Incidental mortality of dolphins in the eastern Pacific Ocean purse-seine fishery: correlates and their spatial association

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ABSTRACT

A zero-inflated Poisson model was used to identify typical fishing practices that contributed to incidental mortality of dolphins in the eastern Pacific purse-seine fishery between 1993 and 2001. The presence of hazardous net conditions (net canopies and net collapses), the duration of the backdown procedure (the primary method of releasing dolphins from the net), the size and species composition of the encircled dolphin herd and the amount of tuna encircled, were all found to consistently contribute to increased dolphin mortality per set. In particular, the presence of net canopies and large biomass in the net contributed to both the development of problematic situations in which mortality could occur and to the mean mortality per set, once a problematic situation had developed. On the other hand, lengthy backdown procedures and the presence of net collapses contributed to the development of problematic situations, but had less effect on the mean mortality per set once a problematic situation had developed. Because some of these variables are partially correlated, the overall conclusion of this analysis is that one of the primary causes of dolphin mortality continues to be the encirclement of large herds. Dolphin mortality can increase with the number of dolphins encircled because: (1) the more animals encircled, the greater the likelihood of entanglement and mortality while confined in the net; and (2) the duration of the backdown procedure increases with the number of animals encircled. The duration of the backdown procedure may, in turn, contribute to increased dolphin mortality by: (1) keeping dolphins in close contact with the net for longer periods of time, thereby increasing the chances for entanglement; and (2) leading to the formation of net canopies. Dolphin mortality increases in the presence of net canopies because animals can be trapped below the sea surface in the areas of canopies. Spatial distributions of encircled herd size, duration of the backdown procedure, presence of net canopies and presence of dolphin mortality show similar patterns. Encircled herd size tended to be greatest south of the equator and north of the equator along the offshore margin of the fishery. In these areas, the duration of the backdown procedure tended to be longer and there was often an increased probability of net canopies and dolphin mortality, but also larger catches of tuna. These consistent spatial patterns suggest that reallocation of fishing effort to other areas may be an effective means of reducing the current level of dolphin mortality. Predictive models could be developed to assess tradeoffs between dolphin mortality and tuna catches at varying levels of fishing effort in areas where large herds are targeted by fishermen and different strategies for reallocation of fishing effort to other areas or to purse-seine sets on unassociated tunas.

KEYWORDS: DOLPHIN; INCIDENTAL CATCHES; FISHERIES; PACIFIC OCEAN; BYCATCH; MODELLING

INTRODUCTION

In the eastern Pacific Ocean (EPO), purse-seine fishermen use the association of tunas with dolphins as one means of locating and catching tunas (National Research Council, 1992). Yellowfin tuna (*Thunnus albacares*) is found in association with several species of dolphins in the EPO, primarily the spotted dolphin (*Stenella attenuata*), the spinner dolphin (*S. longirostris*) and to a lesser extent the common dolphin (*Delphinus delphis*) (Allen, 1985; Hall *et al*., 1999). Fishermen search for signs of dolphins at the sea surface such as splashes, associated birds or the mammals themselves. To catch the tuna, the fishermen chase and attempt to encircle the herd of dolphins with the purse-seine net. If the fishermen are successful, encircling some percentage of the dolphin herd will also result in capture of tuna. Once the bottom of the net has been pursed to prevent the tuna from escaping, fishermen attempt to release the dolphins before loading the fish. This is made possible because vertical stratification of the tuna and dolphins typically occurs within the net, with the dolphins being closest to the surface. Incidental mortality of dolphins can occur if they become entangled prior to release.

Efforts to reduce dolphin mortality have resulted in a decrease in incidental mortalities from an estimated hundreds of thousand of animals annually in the 1960s (Lo and Smith, 1986; Wade, 1995) to less than 5,000 animals per year since 1993 (IATTC, 2002). Mortality reduction has been approached from several angles. Modifications to fishing gear and adoption of release techniques since the late 1950s (National Research Council, 1992) have made significant gains toward eliminating dolphin mortalities. Perhaps the most important release technique developed, the 'backdown' procedure, allows fishermen to pull the net, once pursed, out from under the dolphins, which being air breathers, remain close to the surface. The backdown procedure forms the net into a channel and dolphins are able to swim out over the net at the end of the channel. Smaller mesh netting in the backdown channel (Medina Panel or dolphin safety panel) helps reduce entanglement. Rescue efforts by vessel crew, from rafts and as swimmers within the net, or from small boats outside the net, have also contributed to the reduction in mortality. During such rescue efforts, crewmembers attempt to free any entangled animals and guide them out of the net.

Analyses of data collected by fisheries observers onboard tuna vessels have also been undertaken as part of efforts to reduce the incidental mortality of dolphins. Previous studies have been conducted to explore the efficacy of gear modifications and rescue efforts in reducing mortality (e.g. Fox and Lenarz, 1975 and references therein; Everett *et al*., 1976; Powers *et al*., 1979; IATTC, 1984). Previous studies have also shown that mortality of dolphins per set varied with fishing parameters such as the catch of tunas, the species of dolphin and the size of the encircled herd, the area of the set, the time of the set (sets completed during the day versus sets completed in darkness), the duration of the backdown procedure and the presence of strong currents, gear malfunctions, net canopies (billows of netting formed along the sides of the net) and net collapses (collapses of the

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purse) (e.g. Fox and Lenarz, 1975 and references therein; Everett *et al.*, 1976; Powers *et al.*, 1979; IATTC, 1984; 1987; 1989). Insights gained from these analyses are still used in seminars to advise new captains of risky fishing conditions (IATTC, 2002). However, fishery parameters that affect dolphin mortality may not act independently or may be correlated (see below) and to our knowledge, recent analyses of relationships between dolphin mortality and fishery parameters have considered only one parameter at a time. Thus, there may be new information to be learned from application of multivariate approaches.

Over the last decade, the large reductions in mortality have been spurred by international agreements, yet corresponding analyses of fishery observer data that would provide insight on any changes in the relationships between mortality and fishery parameters have not kept pace. National legislation to establish fleet-specific incidental dolphin mortality limits has served to promote reductions in mortality since the early 1970s (Joseph, 1994; Hall, 1998; Gosliner, 1999). In 1993, an international agreement (Bayliff, 2001) established annual individual-vessel dolphin mortality quotas for the first time in this fishery. Following the implementation of these annual vessel limits, mortality per set has decreased to about one seventh the 1992 level (IATTC, 2002). With such a substantial reduction in mortality per set, it is of interest, especially from a management perspective, to determine which aspects of typical fishing conditions continue to lead to dolphin mortality. Generalised linear model (GLM) techniques are used to identify typical fishing practices and environmental conditions that contributed to dolphin mortalities over the 1993-2001 period. Spatial relationships between the most influential variables identified by the GLM analyses and dolphin mortality are summarised and areas for further study to reduce mortality are proposed.

DATA

Data collected by observers onboard tuna vessels of the international purse-seine fleet between 1993 and 2001 were used in this analysis. Sampling coverage by Inter-American Tropical Tuna Commission (IATTC) observers over this nine-year period was greater than 65% annually. Data collected by the national observer programme of Venezuela for 2000-2001 were also used. Only purse-seine sets targeting tunas associated with dolphins ('dolphin' sets) were considered. Dolphin sets for which data were not available on all the variables of interest (Table 1) were excluded prior to analysis.

In addition, some dolphin sets were excluded prior to analysis for a variety of reasons: (1) sets during which the visibility was less than two nautical miles – low visibility may interfere with the observer's ability to view the encirclement process; (2) sets during which fishing operations violated procedures prohibited under the Agreement on the International Dolphin Conservation Program (available at *www.iattc.org*), such as sets completed after sunset – the Agreement bans setting after sunset (Bayliff, 2001) and thus sets that occur during these conditions are likely the result of gear malfunctions that have severely hampered the normal fishing activities; (3) sets on species other than spotted dolphins, spinner dolphins and common dolphins, the three species typically found in association with tunas (Allen, 1985; Hall *et al.*, 1999); (4) sets where the observer's estimate of the number of dolphins encircled was zero – either the observer was not able to obtain a good estimate of the number of animals encircled or dolphin mortality was not an issue because no animals were in the pursed net (mortalities that are hypothesised to occur outside the period of observation of the dolphins by the observer (Archer *et al.*, 2001) were not considered); (5) repeat sets on the same herd – multiple sets can be made on the same herd of dolphins, if, for example, the fish escape capture during the first set; (6) sets for which speedboats were not used during the backdown procedure and, for the 1998-2001 period, sets for which no rescue swimmers were used during the backdown procedure – there were too few sets without speedboats and rescue swimmers during the backdown procedure in the database to create their own category and pooling with other categories seemed unwise.

Finally, one set in 2001 was excluded because of exceptionally high mortality. Preliminary analysis suggested that this set, which had a mortality almost 17 times the next largest mortality per set value in 2001, was very influential on model fit. This set was excluded because the goal of this analysis is to identify typical rather than unusual fishing operations that led to mortality.

After trimming the dataset, 3,173 to 4,557 dolphins sets were available annually for final analysis. On average, 54% of the mortality and 59% of the dolphin sets were retained annually.

