that uses a SLED approved by MFish.
Attributed captures	For a tow, the number of sea lions equal to: either the number of interactions if the tow is closed or has a non-approved open-net SLED; or the number of sea lion deaths or landed captures if the tow has an approved open-net SLED, under the assumption that each sea lion interacting with the net has a 0.8 probability of being landed or not surviving (see below for the motivation for this quantity).

The management of the 2004 to 2006 SQU6T fisheries with the official strike rate (a nominal 5.3% per tow) discounted by 20% for tows with approved SLEDs suggests that the total attributed captures is a quantity that might be usefully predicted. The 20% discounting (80% scaling) of the official strike rate for a tow with an approved SLED is equivalent to saying that a sea lion interacting with an approved SLED has an 80% chance of either being captured or not surviving the exclusion from the SLED. Therefore we consider the nominal quantity *total attributed captures*, which comprises all interactions for tows with a non-approved SLED plus a random number of the total of all the interactions for tows with approved SLEDs, each interaction being included with probability 0.8. It differs from the official definition of the total fishing related sea lion mortality because it is predicted by replacing the constant official strike rate with estimates of the mean interaction rates for each tow.

Neither the official total fishing related mortality nor the attributed captures can be considered to be estimates or predictions of the actual number of sea lion deaths because they ignore sea lion exclusions from open SLEDs that have not been MFish approved (2459 – 1925 = 534 tows in 2006, see Table 2). Furthermore, the predetermined strike rate of 5.3% is not based on any data from the 2004 to 2006 seasons, when the approval programme was used. Following the formula, the official total sea lion fishing related mortality in SQU6T in 2006 was 0.053×(2459 – 0.2×1925) = 109.9 sea lions (2459 tows of which 1925 were MFish approved tows, which received the 20% discounted rate), which was well below the final FRML of 150 for the season. For the 2005 season the official total sea lion fishing related mortality was 0.053×(2693 – 0.2×2444) = 116.8, which was just above the FRML of 115. For the 2004 season the official total sea lion fishing related mortality was 0.053×(2597 – 0.2×1747) = 119.1, which was below the effective FRML of 124. The FRMLs are given by Ministry of Fisheries Science Group (2007).

The numbers of observed and unobserved vessels in Table 2 do not add to the total number of vessels in each season because several vessels have both observed and unobserved tows. In the 2006 season: all tows were observed for 1 vessel, some tows were observed and some tows were unobserved for 16 vessels, and all tows were unobserved for 16 vessels, making 33 vessels in total.

If the survival probability of a sea lion excluded from open SLEDs were known, then the predictive distribution of the total number of sea lions either retained in the net or dying after escaping could easily be obtained using our methods. Even if the survival probability were not known exactly, the uncertainty could be modelled and the method would then give a predictive distribution with this uncertainty included. In both scenarios the total number of sea lions captured or dying after escaping would be between the total number of landed captures and the total number of interactions.

Table 2: Numbers of observed and unobserved tows, with percentages in parentheses, in SQU6T in the 2004 to 2006 seasons by SLED use and MFish approved SLED use. All SLEDs were used with the cover net open.

Season		Vessels	Tows by SLED use			Total tows
			no SLED	SLED	Approved-SLED	
2004						
	Observed	21	59 (7.4)	735 (93)	492 (62)	794 (31)
	Unobserved	31	19 (1.1)	1 784 (99)	1 255 (70)	1 803 (69)
	All	32	78 (3.0)	2 519 (97)	1 747 (67)	2 597 (100)
2005						
	Observed	23	35 (4.2)	770 (96)	762 (95)	805 (30)
	Unobserved	36	11 (0.1)	1 877 (100)	1 682 (89)	1 888 (70)
	All	36	46 (1.7)	2 647 (98)	2 444 (91)	2 693 (100)
2006						
	Observed	17	0 (0.0)	688 (100)	396 (58)	688 (28)
	Unobserved	32	0 (0.0)	1 771 (100)	1 529 (86)	1 771 (72)
	All	33	0 (0.0)	2 459 (100)	1 925 (78)	2 459 (100)

2.1.2 Data

A set of observer data was built from that used in earlier New Zealand sea lion capture work (Smith & Baird 2007b) by adding data for the 2005–06 year from the MFish *obs* and *obs_lf* databases. Additional information concerning sea lion captures was obtained from autopsy results provided by MFish and observer diaries. Data grooming and resolution of data conflicts from the different sources were carried out. The observer data were used for model fitting and for identifying which tows in the commercial data were unobserved.

The numbers of tows, vessels, and sea lion captures by season for the observer data used for fitting the model are given in Table 3.

Table 3: Observed effort and New Zealand sea lion captures in SQU6T in the seasons 1992 to 2006.

Season	Tows	Vessels	Captures		
			Males	Females	Total
1992	218	7	5	3	8
1993	197	9	2	3	5
1994	433	7	2	2	4
1995	286	7	4	4	8
1996	555	9	3	10	13
1997	731	14	20	9	29
1998	337	10	11	4	15
1999	156	11	1	4	5
2000	438	11	13	11	25*
2001	576	23	16	22	38
2002	563	12	6	16	22
2003	420	11	4	6	10
2004	794	21	2	14	16
2005	805	23	4	5	9
2006	688	17	1	10	11
Total	7 197	74	94	123	218

* One sea lion was unsexed

The commercial data used for predicting sea lion captures in the 1995 to 2006 seasons are a subset of the data on Trawl Catch Effort Processing Returns (TCEPR) forms (no tows in SQU 6T were recorded on Catch Effort Landing Returns (CELR) forms) obtained for the analysis of New Zealand fur seal captures as part of the PRO2006/05 project. The SQU 6T fishery subset of the data comprised all tows targeting squid within the Auckland Islands part of SQU 6T. Details of the collection and grooming of the complete commercial data set were given by Smith & Baird (2009). Identification of the commercial tows in the SQU 6T fishery that were observed was made by matching tows with the observer data. Identification of the tows that used open SLEDs and the tows that used MFish approved SLEDs was made from data supplied Paul Starr of Seafood Industry Council (SeaFIC).

Summaries of the numbers by season of observed and commercial tows by SLED use and of observed and commercial and observed vessels are given in Table 4.

Table 4: Numbers of observed and commercial tows in SQU6T for the seasons 1995 to 2006. The numbers of open and closed tows and numbers of vessels are also given for the observed and commercial data and observer coverages are included.

	Obs.	Observed tows			Com.	Commercial tows			Obs. Coverage (%)		
Season	vessels	Open	Closed	All	vessels	Open	Closed	All	Open	Closed	All
1995	7		286	286	50		4 003	4 003		7.1	7.1
1996	9		555	555	52		4 459	4 459		12.4	12.4
1997	14		731	731	42		3 710	3 710		19.7	19.7
1998	10		337	337	36		1 463	1 463		23.0	23.0
1999	11		156	156	35		402	402		38.8	38.8
2000	11		438	438	26		1 207	1 207		36.3	36.3
2001	23	278	298	576	23	279	306	585	99.6	97.4	98.5
2002	12	125	438	563	28	825	823	1 648	15.2	53.2	34.2
2003	11	24	396	420	28	1 069	402	1 471	2.2	98.5	28.6
2004	21	735	59	794	32	2 519	78	2 597	29.2	75.6	30.6
2005	23	770	35	805	36	2 647	46	2 693	29.1	76.1	29.9
2006	17	688	0	688	33	2 459	0	2 459	28.0	0.0	28.0
Total	60	2 620	3 729	6 349	103	9 798	16 899	26 697	26.7	22.1	23.8

Since the 1999 season, the observer coverage rate has been at least 28% with an exceptional season in 2001 when almost every tow was observed. SLEDs were first trialled in the 2000 season, when they were used on 158 of the 438 observed tows that season (see Table 1). All SLEDs were closed net and no SLEDs were used on any unobserved tow. For the next three seasons, 2001 to 2003, many observed and unobserved tows used SLEDs both with and without a cover net in place (Table 4). In the last three seasons, 2004 to 2006, when the fishery was managed using a discounted strike rate for use of an approved SLED, almost all tows used SLEDs (all of which were used without cover nets). Table 2 also gives numbers of tows where approved SLEDs were used.

The start positions of all commercial and observed tows (including those observed tows with sea lion captures) for the seasons 1995 to 2006 are shown in Figure 1 and Figure 2 shows the start positions of observed tows (including those with sea lion captures) combined for all the seasons 1992 to 2006.

2.2 Sea lion capture model

To predict the number of New Zealand sea lion captures and interactions a fully Bayesian model-based approach is used. The model is hierarchical (involving random effects) and parameter effects act on the sea lion interaction rates in a multiplicative way (the model is loglinear). The fully Bayesian approach to the prediction of total captures incorporates both the variability of parameter estimates and the uncertainty in the numbers of captures predicted from those estimates.

2.2.1 Description of the model used for fitting the observer data

The model used for fitting the observer data and for predicting sea lion captures and interactions in this study is the same as Model 1 used by Smith & Baird (2007b) and used the same three covariates. However, the 2006 season observer data were not available when Smith & Baird (2007b) fitted their model, and consequently their parameter estimates differ from ours. The model is described in terms of the mean number of sea lion interactions for each tow. The mean number of sea lion interactions for the k^{th} tow by the j^{th} vessel in the i^{th} season is given by the mean interaction rate (per tow) parameter and denoted by μ_{ijk}. The actual number of interactions that occur for tow *ijk* is then a random variable with mean μ_{ijk} and distribution given by the error distribution of the model. The model allows the mean interaction rate parameter to vary among tows by assuming that each is built by scaling the base season interaction rate by a number of effects. These are:

1. A set of season mean base interaction rate parameters, λ_i.
2. A set of multiplicative vessel-season random effects, v_{ij}.
3. Covariates that appear in the model in log-linear form. That is, as a scaling of the capture rate through an exponential function of a linear model.
4. A multiplicative retention probability for a sea lion interacting with an open net, denoted by π. Tows with SLEDs that have cover nets in place are treated the same as tows with no SLEDs (both are closed tows).

Thus, the mean interaction rate parameter μ_{ijk}, for the ijk^{th} tow is given by

$$\mu_{ijk} = \lambda_i v_{ij} \exp\left(\mathbf{x}_{ijk}\boldsymbol{\beta}\right) \tag{1}$$

$\mathbf{x}_{ijk}$ is the row matrix of transformed covariate values for tow *ijk* and $\boldsymbol{\beta}$ is the column matrix of coefficients. This is equivalent to the loglinear mixed effects model

$$\log\left(\mu_{ijk}\right) = \log\left(\lambda_i\right) + \log\left(v_{ij}\right) + \mathbf{x}_{ijk}\boldsymbol{\beta}\ .$$

The form that each mean parameter takes for other types of captures includes an effect for the type of mitigation used for the tow (closed, open, and approved SLED). Thus the mean landed capture rate parameter μ_{ijk}^{L}, for the ijk^{th} tow is then given by

$$\mu_{ijk}^{\text{L}} = \begin{cases} \pi\mu_{ijk}, & \text{tow } ijk \text{ is open-net,} \\ \mu_{ijk}, & \text{tow } ijk \text{ is closed-net.} \end{cases} \tag{2}$$

The mean exclusion rate parameter is the difference between the mean interaction rate and the mean landed capture rate and is

$$\mu_{ijk}^{\text{E}} = \mu_{ijk} - \mu_{ijk}^{\text{L}}, \tag{3}$$

which will be 0 for closed tows. The attributed mean capture rate parameter depends on whether the tow has an approved SLED and is

$$\mu_{ijk}^{\text{A}} = \begin{cases} 0.8\mu_{ijk}, & \text{tow } ijk \text{ uses an approved SLED,} \\ \mu_{ijk}, & \text{otherwise,} \end{cases} \tag{4}$$

which incorporates the nominal 20% discount on the capture rates for tows with an approved SLED.

