Common dolphin (*Delphinus delphis*) bycatch in New Zealand mackerel trawl fisheries, 1995–96 to 2008–09

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EXECUTIVE SUMMARY

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Common dolphins (*Delphinus delphis*) are the most frequently observed caught cetacean in New Zealand trawl fisheries. Between the 1995–96 and 2008–09 fishing years, there were 108 common dolphin captures reported by Ministry of Fisheries observers in the mackerel trawl fishery on the west coast of the North Island. All captures were by vessels over 90 m length. The pattern of captures was similar across fishing years, with a general increase in fishing effort and a concomitant increase in common dolphin captures over the 14-year period. In the most recent fishing year, 2008–09, fishing effort was comparatively lower than in preceding years, and 11 common dolphins were caught in 4 of 510 tows. Capture events frequently involved the capture of more than one individual, with a maximum of 9 common dolphins observed caught in a single tow.

Based on observer data, a statistical model was built that estimated the total number of common dolphin captures in the large vessel 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 to estimate the number of dolphin captures, given that there was a capture event. The model was also used to explore which covariates were related to common dolphin captures.

There was little effort in the large vessel mackerel fishery before 2001–02, with fewer than 1000 tows per year. The estimated number of common dolphin captures was also relatively small, with a median of less than 12 captures annually. As the effort in this fishery expanded to over 2000 tows by 2002–03, there was an initial increase in the estimated number of common dolphins caught per year to 182 (95% c.i.: 72 to 389). Since then, the number of captures has decreased, although fishing effort has remained relatively high. In 2008–09, there were an estimated 25 (95% c.i.: 13 to 52) common dolphins killed in the large vessel mackerel fishery. The reasons for the decrease in common dolphin captures since 2002–03 are unknown. Lack of dolphin abundance data prevents assessment of the impact of these mortalities on the common dolphin population in the mackerel fishing area.

The model found that headline depth (distance of the headline below the surface) was the covariate that best explained the occurrence of common dolphin captures. Both the model and observer data suggest that restricting trawls with shallow headlines would reduce dolphin bycatch. Of the observed capture events, 50% were during the 10% of observed trawls where headline depth was less than 30 m below the surface. All capture events in 2008–09 occurred on trawls with a headline depth of 20 m or less. Increasing the headline depth by about 13 m would halve the probability of a dolphin capture event on a tow. Light condition, trawl duration, and sub-area were all also identified as covariates associated with dolphin bycatch. The model estimated that there was a higher bycatch on trawls hauled between midnight and dawn, on longer trawls, and on trawls in the northern sub-area of the fishing region (above $30^\circ\ 18'$ S).

In addition to the large vessel mackerel fishery, there have been observed common dolphins captured in inshore trawl fisheries. Although there are large fisheries targeting inshore fisheries (e.g., 78% of all trawls on the west coast of the North Island in the 2008–09 fishing year), observer coverage has been limited to 0–0.5% per fishing year. Because of the low observer coverage, it is not possible to estimate the number of common dolphins caught in inshore fisheries.

1. INTRODUCTION

Direct interactions between fisheries and marine mammals frequently occur when fishing operations overlap with the distribution of pinniped and cetacean populations (Read et al. 2006). Entanglement and entrapment in fishing gear result in injury and mortality, and incidental captures of marine mammals have been documented for a variety of fisheries worldwide (Reeves 2003). For some marine mammal populations and species, these incidental captures pose a serious threat (Dawson & Slooten 2005). Cetaceans are particularly vulnerable as they are long lived, slow to reproduce, and have limited potential for population increase (Read 2008). At the same time, they may be attracted to fishing vessels, with a number of species being reported feeding in association with trawlers (Chilvers & Corkeron 2001, Rayment & Webster 2009).

One species that features prominently in bycatch reports across different fisheries and regions is the common dolphin (*Delphinus delphis*) (Northridge 1996, Tudela et al. 2005). This species is globally distributed in temperate, subtropical and tropical regions, where it is often abundant in coastal waters (Danil & Chivers 2007). Based on its global distribution and abundance, the conservation status of common dolphin is "least concern" using the IUCN classification system (Hammond et al. 2008). On a smaller spatial scale, however, there are several separate sub-populations that are in serious decline, such as in the Mediterranean and Black seas (Reeves 2003). Furthermore, distinct morphological differences indicate the existence of potential subspecies in some regions (Hammond et al. 2008).

In New Zealand waters, common dolphins are present in coastal areas throughout the country (Bräger & Schneider 1998, Stockin et al. 2008). Although there are no population estimates for this region, they are considered to be abundant, often forming schools of up to several thousand (Stockin 2008). As has been documented for populations elsewhere (Forney & Barlow 2006), common dolphins in New Zealand show differences in their distribution and habitat use (Stockin et al. 2008). They exhibit seasonal inshore-offshore movement, residing in coastal waters during spring and summer, before moving further offshore during autumn (Neumann 2001b). This inshore-offshore migration also occurs on a diel basis, which seems to correspond with the exploitation of different food sources and the movement of prey (Meynier et al. 2008).

Common dolphins feed predominantly on epipelagic and pelagic species, such as schooling fishes and squids (Perrin 2002, Rossman 2010). In New Zealand, their dominant prey are jack mackerel (*Trachurus* spp.), anchovy (*Engraulis australis*), and arrow squid (*Nototodarus* spp.) (Meynier et al. 2008). Their preference for prey species that are also targeted by commercial fisheries has been linked to the bycatch of common dolphins in trawl fisheries (Morizur et al. 1999).

