Dolphin bycatch in New Zealand trawl fisheries, 1995–96 to 2006–07

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New Zealand Aquatic Environment and Biodiversity Report No. 36
2009

Published by Ministry of Fisheries
Wellington
2009

ISSN 1176-9440

Citation:
Thompson, F.N.; Abraham, E.R. (2009).
Dolphin bycatch in New Zealand trawl fisheries, 1995–96 to 2006–07
New Zealand Aquatic Environment and Biodiversity Report No. 36. 24 p.

This series continues the
Marine Biodiversity Biosecurity Report series
which ceased with No. 7 in February 2005.

EXECUTIVE SUMMARY

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In the 12 years from 1 October 1995 to 30 September 2007, a total of 107 dolphin captures were reported by Ministry of Fisheries observers in trawl and longline fisheries within New Zealand's Exclusive Economic Zone. These captures included 80 common dolphins, 9 pilot whales, and 7 dusky dolphins that were reported killed in trawl fisheries. In longline fisheries over the same period, eight dolphins were captured and released alive, with one common dolphin and two pilot whales reported killed. There have been few observations in inshore trawl fisheries, and no data were available from setnet fisheries. Hector's dolphin captures have previously been reported from both setnet and inshore trawl fisheries, but the observer database does not contain enough information to estimate the captures of either Hector's or Maui's dolphins.

The jack mackerel trawl fishery, operating off the west coast of the North Island, was responsible for 91% of observed dolphin mortalities in trawl fisheries. Most of these mortalities were of common dolphins. Only 15 vessels participated in this fishery, with over 95% of the effort being carried out by just 7 vessels. A Bayesian model was developed to estimate dolphin captures in the jack mackerel fishery. This was the only fishery with sufficient observed captures to allow a reliable estimate of total captures to be made. There were 0.8 capture events per 100 observed tows in the 2006–07 fishing year. Dolphins are often caught in groups; the mean number killed in a single capture event was 2.5 dolphins. The model had two stages: first the probability that a dolphin capture event occurred on a tow was predicted, then if a capture event occurred, the number of dolphins killed was estimated. The model was fitted using Markov chain Monte Carlo techniques.

Four covariates explained variation in the probability of a capture event occurring during a trawl: headline depth, the depth of the top of the trawl net; trawl duration, time spent trawling, from shooting the net to hauling; light condition at haul time, which depended on the time of day and the illumination of the moon; and whether the tow was north or south of Mount Taranaki. Headline depth had the most explanatory power, with more dolphins being caught when the headline depth was shallower. The model estimated that deepening the headline depth of a tow by 21 metres would have halved the probability of a dolphin capture event.

Annual trawl effort in the jack mackerel fishery has increased dramatically since the late nineties, from 405 tows by three vessels in the 1995–96 fishing year, to 2164 tows by eight vessels in the 2006–07 fishing year. Observed dolphin captures have also increased over the period, with 11 dolphins caught during observed tows in this fishery in 2006–07.

The model estimated that there were fewer than 5 dolphin captures a year between 1995–96 and 1998–99. As effort in the fishery increased there was initially a large increase in the estimated number of dolphin mortalities, which peaked at 174 (95% c.i.: 74 to 366) dolphins in 2002–03. Since then the number of dolphins caught each year has decreased. In 2006–07 the model estimated that 52 dolphins were killed in the large vessel jack mackerel fishery (95% c.i.: 22 to 106). This decrease has occurred despite the number of tows in the fishery remaining steady since 2002–03, at over 2000 tows per year.

The abundance of common dolphin on the west coast of the North Island is unknown, and so there is no basis for estimating the impact of the fisheries mortalities on the local population.

1. INTRODUCTION

This report has been prepared as part of Ministry of Fisheries project PRO2007/02. The project has the objective “to estimate the total numbers, releases, and deaths of selected marine mammals, where possible by species, fishery and fishing method, caught in commercial fisheries for the fishing years 2006–07, 2007–08 and 2008–09”. This report covers only the capture of common dolphins, with particular reference to the 2006–07 fishing year. The captures of fur seals and sea lions will be presented separately, and captures in 2007–08 and 2008–09 will be presented in due course.

Dolphins are caught in fisheries throughout the world (for a review see Reeves (2003)). In New Zealand, there have been occasional reports of dolphin captures in commercial trawl fisheries, with captures before 1995 summarised by Fertl & Leatherwood (1997). These early reports included captures of Hector’s dolphins (*Cephalorhynchus hectori*), common dolphins (*Delphinus delphis*), dusky dolphins (*Lagenorhynchus obscurus*), bottlenose dophins (*Tursiops truncatus*), a pilot whale (*Globicephala melas*), a killer whale (*Orcinus orca*), and an unidentified beaked whale. In the 1997–98 fishing year Department of Conservation observers were placed on commercial vessels fishing in the Canterbury region. Over 400 bottom trawls and close to 200 setnet hauls were observed (Starr & Langley 2000, Baird & Bradford 2000). Eight Hector’s dolphins were caught during the setnet fishing (six were killed and two were released alive), and a Hector’s dolphin was caught and killed during a bottom trawl.

A summary of more recent dolphin captures reported by Ministry of Fisheries observers was included by Abraham & Thompson (2009). Between 1998–99 and 2006–07, common dolphin was the species that was most frequently caught in observed trawl and longline fishing. Over 90% of the observed dolphin captures were in trawl fisheries, and of those over 90% were caught by vessels targeting jack mackerel (*Trachurus declivis*, *T. murphyi*, and *T. novaezelandiae*) on the west coast of the North Island. All dolphins caught in trawls were killed. In this report, Ministry of Fisheries observer records of dolphin captures from the 1995–96 to the 2006–07 fishing years are presented. A statistical model is used to estimate total dolphin captures in the jack mackerel trawl fishery on the west coast of the North Island by extrapolating from observed captures to captures during unobserved fishing. This is the only observed fishery where dolphin captures occur sufficiently frequently to allow a reliable estimate of total captures to be made. There have been previous reports of dolphin captures in the jack mackerel fishery (Baird 2004), and some statistical modelling has investigated the factors that are associated with dolphin capture rates in this fishery (Du Fresne et al. 2007). In this report, there is further exploration of the covariates that are related to dolphin captures, and estimates of total dolphin captures are made.

Although dolphins are caught in setnet fisheries, by both recreational and commercial fishers (Dawson 1991, Starr & Langley 2000, Baird & Bradford 2000, Dawson & Slooten 2005), there were no Ministry of Fisheries observer data available from setnet fisheries that could be used to assess captures. Another limitation of the observer dataset is the lack of coverage of trawlers fishing for inshore species. During the nine year period covered by Abraham & Thompson (2009), only 552 of 586 239 inshore trawls were observed (less than 0.1%). Because of this low coverage, the observer database does not contain sufficient information to estimate dolphin captures by inshore trawlers. Hector’s dolphin and Maui’s dolphin (*Cephalorhynchus hectori maui*) are listed as endangered and critically endangered, respectively (Reeves et al. 2008a, 2008b), with fishing impacts cited as a principal cause of their population decline. The current Ministry of Fisheries observer dataset does not contain information that can be used to estimate how many of these dolphins are killed by trawlers, as they are resident in inshore waters (Ferreira & Roberts 2003, Slooten et al. 2005, 2006).

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). Trawlers record details of fishing effort on Catch Effort Landing Return (CELR), Trawl Catch Effort Processing Return (TCEPR), or more recently, Trawl Catch Effort Return (TCER) forms. The forms record the date and time of trawl effort, the target species, catch weight, and various details regarding the gear used. The location of the start and end of a tow is recorded on CELR forms as a general statistical area, and as a latitude and longitude on the TCER and TCEPR forms. The *warehou* data were assumed to be a complete record of trawl effort, and were used as the authoritative source for tow time and location information required for the modelling. All the fishing effort from the large vessel jack mackerel fishery has been reported on TCEPR forms.

The Ministry of Fisheries observer programme collects data on mammal and sea bird captures in New Zealand fisheries, including dolphin captures. Observers on trawlers identify the species of any non-fish bycatch, and record the time and location of every tow they observe. These data are housed into databases managed by the National Institute of Water and Atmospheric Research (NIWA) on behalf of the Ministry of Fisheries (Ministry of Fisheries 2008).

An extract from the *warehou* and observer databases was obtained, providing records of all trawl events in the New Zealand Exclusive Economic Zone (EEZ) and territorial sea between 1 October 1998 and 30 September 2007. The data were groomed, correcting for errors in date, time, and position fields, following the rules given by Abraham & Thompson (2009). Where there were missing values in the trawl depth and height fields, they were set to the median value for that vessel. Missing or improbable position fields were set to the mean position taken from the previous and next trawl. Some grooming of fields used as potential model covariates was also required, in particular missing catch weight records were set to zero, the headline depth was set to zero if it would otherwise have been above the water, missing vessel speed was set to the median of speeds by vessels in the same length class (shorter or longer than 90 metres), and missing or zero fishing duration records were set to 1 minute.