The loglinear covariate component of the model used is the same as that used by Smith & Baird (2007b) and is log(*dist.col*) + log(*duration*) + *subarea*,

where:

dist.col distance from start of tow to the nearest New Zealand sea lion breeding colony. Continuous variable transformed by the logarithm in the linear model component.

duration duration of tow. Continuous variable transformed by the logarithm in the linear model component.

subarea subarea of SQU 6T for start of tow (see Figures 1 and 2). Factor variable with levels:

- S&E – tows starting in the Auckland Islands part of SQU 6T that have latitude south of 50º 30´ S; or longitude east of 167º 06´ E; or latitude north of 49º 48´ S and longitude east of 166º 48´ E
- NW – (base level) tows starting in the Auckland Islands part of SQU 6T that are not in the S&E subarea.

A small change to the boundary between the NW and S&E subareas from that used in Smith & Baird (2007b) was made to separate the tows in the northwest from those near the 250m depth contour to the east and south (see Figures 1 and 2).

The model includes some parameters as random effects and is therefore a hierarchical model. Both the base interaction rates λ_i and the vessel-season effects v_{ij} are random effects. The distribution of each λ_i is assumed to be lognormal with mean and variance hyper-parameters. The distribution of each vessel-season effect is assumed to be gamma with a single hyper-parameter, the shape parameter θ^{VS}. The rate hyper-parameter of the gamma distribution is set equal to θ^{VS}, which ensures that the vessel season effects have mean equal to 1 and that the variance is equal to the reciprocal of θ^{VS}. The use of random effects helps avoid over-fitting of multiple parameters. For the vessel-season effects, it also allows for the inclusion of the unknown vessel-season effects for any vessel that is unobserved in the season, as extra variation in any predictions.

Finally, the error assumption of the model is that the errors have the negative binomial distribution, extra-dispersion (compared with a Poisson model) is included in the model and the extent of the extra-dispersion, as measured by the shape parameter of the negative binomial error model θ, can be estimated. Thus, the error assumption of the model is that the number of sea lion interactions for the k^{th} tow by the j^{th} vessel in the i^{th} season has a negative binomial distribution with mean rate parameter μ_{ijk} and a shape parameter θ, that is the same for all tows. The numbers of landed captures, exclusions, and attributed captures for the ijk^{th} tow will also, as a consequence, have negative binomial error models with the mean rates μ^{L}_{ijk}, μ^{E}_{ijk}, and μ^{A}_{ijk} respectively, and common shape parameter θ.

The negative binomial error assumption is equivalent to applying extra-dispersion to the Poisson distribution by scaling the mean rate for each tow by independent *extra-dispersion effects* that are gamma distributed with mean 1 and shape parameter equal to θ. The shape parameter of the negative binomial error is then interpreted as the reciprocal of the variance of the distribution of the individual tow extra-dispersion effects. See Smith & Baird (2007b) where the negative binomial error model was used for modelling sea lion captures in the SQU 6T fishery and also Baird & Smith (2008) and Smith & Baird (2009) where negative binomial error models are used in the modelling of seabird and fur seal captures in New Zealand waters.

2.2.2 Model assumptions

The model described includes a number of implicit and explicit assumptions and the fitting process also requires the specification of prior distributions. These are set out in detail below.

Model

1. All landed captures are observed for tows with an observer present.
2. The distributions of the numbers of captures for each tow have independent negative binomial distributions, conditional on the mean rate parameter for the tow and the shape parameter θ.
3. The shape parameter θ, of the negative binomial error model is the same for all tows.
4. Base season capture rate parameters (λ_i) are hierarchical (random) being an independent sample from a single lognormal distribution.
5. The vessel-season effects (v_{ij}) are hierarchical (random) being an independent sample from a single gamma distribution with mean 1 and variance (equal to the reciprocal of θ^{VS}) that is the same for all seasons and observed and unobserved vessels.
6. The retention probability (π) is the same for all seasons when open nets were used.
7. The coefficients ($\boldsymbol{\beta}$) in the log-linear contribution from the covariates are the same for all seasons.

Prior distributions for fitting the observer data

8. The prior distribution for the mean (in log space) of the lognormal hierarchical distribution of the season base interaction rate parameters (λ_i) is normal, mean = -4 and standard deviation = 100.
9. The prior distribution for the standard deviation parameter (in log space) of the lognormal hierarchical distribution of the season base interaction rate parameters is a folded Student's-t distribution (advocated by Gelman 2006).
10. The prior on the shape parameter θ^{VS} for the gamma distribution of the hierarchical vessel-season effects, v_{ij}, is the uniform shrinkage prior which has density

    $$f(x) = \frac{\zeta}{(\zeta + x)^2}, x > 0$$

    where the median ζ, is set equal to the mean number of observed sea lion captures per vessel (see Christiansen & Morris 1997 and Natarajan & Kass 2000).
11. The prior on the shape parameter θ of the negative binomial errors is also the uniform shrinkage prior as given above but with the median ζ set equal to the mean number of observed sea lion captures per tow.
12. The prior distribution for the retention probability (π) is uniform on (0, 1).
13. The prior distribution for each of the coefficients ($\boldsymbol{\beta}$) in the log-linear contribution of the covariates, is normal with mean = 0 and standard deviation = 100.
14. All prior distributions are independent.

The priors, as specified, can be considered to be non-informative because they are highly dispersed (apart from that for π, which is uniform on the interval (0, 1) and can therefore be considered non-informative). All the normal distribution priors have standard deviations of 100 and the prior distributions for the variance parameters all have infinite means and variances. Care is required in choosing priors for the hyper-parameters associated with hierarchical parameters as an improper prior for the variance hyper-parameter generally leads to an improper joint posterior distribution for all the model parameters (see Smith & Baird (2007a) for further discussion). Bayesian inference from an improper posterior distribution is meaningless and the use of Markov chain Monte Carlo (MCMC) methods produces chains that never converge (although this fact is often not obvious from the chains themselves). Slow convergence of MCMC chains can occur for models with a prior distribution that would have been improper but for truncation, and for hierarchical models where the prior distribution for a hyper-parameter is close to being improper. A prior distribution is improper if the total probability, when added or integrated, is infinite (rather than 1).

2.2.3 Model fitting and parameter estimates

Model fitting was carried out using the WinBUGS program (Spiegelhalter et al. 2003) to generate MCMC samples from the posterior distribution of the model parameters. Unfortunately the negative binomial distribution as implemented in WinBUGS does not allow the shape parameter θ to be continuous in the range 0 to infinity. The problem is overcome by using the Poisson error model together with multiplicative gamma random extra-dispersion effects (with mean 1) for each tow. This solution was used for sea lion captures by Smith & Baird (2007b), seabird captures by Baird & Smith (2007a), and fur seal captures by Baird & Smith (2007b) and Smith & Baird (2009).

The final run of the model fitting by WinBUGS each involved a burn in of 100 000 iterations followed by a further 100 000 iterations keeping every 20^{th} and thus retaining 5000 iterations for use in the prediction of captures. Convergence of the MCMC chain for fitting the model was checked using the Geweke diagnostic (Geweke 1992) and the stationarity test of Heidelberger and Welch (Heidelberger & Welch 1983).

Characteristics of the posterior distributions of the model parameters (other than the 192 vessel-season effects) are given in Table 5. The base interaction rate parameters (λ_{92} etc) need careful interpretation. They are the mean capture rates for each season, for a closed tow in the NW subarea, at a distance from the nearest colony equal to the geometric mean of all the observed distances from the nearest colony (48.0 km) and of duration equal to the geometric mean of all the observed tow durations (3.42 h). In this sense the base parameters are standardised relative sea lion interaction rates (relative because they are for tows in the NW subarea). Estimated strike rates for a season have to be calculated allowing for the distribution of the covariates for all the tows in that season.

The other parameters are more easily interpreted, using posterior means as point estimates. The probability that any sea lion interacting with an open net is retained is 28%, with a 95% credibility interval of (16%, 45%). Assuming all other covariate values and the vessel for the tow are the same, the interaction rate changes with distance from the nearest colony to the power of -1.00 (with a 95% credibility interval of (-1.56, -0.46)) and, similarly, the interaction rate changes with tow duration to the power of 0.73 (with a 95% credibility interval of (0.40, 1.08)). Again, keeping everything else the same, the mean interaction rate for a tow in the S&E subarea is 52% that for a tow in the NW subarea (with a 95% credibility interval of (35%, 74%)). Because there were only 198 tows with sea lion capture incidents and 218 captures in total in the observer data, there are quite large uncertainties about the parameter values and these are reflected in the relatively wide credibility intervals. The *dist.col* and *duration* exponents are both significant because the 95% credibility intervals do not include 0. Similarly, the (multiplicative) *subarea* S&E effect is significant because the 95% credibility interval does not include 1.

The variance of the vessel season effects is 0.51 (corresponding to a c.v. of 71%, since the mean effect is 1) and the variance of the extra-dispersion added by the negative binomial error model is 2.26, which corresponds to an error variance of about 1.1 times the mean interaction rate. (For a Poisson error model the variance would equal the mean interaction rate.)

Plots of the MCMC traces and kernel density estimates of the posterior distributions of the more important parameters are presented in Figure 3. The plots of the MCMC traces show no evidence that the chains have not converged. Kernel density plots of the MCMC iterations from the posterior distributions of the 15 season base effects are shown in Figure 4 and kernel density plots of the MCMC iterations from the posterior distributions of the vessel-season effects for the 17 vessels observed in 2006 are shown in Figure 5. It is clear, from Figure 5, which observed vessels caught sea lions, namely those vessels with mean effects greater than 1. Vessels 3 and 15 caught 2 sea lions each, vessel 1 caught 3, and vessel 10 caught 4. The length of the 95% credibility intervals of each vessel effect is largely determined by the numbers of tows observed.

Table 5: Characteristics of the posterior distributions of important parameters in the fitted model.

			Percentiles				
Parameter	Mean	Std dev	2.5%	25%	50%	75%	97.5%
1992 base interaction rate, λ_{92}	0.0513	0.0169	0.0254	0.0399	0.0489	0.0597	0.0922
1993 base interaction rate, λ_{93}	0.0445	0.0153	0.0207	0.0341	0.0425	0.0527	0.0792
1994 base interaction rate, λ_{94}	0.0305	0.0125	0.0112	0.0212	0.0290	0.0384	0.0576
1995 base interaction rate, λ_{95}	0.0429	0.0150	0.0196	0.0323	0.0411	0.0513	0.0782
1996 base interaction rate, λ_{96}	0.0381	0.0116	0.0193	0.0299	0.0368	0.0451	0.0635
1997 base interaction rate, λ_{97}	0.0539	0.0135	0.0327	0.0446	0.0521	0.0614	0.0848
1998 base interaction rate, λ_{98}	0.0494	0.0143	0.0274	0.0394	0.0475	0.0571	0.0823
1999 base interaction rate, λ_{99}	0.0461	0.0155	0.0217	0.0354	0.0443	0.0540	0.0823
2000 base interaction rate, λ_{00}	0.0722	0.0232	0.0397	0.0557	0.0676	0.0846	0.1294
2001 base interaction rate, λ_{01}	0.0906	0.0294	0.0481	0.0689	0.0864	0.1072	0.1598
2002 base interaction rate, λ_{02}	0.0513	0.0138	0.0299	0.0417	0.0495	0.0589	0.0836
2003 base interaction rate, λ_{03}	0.0373	0.0118	0.0177	0.0289	0.0362	0.0444	0.0629
2004 base interaction rate, λ_{04}	0.0574	0.0190	0.0304	0.0446	0.0541	0.0667	0.1025
2005 base interaction rate, λ_{05}	0.0497	0.0173	0.0241	0.0382	0.0472	0.0583	0.0904
2006 base interaction rate, λ_{06}	0.0452	0.0153	0.0215	0.0344	0.0432	0.0532	0.0813
Retention probability, π	0.276	0.077	0.155	0.221	0.266	0.322	0.453
dist.col coefficient	-0.995	0.284	-1.561	-1.185	-1.000	-0.800	-0.461
duration coefficient	0.734	0.170	0.404	0.618	0.736	0.845	1.077
subarea S&E effect	0.522	0.101	0.347	0.451	0.514	0.582	0.739
Vessel-season effects variance, $1/\theta^{VS}$	0.506	0.212	0.137	0.353	0.488	0.644	0.963
Extra-dispersion variance, $1/\theta$	2.258	0.806	0.814	1.687	2.205	2.766	3.971

The first measure of goodness of fit used was the comparison of the observed capture frequencies, with the expected capture frequencies predicted from the model using the MCMC iterations. For each iteration in the MCMC, the frequencies of 0, 1, and 2 or more captures for every tow in the observer data are obtained using the negative binomial distribution with mean and shape parameters equal to the current iterations of the mean landed capture rate and the shape parameter θ, respectively. These frequencies are summed by season for the tows in the fit data and then averaged over all the iterations in the MCMC to obtain the expected frequencies by season. Observed and predicted frequencies for the observer data by season and in total are compared in Table 6.