The goal of this analysis was to identify typical fishing practices that continue to lead to dolphin mortality. Environmental conditions, operational problems, fishing operations, use of rescue equipment and biomass characteristics were considered in this analysis. These variables are discussed briefly below; a detailed description of each variable is presented in Table 1. Environmental variables that may hamper fishing operations include the presence of strong currents, the sea state and the weather (e.g. fog or rain). Season was also included as a factor to address environmental effects that were possibly missed. Habituation of animals to the fishery may affect their behaviour during fishing operations. Because the historical presence of the fishery has been greatest closest to the coast, the fishing grounds in the EPO were divided into three areas, based on the cumulative fishing effort from 1959 to 1992 (Fig. 1). Operational problems potentially contributing to mortality were modelled by including variables indicating the presence of gear malfunctions, net collapses, net canopies and the extent to which the dolphin safety panel covered the backdown channel. A net collapse refers to the condition when the sides of the net come into contact, reducing the size of the unobstructed volume within the pursed net. A net canopy refers to a billowing in the netting that forms along the sides of the net. The analysis also included an indicator of the level of the captain's skill at fishing for tuna associated with dolphins. Captains with more experience at setting on tuna associated with dolphins may handle gear malfunctions or adverse environmental conditions more effectively. The average number of dolphin sets made by captains in the previous three years was used as an indicator of the level of captain skill. The effects of temporal aspects of fishing operations on dolphin mortality were explored by including in the analysis the start time of the set and the durations of the various components of the setting process: the approach, the chase, the capture, the pre-backdown net retrieval and the backdown procedure. Variables indicating the use of equipment to rescue dolphins during the backdown procedure, such as speedboats and rafts and the deployment of swimmers and divers, were included to model the effects of rescue efforts on mortality. Finally, variables describing characteristics of the biomass in the net were also included: number and species of

Table 1

Variables considered in the analysis of mortality per set. The abbreviations used in Tables 2-4 are shown in parentheses. For continuous variables, the minimum, median and maximum, are shown (data pooled across years). For categorical variables, the number of levels is shown in parentheses.

Variable	Type	Units (or levels)
Environmental variability (E)		
Weather (WTH)	Categorical (3)	Fog, rain, haze.
Season (SSN)	Categorical (3)	January through April; May through August; September through December.
Strong currents (CUR)	Categorical (2)	Presence/absence.
Sea state (BEA)	Continuous	Beaufort scale (0;2;8).
Fishing area (FSH)	Categorical (3)	Historical fishing activity (number of dolphin sets, 1959-1992, all vessels sizes) (Fig. 1): (1) ≤ 3,000 sets; (2) 3,001-6,092 sets; (3) >6,092 sets. Estimates of numbers of dolphin sets are based on the sum of observer tallies of sets for sampled trips of the IATTC, and national observer programmes of the USA and Venezuela, and tallies from fishermen's logbooks for unsampled trips. This sum was adjusted upwards using tuna catch information to account for trips for which neither observed data nor logbook data were available.
Operational problems (O)		
Gear malfunctions (MLF)	Categorical (3)	No malfunctions, minor malfunctions and major malfunctions. Major malfunctions include: webbing wrapped on purse cable; failure of the vessel's main hydraulics; failure of the net skiff; winch failure; ripped purse-seine net; broken purse cable; fouled/broken bunch line or corkline; netting caught on vessel's stern. Minor malfunctions include: speed boat failure; failure of vessel's bow thrusters, main engine failure, power block failure; broken chain; broken skiff tow, broken vang cable; webbing in the rings; other. Major malfunctions directly affect the ability of captain and crew to manipulate the net and release marine mammals.
Net collapse (CLP)	Categorical (2)	Presence/absence. Net collapses occur when opposite sides of the purse-seine come together. Presence does not include intentional net collapse.
Net canopies (CNP)	Categorical (2)	Presence/absence. Net canopies are billows of webbing that form along the sides of the net.
Dolphin safety panel (SPC)	Categorical (2)	Presence/absence of adequate coverage of the backdown channel.
Captain skill (CPT)	Categorical (2)	Previous fishing activity (average number of dolphin sets per year for the previous three years, computed using a moving average): <30 dolphin sets per year; ≥30 dolphin sets per year. On average, about 30 dolphin sets were made per trip for those trips of fishermen fishing on tunas associated with dolphins.
Fishing operations (F)		
Start time of the set (TME)	Continuous	Local time of the release of the net skiff, 24-hour clock (05:45; 12:08; 18:46).
Duration (decimal hours) of:		
Approach (APR)	Continuous	Time between initial sighting and release of the first speed boat (0.02; 0.57; 7.58).
Chase (CHS)	Continuous	Time between the release of the first speed boat and release of the net skiff (0.02; 0.43; 5.73).
Capture time (ENC)	Continuous	Time between the release of the net skiff and the point at which the bottom of the net is pursed and the rings are above the water ('rings up') (0.02; 0.67; 4.47).
Net retrieval (RET)	Continuous	Pre-backdown net retrieval. Time between 'rings up' and the start of the backdown procedure (0; 0.57; 10.07).
Backdown (BCK)	Continuous	The backdown procedure (0; 0.2; 2.73).
Rescue equipment use during backdown (R)		
Speedboats (SPB)	Categorical (2)	Rescue, rescue with mask.
Rafts (RFT)	Categorical (3)	None, rescue with raft, rescue with raft and mask (either snorkeling or SCUBA).
Swimmers, divers (SWM)	Categorical (3)	None (only used for 1993-1997 because of sample size), swimmer with or without mask, SCUBA diver.
Biomass characteristics (B)		
Number of dolphins (DPH)	Continuous	Number of animals in the purse-seine net once the net has been pursed. Computed as the sum of the observer's individual estimates of the number of animals that were killed, injured, or unknown status, escaped over the net, released before backdown, released through the backdown procedure, released by hand during backdown, released after backdown, and released from the sack. When any of these estimates were unavailable, the observer's estimate of the number of animals in the net at the time it is pursed was used, if available. The former is preferable to the latter because it is typically based on the sum of smaller counts that the observer can edit as he feels necessary over the course of the set. On the other hand, the observer's estimate of the number of animals in the net at the time it was pursed is used for management purposes and must not be changed after the beginning of the backdown procedure. (1; 369; 5,000).
Dolphin species (SPP)	Categorical (3)	Species of dolphin encircled: spotted dolphins, spotted and spinner dolphins or spinner dolphins alone, common dolphins.
Tons of tuna (TUN)	Continuous	Metric tons of tuna in the purse-seine net once the net has been pursed. (0; 13.61; 300).
Herd cohesion (HCC)	Categorical (3)	Number of groups in the herd at the time of chase: all animals in one group; animals in several groups; animals in many groups.

dolphins encircled, the degree of cohesiveness of the herd at the time of chase (a possible indicator of behaviour prior to encirclement) and the amount of tunas encircled.

The total mortality of dolphins reported by the observer for each set was used for dolphin mortality per set. Although it is not known exactly when during the set that the mortality occurred, it is generally believed that most of the reported mortality occurs before the end of the backdown procedure. A rough annual estimate of the number of mortalities that occurred after the backdown procedure was computed as the sum of the number of animals reported to be alive in the net after the end of backdown less the sum of the number of animals reported to be released alive after the end of backdown (IATTC data). For six of the nine years, this difference was less than or equal to 5% of the total mortality.

Both the amount of tuna captured and the number of dolphins encircled were log transformed (natural logarithm) prior to analysis. This transformation linearised the relationship between tuna capture and the number of dolphins encircled. A value of 1.0 was added to the tuna capture prior to computing the transformation; tuna may escape during encirclement leaving only dolphins in the pursed net. On average, annually only 3% of the sets involved no catch of tunas.

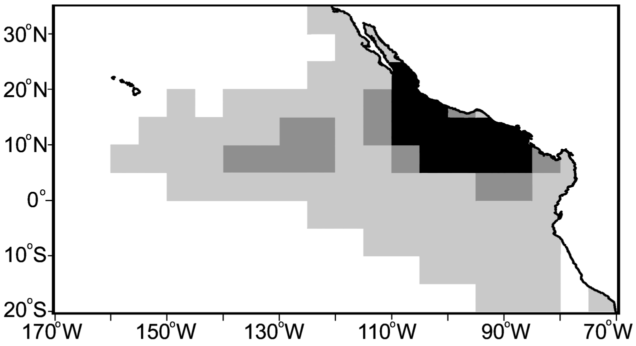

Fig. 1. Areas representing the different levels of historical fishing effort, based on the number of dolphin sets during 1959-1992. Light grey: =3,000 sets; dark grey: 3,001 to 6,092 sets; black: >6,092 sets.