Observer records can be linked to the fisher effort data coming from *warehou* by matching the start and end times, positions, and vessel identifiers of observer and fisher reported trawls. The linking associates observed dolphin captures with the TCEPR reported trawl effort. To accurately predict captures on the unobserved tows it was necessary to use data that were available on all the tows, including those that had not been observed. This limited the available data to those recorded by the fishers. The linking rules given in Table 1 were applied sequentially to the data. After these rules had been applied, there remained 113 observer records (2.6% of the total) that could not be linked to the fisher reported data. There were no dolphins caught on these unlinked tows. There were also 57 fisher reported tows from observed trips that could not be linked to the observer data. It was assumed that these tows had not been observed, and dolphin captures on these tows were estimated.

An area on the west coast of the North Island was used to select data for modelling and analysis. This area was enclosed by a line extending north along longitude 173°2.8′ E, a line across Cook Strait at latitude 41° S, a line extending west from Farewell Spit at 37°35.6′ S, a western boundary at 171° E, and the boundary of New Zealand's EEZ. This is the WCNI9 area defined by Abraham & Thompson (2009), with the additional exclusion of fishing effort west of 171° E.

Table 1: Summary of linking between observer and fisher reported tows. All linking is made between tows with the same vessel key in both databases. The table gives a description of the rules used to link the data, in the order that they are applied, and the number of tows linked by each rule. Observer and fisher reported tows were considered to be at the same time if both the start and end times were within 10 minutes of each other and at similar times if they were within 70 minutes of each other. Tows were considered to be at the same position if the latitude and longitude of the start and end positions from both records were within 1 minute of each other.

Description	Observed tows
Tows at same time, not in summer	1309
Tows at same time, in summer	362
Tows at same time, adjusted to NZST, and same position, summer	1819
Tows at same time, adjusted to NZST, and same position, not summer	3
Tows at same time, incorrectly adjusted to NZST, same position	1
Tows at similar time, trip already matched, summer	439
One unmatched tow on each dataset on the same day	187
One unmatched tow on each dataset, same day, over midnight	26
Gap of one tow between matched tows on both datasets	54
Gap of one tow before first matched tow at trip start	1
Gap of one tow after last matched tow at trip end	4
Gap of more than one tow between matched tows on both datasets	74
Gap of more than one tow before first matched tow at trip start	7
Gap of more than one tow after last matched tow at trip end	2
Unmatched	113
Total observed tows	4401

2.2 The dolphin capture model

A statistical model was built to estimate total captures in the large vessel jack mackerel fishery from the observed captures in that fishery. There was a total of 3092 observed tows over the 12 year period covered by the data, and dolphins were caught on 35 tows. This was an average rate of 1.1 capture events per 100 tows. When dolphins were caught, typically more than one was caught at a time. A total of 86 dolphins were observed killed, a mean of 2.5 dolphins per event.

The large number of tows without captures suggested the use of a two stage model that separately predicted the probability of capture events occurring and the number of dolphins captured. Two stage models of this kind are called hurdle models (Mullahy 1986, Ridout et al. 1998), and are appropriate in situations where different processes are influencing the occurrence of captures and the number of animals caught (e.g., Fletcher et al. 2005). The model estimated the probability, π_i, of capturing dolphins on a tow, i. A base probability, λ_j was estimated for each year, j, that represented the annual variation in observed capture event rates. This base probability was then modified by the value of covariates on the particular tow, such as the light condition at the time of haul, or the trawl duration. The contribution of each covariate, c, was governed by a regression coefficient, β_c, that was estimated by the model. The logit transform of the capture event probability was defined as the sum of the base year probability $\lambda_{j[i]}$, and the covariates:

$$\text{logit}(\pi_i) = \lambda_{j[i]} + \sum_c \beta_c x_{ic}, \tag{1}$$

where x_{ic} was the value of covariate c on tow i. Diffuse normal priors were given to the regression coefficients, β_c, and to the mean of the year effects, λ_j. A half-Cauchy prior, with a scale of 25, was given to the variance of the year effects.

On tows where there were dolphin captures, the captures were assumed to follow a zero-truncated Poisson distribution with size μ. The zero-truncated distribution reflects the structure of the hurdle model (if a capture event occurs the number of dolphins caught must be one or more). The probability that y_i dolphins were captured on tow i was given by

$$\Pr(y_i = y) = \begin{cases} (1-\pi_i) & \text{if} \quad y = 0 \\ \pi_i \frac{e^{-\mu}\mu^y}{(1-e^{-\mu})y!} & \text{if} \quad y > 0. \end{cases}$$

The size of the Poisson distribution, μ, was given a prior that was uniform between 0.5 and 30. It would be possible for the size of the truncated Poisson distribution, μ, to vary with the value of covariates on each tow. However, the 35 capture events observed did not provide enough information to estimate variation in the size parameter.

In the range of values less than 0.1, the inverse logit function is approximately equal to the exponential function. The year base effect can then be presented as a probability, and the covariate contributions can be defined as multipliers to that probability:

$$\begin{aligned} \pi_i &= \text{logit}^{-1}\left(\lambda_{j[i]} + \sum_c \beta_c x_{ic}\right) \\ &\simeq \exp\left(\lambda_{j[i]}\right) \prod_c \exp\left(\beta_c x_{ic}\right) \end{aligned}$$

The covariates were normalised so that the covariate contribution, $\exp(\beta_c x_{ic})$, had a geometric mean of one across all 12 years of observations. Variations about this mean indicate changing influence of the covariates on the capture probability.

A simpler version of the model was also tested, with a single base probability fixed for the whole 12 year period, rather than a random year effect:

$$\text{logit}(\pi_i) = \beta_0 + \sum_c \beta_c x_{ic}$$

This model allowed testing of whether the inclusion of a random year effect was necessary, or whether the variation in catch rate from year to year could be explained by variations in the covariates.

Both variations of the model were coded in the BUGS language (Spiegelhalter et al. 2003), a domain specific language for describing Bayesian models. The models were fitted with the software package JAGS (Plummer 2005), using Markov chain Monte Carlo (MCMC) methods. To ensure that the model had converged, a burn-in of 10 000 iterations was made. From there, the model was run for another 100 000 iterations and every 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). To test whether the model produced a suitable representation of the data, simulations of observed captures were made using randomly chosen samples from the Markov chains and visually compared with the actual observed captures (Gelman et al. 2006). A comparison was made of the frequency distribution of the number of dolphins caught during capture events, between the observed data and predictions from samples from the Markov chains.

Estimates were prepared for groups of trawls, grouped by fishing year, y, and vessel, v. The estimated total number of dolphins captured in a group, D_t, was calculated as the sum of actual reported captures on observed tows, d_o, and predicted captures on the unobserved tows, D^e_{yv},

$$D^t_{yv} = d^o_{yv} + D^e_{yv} \tag{2}$$

Total captures in a year were obtained by summing the captures over all vessels fishing in that year, $D^t_y = \sum_v D^t_{yv}$.

Table 2: Potential covariates presented to the step analysis

Covariate	Unit	Description
Trawl speed	Knots	Fishing speed in knots from the TCEPR data.
Trawl duration	Hours	The duration of trawls from start and end times recorded on TCEPR forms.
Headline depth	Metres	The depth of the top of the net, derived by subtracting the headline height from the ground rope depth (both recorded on TCEPR forms). Indicates the depth of the top of the net.
Bottom depth	Metres	Minimum depth at either the start or end positions of trawls, derived using ETOPO2v2 bathymetric data (Smith & Sandwell 1997, National Oceanic and Atmospheric Administration 2006).
Depth factor	Shallow, deep	Bottom depth as a factor, with trawls in water less than 210 m being shallow, and other trawls being deep.
Catch weight	Tonnes	Total catch weight of each trawl as recorded on the TCEPR forms.
Sub-area	North, south	The west coast North Island region was divided into two sub-areas (north and south of $39°18'$ S) and these were included as a factor variable.
Light condition	Light, dark, black	After initial exploration, a three valued factor was derived that classified tows according to the time of the haul and the phase of the moon. The three levels were light (net hauled between dawn and dusk, or between dusk and midnight on a moonlit night), dark (net hauled between dusk and midnight on a dark night, or between midnight and dawn on a moonlit night), and black (net hauled between midnight and dawn on a dark night). The illumination of the moon and time of dawn and dusk were calculated using algorithms from Meeus (1991). The night was classified as moonlit if more than 17% of the moon's disc was illuminated. Dawn and dusk were defined as when the center of the sun's disk was 6° below the horizon (civil dawn and dusk).
Moon illumination	Percentage	Fractional illumination of the moon's disk, calculated using algorithms from Meeus (1991).
Night hours	Hours	The number of night hours during a trawl, calculated as the number of hours of the tow between civil dawn and dusk.
Month	Months	Months of the year as a factor variable
Season	Quarters	A grouping of months into quarters (January to March, April to June, July to September and October to December), included as a factor variable.

