Common dolphin (*Delphinus delphis*) bycatch in New Zealand mackerel trawl fisheries, 1995–96 to 2007–08

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EXECUTIVE SUMMARY

Common dolphins (*Delphius delphis*) are the most frequently caught cetacean in New Zealand trawl fisheries. Between the 1995–96 and 2007–08 fishing years, there were 97 common dolphin captures reported by Ministry of Fisheries observers in the mackerel trawl fishery on the west coast of the North Island. These captures were all made by vessels over 90 m in length. Capture events were infrequent, with 1 trawl in every 100 recording common dolphin captures. However, when common dolphins were caught, they were often caught in groups. In 2007–08, 20 common dolphins were caught on 5 of 725 observed tows. There were 9 common dolphins caught on a single trawl.

A statistical model was built that used the observer data to estimate the total common dolphin captures in the mackerel fishery. A two-stage Bayesian hurdle model was used, with a logistic generalised linear model predicting whether any common dolphin captures occurred on a given tow, and a zero-truncated Poisson distribution being used to estimate the number of dolphin captures, given that there was a capture event.

Of the observed capture events in the large vessel mackerel fishery, 54% were during the 9% of observed trawls where the top of the net was less than 30 m below the surface. All the 2007–08 capture events occurred on trawls with a headline depth of 20 m or less. The model found that headline depth was the covariate that best explained the occurrence of common dolphin captures, with the probability of a dolphin capture event on a tow being halved by increasing the headline depth by 17 m. Both the model and the raw data suggest that restricting trawls with shallow headlines would reduce dolphin bycatch. Trawl duration, light condition, and region were all also identified as covariates associated with dolphin bycatch. The model estimated that there was a higher bycatch on longer trawls, trawls hauled between midnight and dawn, and trawls in the region to the north of 30° 18′ S.

There was little effort in the large vessel mackerel fishery before 2000–01; fewer than 600 tows per year. The estimated number of common dolphin captures was also relatively small, with a median of less than 20 captures per year. As the annual effort in this fishery expanded to over 2000 tows by 2002–03, there was an initial increase in the number of common dolphin captures to 184 (95% c.i.: 76 to 394). Since then the number of captures has decreased. In 2007–08 there were an estimated 44 (95% c.i.: 24 to 78) common dolphins killed in the large vessel mackerel fishery. The reasons for the decrease in common dolphin captures since 2002–03 are not known. There are no available estimates of the number of common dolphins living in the region where the mackerel fishery is active, and so there is no basis for assessing the impact of these mortalities on the local common dolphin population.

OBJECTIVES

Overall Objective
To describe the nature and extent of marine mammal captures in New Zealand commercial fisheries

Specific 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, 2008/09.

Project progress
This research report specifically addresses the bycatch of common dolphins in the mackerel fishery for the 2007–08 fishing year and represents one component of the specific objective as outlined above. A preliminary presentation of this report was given to the Aquatic Environment Working Group on July 17th, 2009.

1. INTRODUCTION

Dolphins are caught in fisheries throughout the world, both by targeted exploitation and as incidental bycatch (Reeves 2003). Dolphins are thought to be attracted to fishing activity because of the availability of food, and are frequently observed foraging in association with fishing trawlers (Fertl & Leatherwood 1997, Reeves 2003, Rayment & Webster 2009). Entrapment in fishing gear is considered a serious and widespread threat to dolphin populations (Reeves 2003).

The common dolphin (*Delphinus delphis*) is globally distributed in coastal waters. Although this species is abundant, there are several populations, such as in the Mediterranean and Black Seas, that are in serious decline (Reeves 2003). Common dolphins are caught in large numbers as incidental bycatch in fisheries throughout Peru, Ecuador, Sri Lanka and India. With markets for dolphin products in these countries, there is little incentive to release captured animals or to introduce bycatch reduction measures (Reeves 2003). In New Zealand, common dolphins are found in coastal waters throughout the country and are the cetacean species most frequently caught in trawl and longline fisheries. Although they are considered to be numerous, often forming schools of up to several thousand, New Zealand population figures are unknown (Stockin 2008).

In New Zealand waters, dolphin captures are reported by Ministry of Fisheries and Department of Conservation observers when they are onboard vessels. There have been previous summaries of common dolphin captures in New Zealand commercial trawl fisheries before 1995 (Fertl & Leatherwood 1997), during the 1999–2000 fishing year (Baird 2004) (the New Zealand fishing year runs from 1 October to 30 September), and between the 1994–95 and 2004–05 fishing years (Baird 2008). Observer data on all dolphin captures between the 1995–96 and 2006–07 fishing year have been summarised elsewhere (Abraham & Thompson 2009, Thompson & Abraham 2009). During this period, a total of 107 dolphin captures were reported by observers. Out of these captures 82 were common dolphins. Of the common dolphin captures, 80 were in trawl fisheries and of those, 79 were caught and killed by vessels targeting jack mackerel (*Trachurus declivis*, *T. murphyi*, and *T. novaezelandiae*) or blue mackerel (*Scomber australasicus*) on the west coast of the North Island. Observer photographs of a common dolphin capture event in this fishery, taken during the 2007–08 fishing year, are shown in Figure 1. Pilot whales (*Globicephala melas*) have also been caught in the west coast North Island mackerel fishery, with 9 being caught between 1995–96 and 2006–07.