In New Zealand waters, dolphin captures are recorded 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), and between the 1994–95 and the 2004–05 fishing years (Baird 2008). Subsequent common dolphin captures are included in more recent summaries of all dolphin captures between the 1995–96 and 2007–08 fishing years (Abraham & Thompson 2009, Thompson & Abraham 2009, Abraham et al. 2010). Over the 14 year period from 1996–96 to 2008–09, there were a total of 143 observed dolphin captures, of which 123 were common dolphins. Of the common dolphin captures, 121 were in trawl fisheries and of those, 108 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.

Observed common dolphin captures in the west coast North Island mackerel fishery occurred sufficiently frequently to allow the development of a statistical model for the estimation of total captures between

1995–96 and 2006–07 (Thompson & Abraham 2009). The statistical model used was a two-stage model 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 is then estimated by sampling from a zero-truncated Poisson distribution. As well as providing an estimate of total common dolphin bycatch, the model explores which covariates are related to dolphin captures in this fishery. In this report, the model is updated to include recent data from the west coast North Island mackerel fishery during the 2007–08 and 2008–09 fishing years.

2. METHODS

2.1 Data sources

Commercial trawl vessels return a record of all fishing effort to the Ministry of Fisheries. Skippers complete either a Trawl Catch Effort Processing Return (TCEPR), a Trawl Catch Effort Return (TCER), or a Catch Effort Landing Return (CELR). Information recorded on these forms includes the date and time of trawl effort, the target species, catch weight, and details regarding the gear used. These data were assumed to be a complete record of the mackerel trawl effort, and were used as the authoritative source for tow time and location information required for modelling. Data on marine mammal and sea bird captures in New Zealand fisheries, including common dolphin captures, are collected through the Ministry of Fisheries' observer programme. Observers on trawlers identify the species of any non-fish bycatch, and record the time and location of every tow they observe.

Records included in this report were of trawl events in the New Zealand Exclusive Economic Zone (EEZ) and territorial sea between 1 October 1995 and 30 September 2009. These 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 m), 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. This linking associated 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 requirement limited available data to those recorded by the fishers. Only 46 observer records (0.5% of 8411 observations) from mackerel trawlers could not be linked to the fisher-reported data. All observed tows in 2008–09 were linked to 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, as it included the mackerel fishery region where common dolphin captures have been observed. This area was enclosed by a line extending north along longitude 173°2.8′ E, a line across Cook Strait at 41° S, boundary at 171° E, and the boundary of New Zealand's EEZ (Figure 1). To provide higher spatial resolution, the area was divided into northern and southern sub-areas by a line at latitude 39°18′ S.

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:

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

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, but initial exploration suggested that there was no consistent variation of the size of 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, and the model was subsequently run for another 100 000 iterations, with every 20$^{\text{th}}$ iteration kept. Two chains were fitted to the model, and the output included 5000 samples of the posterior distribution from each chain. Model convergence was assessed 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 (see list of potential covariates in Table 1). At each stage of the analysis, the model was fitted repeatedly, with each of the covariates included (or removed) in turn and selection of the covariate 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. Catch weight, trawl duration, night hours, bottom depth, and fishing depth, were all included both directly and as a log-transform (with 1 tonne and 1 hour added to catch weight and night hours, respectively, before performing the transformation).

3. RESULTS

There were 108 common dolphin captures on observed tows in the mackerel fishery. All captures occurred on vessels longer than 90 m, with most captures on vessels longer than 100 m. Estimation of total common dolphin captures was restricted to trips by vessels over 90 m length that reported targeting jack or blue mackerel on at least one tow per trip. These trips were defined as the large vessel mackerel fishery. A total of 18 807 tows was reported by this fishery over the 14-year period. Amongst these were 872 tows recorded as targeting other fish species; no dolphin captures were observed on any of these tows. Common dolphins were caught on 42 of the 4299 tows observed, reflecting an average rate of 0.98 capture events per 100 tows. When common dolphins were caught, typically more than one was caught in a capture event. These multiple captures most frequently involved 2 or 3 dolphins, with a maximum of 9 dolphins caught in a single event. The total of 108 common dolphin captures equates to a mean of 2.6 dolphins per event or 2.5 dolphins per 100 tows (Table 2).

Fishing effort by the large vessel mackerel fishery was distributed along the west coast of the North Island, with a similar spatial spread in observer coverage (Figure 1). Observed common dolphin captures were predominantly in the shoreward parts of the region, occurring in both sub-areas. When considering fishing effort over time, there was a marked development in the fishery over the 14-year period (Table 2). Before the 2001–02 fishing year, there were fewer than 1000 tows per year and few common dolphins were observed captured. Since then, fishing effort has increased, with over 2000 tows per year since 2002–03, except for the most recent fishing year (2008–09) with 1187 tows. There was a concomitant increase in the number of observed capture events and observed common dolphin captures. The largest increase in the number of observed common dolphin captures was in 2002–03, and observed captures remained relatively high in subsequent fishing years. Observer coverage varied greatly over the reporting period, with 7–70% of all tows observed in this fishery. The rapid increase in fishing effort initially coincided with minimum observer coverage of 7–10% (2001–02 to 2003–04), which has since then remained above 20%.

Other, mostly smaller, vessels accounted for 40.0% of all fishing effort in the west coast North Island region, but there were only 646 observed tows in these other fisheries. Moreover, only 79 of these observations were in the same area where the mackerel fishery takes place (south of 36°40′ S), and there were no observations in the 2008–09 fishing year. The lack of observer coverage on the small vessels prevents any estimate of dolphin captures in this fleet.