2.3 Covariate selection

The model structure allowed for the dolphin capture event probability to depend on covariates. A step analysis was used to select the covariates that had explanatory power (Venables & Ripley 2002). Maximum likelihood methods were used to fit a binomial generalised linear model to the observed capture events, trying different combinations of factors. At each stage of the analysis the model was fitted repeatedly, with each of the covariates included (or removed) in turn. The covariate was selected that produced the greatest reduction in the AIC (Aikake Information Criterion, Akaike 1974). Steps continued until the deviance was not reduced by more than 1%. Placing a requirement on the deviance reduction prevented the inclusion of covariates that had little explanatory power. The potential covariates listed in Table 2 were presented to the step analysis. Catch weight, trawl duration, night hours, and bottom depth were all included both directly and as a log-transform (with one tonne and one hour added to catch weight and night hours, respectively, before taking the logarithm).

3. RESULTS

A summary of the reported and confirmed dolphin captures in all fisheries within the New Zealand EEZ, over the 12 year period is given in Table 3. Most dolphin captures occurred in trawl fisheries on the west coast of the North Island. All animals caught in trawl fisheries were killed. Of the 88 animals caught on the west coast of the North Island, two common dolphins were caught on an inshore trawler targeting trevally (*Pseudocaranx dentex*). The remaining 86 were all caught on trips that targeted jack mackerel. These captures were reported as 74 common dolphins, 3 pilot whales, 6 Risso's dolphins (*Grampus griseus*), 2 bottlenose dolphins and 1 porpoise. The Risso's dolphins were found from photographs to be pilot whales (Igor Debski, Department of Conservation, pers. comm.). The bottlenose dolphins and the porpoise were later identified as common dolphins from photographs (Stephanie Rowe, Department of Conservation, pers. comm.; Anton van Helden, Te Papa, pers. comm.). The identification of one of the reported bottlenose dolphins as a common dolphin was confirmed by necropsy.

Some dolphin captures were also observed in longline fisheries, and in trawl fisheries in other areas. Most dolphins (8 out of 11) captured in longline fisheries were released alive. The animals that were killed in longline fisheries were one common dolphin and two pilot whales. The identity of these animals was not confirmed by necropsy. Dusky dolphins, a bottlenose dolphin and a porpoise were also reported by observers as being caught and released alive. Observers have used the code for porpoise as a generic term for dolphin. There was no photograph taken of the reported porpoise capture, however the observer recorded in their notes of this incident that there was 'one dolphin hooked and released'. This animal is classified here as an unidentified dolphin.

In trawl fisheries in other areas, eight dolphins were killed on observed tows. These included five dusky dolphins killed by squid trawlers operating south of Stewart Island, one dusky dolphin killed by a trawler targeting jack mackerel on the Chatham Rise, one dusky dolphin killed by a trawler targeting hoki (*Macruronus novaezealandiae*) in Cook Strait, and one common dolphin killed by a trawler targeting barracouta (*Thyrsites atun*) on the west coast of the South Island.

All the 86 dolphin captures on observed tows in the jack mackerel fishery were on vessels longer than 90 m, with most captures being on vessels longer than 100 m (Figure 1). Estimation of total dolphin captures was restricted to trips by vessels over 90 m long that reported targeting jack mackerel on at least one tow on a trip. These trips were defined as the large vessel jack mackerel fishery. There were a total of 15 774 tows reported by this fishery over the 12 year period. Amongst these there were 276 trawls that targeted barracouta, 61 trawls that targeted blue mackerel (*Scomber australasicus*), 3 tows that targeted hoki, and 1 tow that targeted hake (*Merluccius australis*). No dolphins were observed on the tows included with the jack mackerel fishery where jack mackerel was not the recorded target species.

Table 3: Observed dolphin captures by species, between 1 October 1995 and 30 September 2007. The table gives the numbers of dolphins of each species captured killed, and whose identity was confirmed by necropsy in longline fisheries, trawl fisheries on the west coast of the North Island, and trawl fisheries in other areas.

	Longline			Trawl, west coast			Trawl, other areas		
Species	cap.	kil.	nec.	cap.	kil.	nec.	cap.	kil.	nec.
Common dolphin (*Delphinus delphis*)	2	1	0	79	79	6	1	1	0
Dusky dolphin (*Lagenorhynchus obscurus*)	2	0	0	0	0	0	7	7	5
Pilot whale (*Globicephala melas*)	5	2	0	9	9	0	0	0	0
Bottlenose dolphin (*Tursiops truncatus*)	1	0	0	0	0	0	0	0	0
Unidentified dolphin	1	0	0	0	0	0	0	0	0
Total	11	3	0	88	88	6	8	8	5

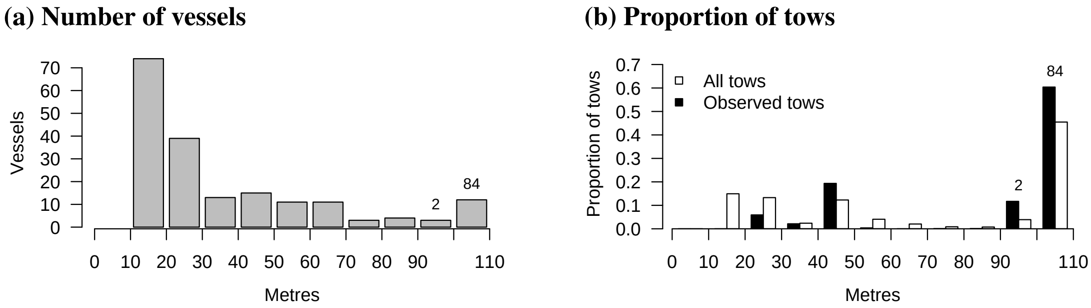

Figure 1: Structure of the west coast North Island jack mackerel fishery showing (a) the number of vessels in each length class, and (b) the proportion of effort and observed effort by length class. The number of observed dolphin captures in each length class is also indicated.