It is apparent from Table 6 that the model predicts the observed data for individual seasons well, with observed frequencies being quite close to the expected frequencies predicted by the model. Unlike the Poisson-based model used by Smith & Baird (2007a), which showed evidence of the being under-dispersed, the new model appears to account for most of the extra-dispersion that is apparent in the observed frequencies. This has been achieved despite the restrictive assumption that the extra-dispersion parameter θ is the same for each season. It is almost certain that different seasons will have different extra-dispersion parameters: it seems that 2000 and 2001 could have smaller extra-dispersion than the other seasons (from Table 6) but, because dispersion parameters are notoriously difficult to estimate, assuming constant extra-dispersion and therefore only one parameter is a reasonable compromise.

Further checks of the fit of the model were carried out by plotting randomised quantile residuals (see Dunn & Smyth 1996) against the fitted mean capture rate values and against the covariate values (Figure 6). These residuals are the only useful residuals available for data that take only a few distinct values, as seen in observed tow-by-tow sea lion captures where the number of captures effectively only take the values 0, 1, or 2. The randomised quantile residuals are calculated from the negative binomial distribution using mean capture rate parameters equal to the posterior means for each tow in the observer data and shape parameter equal to the posterior mean of θ. Trend lines in the randomised residuals, calculated using the local regression smoother loess, are included in the plots. The plots show very little evidence of any systematic trend in the residuals suggesting that the model does not have any fit problems. The Q-Q normal plot of the randomised quantile residuals shows that they follow a normal distribution closely. Because the randomised quantile residuals are the result of a transformation that assumes the negative binomial error distribution, the fact that the randomised quantile residuals follow the normal distribution provides some confirmation that the use of the negative binomial error model is appropriate.

Table 6: Comparison of observed frequencies of numbers of captures with the expected frequencies predicted from the fitted model. The frequencies in the column headed by 2+ are the expected frequencies of tows with 2 or more captures.

	Observed frequencies					Expected frequencies		
Season	Number of captures per tow					Number of captures per tow		
	0	1	2	3	4	0	1	2+
1992	211	6	1	0	0	211	6.1	0.6
1993	192	5	0	0	0	192	5.0	0.4
1994	430	2	1	0	0	426	6.9	0.4
1995	278	8	0	0	0	277	8.0	0.6
1996	543	11	1	0	0	541	13.3	1.0
1997	706	21	4	0	0	706	22.2	2.4
1998	322	15	0	0	0	324	12.1	1.3
1999	151	5	0	0	0	151	5.0	0.5
2000	414	23	1	0	0	419	16.8	2.1
2001	541	32	3	0	0	548	23.9	3.7
2002	545	16	1	0	1	544	17.5	1.7
2003	410	10	0	0	0	409	10.5	0.9
2004	780	12	2	0	0	780	13.4	0.8
2005	796	9	0	0	0	796	8.6	0.4
2006	680	6	1	1	0	677	10.7	0.5
Totals	6 999	181	15	1	1	7 000	179.9	17.5

Box-whisker plots of the randomised quantile residuals against the levels of factor covariates, given in Figure 7, also show very little evidence of any fit problem for the model. The residuals are centred on 0 for both levels of the SLED use (net open or closed) and the *subarea* factors. The box-whisker plots of residuals by season in Figure 8 show some variation from 0 in their centres. This is to be expected because of the smoothing (shrinkage towards the mean) from treating the base season interaction rates as random effects.

2.3 Predicted captures in SQU6T for the 1995 to 2006 seasons

The main focus of this work is to estimate NZ sea lion captures in SQU6T in the 1995 to 2006 seasons. We use the fitted model to estimate the mean strike rate for each season and to predict, for each season, the total numbers of sea lion interactions, landed sea lion captures, sea lions excluded from open tows, sea lion captures under the assumption any sea lion excluded from an open tow has a 50% chance of survival, and attributed sea lion captures.

Even though we are predicting totals for each season, we will drop the season index (i) from the earlier notation for the various tow by tow capture, exclusion, or interaction rate parameters (μ_{ijk} etc.) and consider the parameters to be in a generic season. It is not necessary to refer to individual vessels so we also drop the vessel index (j) from the notation. k will then range from 1 to n, where n is the number of commercial tows in the generic season. We will, however, retain the superscript which identifies the type of rate parameter. For example, μ_k and μ_k^{L} denote the mean interaction rate and the mean landed capture rate for the k^{th} tow in the season.

The procedure for estimating mean strike rates and predicting the total numbers of captures of the four types (interactions, landed captures, exclusions from open SLEDs, and attributed captures) for a single season was described by Smith & Baird (2007b) and is included here for completeness.

The procedure makes use of the 5000 MCMC iterations from the joint posterior distribution of the model parameters obtained from fitting the observer data to obtain iterations of the individual tow mean capture rate parameters. The model parameters required for predictions in a season are: the base interaction rate λ for the season, the retention probability π, the three βs (exponents for the covariates *dist.col* and *duration*, and the coefficient giving the S&E effect for the factor *subarea*), the vessel-season effects for the vessels observed in the season, the shape parameter for the vessel-season effects θ^{VS}, and the shape parameter for the negative binomial distribution θ.

The procedure for each season starts with the 5000 iterations of the model parameters and, from each iteration, a realisation from each of the predictive or posterior distributions of the various quantities of interest is derived. For the current iteration, the mean interaction rates μ_k, k = 1, 2, …, n, are calculated by substituting the current iteration of the model parameters into Equation 1 in Section 2.2.1. For tows by any vessel that was not observed in the season, no current iteration of the vessel-season effect parameter is available and a simulated value generated from the gamma distribution with shape parameter equal to the current iteration of θ^{VS} is used instead. For each realisation the same simulated value of the vessel-season random effect is used for every tow by that vessel. A different simulated value is generated for each different unobserved vessel. A realisation of the set of mean landed capture rates μ_k^{L}, k = 1, 2, …, n, is obtained by multiplying the mean interaction rates for open tows by the current iteration of π (Equation 2). Similarly, a realisation of the set of mean attributed capture rates μ_k^{A}, k = 1, 2, …, n, is obtained multiplying the mean interaction rates for approved open tows by 0.8 (Equation 4). The set of mean exclusion rates μ_k^{E}, k = 1, 2, …, n, is obtained by subtracting μ_k^{L} from μ_k (Equation 3).

Current realisations from the model-based predictive distributions of the quantities: *total interactions T*, *total landed captures* T^{L}, *total attributed captures* T^{A}, and *total exclusions* T^{E}, are obtained by adding simulated numbers of total unobserved captures to the total number of observed landed captures. We also denote the total number of observed captures in the season by T^{O}. For example, in the 2006 season 11 landed captures of sea lions were observed ($T^{\mathrm{O}} = 11$). The procedure requires that individual captures (of the various types) be simulated for each tow using the current iteration of the appropriate mean rate for the tow and the current iteration of the negative binomial shape parameter θ.

A set of realisations of the tow-by-tow interactions x_k, k = 1, 2, …, n, is obtained by generating values from the negative binomial distributions with means equal to the current realisations of μ_k and shape parameter equal to the current iteration of θ. Next, a set of simulated landed captures x_k^{L}, k = 1, 2, …, n, is obtained from the x_k by generating values from binomial distributions for each k, with size parameter = x_k and probability parameter = p_k^{L}, where p_k^{L} is either 1 or π (the current iteration thereof) if the k^{th} tow is either open or closed, respectively. Lastly, a set of realisations of the attributed deaths among any sea lions excluded from approved or non-approved open tows, $x_k^{\mathrm{A\text{-}L}}$, k = 1, 2, …, n, are obtained by generating values from the binomial distributions, for each k, with size parameter = x_k and probability parameter = $p_k^{\mathrm{A\text{-}L}}$, where $p_k^{\mathrm{A\text{-}L}}$ is either 0.8 – π (the current iteration thereof) if the k^{th}

tow is open and uses an approved SLED, $1 - \pi$ if the k^{th} tow is open but uses a non-approved SLED, or 0 if the k^{th} tow is closed. Using binomial distributions in this way preserves the correct joint distribution between the realisations of the various combinations of the x_k values that are used together in the calculations below.

Realisations from the predictive distributions of the various types of totals T, T^{L}, T^{E}, and T^{A} are then obtained as follows:

total interactions, T. The current realisation of T is the sum of the total number of observed captures, the current realisations of the numbers of exclusions for the observed tows, and the current realisations of the numbers of interactions for the unobserved tows. Thus

$$T = T^{\text{O}} + \sum_{\{\text{observed tows}\}} \left(x_k - x_k^{\text{L}} \right) + \sum_{\{\text{unobserved tows}\}} x_k$$
$$= T^{\text{O}} + \sum_1^n x_k - \sum_{\{\text{observed tows}\}} x_k^{\text{L}} . \qquad (5)$$

total landed captures, T^{L}. The current realisation of T^{L} is the sum of the total number of observed captures and the current realisation of the numbers of landed captures for unobserved tows. Thus

$$T^{\text{L}} = T^{\text{O}} + \sum_{\{\text{unobserved tows}\}} x_k^{\text{L}}$$
$$= T^{\text{O}} + \sum_1^n x_k^{\text{L}} - \sum_{\{\text{observed tows}\}} x_k^{\text{L}} .$$

total exclusions, T^{E}. The current realisation of T^{E} is the difference between the current realisation of the total interactions and the current realisation of the total landed captures. Thus

$$T^{\text{E}} = T - T^{\text{L}} .$$

total attributed captures, T^{A}. The current realisation of T^{A} is the sum of the current realisation of the total landed captures and the current realisation of the numbers of attributed deaths among sea lions excluded from open nets. Thus

$$T^{\text{A}} = T^{\text{L}} + \sum_1^n x_k^{\text{A-L}} .$$

Because there is no way of estimating the survival rate of any sea lion excluded from a net incorporating a SLED at this time, we are unable to predict the total number of sea lions in a season that are either captured or die as a consequence of being excluded from nets. However, if a value for the survival probability is assumed (or a probability distribution for the survival probability that reflects the uncertainty in its value is given), then it is easy to obtain a sample from the predictive distribution of the total number of captures or deaths for the season from the MCMC samples for T^{L} and T^{E}. As an example, we have assumed that 50% of sea lions excluded from a net with an open SLED do not survive. Five thousand iterations from the predictive distribution of the total captures and deaths of sea lions $T^{50\%}$ for a season can be obtained directly from the iterations of the pair $(T^{\text{L}}, T^{\text{E}})$. For each iteration the current value of $T^{50\%}$ is obtained by $T^{\text{L}} + Y$, where Y is one realisation from a binomial distribution with $n = T^{\text{E}}$ and $p = 0.5$.

Because mean interaction rates vary, a new definition of strike rate was introduced by Smith & Baird (2007a). The *mean strike rate* parameter μ^{SR}, which replaced the (previously assumed constant) strike rate parameter, was defined there as

$$\mu^{\text{SR}} = \frac{1}{n} \sum_{k=1}^{n} \mu_k$$

and is the average of the mean interaction rates over all tows in the fishery. This definition takes into account the varying interaction rates for all the fishing effort in the fishery. μ^{SR} is an unknown parameter that needs to be estimated. We use the estimator first used by Smith & Baird (2007b) to estimate μ^{SR}. This estimator adds the total observed landed captures, the estimated mean total number of exclusions for the observed tows, and the estimated mean total interactions for the unobserved tows; then divides the sum by *n*. It mimics the observed strike rate in the sense that if all tows were closed and observed then the estimated mean strike rate and the old observed strike rate estimate would coincide.