The selection of covariates (defined in Table 1) revealed four important covariates, which were headline depth, light condition, trawl duration, and sub-area (Table 3). Headline depth was identified as the

Table 1: Potential covariates considered in 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 centre of the sun's disk was 6° below the horizon (civil dawn and dusk).
Moon illumination	Percentage	Fractional illumination of the moon's disc, 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).

strongest predictor of dolphin capture events, with light condition having the next highest explanatory power. Trawl duration and sub-area also explained more than 1% of the residual deviance. Based on this analysis, these four observed covariates were included in the Bayesian model. Their distributions show that each one was broadly representative of the total fishing effort, evident in the close agreement between observed and modelled data in all cases (Figure 2). There were clear associations between observed common dolphin captures and these covariates, most notably headline depth. The vast majority of dolphin captures were associated with shallow headline depths, between 10 and 40 m, with no captures at headline depths exceeding 110 m. The mackerel fishery uses predominantly large midwater nets, and the only tows with bottom trawls were by a single vessel that left the fishery after the 1997–98 fishing year, and four tows in 2004–05. All other fishing was with midwater nets. The median net opening, across all data, was 35 m (inter-quartile range of 30 to 60 m), and as fishing occurred in relatively shallow water (median depth of 110 m, inter-quartile range of 99 to 145 m), nets typically occupied a large fraction of the water column (median 30%, inter-quartile range of 25 to 40%). Dark and black light

Table 2: Summary of common dolphin captures in the mackerel trawl fishery on the west coast of the North Island by fishing year. Data are from vessels longer than 90 metres that targeted mackerel. Included are the total number of tows (Effort), the number and percentage of observed tows, the number and rate of capture events, and common dolphin captures (number per fishing year and per capture event, rate). Rates are per 100 tows.

		Observed		Capture events		Dolphin captures		
Year	Effort	Tows	% obs	Events	Rate	Dolphins	Per event	Rate
2008–09	1187	510	43.0	4	0.78	11	2.75	2.16
2007–08	2164	735	34.0	5	0.68	20	4.00	2.72
2006–07	2164	616	28.5	5	0.81	11	2.20	1.79
2005–06	2119	647	30.5	1	0.15	2	2.00	0.31
2004–05	2424	561	23.1	10	1.78	21	2.10	3.74
2003–04	2309	164	7.1	7	4.27	17	2.43	10.37
2002–03	2249	222	9.9	6	2.70	21	3.50	9.46
2001–02	1577	111	7.0	1	0.90	1	1.00	0.90
2000–01	972	122	12.6	1	0.82	1	1.00	0.82
1999–00	415	72	17.3	1	1.39	1	1.00	1.39
1998–99	350	85	24.3	0	-	0	-	-
1997–98	292	217	74.3	0	-	0	-	-
1996–97	183	117	63.9	0	-	0	-	-
1995–96	402	120	29.9	1	0.83	2	2.00	1.67
All	18 807	4299	23	42	0.98	108	2.57	2.51

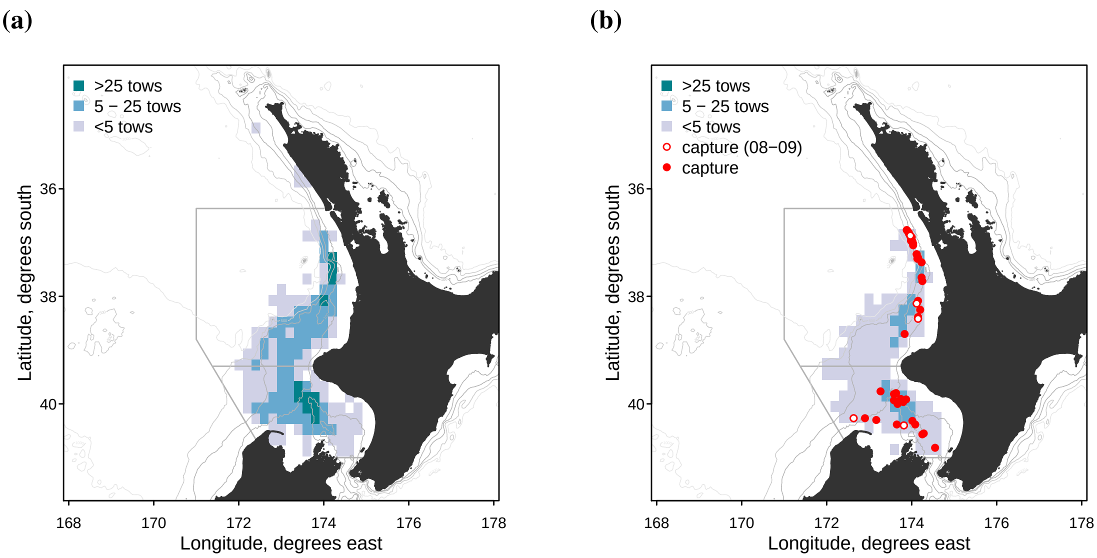

Figure 1: Trawl effort on the west coast, between 1 October 1995 and 30 September 2009. (a) Trawls by vessels longer than 90 m on trips targeting mackerel, (b) observed trawls from vessels longer than 90 m on trips targeting mackerel. The locations of observed common dolphin captures are indicated. The 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.