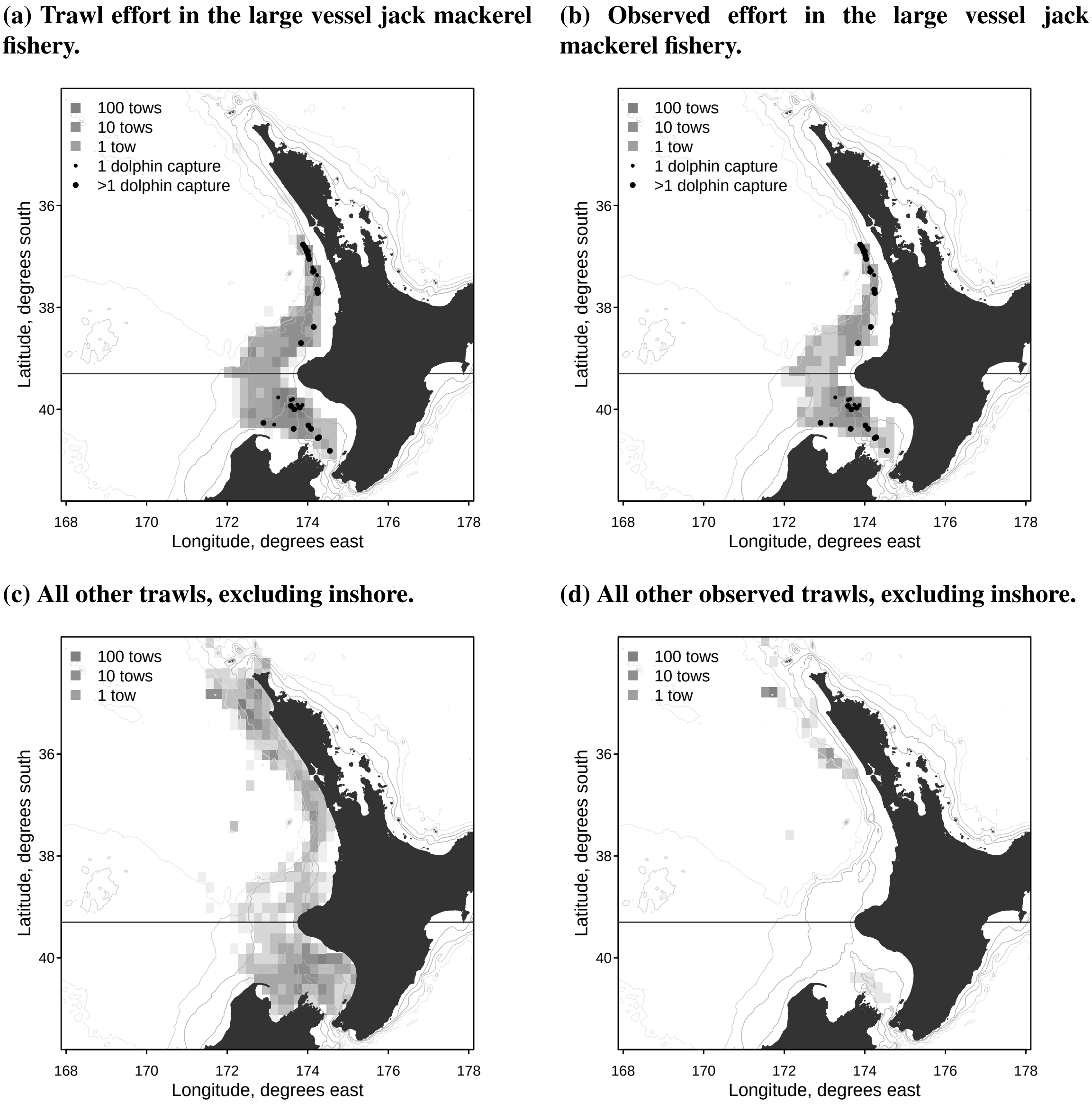

Figure 2: Trawl effort in the west coast North Island area, between 1 October 1995 and 30 September 2007. (a) Trawls by vessels longer than 90 m on trips targeting jack mackerel, (b) observed trawls from vessels longer than 90 m on trips targeting jack mackerel, (c) all other trawl effort, excluding inshore fisheries, and (d) all other observed effort. The locations of common dolphin captures are indicated.

Table 4: Annual summary of dolphin captures in the west coast North Island region. The table gives the total number of tows, the number of observed tows, capture events, and total dolphins captured. The three groups are from vessels longer than 90 metres that targeted jack mackerel, by sub-area, and from other vessels in the region. Trawls that targeted inshore fish species have been excluded.

	North, large vessel, jack mackerel				South, large vessel, jack mackerel				Other	
Year	Eff.	Obs.	Events	Dolphins	Eff.	Obs.	Events	Dolphins	Eff.	Obs.
2006–07	1131	267	2	3	1033	341	3	8	374	125
2005–06	1072	274	0	0	1047	373	1	2	436	52
2004–05	1760	381	11	27	664	180	0	0	403	24
2003–04	1891	144	6	16	418	20	1	1	410	46
2002–03	713	3	0	0	1536	219	6	21	760	61
2001–02	237	4	0	0	1340	107	1	1	1197	53
2000–01	69	1	0	0	903	121	1	1	1352	-
1999–00	23	0	-	-	392	72	2	4	1021	78
1998–99	6	0	-	-	344	85	0	0	1224	34
1997–98	198	122	0	0	360	95	0	0	1221	-
1996–97	60	47	0	0	171	116	0	0	989	-
1995–96	65	12	0	0	340	108	1	2	1186	1
Total	7225	1255	19	46	8548	1837	16	40	10573	474

Maps of fishing effort, observations and dolphin captures in the west coast North Island region are given in Figure 2. The region is further divided into northern and southern areas by a line at latitude 39°18′ S. Annual summaries of the data are given in Table 4. The development of the jack mackerel fishery over the twelve year period is clearly seen. Before the 2003–04 fishing year, the small amount of large vessel jack mackerel effort was concentrated south of Taranaki. In 1995–96 there were only 405 trawls by jack mackerel vessels, and of these 84% were in the southern sub-area. Since then fishing effort, and dolphin captures, have increased, with over 2000 trawls being made on jack mackerel trips during each year since 2002–03. The concentration of effort in the northern sub-area was greatest in 2003–4, with 82% of effort being in the northern region in that year. Since then the effort has become evenly divided between the two regions.

While fishing effort by other vessels accounts for 40.1% of all effort in the west coast North Island area, there have been only 474 observed tows in these other fisheries. Moreover, only 33 of these observations have been in the same region where the jack mackerel fishery takes place (south of 36°40′ S). The lack of observer coverage on the small vessels means that no estimate can be made of dolphin captures in this fleet.

3.1 Model covariates

The distribution of the potential covariates (defined in Table 2) is shown in Figure 3. In all cases, observer coverage was broadly representative of the total fishing effort. Fishing was approximately evenly split between the northern and southern sub-areas, with a higher dolphin catch rate in the northern sub-area (Figure 3a). The jack mackerel fishery was active in most months, with most fishing effort in the spring (October to December) (Figure 3b,c). There were some dolphin captures throughout the year, with fewer captures in the winter. No dolphin captures were observed in June, July, or August. There was a clear relationship between headline depth and the capture rate (Figure 3d) with 51 captures occurring when the headline depth was less than 40 m. All three light conditions were observed (Figure 3e). Although only 4% of tows fell into the black category, the observed incidence rate (6.4 events per 100 tows) was more than 10 times higher than the incidence rate in the light category (0.5 events per 100 tows). For other covariates, the relationship with dolphin captures was less clear.

The results of the covariate selection are given in Table 5. Four covariates were found to be important, with the headline depth identified as the strongest predictor of dolphin capture events. Light condition was the covariate with the next highest explanatory power, with trawl duration and sub-area also explaining more than 1% of the residual deviance. Based on this analysis, four covariates of the capture event probability were included in the Bayesian model: headline depth, light condition, the logarithm of trawl duration, and sub-area.

3.2 Model parameters

The year effect allows the base capture event probability to vary between years, with variation controlled by drawing values from a normal distribution. The model estimated the mean, μ_λ, and standard deviation, σ_λ, of this distribution. The median value of $\exp(\mu_\lambda)$ was 0.3 capture events per 100 trawls, and the full posterior distribution is plotted in Figure 4a. The year effect was highly variable, with large uncertainty in the 1999–2000 and 2002–03 fishing years. In those two years the observed capture rate was high, while observer coverage was low (see Table 4). In the two most recent years, 2005–06 and 2006–07, the observer coverage has been higher, resulting in smaller uncertainty in the year effect (Figure 4b). Only two dolphins were captured in 2005–06, during a single trawl. This resulted in a very low model estimate for $\exp(\lambda_{06})$, with a median of 0.07%.

The estimated coefficients of the covariates are given in Table 6. The coefficient for the headline depth factor had mean -0.033 m^{-1}, indicating that the effect was negatively correlated: increasing the headline depth would reduce the probability of a capture event. To halve the probability of a capture event the headline depth would need to be increased by 21 metres (95% c.i.: 15 metres to 35 metres).

The mean coefficient of logarithm of the trawl duration was 1.6, implying that decreasing the tow duration would decrease the capture event probability. The average trawl duration was 3.2 hours. To reduce the capture event probability by half, the trawl duration would need to be reduced to 1.8 hours (95% c.i.: 0.5 hours to 2.3 hours).

The exponentiated value of the coefficient for the sub-area factor had mean 0.51, implying that tows south of Mount Taranaki had approximately half the capture event probability of tows in the northern sub-area. From the exponentiated coefficient of the light condition factor, tows hauled in the “light” had a mean of 0.29 times probability of a capture event occurring than of tows in the “dark”, while tows in “black” light conditions were 2.8 times more likely to have capture events than tows in the “dark”.

The median multiplicative contribution of each covariate to the capture event probability is presented in Figure 5, for each of the four covariates. The median product of all the covariate contributions is

Table 5: Analysis of deviance returned from the model selection algorithm. Details displayed are: degrees of freedom, deviance, residual degrees of freedom, residual deviance, percentage of deviance reduced, and the AIC.

	Df	Dev.	Resid. Df	Resid. Dev.	% dev.	AIC
Intercept			3091	383.29		385.29
Headline depth	1	43.33	3090	339.96	11.3	343.96
Light condition	2	14.82	3088	325.13	4.4	333.13
Log of trawl duration	1	8.35	3087	316.78	2.6	326.78
Sub-area	1	5.90	3086	310.88	1.9	322.88