METHODS OF ANALYSIS

Few dolphin sets presently result in mortalities (Fig. 2). A preliminary analysis of these data was done using log-linear models (e.g. McCullagh and Nelder, 1989). However, the data were found to be over-dispersed with respect to the Poisson model. In particular, results of a score test for extra zeros (van den Broek, 1995) suggested that the data contained more zeros than would be expected under the Poisson model. To address this issue, a final analysis of these data was undertaken using a zero-inflated Poisson model (ZIP; Lambert, 1992; Hall, 2000) which accommodated the excess zeros (Fig. 3). Alternative models explored for these data included the delta-gamma model (e.g. Stefánsson, 1996) and the negative binomial model (e.g. McCullagh and Nelder, 1989). The delta-gamma model was ultimately not used to avoid inconsistent parameter estimates resulting from improper specification of the conditional distribution of positive mortalities (Grogger and Carson, 1991; proper specification requires the use of a truncated distribution). As measured by Akaike's Information Criterion (Akaike, 1974; Burnham and Anderson, 1998), both the negative binomial model and the ZIP model were superior to a simple Poisson model, with the negative binomial model out-performing the ZIP model. However, there was some evidence of lack of fit of both negative binomial and ZIP models to the positive counts; the ZIP model was selected over the negative binomial because we believe a zero-inflated model to be more consistent with the process that generated the data. The fitted negative binomial models accommodated the excess zeros by way of large variances for mortality per set, $\mu + \hat{\alpha}\mu^2$, 2.6 $\hat{\alpha} \leq 4.6$, μ the mean mortality per set. On the other hand, we believe that the large proportion of zeros in the data arise from efforts on the part of fishermen to avoid dolphin mortality throughout the set, not from large between-set variability in mortality rates of an otherwise unmodified Poisson process. The observed information matrices from ZIP models fitted with all variables were nonsingular for each year, suggesting that the ZIP model should be estimable for these data (Lambert, 1992).

The ZIP model (Lambert, 1992; Hall, 2000) for dolphin mortality Y in the i^{th} set is given by:

$$Y_i \sim \begin{cases} 0 & \text{probability } p_i \quad \text{('zero-mortality' state)} \\ \text{Poisson } (\lambda_i) & \text{with probability } (1\text{-}p_i) \quad \text{('Poisson' state)} \end{cases}$$

The vectors of parameters p and λ are related to matrices of covariates G and B through canonical GLM relationships (McCullagh and Nelder, 1989): a logistic regression model for the probability of being in the zero-mortality state, logit(p)=Gγ and a log-linear model for the mean mortality per set in the Poisson state, log(λ) = Bβ. No parameters are assumed shared between these two parts of the ZIP model. The covariates are taken to be known without error because of a lack of data with which to do otherwise. Since it is unknown which zero-mortality sets belong to the zero-mortality state and which belong to the Poisson state, this model is fitted iteratively using an EM algorithm (Hall, 2000), where the missing data are indicator variables Z_i: $Z_i = 1$ if the i^{th} set belongs to the zero-mortality state and $Z_i = 0$ if it belongs to the Poisson state. The expectation step of the EM algorithm is the estimation of Z by its conditional mean, given the current estimates of (γ, β). The maximisation step of the EM algorithm involves two parts, one which equates to using logistic regression to update γ and one which equates to using a weighted log-linear Poisson regression to update β. To avoid model misspecification due to changes in the fishery over the nine-year period, the data for each of the nine years were analysed separately.

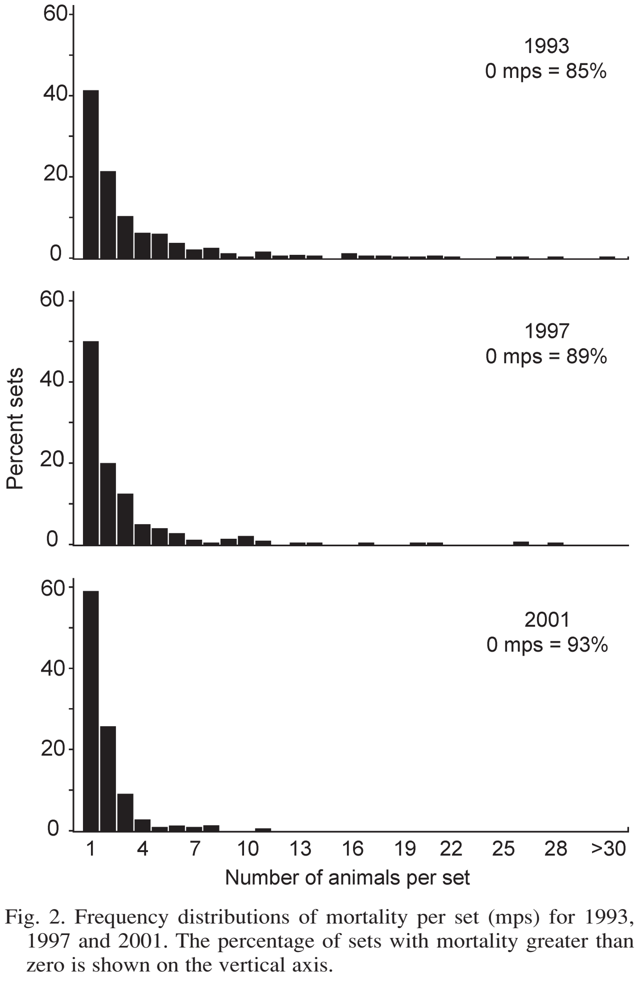

Fig. 2. Frequency distributions of mortality per set (mps) for 1993, 1997 and 2001. The percentage of sets with mortality greater than zero is shown on the vertical axis.

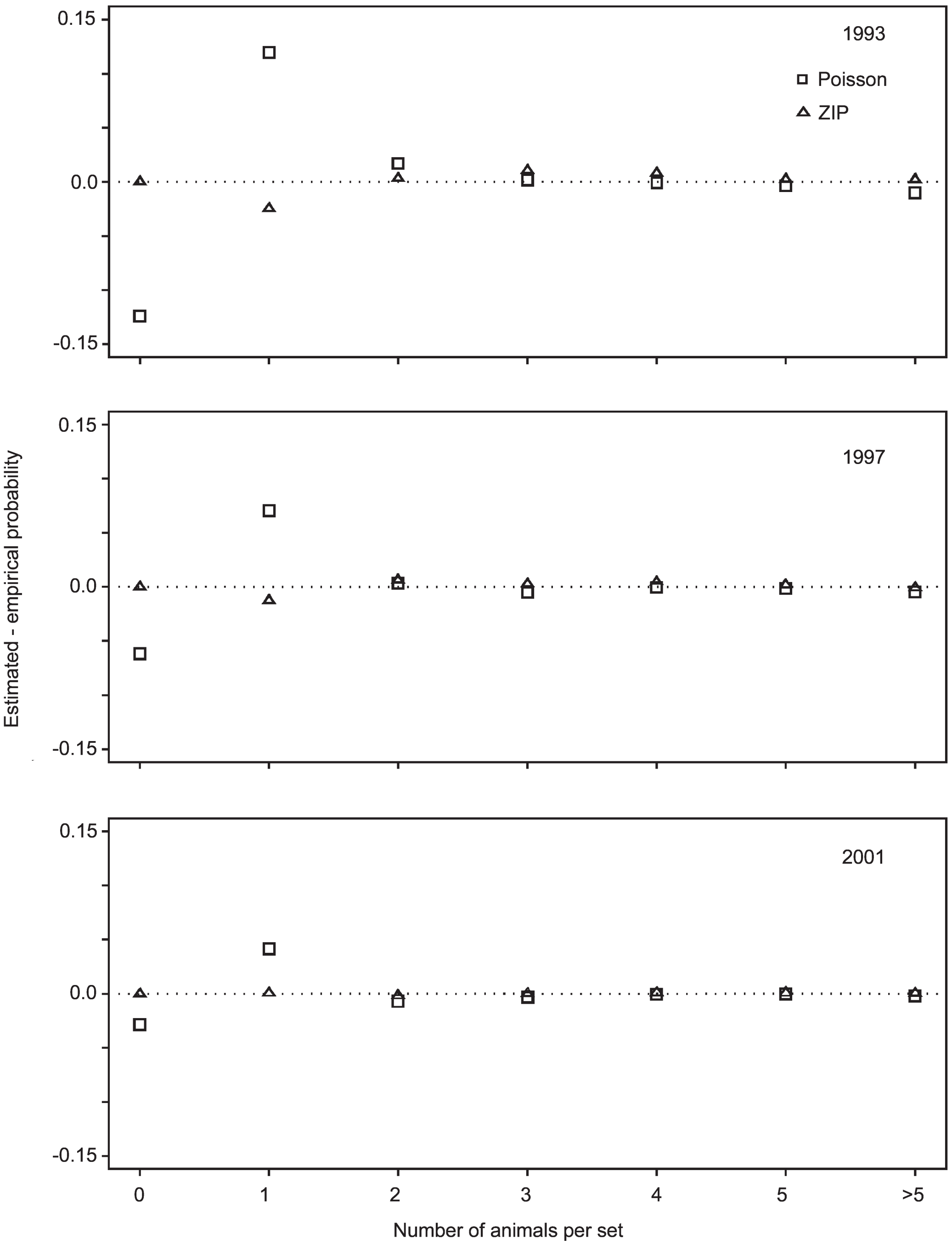

Fig. 3. Difference between estimated and empirical probabilities of mortality for 1993, 1997 and 2001. Empirical probabilities were computed as the sum of the number of sets with a specific mortality value, divided by the total number of sets. Estimated probabilities were based on Poisson and ZIP models fitted to the data using all variables (Table 1).