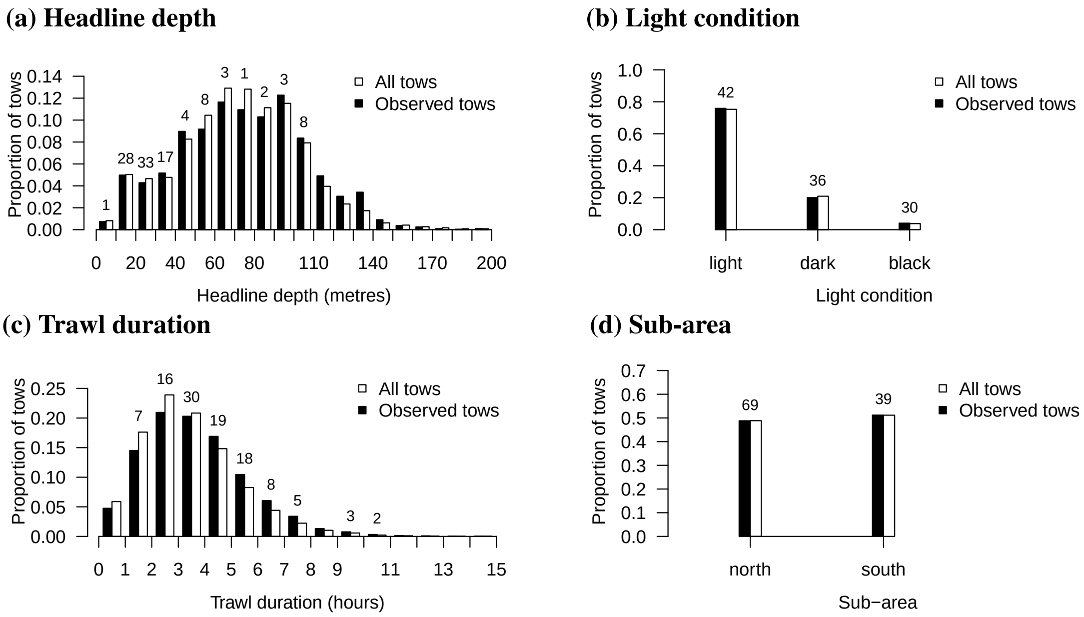

Figure 2: Distribution of the four selected covariates for observed and all trawl effort by large mackerel vessels (> 90 metres length) off the west coast of the North Island, between 1 October 1995 and 30 September 2009. Numbers above bars indicate the number of observed common dolphin captures.

conditions were associated with 64 of the 108 common dolphin captures, and relatively high numbers of dolphin captures were associated with trawls between 2 and 6 h duration. There was also a clear association with sub-area, with 69 dolphin captures in the northern sub-area compared with 39 in the southern one (Figure 2).

Coefficients of the covariates from the Bayesian fit of the hurdle model indicate the way in which the covariates affect the probability of capture events (Table 4). The coefficient for the headline depth factor had a mean of -0.037 m^{-1}, indicating that the effect was negatively correlated and that increasing the headline depth would reduce the probability of a capture event. To halve the probability of a capture event, headline depth would need to be increased, or deepened, by 13.4 m (95% c.i.: 9.8 to 19.6 m). For trawl duration, the mean coefficient of its logarithm was 1.414, 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 trawl duration and capture event probability (at least for low probabilities when the logit function is approximately equal to a log function). From the exponentiated coefficient of the light condition factor, tows hauled in the “light” had a mean of 0.447 times the probability of a capture event occurring relative to tows in the “dark”, while tows in “black”

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			4298	499.88		501.88
Headline depth	1	61.36	4297	438.52	12.3	442.52
Light condition	1	10.15	4296	428.38	2.3	434.38
Log of trawl duration	2	11.72	4294	416.66	2.7	426.66
Sub-area	1	4.32	4293	412.34	1.0	424.34

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, $\beta_{headline}$	-0.037	-0.051	-0.037	-0.026
Log trawl duration, $\beta_{duration}$	1.414	0.560	1.412	2.291
Light condition, light (relative to dark), $\exp(\beta_{light})$	0.447	0.194	0.413	0.884
Light condition, black (relative to dark), $\exp(\beta_{black})$	3.062	1.131	2.767	6.706
Sub-area, south (relative to north), $\exp(\beta_{south})$	0.461	0.179	0.427	0.941

light conditions were 3.062 times more likely to have capture events than tows in the "dark". For the sub-area factor, the exponentiated value of the coefficient had a mean of 0.461, implying that tows in the southern sub-area had about half the capture event probability of tows in the northern sub-area.

Among the seven vessels that accounted for over 95% of the fishing effort in the 14-year period, there was little variation in the covariates (Figure 3). In general, the vessels behaved similarly, with changes in the covariates such as headline depth and light condition occurring at the same time across all vessels. Headline depth peaked in 2003–04, and has since remained relatively constant, with a median depth of over 60 m. The number of tows made by each of these vessels was also similar, with a uniform increase in effort in 2001–02. There was a marked shift to the northern sub-area in 2003–04, with a subsequent return to the southern sub-area in 2007–08, when 37.4% of trawls were in this sub-area. The consistently small variation among vessels suggests that the vessels in this fishery were 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.

The second stage of the model predicted 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.: 1.9 to 2.9) dolphins per capture event (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 a single capture event involving 9 dolphins, which was less likely to occur in the model. Likewise, 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 model predictions (Figure 5), confirming that the model was able to fit the data.

The estimated total number of common dolphins killed each year rose rapidly from the 2000–01 fishing year, when the total estimated mortalities were 11 (95% c.i.: 1 to 43), to a peak of 182 (95% c.i.: 72 to 389) in the 2002–03 fishing year (Figure 5, Table 5). 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 8.11 dolphins per 100 tows (95% c.i.: 3.2 to 17.3) in 2002–03. Since 2002–03, the annual number of captures has fallen, with the model estimating that 25 dolphins were captured in the large vessel mackerel fishery in 2008–09 (95% c.i.: 13 to 52). This decrease was driven by a decline in the estimated catch rate, which fell to 2.11 dolphins per 100 tows (95% c.i.: 1.1 to 4.38) in 2008–09.

Fifteen large vessels operated in the mackerel fishery in the 14-year period from 1 October 1995 to 30 September 2009, and 9 of them were observed. Comparing observed common dolphin captures with the distribution of captures estimated by the model for those 9 vessels showed that the former captures were all within the 95% confidence interval, indicating that the model successfully predicted the variation in captures among vessels (Figure 6).