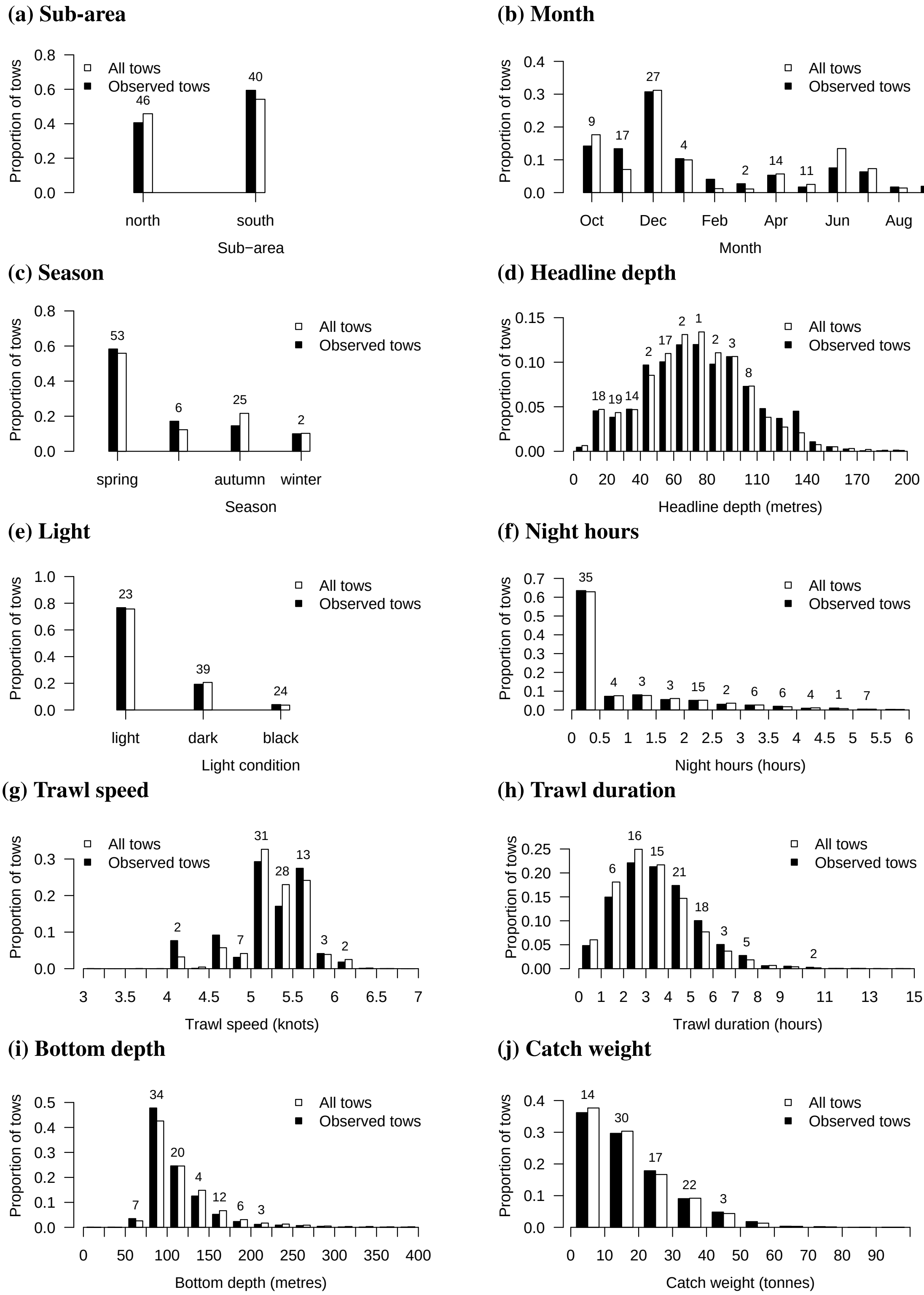

Figure 3: Distribution of selected potential covariates for observed and all trawl effort by large jack mackerel vessels off the west coast of the North Island, between 1 October 1995 and 30 September 2007. Total observed dolphin captures are indicated above the bars.

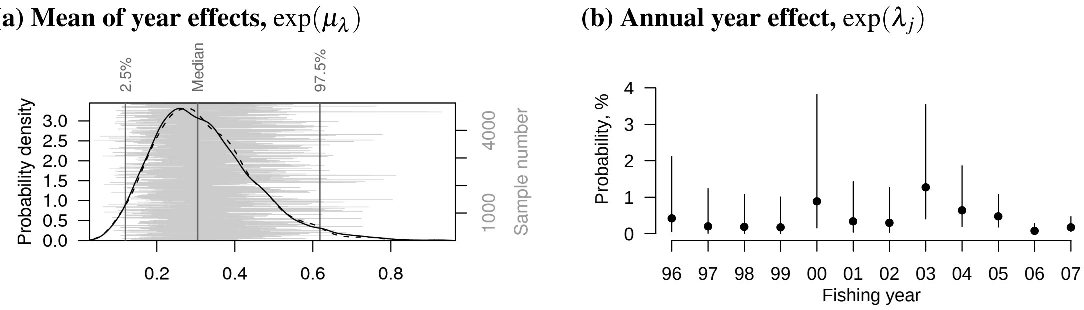

Figure 4: Summary of the estimated year effects. Year effects are drawn from a normal distribution with mean μ_λ, whose trace and distribution are plotted in (a). In (b) the year effect, λ_j, is plotted, with 95% confidence interval. It has been transformed into a probability, with a percentage scale.

Table 6: Summary of the covariate regression coefficients, presented as mean, and 2.5%, 50%, and 97.5% quantiles. The coefficients of the discrete factors have been exponentiated, so that they are multiplicative.

	Mean	2.5%	50%	97.5%
Headline depth, $\beta_{headline}$	-0.033	-0.047	-0.033	-0.020
Log trawl duration, $\beta_{duration}$	1.632	0.651	1.625	2.656
Light condition, light (relative to dark), $\exp(\beta_{light})$	0.291	0.114	0.266	0.609
Light condition, black (relative to dark), $\exp(\beta_{black})$	2.845	0.908	2.526	6.589
Sub-area, south (relative to north), $\exp(\beta_{south})$	0.510	0.170	0.460	1.133

also shown. The greatest variation was in the headline depth. The contribution of headline depth to the capture event probability peaked in 1999–2000 and then fell until 2003–04. Since the 2003–04 fishing year, there was an increase in the contribution from the headline depth. There was also a long term increase in trawl duration from 1998–99 to 2006–07. The median combined contribution was positive after 2003–04, with a large increase in 2006–07 driven by both a decrease in the headline depth and an increase in tow duration.

The Markov chains allow the posterior distribution of the capture event probability in each year to be directly sampled. This is presented as the median value, and the 95% confidence interval, in Figure 6a. The capture event probability followed the year effects, reflecting the low event probability in 2005–06 and the high uncertainty in 1999–2000 and 2002–03. There was some variation in the capture event

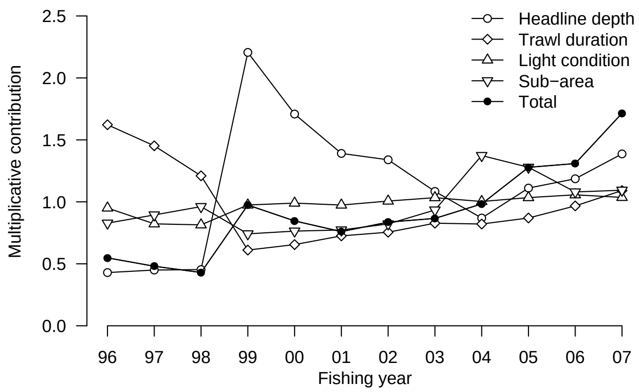

Figure 5: Median multiplicative contribution of the four covariates by fishing year. The total contribution is given by the product of four covariate contributions.

(a) Median, and 95% confidence interval, of capture event probability

(b) Median capture event probability, for each vessel

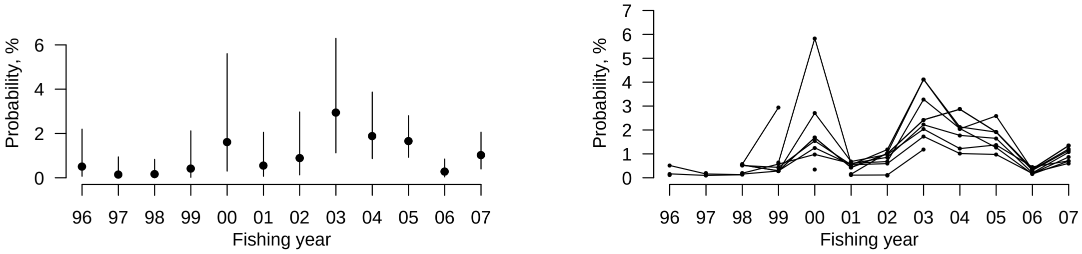

Figure 6: Median yearly capture event probability, with (a) 95% confidence intervals, and (b) by individual vessels. The probabilities are expressed as a percentage (capture events per 100 tows).

(a) Posterior distribution of the mean of truncated Poisson distribution, μ

(b) Distribution of capture event size, observed tows

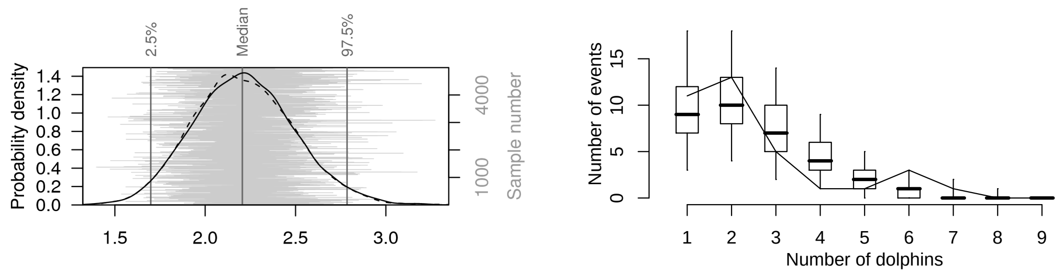

Figure 7: The number of dolphins caught per capture event. (a) The posterior distribution of the size of the zero-truncated Poisson distribution, μ and the Markov chains. (b) A comparison of the predicted distribution of the number of dolphins caught per capture event between the observed captures (shown by the line) and samples from the model posterior (shown by boxplots that indicate the median, quartiles, and 95% confidence interval of the distributions).

probability between vessels (Figure 6b), particularly in the 1999–2000 fishing year; however consistent patterns were seen across all vessels.