Given the data, it was of interest to determine if any variables in Table 1 could be identified as consistently contributing to dolphin mortality. Thus, the ZIP model was used as a variable screening/selection technique, not to develop the optimal predictive model for mortality per set. It is likely that only a subset of those variables listed in Table 1 strongly influence dolphin mortality and some may have no effect at all. Some of the variables shown in Table 1 are correlated (Table 2). The influence of certain variables on dolphin mortality may depend on other variables present in the model. In addition, because of the opportunistic nature of the data collection, confounding is also an issue. For example, the offshore area of the fishery with low levels of fishing effort (Fig. 1) tends to be the area fished predominantly in the summer months (Hall *et al*., 1999), likely producing the apparent relationship between fishing area (E-FSH) and season (E-SSN) (Table 2). Stepwise model selection over all variables (main effects and two-variable interactions) was thus used to select an influential subset of the variables shown in Table 1. The 'null' model, a model that includes only an overall constant, was taken as the starting model. At each step, the model retained was that which best fit the data, where fit was measured by the model deviance plus twice the number of parameters (Akaike's Information Criterion as defined by Hastie, 1987; AIC_H). The deviance (McCullagh and Nelder, 1989) is a log-likelihood measure of the discrepancy between the data and the model. AIC_H was used as opposed to the classic AIC (Akaike, 1974) because this measure of fit was automatically supplied by the statistical software used to

Table 2

An illustration of relationships between predictor variables (Table 1), based on data for 1994. Shown are: (A) sample correlations between pairs of continuous variables; (B) p-values from a chi-square test of independence (Rice, 1988), applied pairwise to categorical variables; and (C) p-values from a chi-square test of independence applied pairwise to categorical and continuous variables, where continuous variables were discretized into values of zero (≤median) and one (>median). In (B) and (C), categorical variables with more than two levels were reduced to presence-absence by taking the first level as 'absence' and the other levels together as 'presence'. A value of 0.00 in (B) and (C) indicates a p-value <0.01.

(A)

	E-BEA	F-TME	F-APR	F-CHS	F-ENC	F-RET	F-BCK	B-DPH
F-TME	0.07							
F-APR	0.01	0.16						
F-CHS	-0.02	0.09	0.06					
F-ENC	-0.03	-0.04	0.04	0.10				
F-RET	0.05	-0.04	-0.01	-0.01	0.12			
F-BCK	-0.01	0.02	0.01	-0.04	-0.01	0.01		
B-DPH	0.07	0.07	0.13	0.11	-0.01	-0.03	0.28	
B-TUN	0.02	0.05	0.18	0.04	0.07	-0.01	0.11	0.45

(B)

	E-WTH	E-SSN	E-CUR	E-FSH	O-MLF	O-CLP	O-CNP	O-SPC	O-CPT	R-SPB	R-RFT	R-SWM	B-SPP
E-SSN	0.02												
E-CUR	0.00	0.52											
E-FSH	0.94	0.00	0.00										
O-MLF	0.05	0.00	0.00	0.23									
O-CLP	0.01	0.35	0.00	0.61	0.00								
O-CNP	0.88	0.02	0.00	0.00	0.00	0.05							
O-SPC	0.00	0.24	0.00	0.18	0.00	0.60	0.44						
O-CPT	0.05	0.00	0.42	0.00	0.20	0.07	0.94	0.00					
R-SPB	0.06	0.10	0.00	0.00	0.00	0.31	0.13	0.00	0.00				
R-RFT	0.08	0.00	0.00	0.59	0.08	0.00	0.02	0.00	0.23	0.00			
R-SWM	0.07	0.00	0.92	0.00	0.26	0.08	0.08	0.01	0.00	0.00	0.28		
B-SPP	0.08	0.00	0.01	0.00	0.26	0.99	0.00	0.00	0.16	0.39	0.00	0.00	
B-HCC	0.30	0.26	0.20	0.00	0.95	0.46	0.17	0.99	0.23	0.02	0.08	0.03	0.40

(C)

	E-BEA	F-TME	F-APR	F-CHS	F-ENC	F-RET	F-BCK	B-DPH	B-TUN
E-WTH	0.00	0.54	0.39	0.08	0.96	0.56	0.11	0.32	0.10
E-SSN	0.00	0.90	0.00	0.07	0.00	0.90	0.01	0.01	0.00
E-CUR	0.00	0.86	0.49	0.46	0.00	0.00	0.00	0.99	0.94
E-FSH	0.00	0.00	0.10	0.14	0.00	0.00	0.00	0.00	0.00
O-MLF	0.00	0.44	0.55	0.24	0.00	0.00	0.33	0.92	0.24
O-CLP	0.09	0.46	0.01	0.35	0.67	0.24	0.00	0.07	0.07
O-CNP	0.12	0.68	0.78	0.59	0.19	0.53	0.00	0.00	0.00
O-SPC	0.76	0.95	0.00	0.00	0.00	0.09	0.00	0.00	0.00
O-CPT	0.00	0.56	0.00	0.84	0.04	0.75	0.10	0.00	0.00
R-SPB	0.20	0.37	0.60	0.37	0.00	0.36	0.40	0.16	0.89
R-RFT	0.00	0.75	0.75	0.00	0.47	0.00	0.00	0.22	0.37
R-SWM	0.00	0.41	0.00	0.00	0.02	0.00	0.00	0.00	0.00
B-SPP	0.01	0.62	0.00	0.49	0.07	0.32	0.00	0.00	0.00
B-HCC	0.52	0.12	0.07	0.00	0.86	0.00	0.22	0.97	0.12

perform the stepwise analysis. Both forward and backward stepping were allowed. Preliminary analyses showed that the most substantial reductions in AIC_H occurred within the first few steps and that reductions in AIC_H thereafter were relatively small (see also Results below). Given the goal of this analysis, the number of steps was limited to 20 to ease the computational burden of both stepwise selection and the EM algorithm. The change in deviance between the null model and the model reached after 20 steps is presented as a rough indicator of model utility.

A stability analysis was performed to determine sensitivity of the fitted ZIP models to unusual observations and relationships amongst predictor variables. The stability analysis borrows conceptually from a technique referred to as bootstrap aggregation (Breiman, 2001 and references therein), but without the final model averaging. The stability analysis was performed by fitting a ZIP model to each of 50 bootstrap samples of the data (drawn with replacement), for each year. Given the results of the stepwise procedure applied to the original data (see below), the stepwise selection for the bootstrap data was limited to seven steps. In each year, the percentage of times each variable was selected within the first seven steps of the 50 fitted models was tabulated. Similarity among the dominant variables selected in the resampling procedure and those of the original fitted model is an indication of model stability.

RESULTS

Changes in the AIC_H statistic versus iteration of the stepwise fitting procedures showed large initial decreases in the first two to three steps, followed by a long series of steps during which other variables and two-variable interactions were added with relatively small improvements (Fig. 4, Table 3). The average reduction in deviance after 20 steps was 32% for the logistic models and 51% for the log-linear models