Five thousand realisations from the posterior distribution of the estimated strike rate for a season are obtained from the realisations of the mean interaction rates and mean landed capture rates as follows. The current realisation of the mean strike rate is obtained by dividing the sum of the total observed captures, the current realisations of the mean exclusion rates for the observed tows, and the current realisations of the mean interaction rates for the unobserved tows by *n*. Thus, the current realisation of the mean strike rate estimate for the season is

$$\mu^{SR} = \frac{T^{O} + \sum_{\{\text{observed tows}\}} \mu_k^{E} + \sum_{\{\text{unobserved tows}\}} \mu_k}{n}$$
$$= \frac{T^{O} + \sum_1^n \mu_k - \sum_{\{\text{observed tows}\}} \mu_k^{L}}{n},$$

which is similar to dividing the current predicted total interactions *T* (see Equation 5) by *n* but with the realisations of the x_k^L and the x_k replaced by the current estimated mean rates μ_k^L and μ_k, respectively. Defining the estimator in terms of the iterations of the mean interaction rates rather than the simulated realisations of the actual captures avoids the extra variability that arises from simulating the realisations. The variability of the new estimator would reduce with increasing observer coverage of the total effort. The mean strike rate should be thought of (in the 2001 to 2006 seasons when open SLEDs were used) as an interaction rate rather than a capture rate, which can be interpreted as the rate of capture if no open SLEDs were used.

2.3.1 Prediction results

For each season, the characteristics of the posterior distribution of the mean strike rate μ^{SR}, and the characteristics of the predictive distributions of the actual total interactions *T*, the actual total landed captures T^L, the actual total exclusions T^E, the actual total captures or deaths assuming that 50% of sea lions excluded do not survive $T^{50\%}$, and the total attributed captures T^A were all obtained from the 5000 iterations for each quantity generated using the procedures described above.

Characteristics of the posterior distributions the mean strike rates for 1995 to 2006 are given in Table 7 and the kernel density estimates of their posterior distributions are plotted in Figure 9. Using the posterior mean as the estimate of the mean strike rate for each season there is no overall trend up or down over the 12 seasons (Figure 9), although there is a suggestion that the last 3 seasons had higher than usual strike rates. The mean strike rate for the 2006 season was 6.0% with a c.v. of 34%. Estimates in the first 5 seasons of the study, when SLEDS were not used, are lower than all other seasons except for 2003, varying between 3.3% and 4.3%. The 2001 season stands out with the largest mean strike rate of 9.2%. This season was unusual in that almost all tows were observed and there were fewer tows than in all other seasons (except for 1999) (see Table 4). It was also the season where SLEDs with open cover nets were first used. The 2004, 2005, and 2006 seasons had the largest estimated mean strike rates apart from the 2001 season, varying between 5.1% and 6.0%. These three seasons were also unusual, because almost all tows used SLEDs with open covers (97% in 2004, over 98% in 2005 and 100% in 2006) (see Table 4). This led to larger c.v.s for those seasons (Table 7 and Figure 9) because of the greater uncertainty resulting from fewer observed captures when open SLEDs are used. Except for the 2001 season, when most tows were observed, the c.v.s of the mean strike rate estimates varied between 20% and 35%.

Table 7: Characteristics of the posterior distributions of the mean strike rate and the predictive distributions of the total interactions for the seasons 1995 to 2006.

Season	Mean strike rate, μ^{SR} (%)					Total interactions, *T*				
	Mean	c.v. (%)	2.5%ile	50%ile	97.5%ile	Mean	c.v. (%)	2.5%ile	50%ile	97.5%ile
1995	4.07	35	1.90	3.87	7.42	163.1	36	72	154	302
1996	3.29	29	1.79	3.18	5.44	146.8	30	76	141	243
1997	3.74	20	2.55	3.65	5.50	138.8	22	90	135	210
1998	4.34	25	2.67	4.17	6.85	63.5	28	36	61	106
1999	3.59	25	2.26	3.45	5.75	14.4	34	7	14	26
2000	5.23	20	3.71	5.06	7.76	63.2	23	42	61	96
2001	9.16	11	7.71	9.00	11.42	53.5	14	43	52	70
2002	4.39	21	2.95	4.24	6.63	72.4	24	45	70	114
2003	3.21	25	1.91	3.13	4.99	47.2	29	25	46	77
2004	5.90	31	3.29	5.60	10.22	153.3	32	82	146	266
2005	5.09	35	2.55	4.79	9.15	136.9	36	66	129	250
2006	5.96	34	2.96	5.64	11.00	146.6	35	71	138	268

Characteristics of the predictive distributions of the total interactions for 1995 to 2006 are given in Table 7 and the kernel density estimates of their predictive distributions are plotted in Figure 10. In the first six seasons the numbers of interactions are the numbers of (landed) captures as no tows with open SLEDs were used then. In the last six seasons numbers of interactions include all captures plus those sea lions excluded by open net SLEDs. The density plots in Figure 10 compared with those in Figure 9 illustrate the effect of the varying amounts of total effort among the seasons. The mean strike rates are essentially the total interactions divided by the number of tows. The mean of the predictive distribution of the total interactions for the 2006 season was 147 with a c.v. 35%. Interestingly, the seasons when most interactions occurred (using means of the predictive distributions as estimates) were 1995 to 1997 and 2004 to 2006, where the estimates varied between 137 and 163. In the middle seasons, 1998 to 2003, the interactions varied between 14 and 72, with the low occurring in 1999 partly because of the low strike rate but mainly because there were very few tows that season. Despite the highest mean strike rate in 2001, that season had the third smallest number of interactions, 54, because of small number of tows. C.v.s, apart from the 2001 season, varied between 22% and 36%.

It is only necessary to consider the 2001 to 2006 seasons in relation to total exclusions, total landed captures, and total captures assuming 50% survival for each sea lion excluded. In the seasons before 2001 the total exclusions were zero, the total landed captures were equal to the total interactions, and the total of the captures assuming 50% survival was irrelevant. It is only possible to predict total attributed captures for the 2004 to 2006 seasons because the designation of MFish approved SLEDs did not exist in earlier seasons.

The means and c.v.s of the predictive distributions of the total exclusions, total landed captures, total captures assuming 50% survival for excluded sea lions, and total landed captures for the 2001 to 2006 seasons are given in Table 8 and kernel density estimates of their predictive distributions from the MCMC iterations are plotted in Figures 11, 12, 13, and 14 respectively. Means of the predictive distributions and 95% prediction intervals for the totals are indicated in the density plots.

The mean of the predictive distribution of the total exclusions for the 2006 season was 109 with a c.v. of 43%. Total exclusions for the six seasons 2001 to 2006 depend upon the numbers of tows that used open SLEDs and, therefore, the largest numbers of exclusions occur in the last three seasons when almost all tows used open SLEDs (see Table 4). The numbers of exclusions varied between 15 and 27 in 2001 to 2003 and between 99 and 110 in 2004 to 2006. The c.v.s for total exclusions are higher than those for the other totals because of their direct dependence on the retention probability parameter.

The mean of the predictive distribution of the total landed captures for the 2006 season was 38 with a c.v. of 27%. Total landed captures for the six seasons varied between 20 in 2003 and 45 in 2002. The last three seasons had similar predicted total landed captures, varying between 37 and 44. These numbers depend to a great extent, on the total numbers of tows and the proportion of those that used open SLEDs. There was very little uncertainty in the 2001 season because only 1.5% of tows were unobserved (see the very truncated kernel density estimate in Figure 12). For seasons 2001 to 2006 the most important results are the predicted total interactions and the predicted total landed captures as these are bounds for the number of sea lion captures in each season in the current state of knowledge where the survival rate of a sea lion excluded by an open SLED is unknown.

Table 8: Means and c.v.s of the predictive distributions of the total exclusions, total landed captures, total captures assuming 50% survival, and total attributed captures for the seasons 2001 to 2006. Means and c.v.s of the predictive distributions of the total interactions are also included for those seasons for comparison.

Season	Interactions, T		Exclusions, T^{E}		Landed, T^{L}		50% survival, $T^{50\%}$		Attributed, T^{A}	
	Mean	c.v. (%)	Mean	c.v. (%)	Mean	c.v. (%)	Mean	c.v. (%)	Mean	c.v. (%)
2001	53.5	14	15.2	47	38.4	2	46.0	9		
2002	72.4	24	27.1	42	45.3	21	58.8	22		
2003	47.2	29	27.0	40	20.2	26	33.7	27		
2004	153.3	32	109.8	41	43.6	22	98.4	28	133.6	32
2005	136.9	36	99.7	44	37.2	28	87.1	32	112.3	36
2006	146.6	35	108.8	43	37.9	27	92.2	31	124.2	35

The mean of the predictive distribution of the total captures or deaths assuming 50% survival is the average of the means of the predictive distributions of the total interactions and the total landed captures. The mean of the predictive distribution of the total captures assuming 50% survival for the 2006 season was 92 with a c.v. of 31%. In the 2004 to 2006 seasons, the numbers of captures assuming 50% survival were larger than in the previous three seasons. They varied between 87 and 98 (with c.v.s between 28% and 32%), whereas in the earlier seasons they varied between 34 and 59 (with c.v.s between 9% and 27%). If the survival rate were 50% then the use of open SLEDs represents an estimated total saving in sea lion mortality of 194 over the seasons 2001 to 2006 (an estimated 416 captures compared with an estimated 610 total interactions).

The numbers of total attributed captures in relation to the numbers of interactions depends on the proportions of tows that are made with MFish approved open SLEDs. The mean of the predictive distribution of the total attributed captures for the 2006 season was 124 with a c.v. of 35%. The predicted total attributed captures are similar over the three seasons, varying between 112 and 134 (compared with 137 to 153 for the predicted total interactions). Of interest is the probability that the total attributed captures exceeds the FRML for each season, which can be calculated from the MCMC iterations drawn from the predictive distributions. (See Figure 14 for kernel density plots of the predictive distributions estimated from these MCMC iterations.) For the 2006 season the FRML was 150 and the probability that the total attributed captures exceeded it is 22%. In 2005 the FRML was 115 and the probability it is exceeded is 39%. In 2004 the FRML was effectively 124 (following changes during the season) and the probability it was exceeded is 53%. In both the 2004 and 2006 seasons the estimated mean strike rate was higher than the strike rate of 5.3% predetermined by MFish for management of the squid fishery (see Table 7).

The imprecision of the predictive distributions for the various totals in 2004, 2005, and 2006 relative to those for the earlier seasons is to be expected. Extensive use of SLEDs meant that relatively few observed capture incidents were available for estimating the base interaction strike rates, for example, 9 incidents with 11 captures in 2006 for estimating the 2006 base interaction rate λ_{06}. Because almost all tows in these seasons were made with open nets, most observed captures were made with open nets and, consequently, estimates made through the model are the product of the retention probability π and the base interaction rates. This means that there is a negative correlation between π and each of the λs. Therefore the quality of the estimates of these interaction rates is critically dependent on how well the retention probability is estimated for those years. This point has also been highlighted by Abraham (2007) and by Smith & Baird (2007a). By assuming a constant retention probability for these and earlier seasons the model is able to combine information about retention probabilities from all the seasons. Also, extra information from the hierarchical distribution of the base interaction rates is used by the estimation and prediction process resulting in better precision than if the approach had not been hierarchical. The lack of information from other sources on retention probabilities has made the assumption that they are constant over seasons necessary.