The second stage of the model predicts the number of dolphins caught in each capture event. The posterior distribution for the size of the zero-truncated Poisson, μ, was approximately normally distributed, with median value 2.2 (95% c.i.: 1.7 to 2.8) dolphins per capture event, and is plotted in Figure 7a. When the numbers of observed captures during capture events were compared between the observed data and the model, the observations were found to all fall within the 95% confidence interval of the model estimates.

3.3 Predicted dolphin captures

The estimated total number of dolphins killed in each year is given in Table 7, with the results also shown in Figure 8. The number of captures rose rapidly from the 2000–01 fishing year, when the total estimated mortalities were 12 (95% c.i.: 1 to 49), to a peak of 174 (95% c.i.: 74 to 366) in the 2002–03 fishing year. This increase was driven both by an increase in trawl effort (from 972 trawls in 2000–01 to 2309 trawls in 2003–04) and an increase in the estimated catch rate, which peaked at 7.74 dolphins per 100 tows (95% c.i.: 3.29 to 16.27) in 2002–03. Since 2002–03, the annual number of captures has fallen, with the model estimating that 52 dolphins were captured in the large vessel jack mackerel fishery in 2006–07 (95% c.i.: 22 to 106). This decrease was driven by a decline in the estimated capture rate, which was 2.4

Table 7: Total number of tows, observed tows, observer coverage, observed dolphin captures, observed catch rate, estimated captures, and estimated catch rate for large jack mackerel trawl effort on the west coast of the North Island between 1 October 1995 and 30 September 2007. The rates are expressed as dolphin captures per 100 trawls.

		Observed		Obs. dolphins		Estimated dolphin captures			
	Effort	Tows	% obs.	Captures	Rate	Captures	95% c.i.	Rate	95% c.i.
2006–07	2164	608	28	11	1.81	52	22 - 106	2.4	1.02 - 4.9
2005–06	2119	647	31	2	0.31	11	2 - 36	0.52	0.09 - 1.7
2004–05	2424	561	23	27	4.81	101	59 - 168	4.17	2.43 - 6.93
2003–04	2309	164	7	17	10.37	110	51 - 221	4.76	2.21 - 9.57
2002–03	2249	222	10	21	9.46	174	74 - 366	7.74	3.29 - 16.27
2001–02	1577	111	7	1	0.9	33	3 - 119	2.09	0.19 - 7.55
2000–01	972	122	13	1	0.82	12	1 - 49	1.23	0.1 - 5.04
1999–00	415	72	17	4	5.56	18	4 - 60	4.34	0.96 - 14.46
1998–99	350	85	24	0	0	2	0 - 18	0.57	0 - 5.14
1997–98	558	217	39	0	0	0	0 - 11	0	0 - 1.97
1996–97	232	163	70	0	0	0	0 - 5	0	0 - 2.16
1995–96	405	120	30	2	1.67	5	2 - 22	1.23	0.49 - 5.43

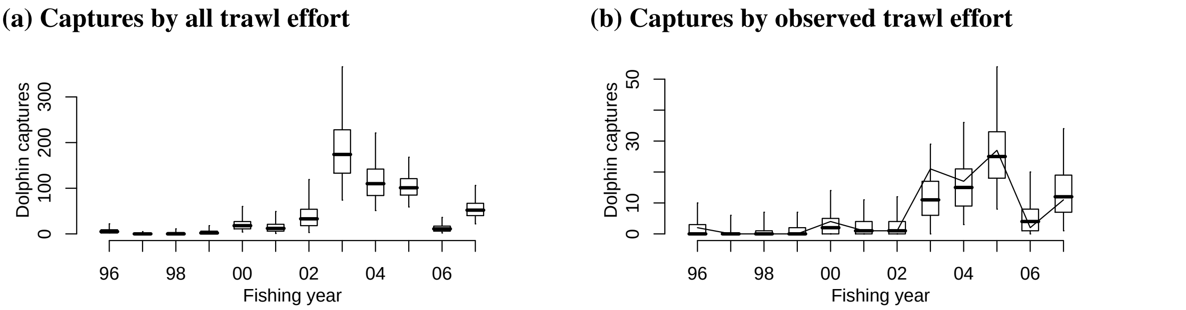

Figure 8: Estimated captures by year (a) during all trawls, and (b) during observed trawls. Observed captures are included on (b) for comparison. The boxplots give the median, interquartile range, and 95% confidence interval of the posterior distributions.

dolphins per 100 tows (95% c.i.: 1.02 to 4.9) in 2006–07. The change in the model estimated capture rate was not due to changes in the covariates, but rather due to changes in the year effects (see Figure 4).

When the model was used to estimate captures on observed tows in each fishing year, the number of observed captures fell within the 95% confidence interval of the model predictions (Figure 8), indicating that the model was able to fit the data.

Fifteen large vessels operated in the jack mackerel fishery in the 12 year period from 1 October 1995 to 30 September 2007, and 10 of these vessels were observed. In Figure 9, observed dolphin captures are compared with the distribution of captures estimated by the model for the those 10 vessels. The observed captures were all within the 95% confidence interval, indicating that the model successfully predicted the variation in captures between vessels. There was no need to include a vessel effect in this model, as the model without a vessel effect was able to describe the data.

In Figure 10, three sets of simulated captures are compared to the observed captures, organised by vessel and year. General features of the observed captures preserved by the simulations include the variation in catch rates between vessels, the distribution of the numbers of dolphins caught per event, and the lower catch rates in earlier years. The simulations also gave an indication of the variability that could be

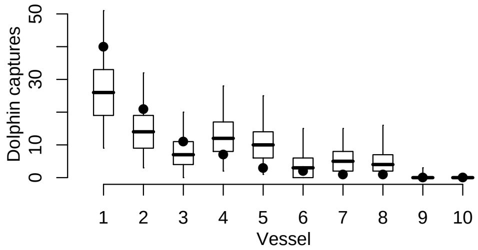

Figure 9: Estimated captures during observed trawls, for each of the observed vessels. The solid dots indicate the observed captures, the boxplots summarise the posterior distribution of the captures for each vessel (the median, inter-quartile range and 95% confidence interval are indicated).

expected due to random variation.

The model-estimated total number of estimated dolphin captures was greater than 10 for 7 of the vessels (Figure 11a). Fishing by these seven vessels accounted for over 95% of trawl effort over the 12 years. Estimated dolphin captures by the seven vessels varied with differences in the amount of trawl effort and the median values of the covariates. In Figure 11b, the catch rate is plotted by vessel, for each of the seven vessels, and indicates that there was still variation between the vessels that was not accounted for by differences in trawl effort. The covariates associated with the seven vessels are presented in Figure 12. The amount of fishing effort by these vessels and the values of the covariates changed in a coherent way through the years. For example, all seven vessels moved north in 2003–04, and back south in 2005–06. The median trawl duration steadily increased over the 12 years, from 2 hours to 3 hours.

3.3.1 Model fitted without year effects

To test whether the inclusion of year effects in the model was necessary, the model was fitted with a single mean capture event probability over all years. Predictions from this model are plotted in Figure 13. As expected, the total estimated captures from the simplified model had less uncertainty and variability between years than the model with random year effects. Even though there was a constant baseline capture probability, the estimated number of captures for 2005–06 was still low. Total captures are calculated as the predicted captures on unobserved tows, plus the actual captures on observed tows, as described in Equation 2. The estimate for 2005–06 was low because there were only two captures on the 31% of effort that was observed.

Observed captures from the simplified model did not fall within the 95% confidence interval of the posterior distribution of estimated captures on the observed tows. Observed captures were underestimated in 2002–03 and 2003–04, and overestimated in 2005–06 and 2006–07. The simplified model was unable to explain the variability of the data, and the inclusion of the random year effects was necessary.