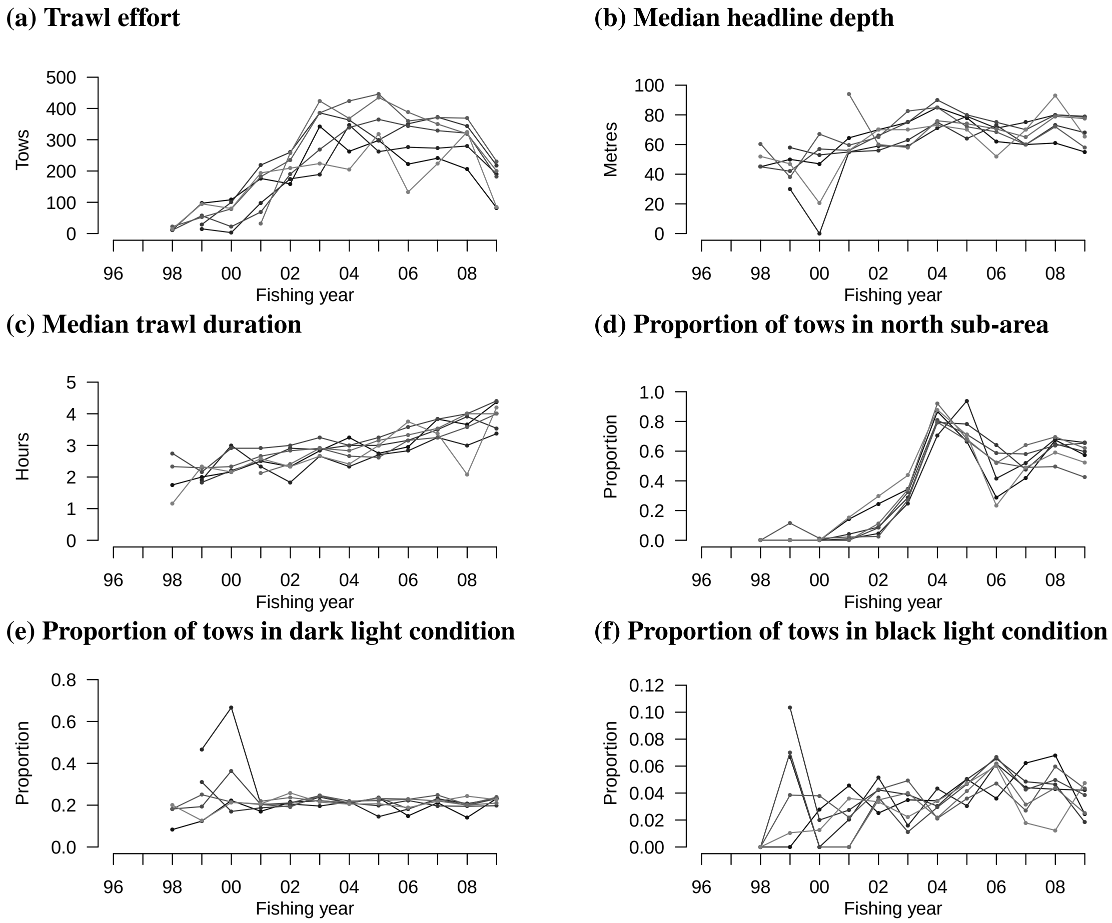

Figure 3: Annual trends of (a) trawl effort, (b) median headline depth, (c) trawl duration, (d) proportion of tows in the north, (e) proportion of tows in dark light conditions, and (f) proportion of tows in black light conditions, for each of the seven vessels responsible for most of the mackerel trawl effort in recent years.

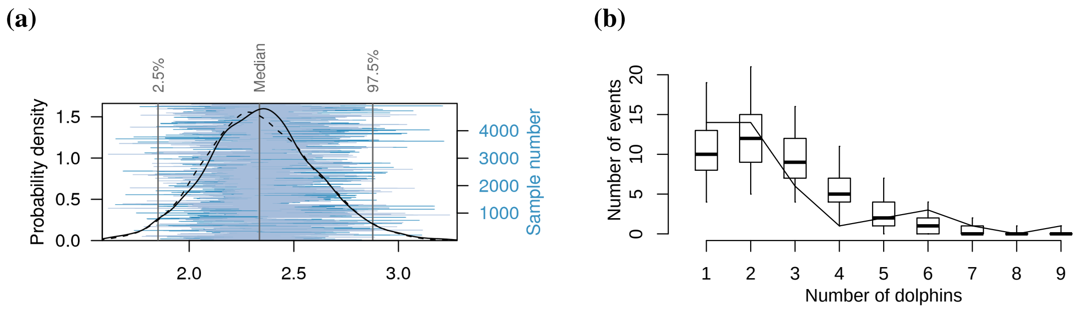

Figure 4: The number of dolphins caught per capture event. (a) The posterior distribution of the size of the zero-truncated Poisson distribution, μ, showing the probability density and trace of the two chains. (b) A comparison of the predicted distribution of the number of common dolphins caught per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

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 2009. 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.
2008–09	1187	510	43.0	11	2.16	25	13 - 52	2.11	1.10 - 4.38
2007–08	2164	735	34.0	20	2.72	43	25 - 75	1.99	1.16 - 3.47
2006–07	2164	616	28.5	11	1.79	55	25 - 113	2.54	1.16 - 5.22
2005–06	2119	647	30.5	2	0.31	11	2 - 37	0.52	0.09 - 1.75
2004–05	2424	561	23.1	21	3.74	88	49 - 151	3.63	2.02 - 6.23
2003–04	2309	164	7.1	17	10.37	102	46 - 207	4.42	1.99 - 8.97
2002–03	2249	222	9.9	21	9.46	182	72 - 389	8.11	3.20 - 17.30
2001–02	1577	111	7.0	1	0.90	29	3 - 108	1.84	0.19 - 6.85
2000–01	972	122	12.6	1	0.82	11	1 - 43	1.13	0.10 - 4.43
1999–00	415	72	17.3	1	1.39	8	1 - 38	1.93	0.24 - 9.16
1998–99	350	85	24.3	0	0.00	2	0 - 17	0.57	0.00 - 4.86
1997–98	292	217	74.3	0	0.00	0	0 - 6	0.00	0.00 - 2.05
1996–97	183	117	63.9	0	0.00	0	0 - 4	0.00	0.00 - 2.19
1995–96	402	120	29.9	2	1.67	4	2 - 19	1.00	0.50 - 4.73