Figure 1: Photographs of common dolphins caught by a trawler targetting mackerel during the 2007–08 fishing year. There were nine common dolphins caught on this trawl, the highest number of common dolphins caught on a single observed trawl. Tags that would reveal the identity of the vessel have been blacked out. Photographs are crown copyright, reproduced by permission of the Department of Conservation and the Ministry of Fisheries.

In this paper, an estimate is made of the total common dolphin captures in the west coast North Island mackerel fishery. This is the only fishery where there have been sufficient observed captures to allow a statistical model to be built. To estimate total captures requires extrapolation from observed trawls to the unobserved fishing. A two stage model is used that separately predicts the probability of capture events occurring and the number of common dolphins captured. 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. The model estimates the probability of capturing dolphins on a tow as a linear function of a number of covariates. Given that there was a capture event, the number of captures was then estimated by sampling from a zero-truncated Poisson distribution.

The estimation closely follows a methodology previously developed for the Ministry of Fisheries, and applied to data from 1995–96 to 2006–07 (Thompson & Abraham 2009). In this paper the model is updated to include data from the 2007–08 fishing year. The only previously published estimate of total captures, in the North Island west coast mackerel fishery, was that before 1995 between 80 to 300 dolphins were killed annually (Slooten & Dawson 1995). Some statistical modelling has also investigated the factors that are associated with common dolphin capture rates in this fishery (Du Fresne et al. 2007). As well as providing an estimate of the total common dolphin bycatch, the model presented here further explores which covariates are related to dolphin captures. It is hoped that the analysis will allow a management response to be identified that will reduce the bycatch of common dolphins.

2. METHODS

2.1 Data sources

Commercial trawler activity is reported to New Zealand's Ministry of Fisheries on the Trawl Catch Effort Processing Return (TCEPR) form. The form records the date and time of trawl effort, the target species, catch weight, and various details regarding the gear used. The data were assumed to include a complete record of the mackerel trawl effort, and were used as the authoritative source for tow time and location information required for modelling. The Ministry of Fisheries' observer programme collects data on mammal and sea bird captures in New Zealand fisheries, including common dolphin captures. Observers on trawlers identify the species of any non-fish bycatch, and record the time and location of every tow they observe.

Records of trawl events in the New Zealand Exclusive Economic Zone (EEZ) and territorial sea between 1 October 1995 and 30 September 2008 were included in this report. 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. The grooming rules affected 1.8% of the trawl records.

Observer records were linked to the fisher effort data 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. Only 46 observer records (1.2% of 3817 observations) from mackerel trawlers could not be linked to the fisher reported data. There were no common dolphins caught on these unlinked observer records, and they were discarded.

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 (Figure 2). This area was chosen as it included the region of the mackerel fishery where common dolphin captures have been observed.

2.2 The dolphin capture model

A statistical model was built to estimate total captures in the large vessel mackerel fishery from the observed captures in that fishery. 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. The model estimated the probability, π_i, of capturing dolphins on a tow, i. A year effect, λ_j was estimated for each year, j, allowing for annual variation in the capture event rates that was unrelated to the covariates, x_{ic}. The contribution of each covariate, indexed by 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 year effect, $\lambda_{j[i]}$, and the covariates:

$$\operatorname{logit}(\pi_i) = \lambda_{j[i]} + \sum_c \beta_c x_{ic}. \qquad (1)$$

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 dolphin captures occurred, the captures were assumed to follow a zero-truncated Poisson distribution with size μ. The use of a zero-truncated distribution reflected 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, 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, an initial exploration suggested that there was no consistent variation of the size μ with any available covariates.

The model was coded in the BUGS language (Spiegelhalter et al. 2003), a domain specific language for describing Bayesian models. The model was fitted with the software package JAGS (Plummer 2005), using Markov chain Monte Carlo (MCMC) methods. To ensure that the model had converged, a burn-in of 10 000 iterations was made. From there, the model was run for another 100 000 iterations and every 20^{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). 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_{yv}, was calculated as the sum of actual reported captures on observed tows, d^o_{yv}, and estimated 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, $D^t_y = \sum_v D^t_{yv}$.

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 Akaike 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 1 were presented to the step analysis. Catch weight, trawl duration, night hours, bottom depth, and fishing 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 performing the transformation).

3. RESULTS

All the 97 common dolphin captures on observed tows in the mackerel fishery were on vessels longer than 90 m, with most captures being on vessels longer than 100 m. Estimation of total common dolphin captures was restricted to trips by vessels over 90 m long that reported targeting jack or blue mackerel on at least one tow on a trip. These trips were defined as the large vessel mackerel fishery. There were a total of 17 938 tows reported by this fishery over the 13 year period. Amongst these there were 424 tows recorded as targeting other fish species; no dolphin captures were observed on any of these tows. Common dolphins were caught on 38 of the 3817 tows observed during the period; an average rate of 1.0 capture event per 100 tows. When common dolphins were caught, typically more than one was caught at a time. A total of 97 common dolphins were observed killed, a mean of 2.6 dolphins per event.

Maps of fishing effort, observations and common 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. In the 2007–08 fishing year, all captures were in the northern area. A summary of the effort, observer coverage and observed common dolphin captures for the whole region is given in Table 2. The development of the mackerel fishery over the 13 year period can be clearly seen. Before the 2001–02 fishing year there were fewer than 1000 tows per year, most of this effort was concentrated in the southern part of the region. Since then fishing effort, and dolphin captures, have increased, with over 2000 trawls being made on mackerel trips during each year since 2002–03 and the effort has been evenly divided between the two regions. In 2007–08, there were 5 capture events, with 9 common dolphins being caught on a single tow.