4. DISCUSSION

4.1 Estimated captures

Captures of common dolphin in New Zealand waters have primarily been observed in the jack mackerel trawl fishery on the west coast of the North Island. Captures in this fishery were all made by vessels over 90 m in length. There were 15 vessels in this category, 10 of which had an observer on board at

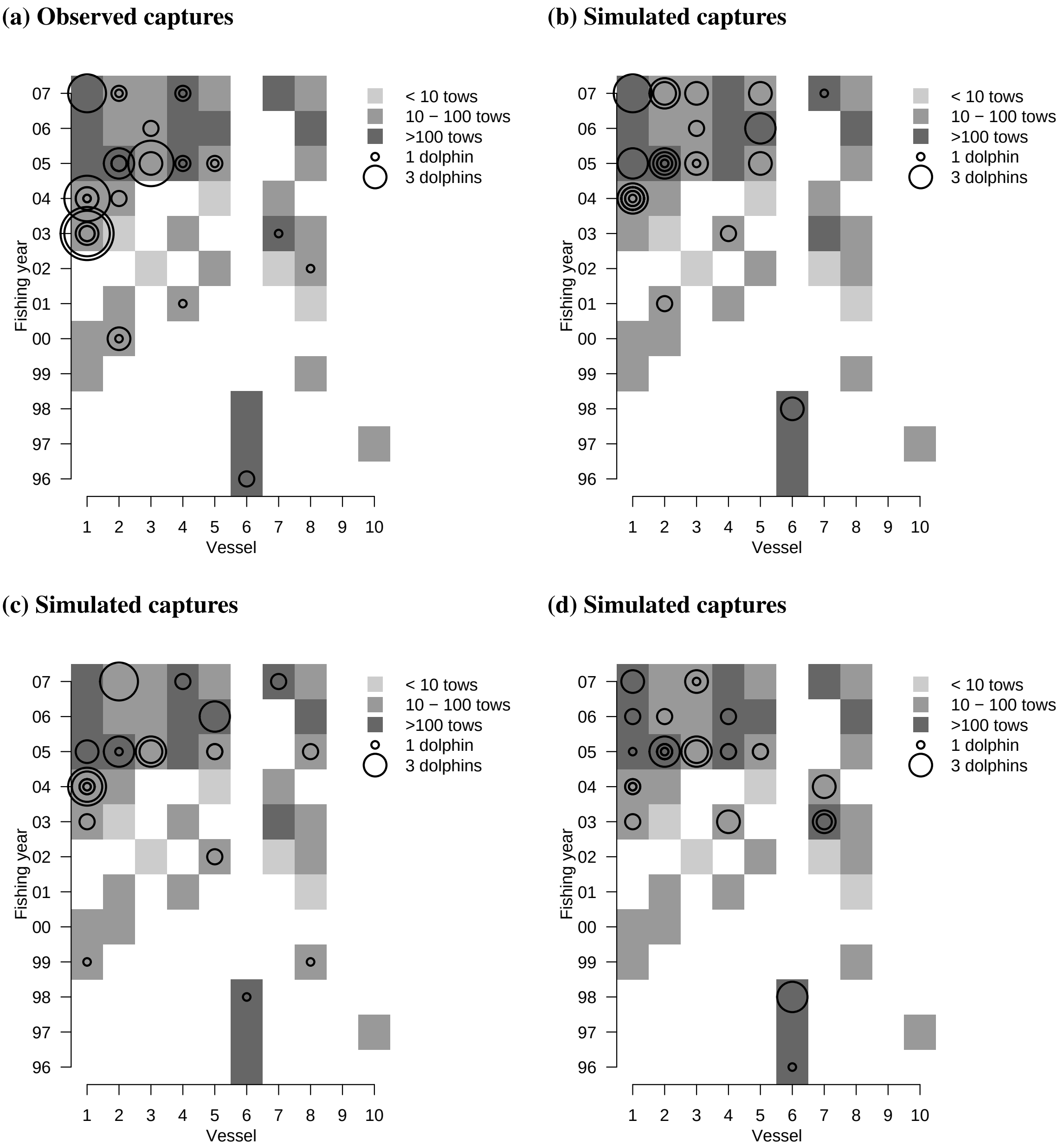

Figure 10: Observed and simulated capture events by fishing year and vessel number. Figure (a) presents actual observed captures, and (b, c, d) present three samples of simulated capture events derived from the model. The observed effort is also indicated with the gray shading.

least once between 1 October 1995 and 30 September 2007. A statistical model was built that estimated the total captures by these vessels. A two-stage hurdle model was used, with a logistic generalised linear model predicting whether any dolphin captures occurred on a given tow, and a zero-truncated Poisson distribution being used to predict the number of dolphin captures on a tow, given that there were some captures. The model appeared to fit the data well, giving plausible estimates when used to predict captures on observed tows.

Seven vessels accounted for over 95% of the fishing effort in the 12 year period. Different numbers of captures by these seven vessels were explained by variations in the amount of effort and by variation in the covariates between vessels. In general, the fleet behaved similarly, with changes in the covariates such as headline depth and light condition happening at the same time across all the vessels. This consistent

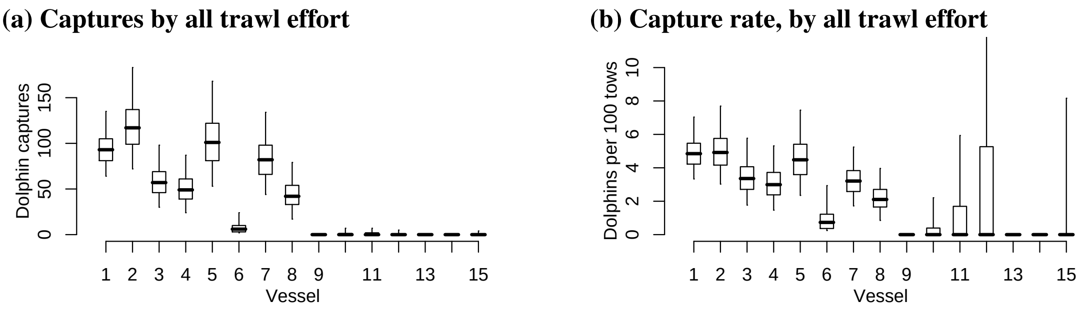

Figure 11: Summary of predicted captures by vessel as (a) predicted dolphin captures on all trawl effort, and (b) predicted dolphin capture rate per 100 tows. The boxplots give the median, interquartile range and 95% confidence interval of the posterior distributions,

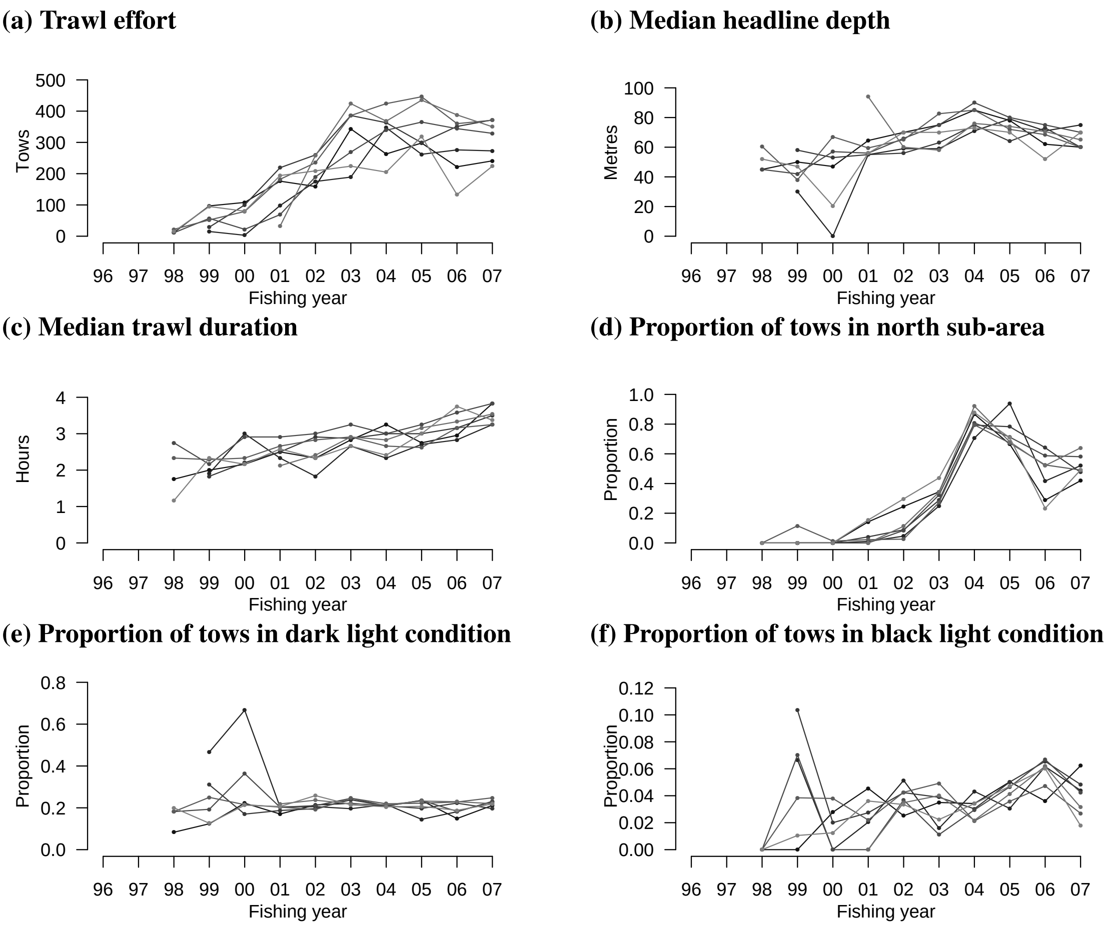

Figure 12: Annual trends of (a) trawl effort, (b) median headline depth, (c) trawl duration, (d) proportion of tows in the north, (e) proportion of tows in dark light conditions, and (f) proportion of tows in black light conditions, for each of the seven vessels responsible for most of the jack mackerel trawl effort in recent years.