2.4 Discussion

In the 2004, 2005, and 2006 seasons in the SQU6T fishery almost all of the observed tows (and commercial tows) used SLEDs with open cover nets (see Table 2). This has necessitated the development of an entirely new approach to the problem of the estimation of sea lion captures. The method used here and by Smith & Baird (2007b) is now well established. By assuming a constant retention probability π (as was also assumed in the ratio method of Breen et al. (2005)) it has been possible to make reasonable estimates of the various types of sea lion captures in the latter seasons. However, the use of SLEDs became widespread from the 2004 season onwards and there is little new information to update estimates of the retention probability and to model possible recent improvements in the SLED technology. Most of the information used to estimate π in the fitted model comes from the observer data before the 2004 season. However, the use of random season base capture rates will have helped to resolve, in part, the problem (since the 2004 season) of the confounding of the season base capture rates and the retention probability.

The method corrects, at least in part, for differences between the capture rates for observed tows and for unobserved tows. It also incorporates the effects of correlation among capture rates for tows by the same vessel, as extra variation through the use of random vessel-season effects. Perhaps the greatest merit in the method lies in the error estimates associated with the posterior and predictive distributions. By using the Bayesian approach, both the uncertainty in the model parameters and the uncertainty resulting from probability distribution of the actual capture numbers are accounted for.

Because of the relatively large c.v.s associated with the time series of estimated mean strike rates it is not possible to infer that there is any trend in the strike rates with any statistical confidence. The larger c.v.s that occurred in the seasons from 2004 compared with earlier seasons (differences which are very obvious in the kernel density plots of the posterior distributions in Figure 9) also have the effect of inflating the posterior means for those seasons. Larger c.v.s mean that the posterior distributions are more right skewed (for distributions that can only take positive values) which in turn results in the means of the posterior distributions lying further to the right of the median. The same inflation effect will occur for the various predicted totals, which are the means of their respective predictive distributions, for the seasons from 2004, again because of the large dispersions. The greater dispersions for those seasons is very apparent in Figures 10–13.

The next two sections report on sea lion captures in other trawl fisheries and sea lion captures reported by fishers for the 2005–06 fishing year.

3. SEA LION CAPTURES OBSERVED IN OTHER TRAWL FISHERIES, 2005–06

In the 2005–06 fishing year five sea lion captures were observed by MFish observers in trawl nets that targeted southern blue whiting (*Micromesistius challengeri*), scampi (*Metanephrops challengeri*), or squid outside the Auckland Islands part of SQU 6T. One sea lion, of unknown sex, was captured and released alive from a midwater tow targeting squid off the southern edge of the Stewart-Snares shelf in March. A total of 631 squid tows were observed off the Stewart-Snares shelf during November–May 2006; these observed data represent about 14% of the 4480 tows reported on commercial returns from October–June.

One dead sea lion, of unknown sex, was caught in a scampi tow off the southeastern edge of the Auckland Islands shelf during November 2005: 1332 tows targeting scampi were made in this area in all months of the fishing year, except January. Observer coverage was limited to October–December, when two of the four vessels operating in this area were observed (30% of the 396 tows).

Three dead male sea lions were reported by observers from two observed southern blue whiting tows east of the Campbell Rise during September 2006. Four of the 13 vessels operating in this fishery area were observed, with observers present for 28% of the 510 tows made during August–October 2006. The captures were reported from one vessel which accounted for about 17% of the observed effort and 6% of the total effort in this area.

Together with the 11 captures in the Auckland Islands part of SQU 6T, 16 sea lion captures were reported by MFish observers in trawl fisheries in the 2005–06 fishing year.

4. CAPTURES OF NEW ZEALAND SEA LIONS REPORTED BY FISHERS, 2005–06

Fishers report the incidental capture of protected species, including New Zealand sea lions, on the completion of each trip. These data are collected on Non-fish Incidental Catch Reporting Forms and stored in the MFish *nonfish_bycatch* database (Sutton & Wei 2003).

During 2005–06, fishers reported 20 New Zealand sea lions from 15 tows during 8 trips by 7 vessels. All were from trawl fisheries: 11 tows caught 1 animal, three tows caught 2 animals and one tow caught 3 animals (Table 9). Captures were from southern blue whiting, scampi, and squid tows. All were landed dead, except for the one capture off the Stewart-Snares shelf.

Table 9: Numbers of New Zealand sea lions reported by fishers during 2005–06

Target	Fishery area	Capture details
SBW	Campbell Rise	3 males landed dead from 2 MFish-observed midwater tows on one vessel in September
SCI	Auckland Islands Shelf	1 unsexed animal landed dead from 1 unobserved tow in October
SQU	SQU 1T (Stewart-Snares shelf)	1 alive female from 1 MFish-observed midwater tow in March
	SQU 6T (Auckland Islands area)	9 animals landed dead from MFish-observed tows in February-March: 2 females in 2 bottom tows, 2 males in 2 midwater tows, 5 females in 2 midwater tows. 5 animals landed dead from company-observed bottom tows in February-March: 1 female and 2 unsexed animals from 3 tows and 2 females in one tow. 1 unsexed animal landed dead from an unobserved bottom tow in March.

4.1 Comparison of fishers' and MFish observer data

All three MFish-observed captures in the southern blue whiting fishery were reported by fishers. The capture reported from a scampi tow was from an unobserved vessel; however, the MFish-observed capture from another vessel in November 2005 was not in the fishers' data. The fisher-reported capture and release of an alive female sea lion occurred on an MFish observed tow on the Stewart-Snares shelf in March 2006, although the observer reported that the animal was unsexed.

Of the 15 sea lions reported by fishers from the 2006 Auckland Islands SQU 6T squid fishery, 9 were reported as being caught on tows observed by MFish observers. In the MFish observer data, 11 sea lion captures in total were reported from the fishery but 3 of these were not in the database of fisher-reported captures; however, one of these animals matched the MFish-observed sea lion that was originally identified by the observer as a fur seal and this capture was reported in the fishers' fur seal data. One of the fisher-reported sea lion captures was wrongly reported as being observed by MFish.

5. ACKNOWLEDGMENTS

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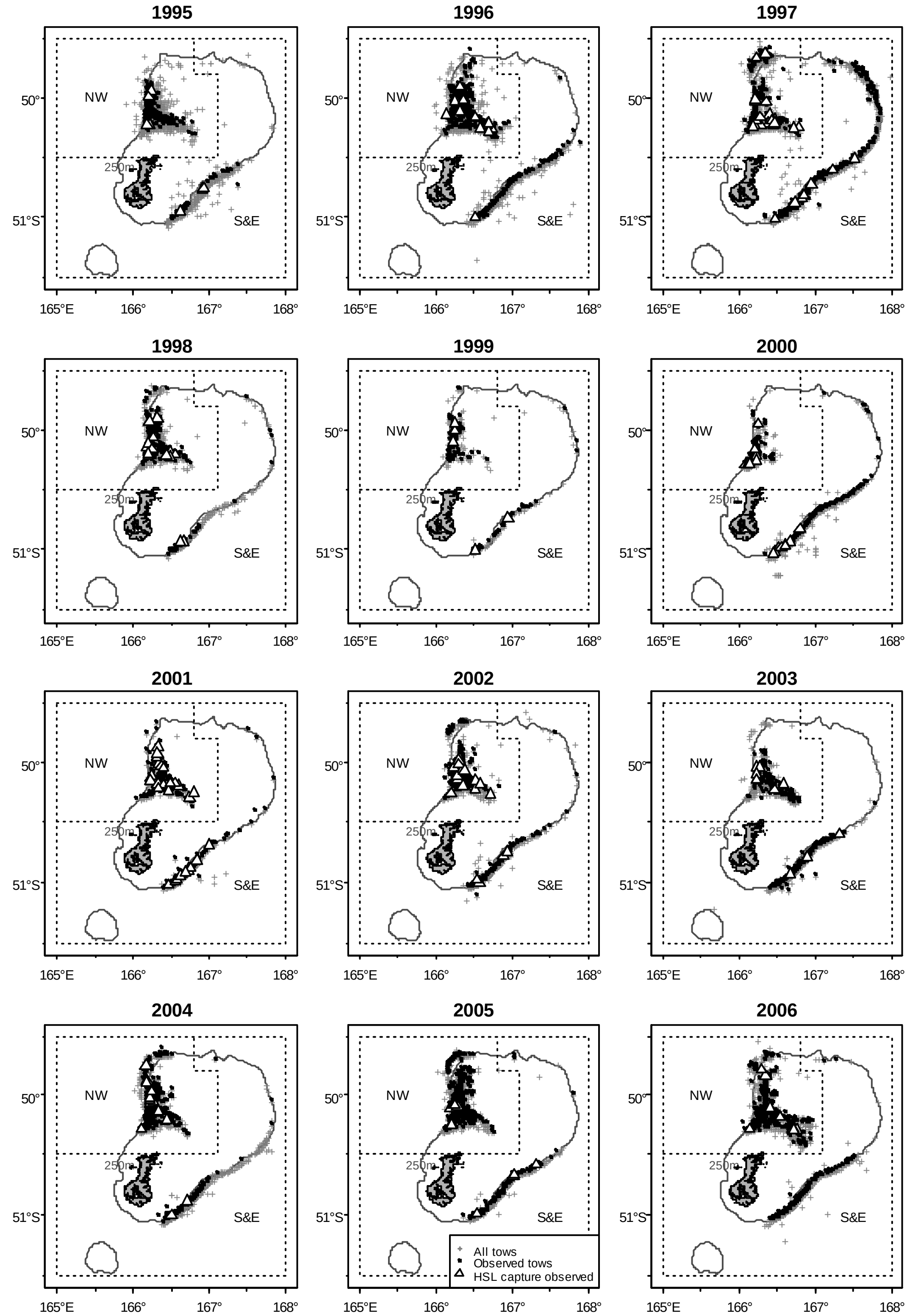

Figure 1: Start positions of all commercial and observed tows (including the observed tows where sea lions were caught) in SQU 6T for the seasons 1995 to 2006. The dotted lines indicate the boundary of the Auckland Islands part of SQU 6T and the boundary between the NW and S&E subareas. The 250 m depth contour is also plotted.

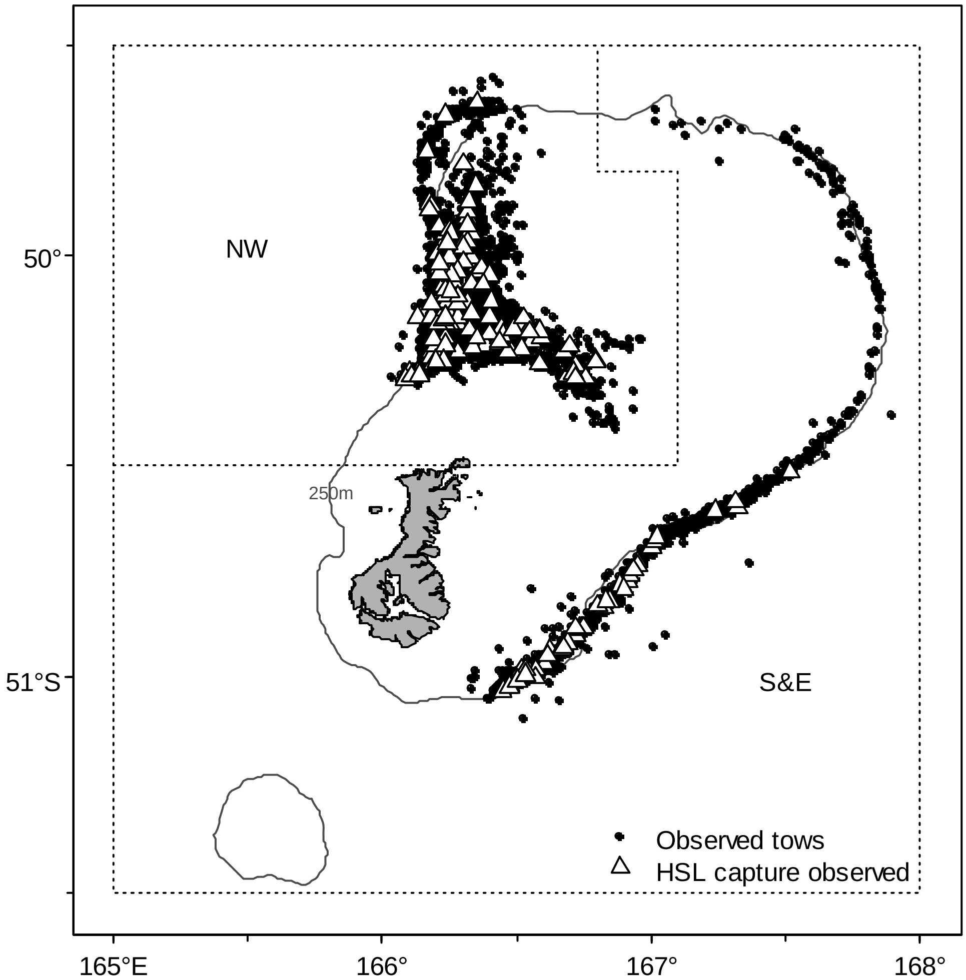

Figure 2: Start positions of tows including those with sea lion capture incidents, for the observer data from the 1992 to 2006 seasons used for fitting the model. The dotted lines indicate the boundary of the Auckland Islands part of SQU 6T and the boundary between the NW and S&E subareas. The 250 m depth contour is also included.