While fishing effort by other, mostly smaller, vessels accounts for 40.7% of all effort in the west coast North Island area, there have been only 566 observed tows in these other fisheries. Moreover, only 79 of these observations have been in the same region where the mackerel fishery takes place (south of 36°40′ S), and there were no observations in 2007–08 fishing year. The lack of observer coverage on the small vessels means that no estimate can be made of dolphin captures in this fleet.

The results of the covariate selection (as defined in Table 1) are given in Table 3. Four covariates were

Table 1: 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.
Fishing depth	Metres	The depth of the net ground line.
Headline height	Metres	The height of the net opening.
Headline depth	Metres	The depth of the top of the net, derived by subtracting the headline height from the ground line 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.
Nation	Flag	Factor indicating which flag the vessel is flying: Russia, New Zealand, Japan, Korea, or FOC (a flag of convenience)

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, these four covariates were included in the Bayesian model. The distributions of the covariates are shown in Figure 3. In all cases, the observed covariates were broadly representative of the total fishing effort. Associations between the covariates and dolphin captures can be seen. In particular, there is a clear association between shallow headline depth and dolphin captures.

A summary of the coefficients of the covariates, from the Bayesian fit of the hurdle model, is given in Table 4. The coefficient for the headline depth factor had a mean of -0.040 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, or deepened, by 17.3 metres (95% c.i.: 12.8 metres to 25.7 metres). The mean coefficient of the logarithm

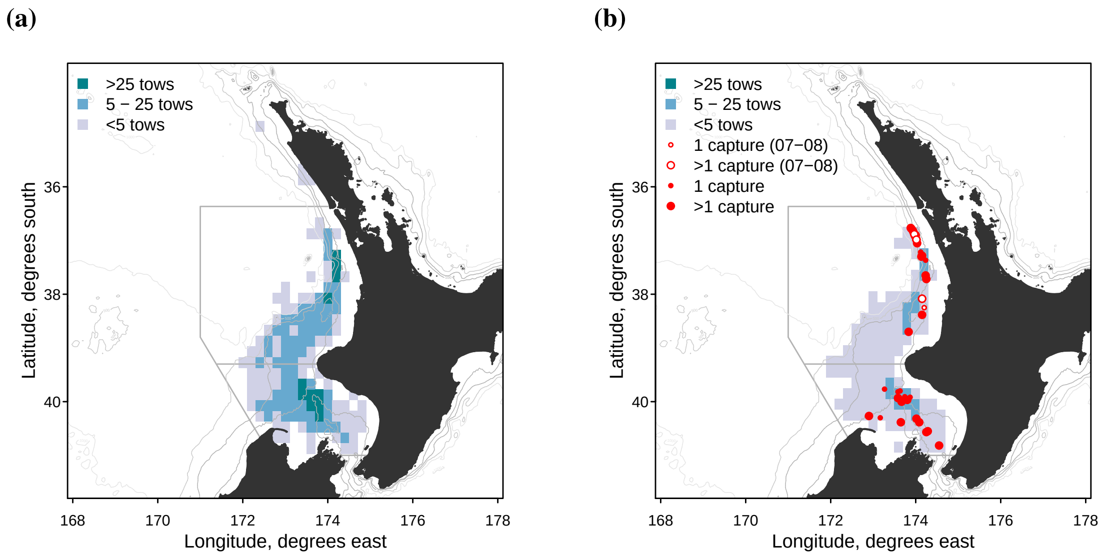

Figure 2: Trawl effort in the west coast North Island region, between 1 October 1995 and 30 September 2008. (a) Trawls by vessels longer than 90 m on trips targeting mackerel, (b) observed trawls from vessels longer than 90 m on trips targeting mackerel. The locations of observed common dolphin captures are indicated. The grey box indicates the boundaries of the area selected for modelling. The horizontal grey line divides the north and south fishing areas used as covariates in the model.

Table 2: Annual summary of common dolphin captures in the west coast North Island region. The table gives the total number of tows (Effort), the number of observed tows, capture events, and total common dolphins captured. The data is from vessels longer than 90 metres that targeted mackerel. The rates are expressed as dolphin captures per 100 trawls.

		Observed		Capture events		Dolphin captures		
Year	Effort	Tows	% obs	Events	Rate	Dolphins	Per event	Rate
2007–08	2164	725	34	5	0.69	20	4.00	2.76
2006–07	2164	608	28	5	0.82	11	2.20	1.81
2005–06	2119	647	31	1	0.15	2	2.00	0.31
2004–05	2424	561	23	10	1.78	21	2.10	3.74
2003–04	2309	164	7	7	4.27	17	2.43	10.37
2002–03	2249	222	10	6	2.70	21	3.50	9.46
2001–02	1577	111	7	1	0.90	1	1.00	0.90
2000–01	972	122	13	1	0.82	1	1.00	0.82
1999–00	415	72	17	1	1.39	1	1.00	1.39
1998–99	350	85	24	0	-	0	-	-
1997–98	558	217	39	0	-	0	-	-
1996–97	232	163	70	0	-	0	-	-
1995–96	405	120	30	1	0.83	2	2.00	1.67
Total	17938	3817	21	38	1.00	97	2.55	2.54