(a) **(b)**

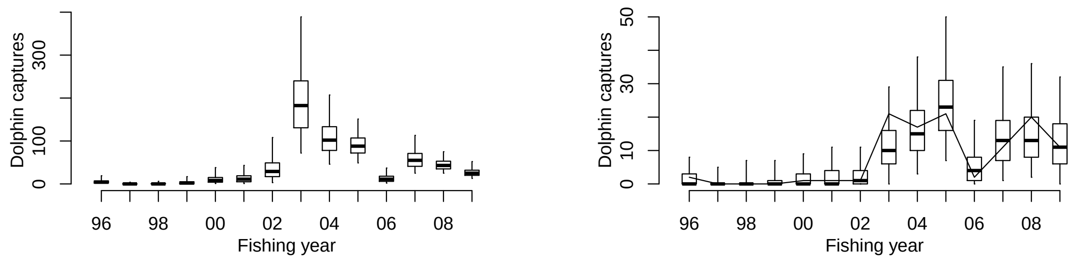

Figure 5: Estimated captures by year (a) during all trawls, and (b) during observed trawls. Observed captures are included on (b) for comparison. The boxplots give the median, interquartile range, and 95% confidence interval of the posterior distributions.

(a) Captures by vessel **(b) Capture rate by vessel**

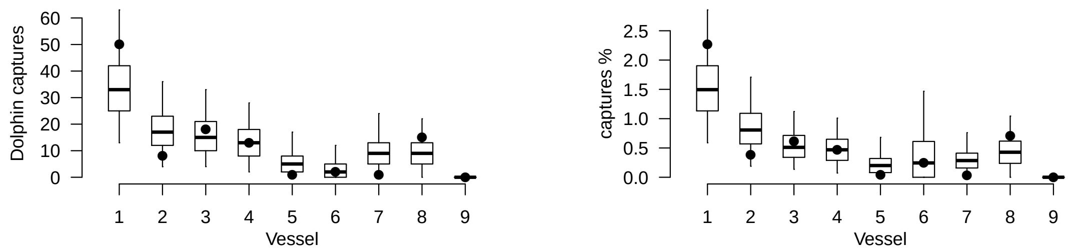

Figure 6: Estimated (a) captures, and (b) capture rate during observed trawls, for each of the observed vessels. The solid dots indicate the observed captures and rates, the boxplots summarise the posterior distribution of the captures for each vessel (the median, inter-quartile range and 95% confidence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