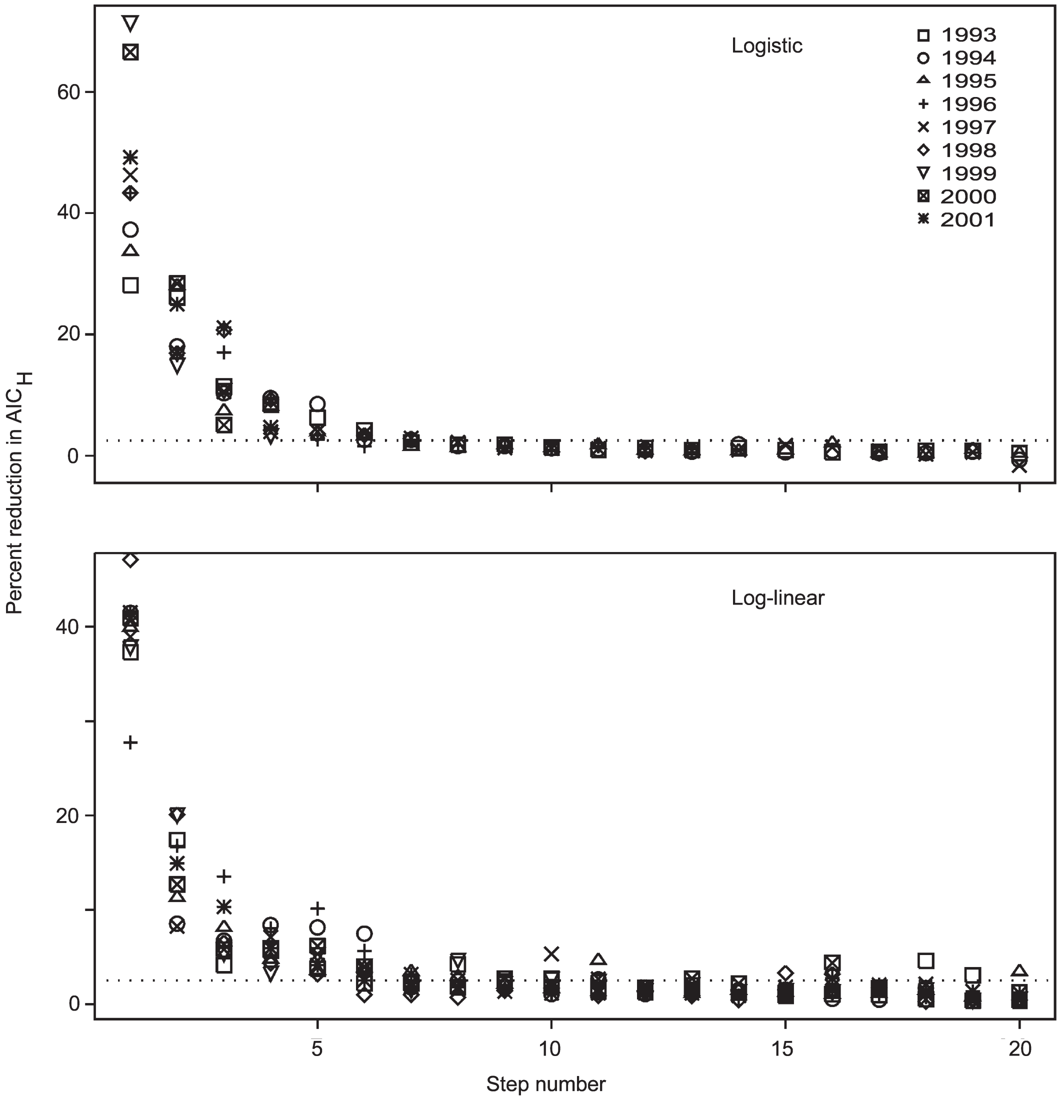

Fig. 4. Percent reduction in AIC_H between sequential steps in the stepwise fitting procedure for the logistic model of the probability of being in the zero-mortality state (upper panel) and the log-linear model of the mean mortality in the Poisson state (lower panel). The percent reduction in AIC_H was computed as the difference in AIC_H between sequential steps, divided by the total reduction in AIC_H achieved over the 20 steps. Different plot symbols represent the different years. Dashed horizontal lines indicate 2.5%.

(Table 3). Once entered, variables were rarely removed. Variables selected across the nine years for the logistic models were largely the same as those selected for the log-linear models. The most notable exception to this, fishing area (E-FSH), appeared in log-linear models in five of the nine years, but in none of the nine years for the logistic model. For both models, when interaction terms were present, they were not consistently the same terms from year to year and most interaction terms appeared in only one to two years, even though some of the variables themselves appeared in more than half the years (e.g. presence of net canopies, F-CNP). Beyond about seven to 10 steps, the relative reduction in the AIC_H levelled off and was typically less 2.5% (Fig. 4) and, thus, in what follows the focus is on the variables that entered within the first seven steps.

Based on fitting the logistic model, it was found that the probability of being in the zero-mortality state decreased in the presence of hazardous net conditions, increasing time animals remained in close contact with the net and characteristics of the biomass in the net, but increased with captain experience (Table 3; Fig. 5). The probability of being in the zero-mortality state was found to decrease consistently with the occurrence of net canopies (O-CNP) in nine of nine years, net collapses (O-CLP) in six of nine years, the duration of the backdown procedure (F-BCK) in eight of nine years, the amount of tuna in the net (B-TUN) in five of nine years and the species of dolphin encircled (B-SPP) in six of the nine years. On the other hand, the probability of being in the zero-mortality state was found to increase consistently with the level of captain experience at fishing on tunas associated with dolphins (O-CPT) in four out of nine years. The probability of being in the zero-mortality state also increased with the use of rescue swimmers and SCUBA divers during the backdown procedure (R-SWM) in three out of the five years where adequate data were available on swimmer/diver use (1993-1997; Table 1), primarily due to the effect of SCUBA divers. Differences between the use of swimmers versus SCUBA divers was not found to strongly influence dolphin mortality in later years (Table 3).

Based on fitting the log-linear model, mean mortality in the Poisson state was found to increase in the presence of hazardous net conditions, gear malfunctions and the characteristics of biomass in the net, but decrease with

Table 3

Variables selected, and their order of selection, in the stepwise procedure for the logistic model of the probability of being in the zero-mortality state (A), and the log-linear model of the mean mortality in the Poisson state (B). Abbreviations are defined in Table 1. Two abbreviations, separated by a colon, indicate an interaction term. Sample size (number of dolphin sets) is shown in parentheses at the top of each column (sample sizes are the same for both models). At the bottom of each column in parentheses is the reduction in deviance (null deviance less residual deviance), associated degrees of freedom, and the percent reduction in deviance (relative to the null deviance). Dashed horizontal lines indicate that no further iterations were taken in the stepwise selection procedure. Abbreviations shown in italics indicate variables (or interactions) that were removed.

	1993 (3,173)	1994 (3,724)	1995 (3,647)	1996 (3,336)	1997 (3,777)	1998 (4,557)	1999 (3,465)	2000 (3,806)	2001 (3,878)
(A)									
(1)	O-CNP	F-BCK	O-CNP	F-BCK	F-BCK	F-BCK	F-BCK	F-BCK	F-BCK
(2)	B-SPP	B-SPP	B-DPH	O-CLP	O-CNP	O-CNP	O-CNP	O-CNP	O-CNP
(3)	F-BCK	O-CNP	O-CLP	R-SWM	B-DPH	B-DPH	B-TUN	B-TUN	B-SPP
(4)	B-TUN	O-CLP	B-SPP	O-MLF	O-CLP	O-CLP	B-SPP	----	F-BCK:O-CNP
(5)	O-CLP	B-TUN	F-BCK	B-TUN	B-SPP	O-CPT	----	----	----
(6)	O-CPT	F-BCK:O-CLP	R-RFT	O-CNP	O-CPT	B-TUN	----	----	----
(7)	R-SWM	R-SWM	O-CPT	F-BCK:O-CNP	R-RFT	B-TUN:F-BCK	----	----	----
(8)	O-MLF	O-CNP:R-SWM	F-RET	F-CHS	B-TUN	----	----	----	----
(9)	O-CLP:O-CPT	B-TUN:R-SWM	O-CLP:R-RFT	R-SPB	E-SSN	----	----	----	----
(10)	O-SPC	F-BCK:R-SWM	E:CUR	F-RET	R-SPB	----	----	----	----
(11)	F-BCK:O-CLP	B-TUN:O-CLP	B-DPH:E-CUR	B-TUN:F-RET	B-SPP:O-CLP	----	----	----	----
(12)	B-SPP:O-SPC	B-SPP:F-BCK	F-APR	B-TUN:F-BCK	B-DPH:F-BCK	----	----	----	----
(13)	E-CUR	R-SPB	O-CLP:O-CNP	F-RET:O-CNP	O-CNP:B-SPP	----	----	----	----
(14)	E-CUR:O-SPC	R-SPB:R-SWM	E-CUR:O-CNP	----	O-SPC	----	----	----	----
(15)	B-TUN:F-BCK	E-BEA	E-WTH	----	O-SPC:R-SPB	----	----	----	----
(16)	F-BCK:O-CNP	B-TUN:E-BEA	F-RET:R-RFT	----	O-SPC:R-RFT	----	----	----	----
(17)	E-CUR:R-SWM	B-TUN:R-SPB	E-WTH:O-CLP	----	B-DPH:O-CNP	----	----	----	----
(18)	F-CHS	B-SPP:O-CLP	F-TME	----	F-BCK:O-CNP	----	----	----	----
(19)	B-SPP:F-CHS	B-SPP:O-CNP	E-CUR:F-TME	----	B-TUN:F-BCK	----	----	----	----
(20)	R-RFT	*B-SPP:O-CNP*	F-BCK:O-CLP	----	*B-SPP:O-CLP*	----	----	----	----
	(787, 25; 33%)	(799, 28; 32%)	(819, 24; 36%)	(741, 15; 43%)	(822, 25; 38%)	(718, 7; 40%)	(320, 5; 28%)	(344, 3; 26%)	(138, 5; 13%)
(B)									
(1)	O-CNP	O-CNP	O-CNP	O-CNP	O-CNP	O-CNP	O-CNP	O-CNP	F-BCK
(2)	B-DPH	F-BCK	F-BCK	B-SPP	E-BEA	B-SPP	B-DPH	B-DPH	O-CNP
(3)	O-MLF	F-ENC	B-TUN	O-MLF	O-CPT	B-SPP:O-CNP	E-FSH	O-MLF	B-TUN
(4)	R-RFT	B-DPH	O-CPT	O-CPT	B-DPH	B-TUN	B-SPP	E-WTH	B-SPP
(5)	B-DPH:O-MLF	B-DPH:O-CNP	B-SPP	B-DPH	O-MLF	E-FSH	B-SPP:O-CNP	E-WTH:O-CNP	E-SSN
(6)	E-BEA	B-HCC	B-SPP:F-BCK	B-DPH:O-MLF	E-SSN	F-APR	B-DPH:E-FSH	E-CUR	E-CUR
(7)	O-SPC	F-RET	E-CUR	R-SWM	E-BEA:E-SSN	F-APR:O-CNP	F-RET	O-CPT	O-SPC
(8)	E-BEA:O-SPC	F-BCK:F-RET	E-CUR:O-CNP	B-HCC	B-TUN	F-BCK	E-FSH:F-RET	B-SPP	B-DPH
(9)	B-DPH:E-BEA	B-DPH:B-HCC	B-SPP:B-TUN	O-CNP:O-MLF	B-SPP	B-SPP:B-TUN	F-ENC	R-RFT	B-DPH:O-CNP
(10)	E-BEA:O-MLF	R-SWM	E-WTH	B-HCC:O-CPT	B-SPP:E-SSN	B-TUN:F-BCK	E-CUR	B-SPP:O-CNP	O-CPT
(11)	O-CNP:O-SPC	B-DPH:R-SWM	E-CUR:E-WTH	B-SPP:O-MLF	B-TUN:O-CNP	R-SPB	E-CUR:O-CNP	O-CNP:R-RFT	B-SPP:E-CUR
(12)	E-BEA:R-RFT	B-SPP	F-BEA	B-TUN	O-CPT:O-MLF	F-APR:R-SPB	O-CLP	B-HCC	E-SSN:O-SPC
(13)	O-MLF:O-SPC	B-SPP:O-CNP	F-RET	E-BEA	E-SSN:O-CPT	O-CNP:R-SPB	E-WTH	B-HCC:E-CUR	B-DPH:B-SPP
(14)	B-DPH:O-CNP	B-DPH:B-SPP	E-FSH	B-DPH:B-HCC	B-DPH:O-CPT	E-SSN	E-CUR:E-WTH	B-HCC:E-WTH	B-DPH:O-CPT
(15)	O-SPC:R-RFT	B-SPP:B-HCC	B-SPP:F-RET	B-DPH:O-CPT	B-DPH:B-TUN	B-TUN:E-SSN	E-SSN	R-SPB	F-ENC
(16)	F-TME	F-BCK:O-CNP	B-SPP:E-CUR	B-SPP:R-SWM	E-FSH	B-SPP:E-SSN	B-SPP:E-SSN	E-CUR:O-SPB	E-CUR:F-ENC
(17)	E-FSH	R-RFT	B-TUN:F-BCK	O-CPT:R-SWM	B-DPH:B-SPP	B-TUN:F-APR	E-FSH:E-SSN	B-SPP:R-SPB	F-BCK:F-ENC
(18)	E-FSH:O-MLF	B-HCC:R-RFT	E-FSH:O-CPT	B-SPP:B-DPH	B-TUN:O-MLF	F-BCK:O-CNP	F-RET:O-CLP	E-CUR:R-RFT	O-CLP
(19)	E-FSH:O-SPC	O-CNP:R-RFT	B-HCC	B-DPH:O-CNP	E-BEA:O-CPT	E-SSN:F-BCK	F-BCK	E-CUR:O-CNP	B-SPP:F-ENC
(20)	E-SSN	F-RET:R-RFT	B-HCC:O-CPT	B-HCC:O-MLF	B-DPH:E-SSN	E-CUR	F-BCK:O-CNP	O-CLP	F-BCK:O-CNP
	(1,114, 37; 46%)	(1,288, 36; 49%)	(1,752, 29; 57%)	(2,320, 46; 70%)	(852, 33; 48%)	(752, 30; 44%)	(871, 33; 52%)	(840, 31; 54%)	(490, 27; 42%)