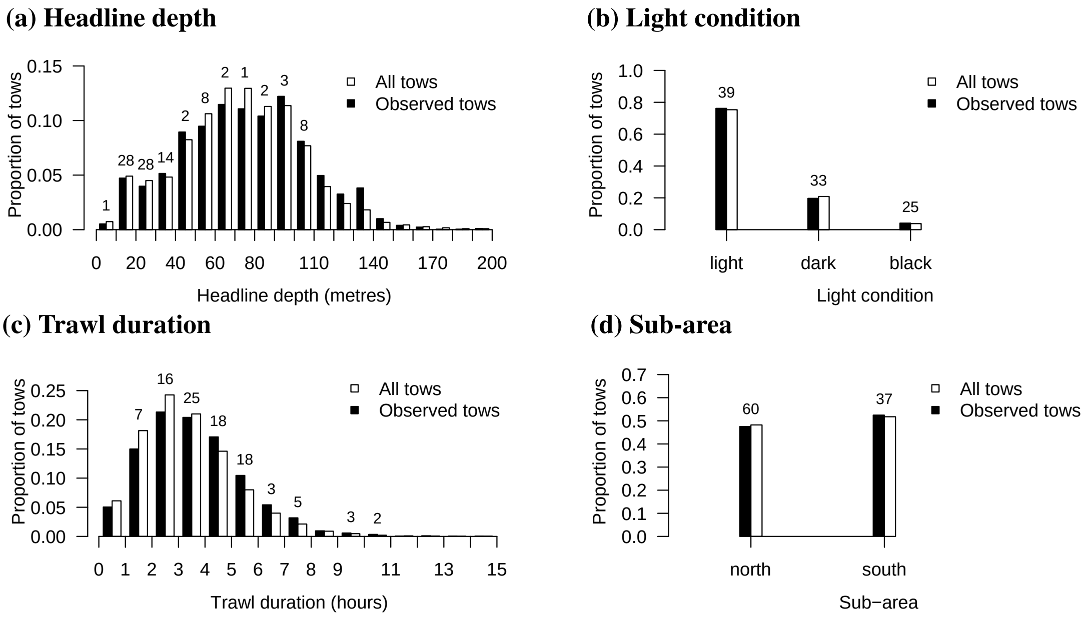

Figure 3: Distribution of the four selected covariates for observed and all trawl effort by large mackerel vessels off the west coast of the North Island, between 1 October 1995 and 30 September 2008. Total observed common dolphin captures are indicated above the bars.

of the trawl duration was 1.355, implying that decreasing the tow duration would decrease the capture event probability. This coefficient was not significantly different from 1, so the model was consistent with a linear relation between the trawl duration and the capture event probability (at least for low probabilities when the logit function is approximately equal to a log function). The exponentiated value of the coefficient for the sub-area factor had a mean of 0.5, implying that tows in the southern sub-area 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 0.43 times the probability of a capture event occurring than of tows in the "dark", while tows in "black" light conditions were 3.0 times more likely to have capture events than tows in the "dark".

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 a median value of 2.3 (95% c.i.: 1.8 to 2.9) dolphins per capture event, and is plotted in Figure 4a. When the numbers of dolphins caught per capture event were compared between the observed data and the model, the observations were found to mainly fall within the 95% confidence interval of the model estimates (Figure 4b). The only exception was the single 9 dolphin capture event, which was less likely to occur in the model. Likewise, when the model was used to estimate captures on observed

Table 3: Analysis of deviance returned from the model selection algorithm. Details displayed are: degrees of freedom (Df), deviance, residual degrees of freedom, residual deviance, percentage of deviance reduced, and the AIC.

	Df	Dev.	Resid. Df	Resid. Dev.	% dev.	AIC
Intercept			3770	443.27		445.27
Headline depth	1	59.40	3769	383.87	13.4	387.87
Light condition	2	11.70	3767	372.17	3.0	380.17
Log of trawl duration	1	7.89	3766	364.28	2.1	374.28
Sub-area	1	4.65	3765	359.62	1.3	371.62

Table 4: 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, $\beta_{headline}$	-0.040	-0.054	-0.040	-0.027
Log trawl duration, $\beta_{duration}$	1.355	0.442	1.344	2.306
Light condition, light (relative to dark), $\exp(\beta_{light})$	0.430	0.176	0.394	0.892
Light condition, black (relative to dark), $\exp(\beta_{black})$	2.962	0.981	2.628	6.773
Sub-area, south (relative to north), $\exp(\beta_{south})$	0.496	0.176	0.450	1.075

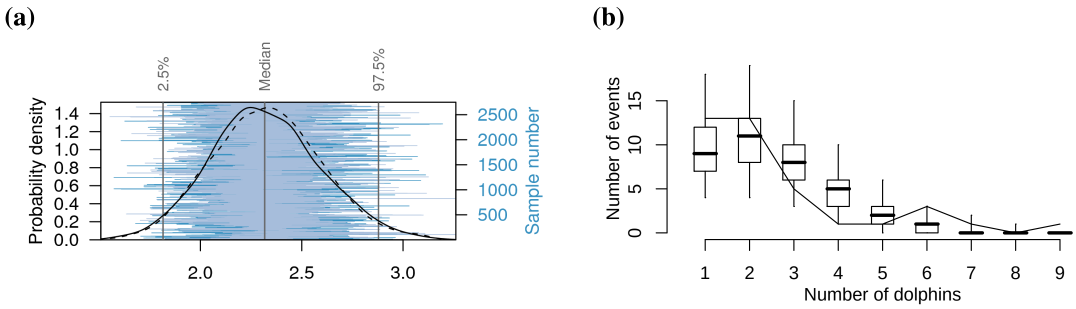

Figure 4: The number of dolphins caught per capture event (a) The posterior distribution of the size of the zero-truncated Poisson distribution, μ, showing the probability density and trace of the two chains. (b) A comparison of the predicted distribution of the number of common dolphins caught per capture 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).

tows in each fishing year, the number of observed captures fell within the 95% confidence interval of the model predictions (Figure 5), indicating that the model was able to fit the data.