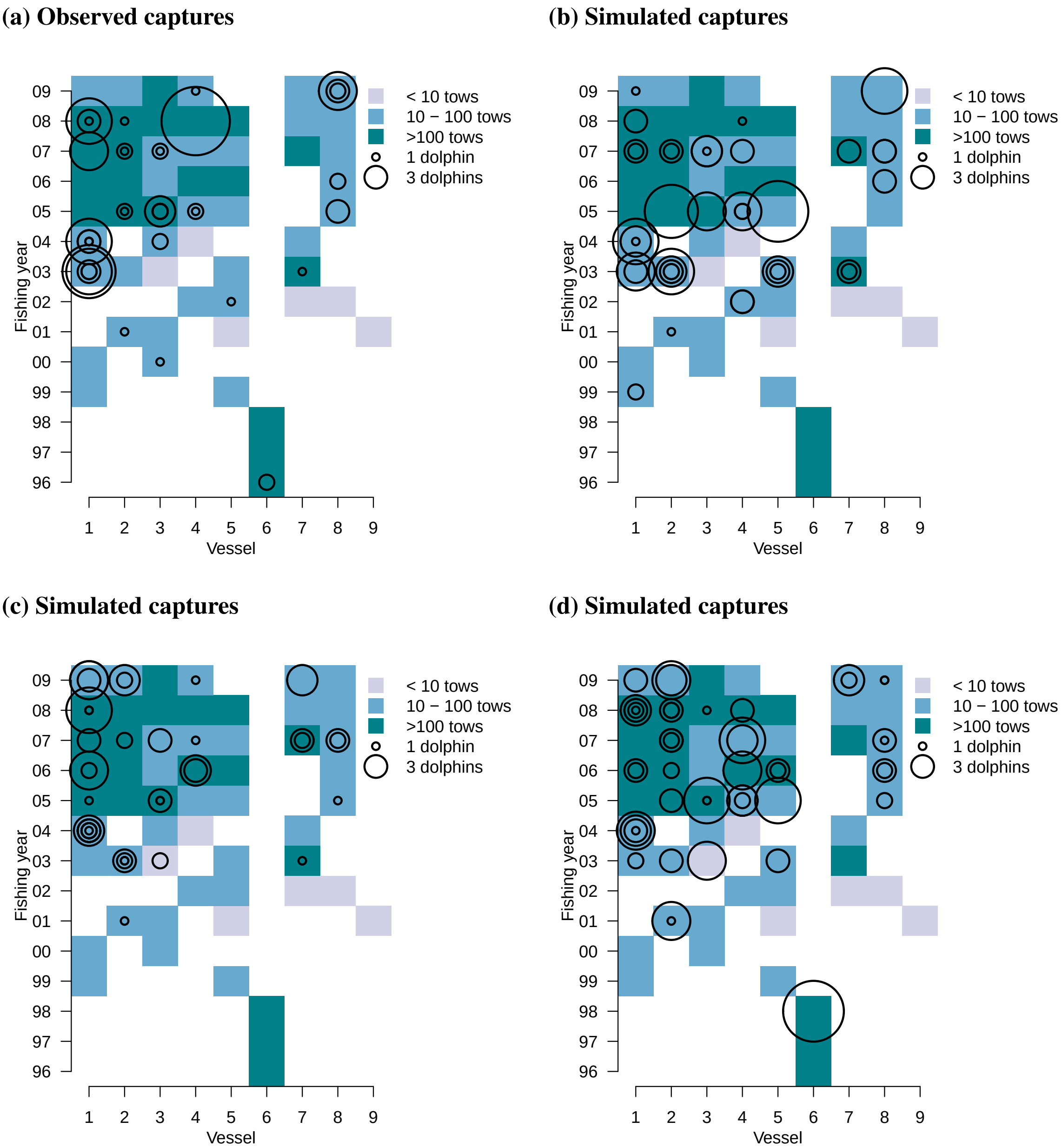

Figure 7: Observed and simulated capture events by fishing year and vessel. Figure (a) presents actual observed captures, and Figures (b, c, d) present samples of simulated capture events derived from the model. The observed effort is indicated with the colour.

Comparing three simulated capture datasets to the actual observed captures (organised by vessel and year) show the similarities between modelled and observed data (Figure 7). These simulations are made by sampling from the Markov chains, and then sampling 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.

4. DISCUSSION

Between 1995–96 and 2008–09, most observed captures of common dolphins in New Zealand waters were in the mackerel trawl fishery on the west coast of the North Island. All 108 captures in this fishery involved vessels over 90 m in length, with 15 vessels falling within this category. Nine of these large vessels had an observer on board at least once between 1 October 1995 and 30 September 2009. Total common dolphin captures in this large vessel mackerel fishery were estimated using statistical modelling, involving a two-stage hurdle model to predict the occurrence of any dolphin capture on a given tow, and the number of dolphin captures per tow, given that there were some captures. The model fitted the data well, providing plausible estimates when used to predict captures on observed tows.

Common dolphin captures occurred in most fishing years, and there was generally close agreement between observed and estimated capture rates. Over the 14-year period, observed capture rates ranged between 0.31 and 10.37, and estimated rates between 0.52 and 8.11 dolphins per 100 tows. Common dolphins are frequently caught in trawl fisheries worldwide (Fertl & Leatherwood 1997), but few studies include sufficient data to estimate capture rates for an entire region or fishery, or to examine temporal trends. As a consequence, previously reported capture rates are based on relatively short-term observer data (i.e., 1–2 fishing seasons or less than 3 fishing years), which were pooled over the entire study period to derive a single capture rate for the fishery. Common dolphin capture rates documented in other trawl fisheries are similar to the higher capture rates reported here. In pelagic trawl fisheries for hake (*Merluccius merluccius*) and sea bass (*Dicentrachus labrax*) in the northeastern Atlantic Ocean, observed capture rates were 7.69 and 10.00 common dolphins per 100 tows, respectively (Morizur et al. 1999); in the blue whiting (*Micromesistius poutassou*) pair trawl fishery in the eastern Atlantic Ocean, 8.37 common dolphins were captured per 100 tows (Fernández-Contreras et al. 2009). Capture rates in the Atlantic trawl fishery for large pelagic species (e.g., tuna and swordfish) were 6.0 common dolphins per 100 tows (Northridge 1996).

Markedly lower capture rates were estimated for the large vessel mackerel fishery before the 2000–01 fishing year (see Table 5). Since 2001–02, there has been an increase in fishing effort accompanied by an increase in the number of estimated dolphin captures, although there was some inter-annual variation in capture estimates. Capture rates were particularly high in 2002–03 and 2003–04 (8.11 and 4.42 captures per 100 tows; 95% c.i.: 3.20 to 17.30 and 1.99 to 8.97, respectively), immediately following the initial expansion of this fishery in 2001–02. The high observed capture rates in those years affected the random-year effect in the model, resulting in the high estimates. Capture rates have subsequently decreased; in the most recent fishing year, 2008–09, the capture rate was 2.11 common dolphins per 100 tows (95% c.i.: 1.10 to 4.38). The reasons for the decrease in common dolphin capture rates are unknown.

Possible reasons for the decrease in estimated captures include a decrease in the number of common dolphins in this fishing region. Capture rates are expected to vary from year to year if the dolphin distribution varies over the same period in relation to the fishery (Northridge 1996). Off the coast of California, common dolphins show changes in abundance owing to seasonal and inter-annual shifts in distribution (Forney & Barlow 2006). As there are no population data available for common dolphins in New Zealand waters (Stockin 2008), there are no abundance estimates for this region. As a consequence, it is impossible to establish whether lower estimated capture rates are related to fluctuations in common dolphin abundance at particular fishing locations.