captain experience (Table 3; Fig. 5). The mean mortality in the Poisson state increased consistently with the presence of net canopies (O-CNP) in nine of nine years, the number of dolphins encircled (B-DPH) in four to six of the nine years, depending on interactions, and the species of dolphins encircled (B-SPP) in five of the nine years. The mean mortality in the Poisson state was found to vary with the presence of gear malfunctions (O-MLF) in four of nine years, but the direction of the effect was not consistent. In two of the four years, malfunctions sometimes led to increased mortality through interactions with encircled herd size (B-DPH:O-MLF). The mean mortality in the Poisson state set decreased consistently with the level of captain experience at setting on tunas associated with dolphins (O-CPT) in four of the nine years.

Neither the probability of being in the zero-mortality state nor the mean mortality in the Poisson state were found consistently to vary strongly with the duration of phases of the set other than that of the backdown procedure (F-BCK), or with environmental conditions (Table 3). The time of the set (F-TME) and the duration of the approach (F-APR), chase (F-CHS), encirclement (F-ENC) and pre-backdown net retrieval (F-RET) were only identified as strongly influencing dolphin mortality in one-two of the nine years. Similarly, the weather (E-WTH), season (E-SSN), sea state (E-BEA) and the area of the set (E-FSH), were only identified as strongly influencing dolphin mortality in one-two of the nine years and the presence of strong currents (E-CUR) in one-three of the nine years.

Although not included expressly in the list of variables, the duration of the set (from the initial sighting to the end of the backdown procedure) was not found to have a strong influence on dolphin mortality per set. No more than three duration variables entered into any one model within the first 20 steps (Table 3). In addition, fitted models that included all variables, without interaction terms, never yielded coefficients for the durations of the various phases of the setting process that were consistently of the same

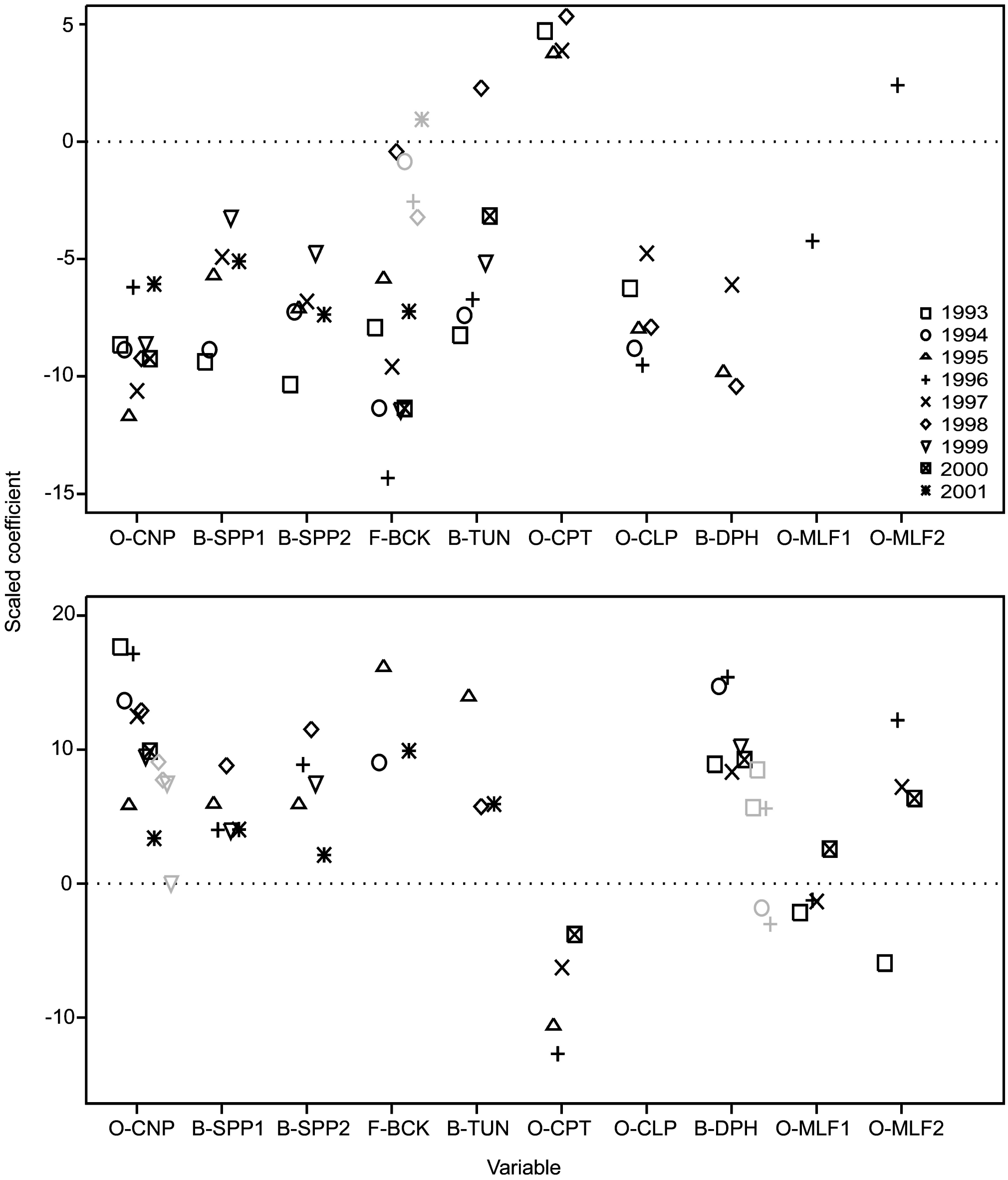

Fig. 5. Estimated coefficients for individual variables, divided by their standard errors, from logistic models of the probability of being in the zero-mortality state (top panel) and log-linear models of the mean mortality in the Poisson state (bottom panel). Models were based on the terms selected within the first seven steps of the stepwise fitting procedure (Table 3). Coefficients adjusted for interaction terms are shown in grey. Interaction terms between continuous and categorical variables are shown as a modified coefficient for the continuous variable.

sign, suggesting that the duration of the entire setting process is likely of secondary importance as compared to the duration of the backdown procedure (F-BCK) (Table 3). A principal components analysis (Seber, 1984) did not yield any reasonable simplification of the description of the setting process, with at most 26% of the variability in durations explained by the first principal component.