Fifteen large vessels operated in the mackerel fishery in the 13 year period from 1 October 1995 to 30 September 2008, and 10 of these vessels were observed. In Figure 6, observed common dolphin captures are compared with the distribution of captures estimated by the model for 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.

In Figure 7, three simulated capture datasets are compared to the actual observed captures, organised by vessel and year. These simulations are made by sampling from the Markov chains, and then sampling

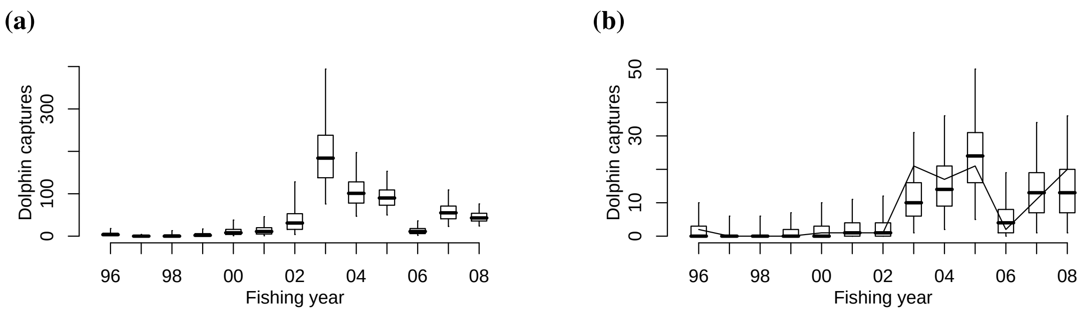

Figure 5: Estimated captures by year (a) during all trawls, and (b) during observed trawls. Observed captures are included on (b) for comparison. The boxplots give the median, interquartile range, and 95% confidence interval of the posterior distributions.

Table 5: Total number of tows, observed tows, observer coverage, observed common dolphin captures, observed catch rate, estimated captures, and estimated catch rate for the large vessel mackerel fishery on the west coast of the North Island between 1 October 1995 and 30 September 2008. The catch 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.
2007–08	2164	725	34	20	2.76	43	24 - 76	1.99	1.11 - 3.51
2006–07	2164	608	28	11	1.81	55	23 - 109	2.54	1.06 - 5.04
2005–06	2119	647	31	2	0.31	11	2 - 36	0.52	0.09 - 1.7
2004–05	2424	561	23	21	3.74	90	50 - 153	3.71	2.06 - 6.31
2003–04	2309	164	7	17	10.37	101	47 - 197	4.37	2.03 - 8.54
2002–03	2249	222	10	21	9.46	184	76 - 394	8.18	3.38 - 17.52
2001–02	1577	111	7	1	0.9	31	4 - 128	1.97	0.25 - 8.12
2000–01	972	122	13	1	0.82	11	1 - 46	1.13	0.1 - 4.73
1999–00	415	72	17	1	1.39	8	1 - 38	1.93	0.24 - 9.16
1998–99	350	85	24	0	0	2	0 - 17	0.57	0 - 4.86
1997–98	558	217	39	0	0	0	0 - 13	0	0 - 2.33
1996–97	232	163	70	0	0	0	0 - 4	0	0 - 1.72
1995–96	405	120	30	2	1.67	3.5	2 - 18	0.86	0.49 - 4.44

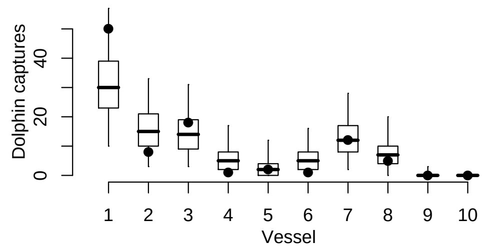

Figure 6: Estimated captures during observed trawls, for each of the observed vessels. The solid dots indicate the observed captures, the boxplots summarise the posterior distribution of the captures for each vessel (the median, inter-quartile range and 95% confidence interval are indicated).

from the resulting model. 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 dolphin catches in earlier years. The simulations also give an indication of the variability that could be expected due to random variation.

The estimated total number of common dolphins killed in each year is given in Table 5, with the results also shown in Figure 5. The number of captures rose rapidly from the 2000–01 fishing year, when the total estimated mortalities were 11 (95% c.i.: 1 to 46), to a peak of 184 (95% c.i.: 76 to 394) in the 2002–03 fishing year. This increase was driven both by an increase in trawl effort (from 972 trawls in 2000–01 to 2249 trawls in 2002–03) and an increase in the estimated catch rate, which peaked at 8.18 dolphins per 100 tows (95% c.i.: 3.29 to 17.61) in 2002–03. Since 2002–03, the annual number of captures has fallen, with the model estimating that 43 dolphins were captured in the large vessel mackerel fishery in 2007–08 (95% c.i.: 24 to 76). This decrease was driven by a decline in the estimated catch rate, which fell to 1.99 dolphins per 100 tows (95% c.i.: 1.11 to 3.51) in 2007–08. The change in the model estimated capture rate was primarily due to changes in the year effect, which fell from a peak median value of 1.3 (95% c.i.: 0.38 to 3.64) in 2002–03 to 0.14 (95% c.i.: 0.04 to 0.37) in 2007–08.