In this context, it is worth noting that relatively high capture rates between 2002–03 and 2004–05 coincided with a shift of the mackerel fishery to the northern sub-area. Before the 2001–02 fishing year, most of the fishing effort was concentrated in the southern part of the region, and subsequently moved to the northern sub-area. Since 2005–06, fishing effort has been evenly divided between the two sub-areas. As the distribution of common dolphins is linked to the occurrence of prey (Neumann & Orams 2003),

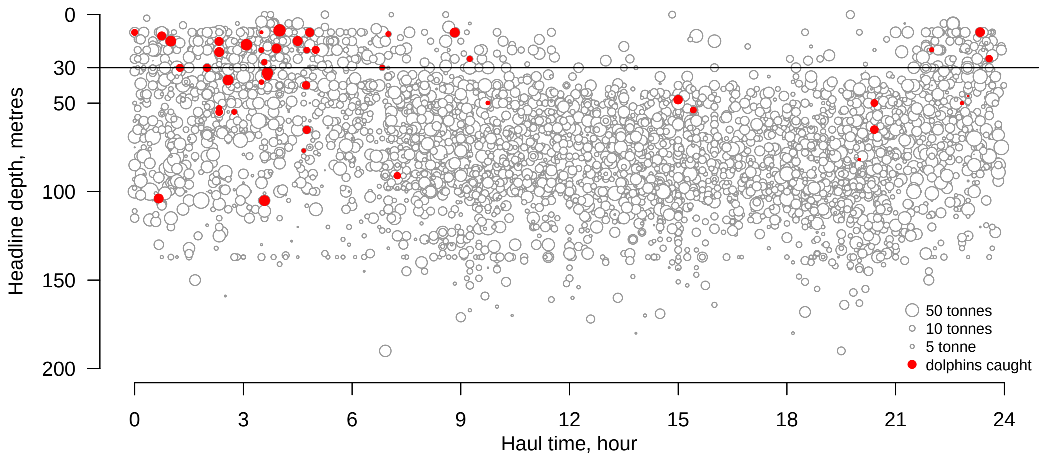

Figure 8: Headline depth versus the haul time for observed trawls in the large-vessel mackerel fishery. The catch weight is indicated by the size of the circles. Tows where an observed common dolphin capture event occurred are filled.

and jack mackerel are one of the main prey species (Neumann 2001a, Meynier et al. 2008), it is possible that the shift and prevalence in fishing effort in the northern sub-area overlapped with high local common dolphin abundance over this period.

Most of capture events involved groups of common dolphins, most frequently 2 to 3 individuals, with up to 9 individuals caught in a single tow. This finding is comparable to observations in other trawl fisheries, which frequently report multiple capture events for this dolphin species. Observer data from different trawl fisheries in the northeast Atlantic Ocean show common dolphin bycatch dominated by groups of 2–4 individuals (Morizur et al. 1999). Similarly, pair-trawlers off the Spanish coast mostly caught groups of 2–4 individuals, with 7 and 15 common dolphins involved in one-off multiple capture events (Fernández-Contreras et al. 2009). These data confirm that multiple capture events of common dolphins are prevalent in trawl fisheries. In the present study, detailed data analysis identified the role of four covariates – headline depth, light condition, sub-area, and trawl duration – in relation to common dolphin captures. The decrease in capture rates in recent fishing years was not associated with a systematic change in any of these covariates. Instead, their consistencies over recent fishing years would suggest an increase in the proportion of trawls with common dolphin captures, not a decrease.

Headline depth (the distance of the headline below the surface) was the covariate that best explained the occurrence of common dolphin captures. Other related quantities that were considered as covariates were bottom depth, ground-line depth, and the height of the net opening, but headline depth had the highest explanatory power. The model estimated that increasing headline depth on a tow by about 13 m would halve the probability of a common dolphin capture occurring. The strong influence of headline depth is also evident in the observer data (Figure 8). Fifty percent of observed capture events, and 54% of common dolphins captured in the large vessel mackerel fishery, occurred on the 10% of observed trawls that had a headline depth of less than 30 m.

Across all effort data, 68% of shallow tows (headline depth less than 30 m) occurred at night. This preference for shallow fishing appears to be related to the behaviour of mackerel. Diel vertical migrations of mackerel have been documented off the coast of Chile (Bertrand et al. 2004), where mackerel move to the surface during the night and form feeding aggregations. In contrast, they are deeper and more dispersed during the day. Fishing followed this diel movement and headline depth was typically shallower at night (Figure 8). A similar relationship between common dolphin captures and diurnal movement of prey has been suggested for squid fisheries in the Atlantic Ocean (Waring et al. 1990). The upward movement and concentration of squid at the surface seem to concentrate feeding dolphins in surface waters, resulting in the observed higher number of dolphins caught at night (2000–0400 h). In addition, if dolphins feed predominantly at night, the likelihood of dolphin captures during the day would be further decreased, as it would spatially separate them from squid during daylight hours (Waring et al. 1990). Apart from following the diurnal surface migration of prey, dolphins may also feed and scavenge around trawlers at night-time to reduce competition with other scavenging species such as seabirds (Morizur et al. 1999).

An increased catch of dolphins at night has also been noted in other pelagic trawl fisheries (Crespo et al. 1997, Morizur et al. 1999). Furthermore, light was identified as a factor associated with common dolphin captures in a previous analysis of the mackerel trawl fishery, although trawl depth was also implicated (Du Fresne et al. 2007). These studies, however, did not directly investigate the role of headline depth in relation to common dolphin captures, precluding direct comparisons with the findings here. Because of the correlation between headline depth and time of day, the light condition factor explained only a relatively small fraction (3.0%) of the residual deviance (see Table 3). Nevertheless, the model showed 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 capture rate 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 30 m or less, augmented 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 0400 h and 0500 h, one occurred on a tow when the net was hauled at 0850 h, and one occurred when the net was hauled at 2320 h. In 2008–09 there were four capture events, with headline depths of 27, 33, 48, and 65 m. Five dolphins were caught on the one tow less than 30 m. All but one of the capture events were hauled between 0300 h and 0500 h. Two dolphins were caught on a tow hauled at 1500 h.

Both the model and observer 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 New Zealand waters. In the 1990s, a measure was introduced by at 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 0200 and 0400 h by at least one fishing company (Baird 2008). Despite this code of practice, fishing is still being carried out between these hours. The analysis presented here supports using restrictions on fishing depth rather than on time of fishing as a method of reducing dolphin captures.

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