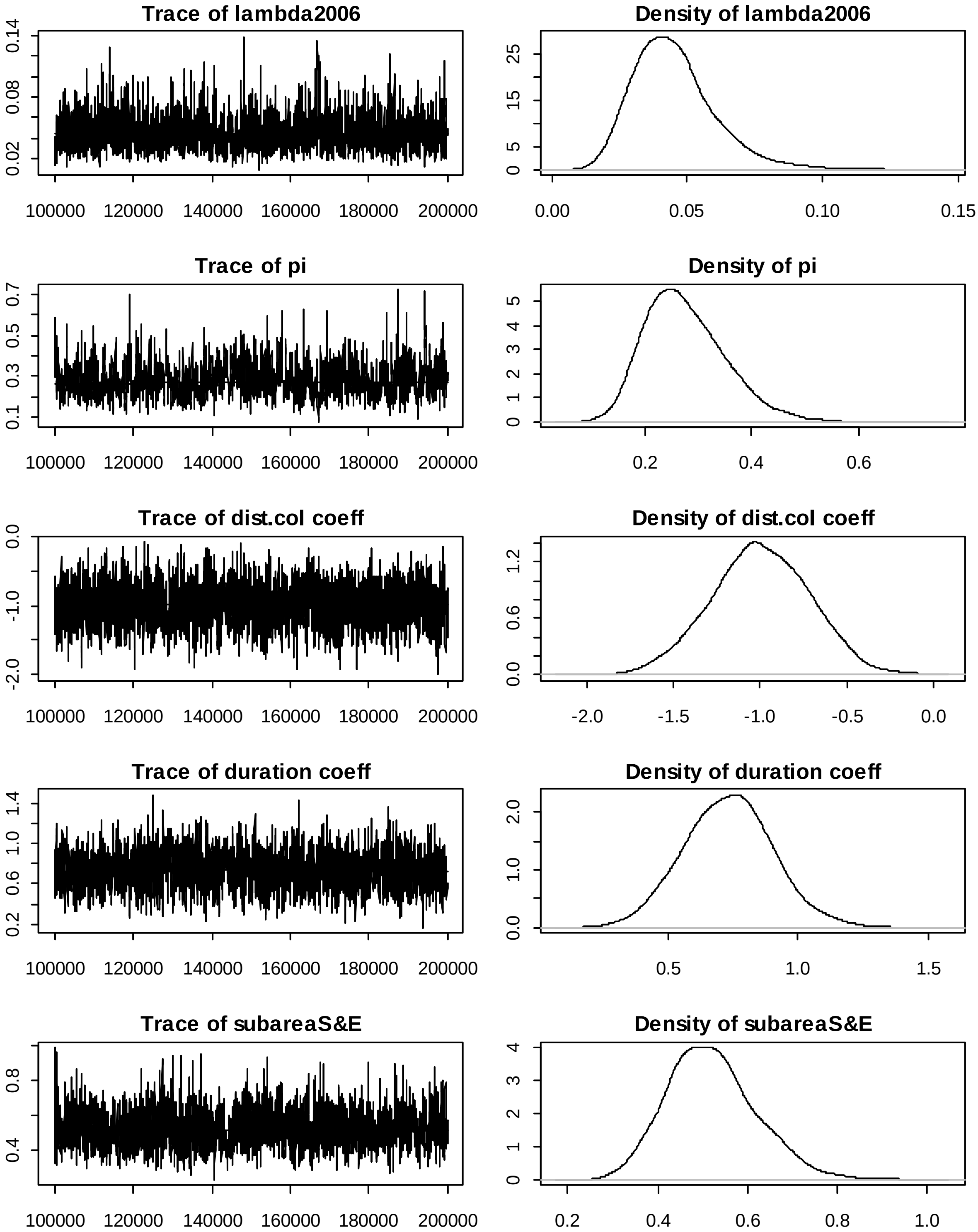

Figure 3: Plots of traces of the MCMC iterations and plots of the kernel densities from the posterior distributions of the 2006 base interaction rate (λ_{06}), the SLED retention probability (π), the coefficients of the logarithms of dist.col and duration, and the effect of the S&E subarea relative to the NW subarea.

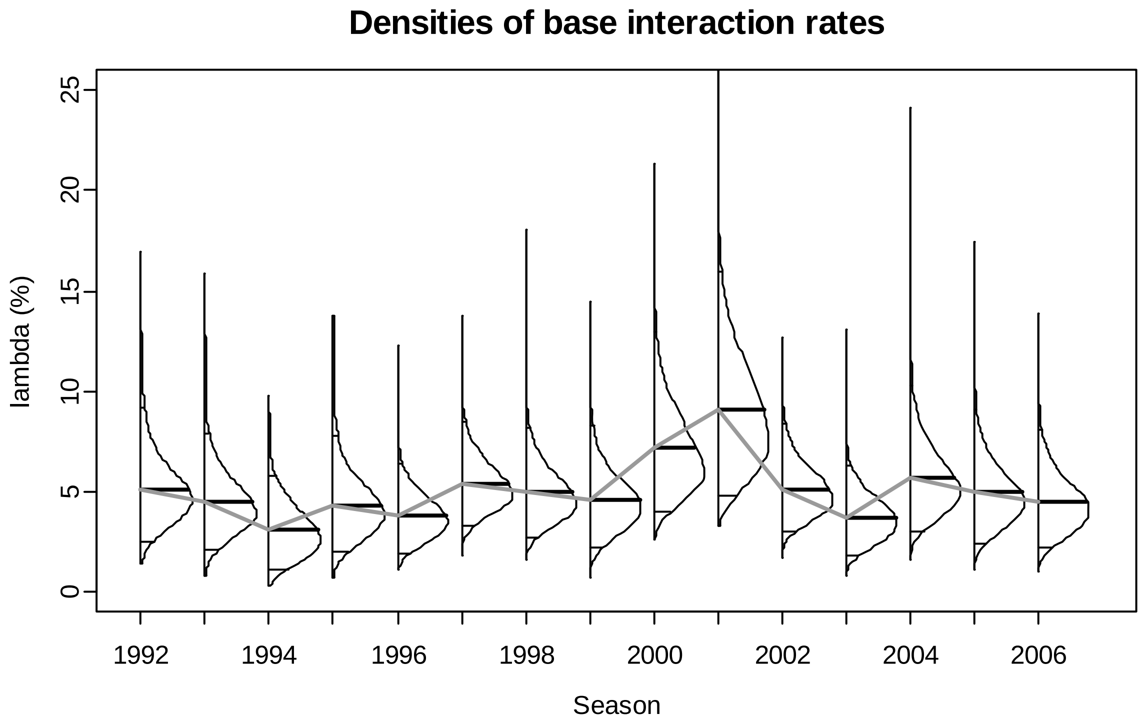

Figure 4: Kernel density plots of the posterior distributions of the base interaction rates (λ_i) for the seasons 1992–2006. The thinner horizontal lines indicate the bounds of the 95% credibility intervals and the thicker horizontal lines indicate the posterior means for the base capture rates. A grey line joins the posterior means.

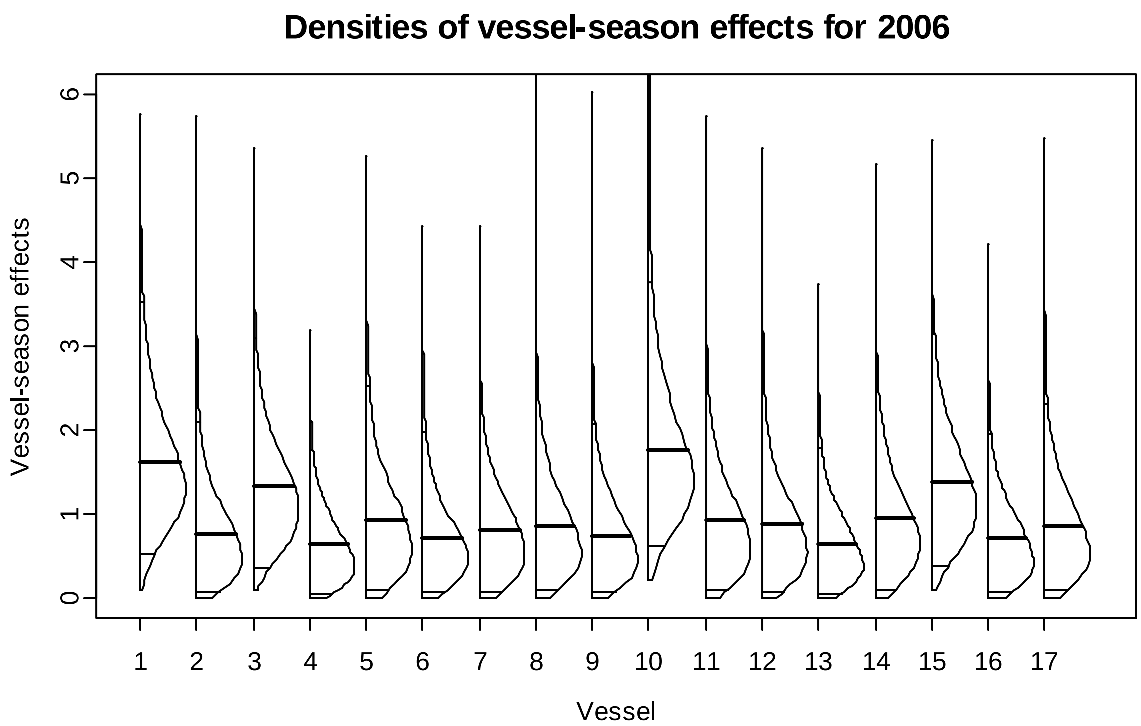

Figure 5: Kernel density plots from the posterior distributions of the vessel-season effects, $\nu_{06,j}$, for the 17 vessels observed in the 2006 season. The thinner horizontal lines indicate the bounds of the 95% credibility intervals and the thicker horizontal lines indicate the posterior means for vessel-season effects.