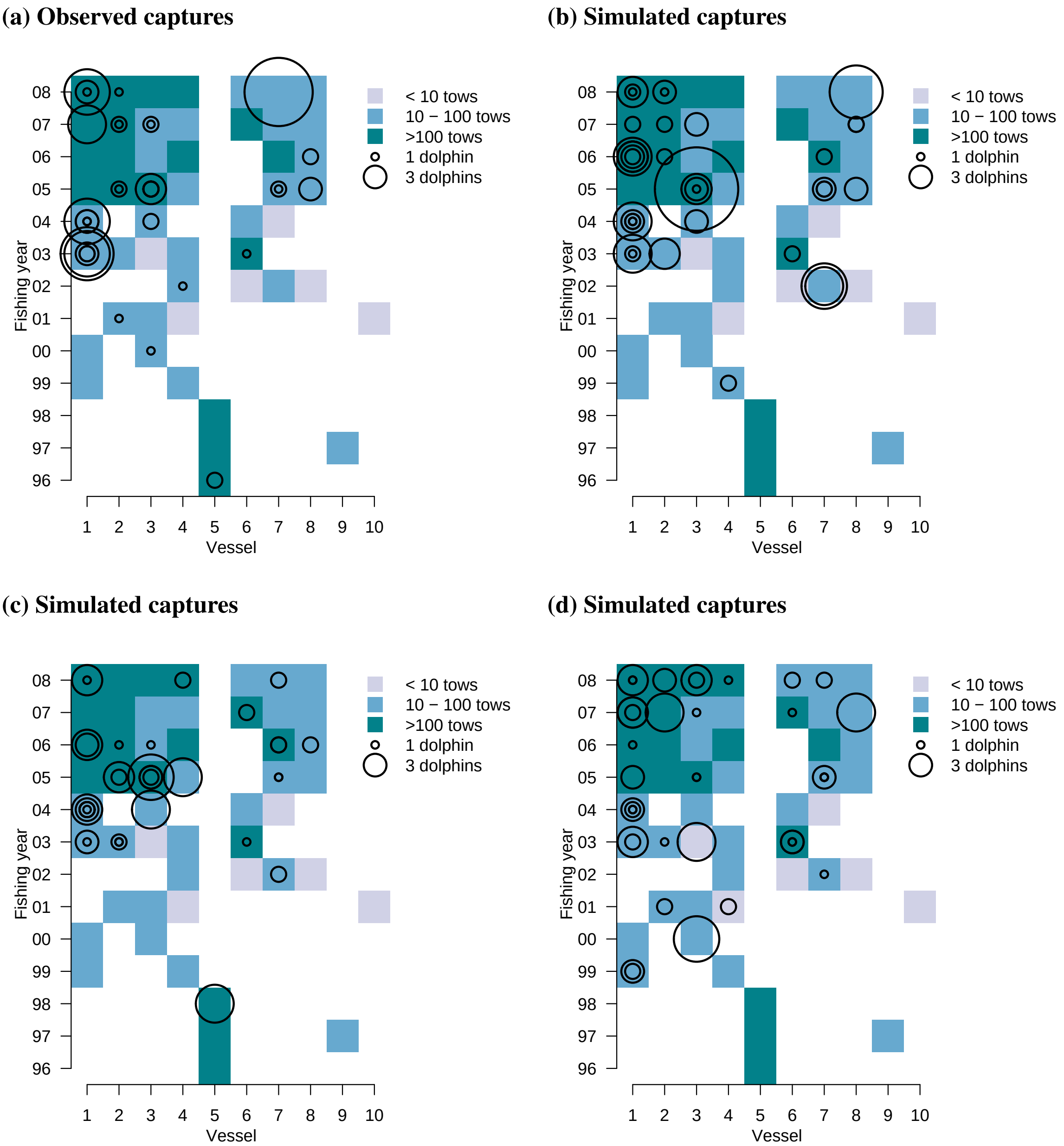

Figure 7: Observed and simulated capture events by fishing year and vessel. Figure (a) presents actual observed captures, and Figures (b, c, d) present samples of simulated capture events derived from the model. The observed effort is indicated with the colour.

4. DISCUSSION

Between 1995–96 and 2007–08, observed captures of common dolphin in New Zealand waters were primarily in the 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 least once between 1 October 1995 and 30 September 2008. A statistical model was built that estimated the total common dolphin captures in the fishery. 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.