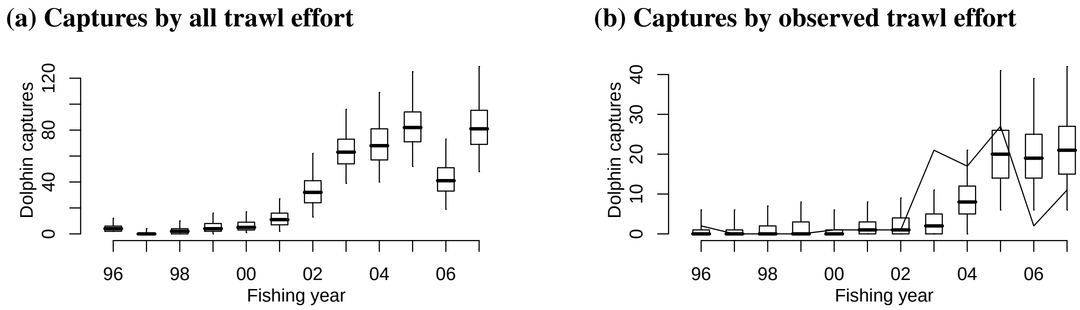

Figure 13: Predicted captures from the model, without year effects, by year on (a) all trawl effort, and (b) observed trawl effort only. Observed captures are included on (b) for comparison. The solid line is at the median, the size of the boxes represent the inter quantile range, the whiskers extend to the 95% confidence interval.

variation suggests that the vessels in this fishery have been organised into a coherent fleet. It was not necessary to include a specific vessel effect in the model. There was no evidence from the modelling that some of the seven main vessels were better or worse than the others at avoiding dolphin bycatch.

Estimates of the number of dolphins killed in the large vessel jack mackerel fishery are summarised in Table 7. There was little effort in this fishery before 2000–01, fewer than 600 tows per year. The estimated number of dolphin captures was also relatively small, with a median of fewer than 20 captures per year. As the effort in this fishery expanded to over 2000 tows by 2002–03, there was an initial increase in the number of dolphin captures to 174 (95% c.i.: 74 to 366). Since then the number of captures has decreased. In 2006-07 there were an estimated 52 (95% c.i. 22 to 106) dolphins killed in the large vessel jack mackerel fishery. The observed tows of this fishery appear to be representative of the total fishing effort, and a simple ratio estimate of total captures in jack mackerel fisheries throughout New Zealand gives similar results (Abraham & Thompson 2009). The ratio estimate of captures in 2002–03 was 213 dolphins (95% c.i.: 58 to 424), and the ratio estimate of captures in 2006–07 was 39 (95% c.i.: 16 to 73).

The reasons for the decrease in dolphin captures since 2002–03 are not known. The decrease has occurred despite the fishing effort remaining at more than 2000 trawls per year. It is not associated with a systematic change in the covariates, rather the covariates suggest that the proportion of trawls with dolphin captures should be increasing. It is possible that either the number of dolphins in the region at the time of the jack mackerel fishery has decreased, or the vulnerability of the dolphins to being caught has decreased, perhaps due to changes in fishing practice or an increased ability of the dolphins to avoid being caught. Observers also record dolphin sightings, and these data could be used to indicate whether the numbers of dolphins visiting jack mackerel vessels has remained constant or declined. It is also possible that the apparent trend is due to chance and will not continue.

There are no available estimates of the number of common dolphins living in the region where the jack mackerel fishery is active, and so there is no basis for assessing the impact of these mortalities on the local dolphin population. Common dolphins are globally distributed, with the population estimated to be in the millions, and fisheries impacts are not a considered a concern at the global population level (Hammond et al. 2008). There has been some recent research on common dolphins in the Hauraki Gulf (e.g., Stockin 2008, Stockin et al. 2008) and the Bay of Plenty (e.g., Neumann 2001, Neumann et al. 2002); however no research on common dolphins has been conducted in the west coast North Island region.

4.2 Model covariates

Headline depth was the covariate that best explained the occurrence of dolphin captures. The model estimated that increasing the headline depth on a tow by 21 metres would halve the probability of a dolphin capture occurring. The strong influence of headline depth is seen in the raw data: 59.3% of observed dolphin captures in the large vessel jack mackerel fishery occurred on the 9.7% of trawls that had a headline depth of less than 40 m. Other factors that were related to the occurrence of dolphin captures included trawl duration, light condition at haul time, and whether the tow was north or south of Mount Taranaki. The probability of a capture event occurring was higher for tows hauled on "black" nights (between midnight and dawn with no moon) than on other nights (a median ratio of 2.9 with a 95% c.i. of 0.9 to 6.6), and lower for tows hauled in the daytime or on moonlit evenings (a median ratio of 0.26 with a 95% c.i, of 0.11 to 0.61). The selection of light condition as a covariate was consistent with the results of Du Fresne et al. (2007), who found that night tows were associated with higher dolphin captures. The increased catch of dolphins at night has also been noted in other pelagic trawl fisheries (Crespo et al. 1997, Morizur et al. 1999). Increasing trawl duration increased the capture event probability. The coefficient of the logarithm of the trawl duration was not significantly different from one, implying that the model was consistent with dolphin bycatch being proportional to the length of a trawl. Dolphin captures were also more likely for fishing in the northern part of the North Island west coast region.

The aim of this report was to estimate total captures, not to explore possible options for reducing the dolphin mortality. However, the model could be used to test the efficacy of different management options, such as restricting night tows or shallow tows, at reducing the dolphin bycatch.

4.3 Dolphin captures in other trawl fisheries

There are other trawl fisheries operating in the same area, including some smaller vessels that also target jack mackerel, but these fisheries have been poorly observed, with only 33 tows being observed in the whole 12 year dataset. Because the other trawl fishing has different characteristics from the large vessel jack mackerel fishery, it is not appropriate to apply the same model to produce an estimate of total dolphin captures. Similarly, there are inshore fisheries around New Zealand that have historically been poorly observed. On the west coast of the North Island there were 159 tows observed in inshore fisheries in the 2005–06 and 2006–07 years. This was 1.3% of the 11 948 trawls made in inshore fisheries in this region over these two fishing years. Two common dolphins were killed during one of the observed trawls. Because there has been only a single event observed, and because of the low observer coverage, a reliable estimate of total captures in these fisheries cannot be made. However, the single observed capture event demonstrates that common dolphin captures do occur in inshore trawl fisheries. During the 1997–98 fishing year, one Hector's dolphin was killed on an inshore trawl targeting red cod (*Pseudophycus bachus*) that was one of 434 bottom trawls observed by Department of Conservation observers during that season (Starr & Langley 2000, Baird & Bradford 2000). This event demonstrates that Hector's dolphin captures occur in inshore trawl fisheries. Inshore trawl fisheries are spatially widespread and diverse, with a large range of target species and vessel sizes. Many more observations are needed in order to quantify the mortality of dolphins in these fisheries.

Dusky dolphin and common dolphin captures have been observed in trawl fisheries not targeting jack mackerel or inshore species. These captures are most frequently seen in squid trawl fisheries to the south of New Zealand. There have been five dolphin captures on observed tows targeting squid over the 12 year period, a capture rate of less than 0.03 dolphins per 100 trawls. From the total effort, this rate may be used to estimate that fewer than three dolphins are caught per year in the squid fishery (Abraham & Thompson 2009). In 2006–07, there were no observed dolphin captures in other trawl fisheries. Aside from an unknown number of dolphin captures by trawlers targeting inshore species, it is assumed that the total number of captures in other trawl fisheries is small compared to the number of captures in the jack mackerel fishery on the North Island west coast

5. ACKNOWLEDGMENTS

This work is dependent on the many observers of the Ministry of Fisheries Observer Programme who collected the data, and this effort is gratefully acknowledged. Thanks are also due to the Ministry of Fisheries and NIWA database teams who supplied the data and handled our questions and queries. We also appreciate continued input from Ministry of Fisheries staff and from members of the Aquatic Environment Working Group. We are especially grateful to Igor Debski of the Department of Conservation for his interest and useful feedback. We are also grateful to Stephanie Rowe of the Department of Conservation and Anton van Helden of Te Papa for help identifying the dolphins. This research was funded by Ministry of Fisheries project PRO2007/02.

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