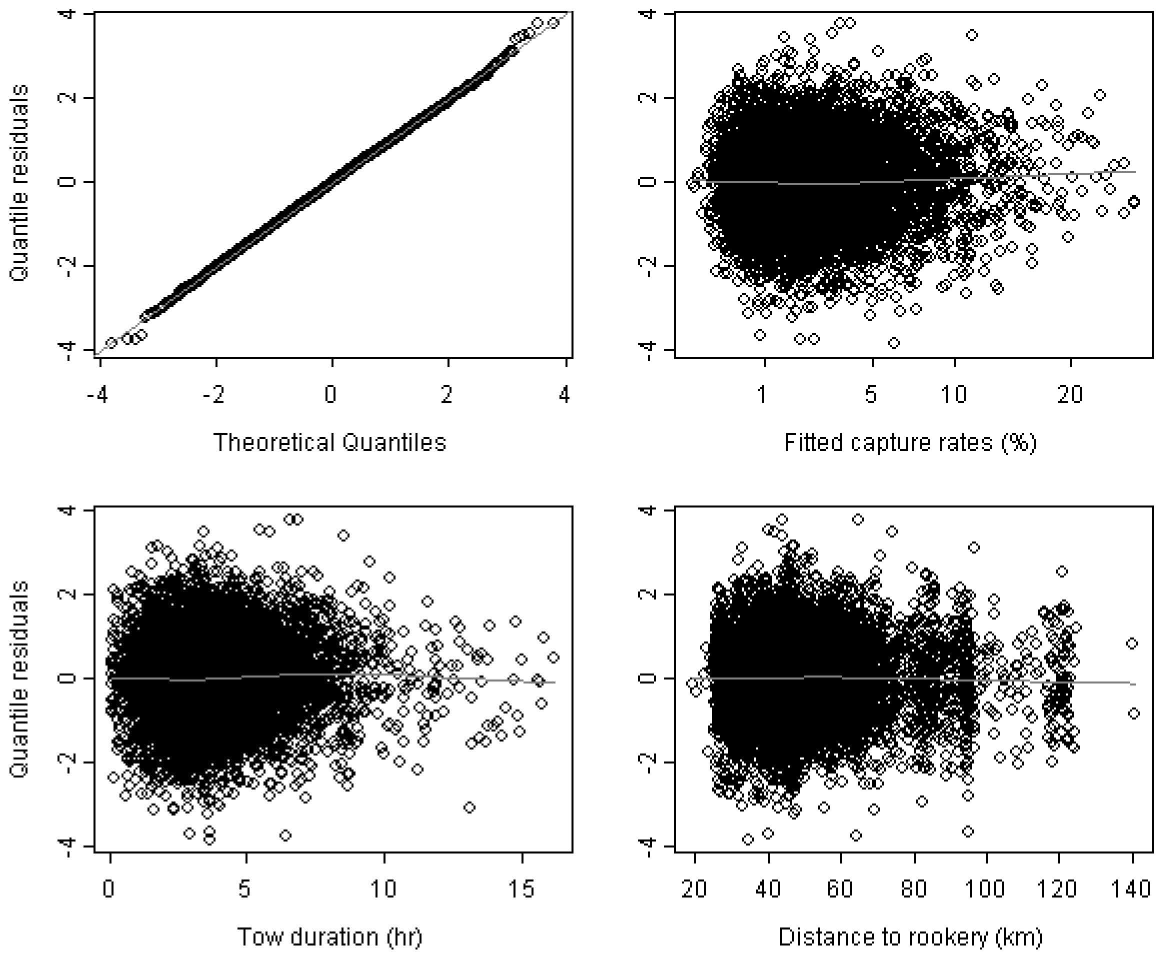

Figure 6: A normal Q-Q plot of the randomised quantile residuals and plots of the randomised quantile residuals against the fitted values of the capture rates, the durations of tows, and the distances to nearest rookery. The Q-Q line is included in the top left panel and the lines in the other 3 panels are local regression lines fitted through the residuals by the loess method.

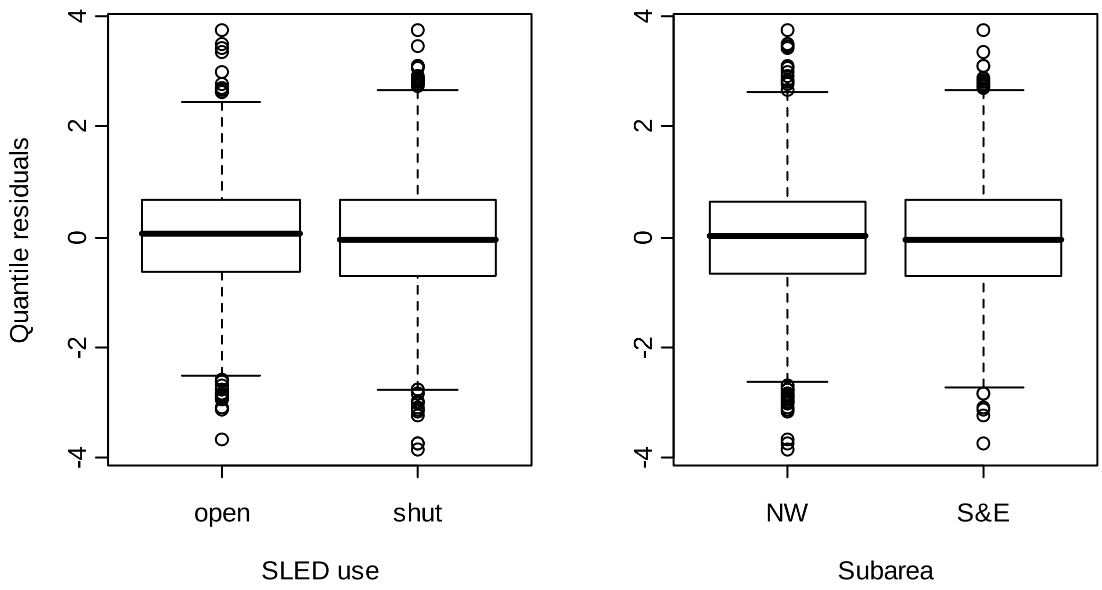

Figure 7: Box-whisker plot of randomised quantile residuals by the levels of the subarea and SLED use factors.

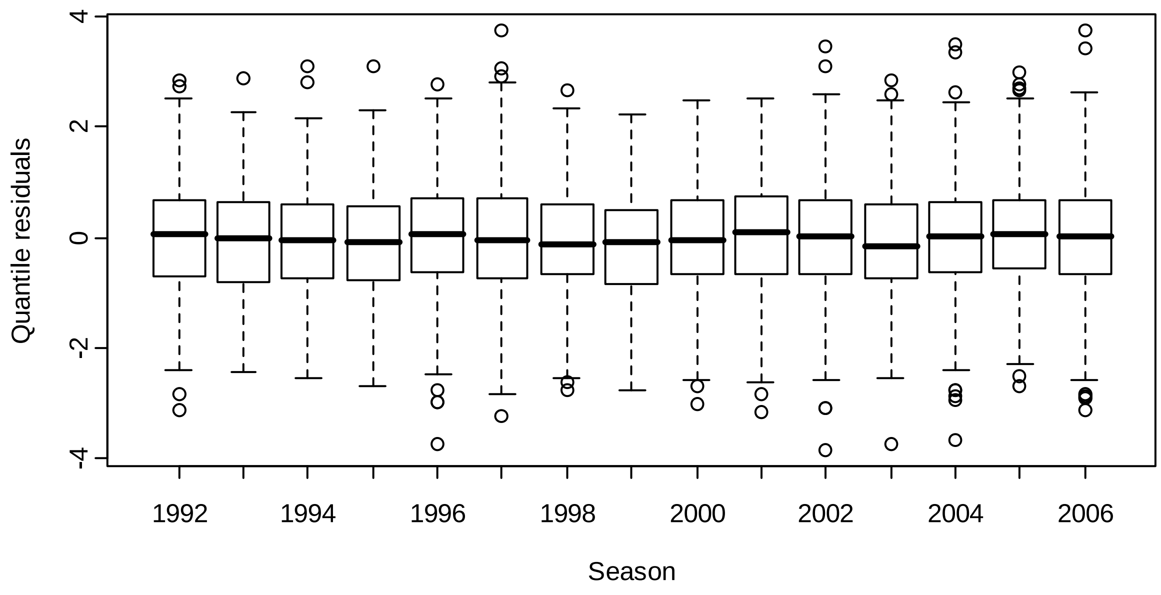

Figure 8: Box-whisker plot of randomised quantile residuals by season .

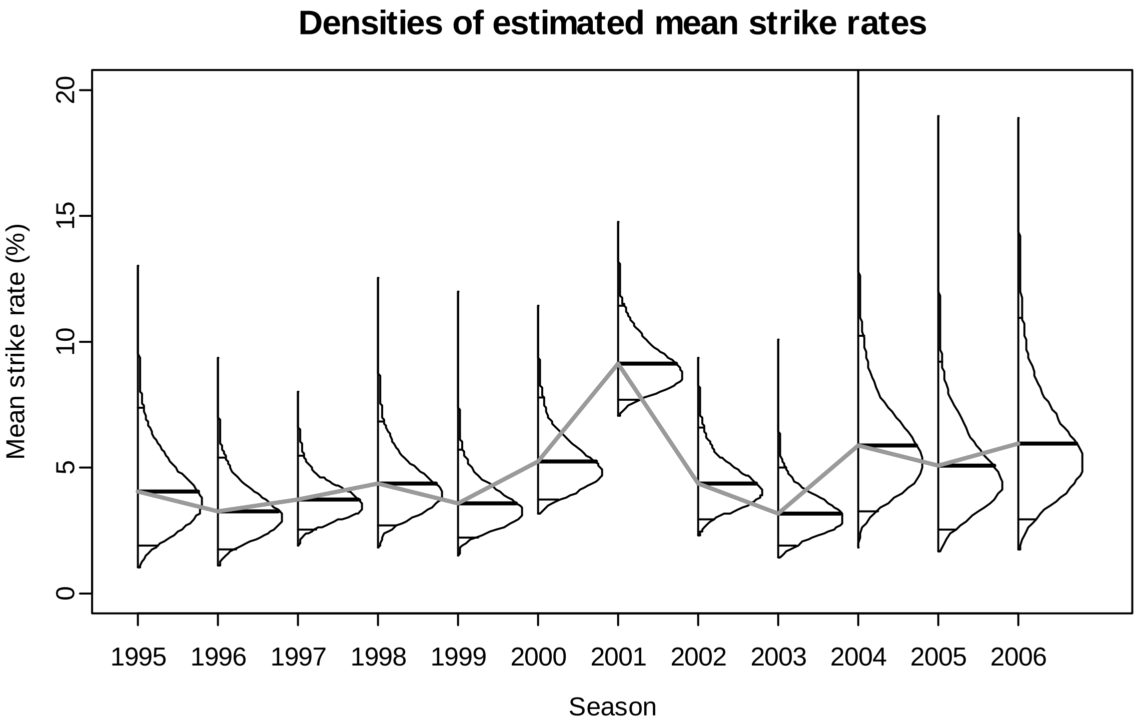

Figure 9: Kernel density plots from the posterior distributions of the estimated mean strike rates (μ^{SR}) for the seasons 1995 to 2006. The thinner horizontal lines indicate the bounds of the 95% credibility intervals and the thicker horizontal lines indicate the means of the posterior distributions. The grey line joins the posterior means for consecutive seasons.