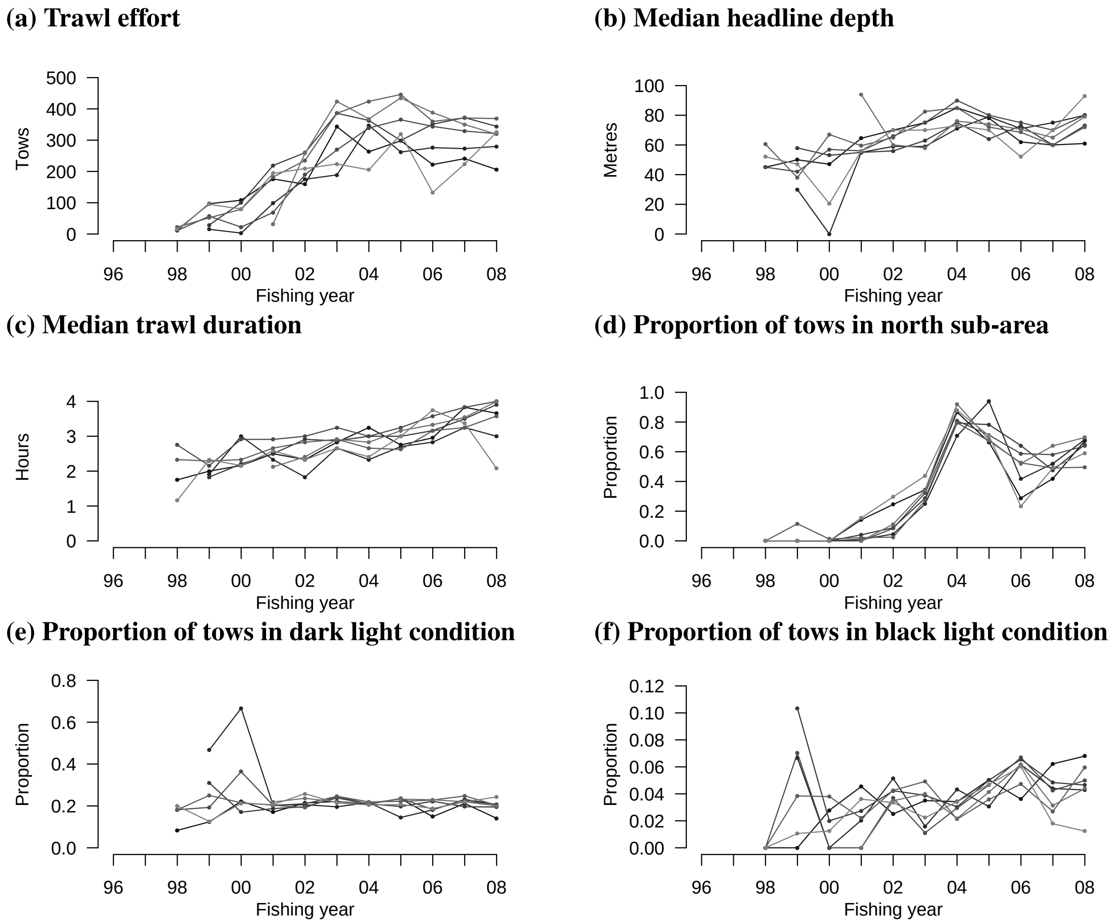

Figure 8: Annual trends of (a) trawl effort, (b) median headline depth, (c) trawl duration, (d) proportion of tows in the north, (e) proportion of tows in dark light conditions, and (f) proportion of tows in black light conditions, for each of the seven vessels responsible for most of the mackerel trawl effort in recent years.

Seven vessels accounted for over 95% of the fishing effort in the 13 year period. Variation in the covariates between these seven vessels are shown in Figure 8. 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. The number of tows made by each of these vessels has also been similar. Headline depth peaked in 2003–04, and has since remained relatively constant, with a median depth of over 60 m. There was a marked shift to the northern area in 2003–04, with a subsequent return to the southern area (in 2007–08, 37.4% of trawls were in the southern area). The consistent variation between the vessels 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, and there was no evidence that some of the seven main vessels were better or worse than the others at avoiding dolphin bycatch.

Headline depth (the distance of the headline below the surface) was the covariate that best explained the occurrence of common dolphin captures. Bottom depth, ground-line depth and the height of the net opening were all tried as covariates, however headline depth was preferred. In the mackerel fishery, large midwater nets are used. The only tows with bottom trawls were tows made by a single vessel that left the fishery after the 1997–98 fishing year, and 4 tows in 2004–05. All other fishing was with midwater nets. The median net opening, across all the data, was 35 m (inter-quartile range of 30 m to 60 m). Fishing was in shallow water (a median depth of 110 m, inter-quartile range of 99 m to 145 m), so the net typically occupied a large fraction of the water column (median 30%, inter-quartile range of 25% to 40%). The model estimated that increasing the headline depth on a tow by 17 metres would halve the probability of a common dolphin capture occurring. The strong influence of headline depth is seen in the raw data (Figure 9). Half of the observed capture events, and 54% percent of common dolphins captured, in the large vessel mackerel fishery occurred on the 9% of observed trawls that had a headline depth less than 30 m.

Diel changes in the behaviour of mackerel have been documented off the coast of Chile (Bertrand et al. 2004). Mackerel migrate to the surface during the night and form feeding aggregations, whereas during the day they are deeper and more dispersed. Fishing follows this movement, and headline depth was typically shallower at night (Figure 9). Across all the effort data, 68% of shallow tows (a headline of less than 30 m deep) occurred at night. An increased catch of common dolphins at night has been noted in other pelagic trawl fisheries (Crespo et al. 1997, Morizur et al. 1999). In a previous analysis, light was also identified as a factor associated with common dolphin captures in the mackerel fishery (Du Fresne et al. 2007). However, these studies did not directly investigate the role of headline depth in relation to common dolphin captures. Because of the correlation between headline depth and time of day, the time of day factor only explained a relatively small fraction (3.0%) of the residual deviance (Table 3). However, the model found that the dolphin capture rate was lower for fishing with hauls made in the day or on moonlit nights than at night (a median ratio of 0.43 with a 95% c.i, of 0.18 to 0.91). Conversely, the dolphin capture rate was increased when the haul was between midnight and dawn (a median ratio of 2.9 with a 95% c.i. of 0.9 to 6.9).