Results of the stability analysis (Table 4) support the importance of those variables selected repeatedly within the first several steps of the original models. Most of the variables frequently selected in the logistic models within the first several steps were selected in the stability analysis with high frequency. In particular, net canopies (O-CNP) and the duration of the backdown procedure (F-BCK) were selected in at least 88% of the models fitted to the bootstrap samples in each year. The species of dolphins encircled (B-SPP), the tons of tuna captured (B-TUN) and net collapses (O-CLP) were also frequently selected in six of nine years. Present to a lesser extent in multiple years were the size of the encircled herd (B-DPH), the level of captain experience (O-CPT) and the use of rescue swimmers and divers (R-SWM). The presence of other terms in the models fitted to the bootstrap data sets in 1999-2001 as compared to the original fitted models (Table 3) suggests decreased model stability in those years. Variables selected repeatedly within the first seven steps of the log-linear original models (Table 3) also tended to be selected consistently in the stability analysis. Net canopies (O-CNP) was selected in at least 96% of the models fitted to the bootstrap samples in each year. The species of dolphin (B-SPP) and size of the encircled herd (B-DPH) were selected with high probability in four to five of the nine years. In addition, the effect of correlation between the encircled herd size (B-DPH) and the tuna captured (B-TUN) can be seen, particularly in the results of for the log-linear models (Table 4B). Either the encircled herd size was a dominant term or encircled herd size and tuna captured were selected with relatively similar frequency.

DISCUSSION

This analysis has attempted to identify the variables consistently contributing to increased dolphin mortality between 1993-2001. Results of fitting a ZIP model to

Table 4

Results of the stability analysis. Shown is the percentage of models fitted to bootstrap samples that contained each variable (or interaction) for: (A) the logistic model of the probability of being in the zero-mortality state, and (B) the log-linear of the mean mortality in the Poisson state. Only those variables found in over 20% of the models in at least two years are shown.

	1993	1994	1995	1996	1997	1998	1999	2000	2001
(A)									
O-CNP	100	100	100	90	100	96	100	100	94
O-CLP	96	100	88	100	86	84	54	4	44
F-BCK	100	100	88	100	100	88	96	98	96
B-SPP	100	100	98	66	62	46	86	70	36
B-TUN	88	86	51	68	40	76	48	44	26
B-DPH	0	0	55	12	34	46	26	2	34
O-CPT	62	2	51	4	52	44	0	20	14
R-SWM	40	32	8	88	20	12	0	0	0
E-CUR	8	0	6	0	0	0	42	36	24
R-RFT	8	2	20	2	22	0	0	0	16
F-RET	0	6	24	18	2	2	14	28	0
O-MLF	6	16	2	40	4	0	8	22	2
O-SPC	10	0	0	0	18	2	28	4	26
F-BCK:O-CNP	4	0	6	18	48	14	8	6	72
F-BCK:O-CLP	26	56	8	0	0	10	10	2	4
B-SPP:O-CNP	6	2	10	8	12	22	10	48	16
B-SPP:F-BCK	2	40	2	6	14	2	20	4	12
(B)									
O-CNP	100	100	100	96	98	100	100	100	98
B-DPH	90	94	45	76	60	64	80	96	44
B-SPP	32	14	78	43	76	96	64	36	88
F-BCK	34	84	92	31	22	36	38	28	88
B-TUN	20	4	61	32	60	40	24	4	58
O-CPT	4	0	59	86	86	6	2	66	18
O-MLF	54	18	12	78	66	2	2	82	0
E-FSH	30	4	8	6	32	52	56	18	0
E-CUR	2	0	29	8	8	10	38	60	34
F-RET	4	32	25	2	2	14	32	2	8
E-SSN	10	6	20	16	8	8	12	8	60
F-ENC	8	60	14	0	2	6	18	4	30
B-HCC	10	90	24	0	6	30	6	6	10
R-SWM	28	24	0	42	10	0	0	0	0
R-RFT	20	8	2	22	0	0	0	8	6
B-SPP:F-BCK	0	0	22	4	0	4	0	0	24
B-SPP:O-CNP	4	0	0	0	8	64	38	24	4

dolphin mortality per set data suggest that only a few variables were of primary importance (Tables 3-4, Fig. 4). The presence of net canopies (O-CNP) was found to contribute to increased dolphin mortality in all nine years (Table 3, Fig. 5). In addition, the duration of the backdown procedure (F-BCK), the number (B-DPH) and species (B-SPP) of dolphin encircled, the amount of tuna captured (B-TUN) and the presence of net collapses (O-CLP) were also found to contribute to increased dolphin mortality in at least five of the nine years (Table 3, Fig. 5). On the other hand, dolphin mortality was found to decrease with increased captain experience at fishing on tunas associated with dolphins (O-CPT) in four of the nine years (Table 3, Fig. 5).

Comparison of these results with those of earlier studies suggests that some of the variables that can be identified as strongly affecting dolphin mortality have remained the same for the last three decades. Consistent with these results, previous analyses of dolphin mortality per set data (Fox and Lenarz, 1975; Everett *et al*., 1976; Powers *et al*., 1979; IATTC, 1984; 1987; 1989) indicated that mortality per set increased with the size of the dolphin herd encircled, the amount of tuna captured, the duration of the backdown procedure, the presence of net canopies, net collapses and gear malfunctions and varied with the dolphin species involved. The results here differ from those of previous studies in that use of a ZIP model has enabled separation of influential variables into those that may contribute to the development of problematic situations (i.e. low probability of being in the zero-mortality state) and those that may influence the amount of mortality that occurs, once a problematic situation has developed (i.e. the mean mortality per set in the Poisson state). For example, lengthy backdown procedures (F-BCK) and the presence of net collapses (O-CLP) were found to contribute consistently to the development of problematic situations (Tables 3-4), but have less influence on the mean mortality per set in problematic situations. On the other hand, the presence of net canopies (O-CNP) and large biomass in the net (B-TUN, B-DPH) contributed consistently to both the development of problematic situations and to the mean mortality per set in problematic situations. In addition, to our knowledge, previous analyses did not incorporate a measure of captain skill, which was indicated in this analysis as reducing mortality per set.

Correlations among these variables (Tables 2, 4) make interpretation of the results, in terms of 'cause and effect', difficult. For example, the number of dolphins encircled (B-DPH) was found to be correlated with the number of tons of tuna captured (B-TUN) and with the duration of the backdown procedure (F-BCK), which was, in turn, related to the presence of net canopies (O-CNP). Nonetheless, all four variables contributed strongly to improving model fit (Tables 3-4, Fig. 4). Clearly, variables may contribute to increased dolphin mortality for several reasons and the process is likely complex. Nonetheless, it is useful to determine if any synthesis of these results can lead to a clearer picture of at least one of the ways in which dolphin mortality occurs. Because net canopies (O-CNP) were identified in both stages of the analysis in all nine years (Table 3) and because net canopies was selected frequently in the stability analysis (Table 4), the presence of net canopies and their relationship to other predictor variables (Table 1) were considered first. The species of dolphins encircled in the net will not be considered further. Consistent with the results (Tables 3-4, Fig. 5), spinner dolphins and especially common dolphins, have been found to have higher mortality rates (Fox and Lenarz, 1975; IATTC, 1989), which may be the result of differences in behaviour within the pursed net (IATTC, 1986; Pryor and Shallenberger, 1991; Schramm, 1997). Historical efforts to reduce such behaviourally-based causes of mortality have included US bans on setting on herds of pure spinner dolphins (*US Federal Register Vol. 51 (2) January 3, 1986*); spinner dolphins are typically encountered by the fishery in mixed herds with spotted dolphins (Scott and Cattanach, 1998; Hall *et al*., 1999), the species more frequently involved in the fishery (Hall *et al*., 1999). Although mortality rates of common dolphins can be high, sets on common dolphins occur much less frequently (Hall *et al*., 1999) and, as a result, common dolphin mortality only accounted for an average of about 11% of the total dolphin mortality annually since 1993 (IATTC, 2002).