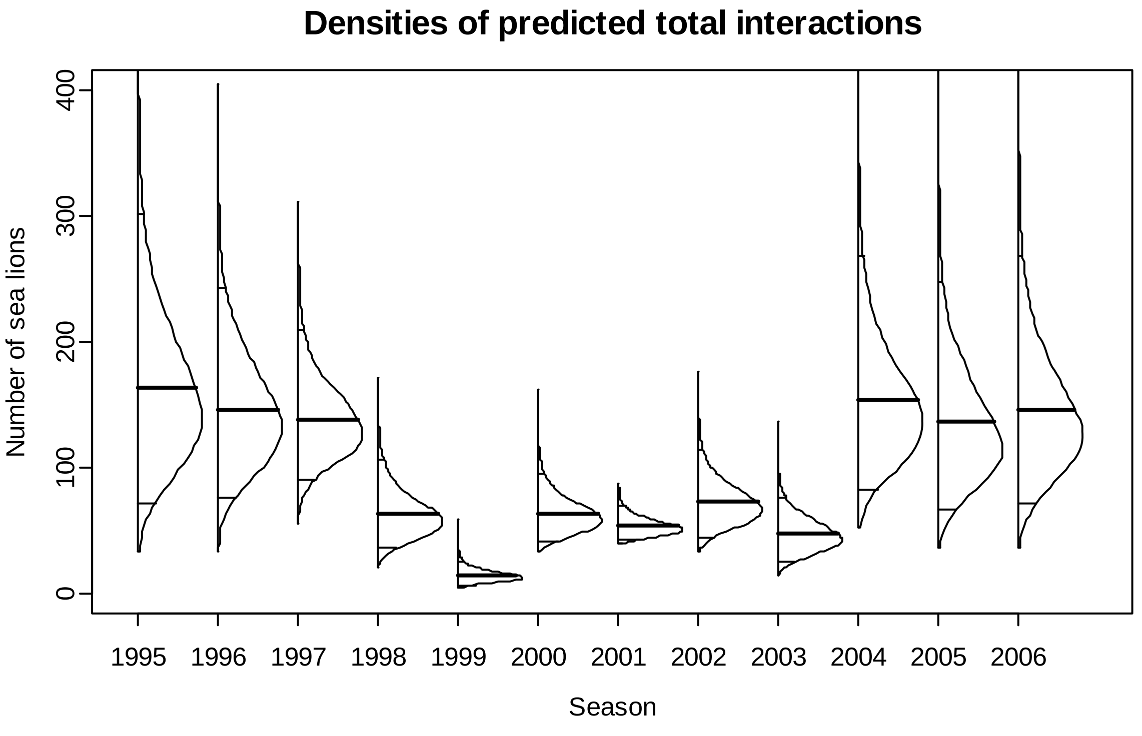

Figure 10: Kernel density plots from the predictive distributions of the total interactions (*T*) for the seasons 1995 to 2006. The thinner horizontal lines indicate the bounds of the 95% credibility intervals and the thicker horizontal lines indicate the means of the predictive distributions.

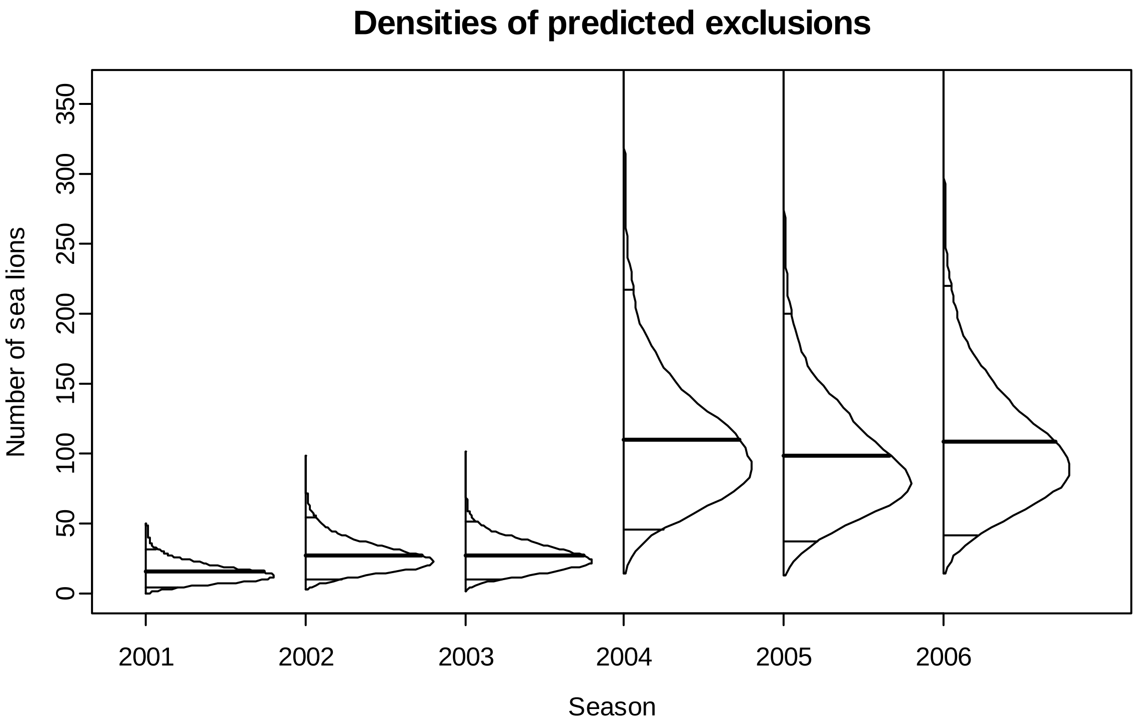

Figure 11: Kernel density plots from the predictive distributions of the total exclusions (T^E) for the seasons 2001 to 2006. The thinner horizontal lines indicate the bounds of the 95% credibility intervals and the thicker horizontal lines indicate the means of the predictive distributions.

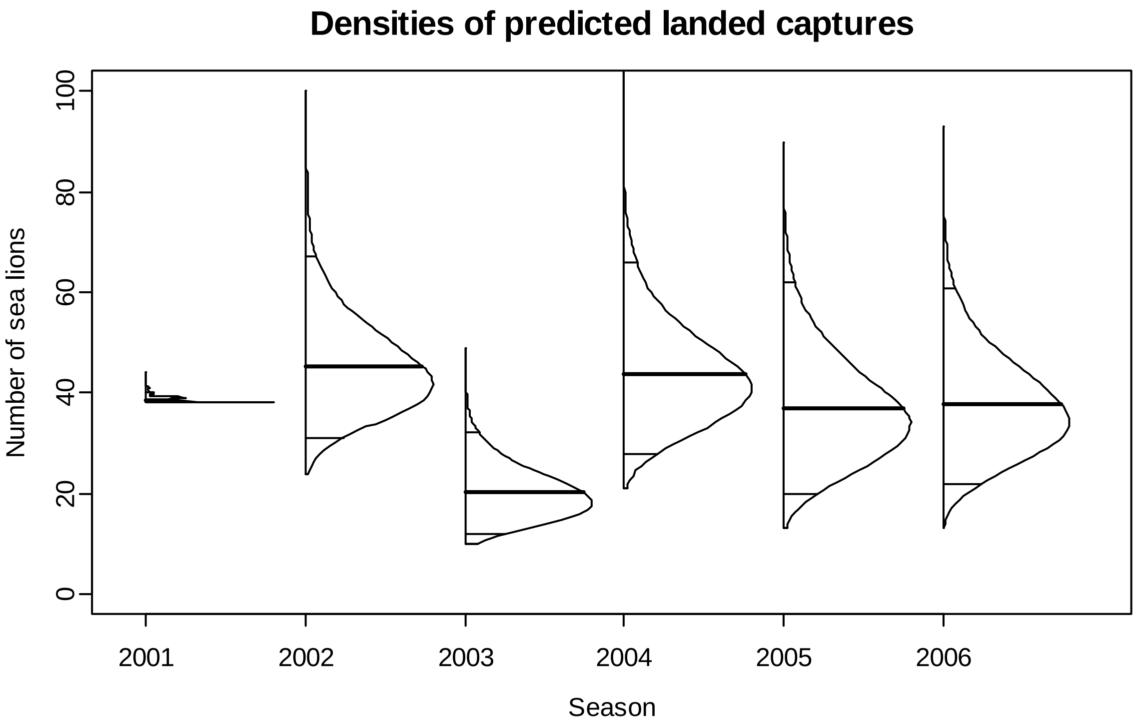

Figure 12: Kernel density plots from the predictive distributions of the total landed captures (T^L) for the season 2001 to 2006. The thinner horizontal lines indicate the bounds of the 95% credibility intervals for the mean strike rates and the thicker horizontal lines indicate the means of the predictive distributions.

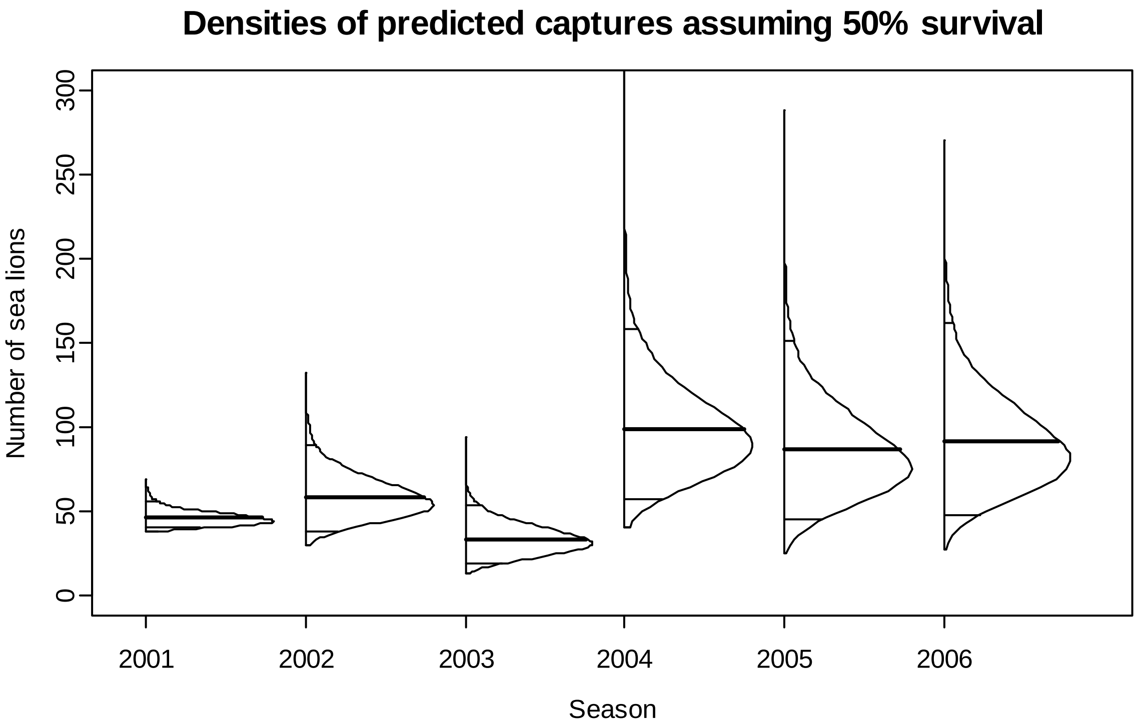

Figure 13: Kernel density plots from the predictive distributions for the seasons 2001 to 2006, of the total captures and deaths assuming any sea lions excluded from an open net have a 50% survival rate (T^{50}). The thinner horizontal lines indicate the bounds of the 95% intervals and the thicker horizontal lines indicate the means of the predictive distributions.

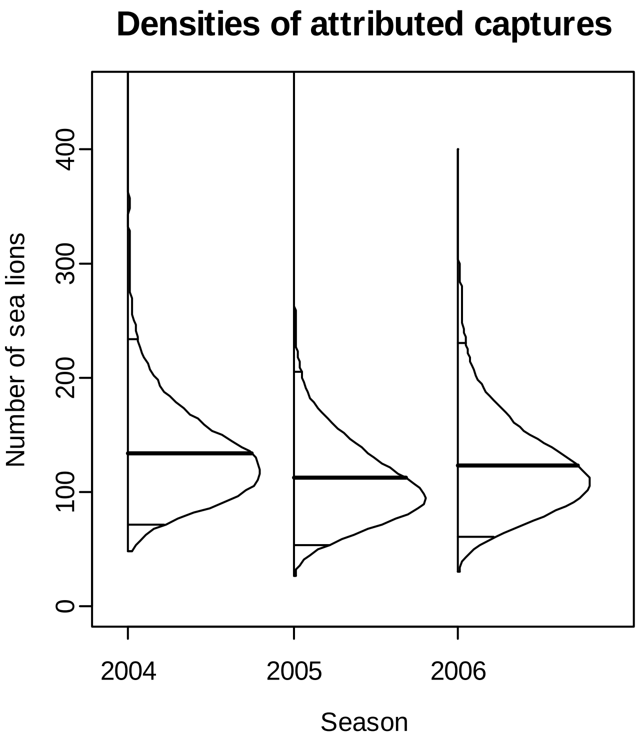

Figure 14: Kernel density plots from the predictive distributions of the total attributed captures (T^{A}) for the seasons 2004 to 2006. The thinner horizontal lines indicate the bounds of the 95% intervals and the thicker horizontal lines indicate the means of the predictive distributions.