The same strong association between headline depth and dolphin capture events was identified when the model was fitted from data up to the end of the 2006–07 year (Thompson & Abraham 2009). In 2007–08 the five capture events occurred when the headline depth was at 9 m (1 event), 10 m (3 events), and 20 m (1 event). The pattern of these captures, all on the 13% of observed tows at depths of 30m or less, reinforced the relationship between headline depth and capture events. In contrast, the time of day of the fishing varied. Three of the 2007–08 common dolphin capture events were when the net was hauled between 4 am and 5 am, one occurred on a tow when the net was hauled at 8:50 am, and one occurred when the net was hauled at 11:20 pm.

Both the model and the raw data suggest that restricting trawls with shallow sets would reduce common dolphin bycatch. There are references in reports to two previous voluntary measures aimed at reducing common dolphin bycatch. In the 1990's a measure was introduced by a least one fishing company that recommended that the net headline either remained below 20 m below the surface, or was hauled partially on deck, while the vessel was turning (Slooten & Dawson 1995). More recently, a voluntary restriction was placed on fishing between 2 am and 4 am by at least one fishing company (Baird 2008). Despite this code of practice, there is still fishing being carried out between these hours. A full enforcement of this ban would not have prevented two of the 2007–08 capture events.

Estimates of the number of common dolphins killed in the large vessel mackerel fishery are summarised in Table 5. There was little effort in this fishery before 2000–01, fewer than 600 tows per year. The estimated number of common dolphin captures was also relatively small, with a median of less 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 common dolphin captures to 184 (95% c.i.: 76 to 394). Since then the number of captures has decreased. In 2007-08 there were an estimated 44 (95% c.i.: 24 to 78) common dolphins killed in the large vessel mackerel fishery. The reasons for the decrease in common 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 common dolphin captures should be increasing. It is possible that either the number of common dolphins in the region at the time of the mackerel fishery has decreased, or the vulnerability of common dolphins to being caught has decreased. Observers also record common dolphin sightings. These data have not yet been collated, however they could be used to

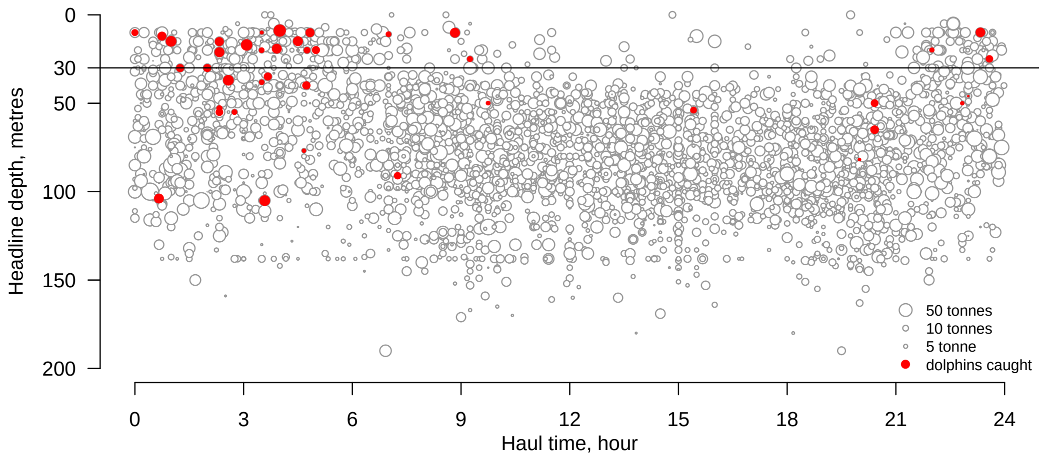

Figure 9: Headline depth versus the haul time for observed trawls in the large-vessel mackerel fishery. The catch weight is indicated by the size of the circles. Tows where an observed common dolphin capture event occurred are filled in red.

indicate whether the numbers of common dolphins visiting mackerel vessels has remained constant or declined.

There are no available estimates of the number of common dolphins living in the region where the 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 although fisheries impacts are not considered a concern at the global population level (Hammond et al. 2008), research in the Hauraki Gulf reported genetic differentiation between populations within New Zealand (Stockin 2008, Stockin et al. 2008). It is unknown whether the west coast North Island population is either resident or migratory.

Dolphins are also occasionally observed caught in other fisheries (Abraham & Thompson 2009). Of potential concern are captures in inshore trawl fisheries. Between 1995–96 and 2006–07 two common dolphins and one Hector's dolphin (*Cephalorhynchus hectori*) were reported killed by trawlers targeting inshore fish species (Starr & Langley 2000, Baird & Bradford 2000). These events demonstrate that dolphin captures occur in inshore trawl fisheries, however these fisheries have been very poorly observed. Before 2004–05, observer coverage was 0.1% or less each year. In 2006–07, coverage increased to 0.5% however the spatially widespread and diverse nature of these fisheries means many more observations are needed in order to quantify the mortality of dolphins in fisheries targeting inshore species.

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