Although the data do not reveal the exact timing of the formation of net canopies, available information suggests that long backdown procedures are strongly associated with the formation of net canopies. Results of building a logistic model for the probability of a net canopy, in a stepwise manner using all other predictor variables in Table 1, indicated a strong relationship between the duration of the backdown procedure and the presence of net canopies. The duration of the backdown procedure was selected first in all nine years, resulting in a 6-12% reduction in deviance (71-156, 1 degree of freedom). A likely mechanism for this

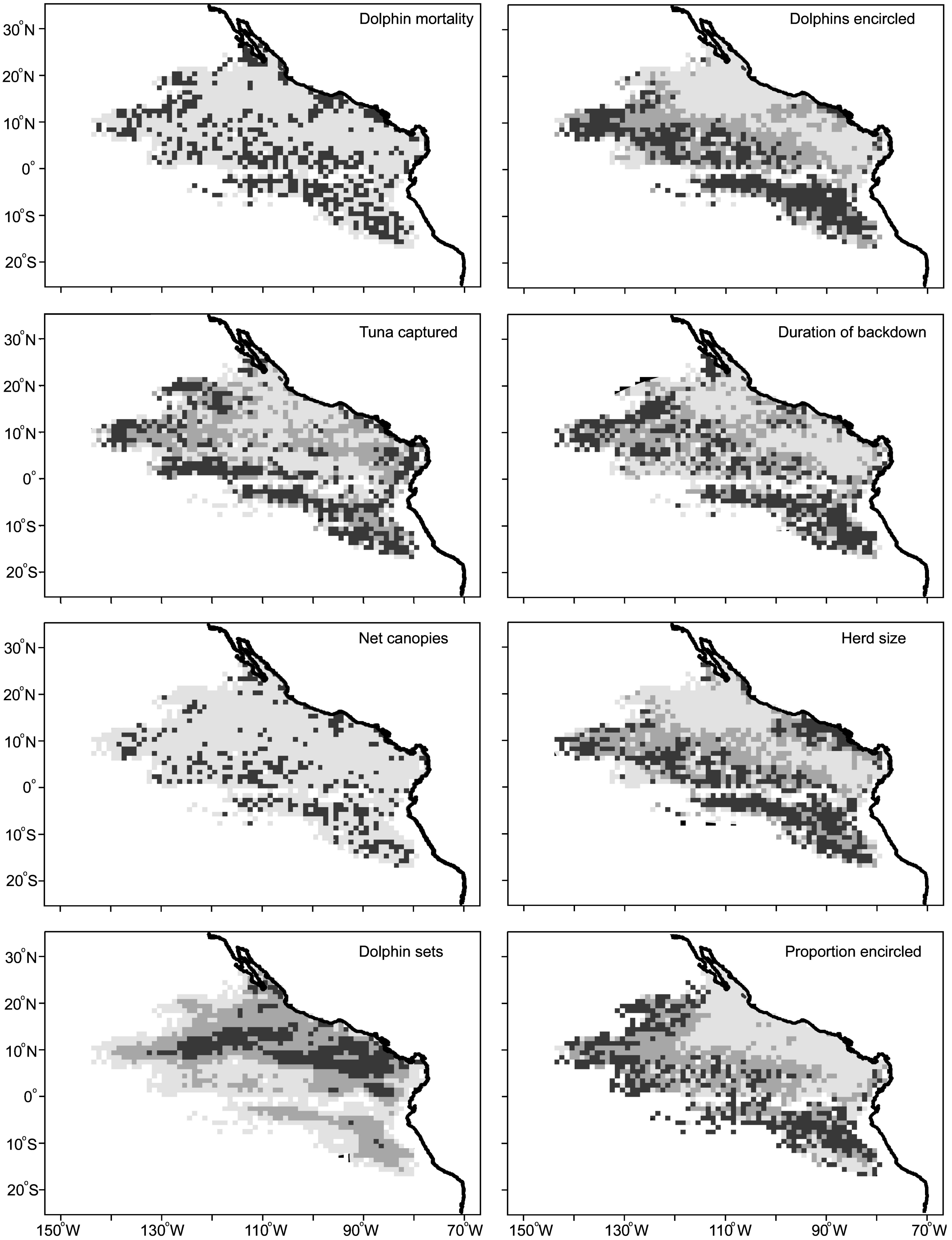

Fig. 6. Spatial distributions of the proportion of sets with dolphin mortality (≤0.15; >0.15), standardised number of dolphins encircled per set, standardised capture of tunas per set, standardised duration of backdown, proportion of sets with net canopies (≤0.10; >0.10), standardised herd size, number of dolphin sets (≤10 sets; 11-50 sets; >50 sets) and the standardised ratio of the number of dolphins encircled to the herd size (proportion encircled), 1993-2001. For standardised quantities, light grey indicates 1° square areas with values ≤ the 0.40th quantile of standardised values, dark grey indicates 1° square areas with values between the 0.40-0.70th quantiles of standardised values, black indicates 1° square areas with values > the 0.70th quantile of standardised values. Standardisation was done in the following manner. First, the average of the particular quantity (e.g. number of dolphins encircled) was computed by 1° square area for each year. Annually, 1° square averages were then standardised by subtracting the median of 1° square values and dividing by the inter-quartile range of 1° square values. These annual standardised values were combined across years for each 1° square by computing a weighted average, weights equal to the number of dolphin sets in each year in the particular 1° square.

association is the physical dynamics of extended backdown procedures. Long backdown procedures tend to cause the floor of the purse-seine to rise toward the surface. This deformation of the net can produce net canopies along the sides of the backdown channel.

The duration of the backdown procedure was, in turn, found to be strongly associated with the size of the encircled herd. This relationship was demonstrated clearly in the stepwise procedures for fitting the ZIP models. The significance of the number of dolphins encircled was often reduced once the duration of the backdown procedure was added to the model (and vice versa). In a stepwise GLM procedure modelling the natural logarithm of the duration of the backdown procedure (assuming a gamma distribution for the stochastic component), the number of dolphins encircled was selected first in all nine years, resulting in a 13-24% reduction in deviance (89-143, 1 degree of freedom). The duration of the backdown procedure was, however, not found to be strongly related to the amount of tuna captured (see also Table 2). In fact, correlation between the duration of the backdown procedure (F-BCK) and the number of dolphins encircled (B-DPH) (Table 2) is likely the reason that the amount of tuna captured (B-TUN) was most influential on the probability of being in the zero-mortality state, while the number of dolphins encircled was most influential in determining the mean mortality in the Poisson state (Tables 3-4). Because tuna capture is correlated with encircled herd size (Table 2), we believe the importance of tuna capture in the ZIP models to largely reflect complications associated with manipulating large dolphin biomass within the pursed net.

Thus, we believe that the results of this analysis support a continuing relationship between dolphin mortality and the encirclement of large herds. The results would be consistent with the following scenario. Encirclement of large herds leads to dolphin mortalities because of the sheer magnitude of the number of animals confined within the pursed net and because it extends the duration of the backdown procedure, which, in turn, leads to prolonged close confinement of the dolphins within the backdown channel and may, in turn, lead to the formation of net canopies. It is also believed that dolphin mortalities result from setting in areas of strong currents and from poor gear maintenance, which leads to failure of equipment essential to the release of dolphins from the pursed net. Consistent relationships between strong currents and dolphin mortality and between gear malfunctions and dolphin mortality, were not identified in this analysis of these data. This may be because these factors are of secondary importance in the present fishery, because the definitions of strong currents and gear malfunctions are not adequate to reveal relationships to dolphin mortality with these data, given the current low levels of reported mortality and/or because their effects on mortality are instead captured by variables such as the presence of net canopies and net collapses (Table 2).

Spatial distributions of the occurrence of mortality, the presence of net canopies, the duration of the backdown procedure and the size of the encircled herd show very similar patterns (Fig. 6). In general, the largest encircled herds occurred south of the equator and along the offshore margin of the fishery north of the equator. This area tended to be where the duration of the backdown procedure was longest and where net canopies were more common. This was also an area that yielded some of the largest captures of tunas (Fig. 6). Although large encircled herds show a spatial correspondence with areas of high probability of dolphin mortality, the areas of the largest encircled herds were not always the areas where the largest herds were targeted by fishermen (Fig. 6). For example, large herds were targeted consistently by fishermen nearshore between the Gulf of Tehuantepec, Mexico and Cabo Velas, Costa Rica, as well as north of the equator along the offshore margin of the fishery and south of the equator. However, the proportion of the herd that was encircled was typically greatest south of the equator and north of the equator along the offshore margin of the fishery (Fig. 6).

Low values of the proportion of the herd that was encircled between the Gulf of Tehuantepec and Cabo Velas (Fig. 6) have been related to spatial differences in evasive behaviour of dolphins (IATTC, 1986; Heckel *et al.*, 2000; Lennert-Cody and Scott, In press). Spatial patterns in evasive behaviour have been hypothesised to arise from spatial differences in the amount of exposure to the fishery (Heckel *et al.*, 2000; Lennert-Cody and Scott, In press) and from the timing of first exposure to the fishery since purse-seining on tunas associated with dolphins began in the late 1950s (Lennert-Cody and Scott, In press). This suggests that dolphin behaviour may be involved in determining the occurrence of mortality, not only as a result of the species involved, but also indirectly as a result of learned evasive behaviours.

Given the dependence of dolphin mortality on the encirclement of large herds, the results suggest that the current level of dolphin mortality could be further reduced by increasing efforts to avoid encircling large herds of dolphins and by reallocating fishing effort to areas where encircled herd size is typically small. Currently, fishermen encircle fewer dolphins by attempting to split the herd prior to the beginning of encirclement. This technique is productive if the tuna remain with only part of the dolphin herd. On the other hand, establishing a maximum targetable herd size is not likely to be a realistic management option because herd size is difficult to estimate accurately. An observer's best estimate of herd size is based on having the opportunity to observe the herd for an extended period of time over the entire setting process.

Reallocating fishing effort to areas where encircled herd size is typically small warrants further consideration because spatial patterns in encircled herd size do not appear to be sensitive to short-term environmental fluctuations such as those caused by El Niño events. A major El Niño event occurred in the EPO in 1997-98, resulting in distinct spatial variability in biological measures such as surface chlorophyll (Wilson and Adamec, 2001), but no overall change in the spatial relationship between encircled herd size and dolphin mortality. While the southern area of the fishery and the offshore margin of the fishery north of the equator are areas of larger catches of tunas, large catches of tunas can be seen to occur in other areas of the fishery, including inshore areas where lesser numbers of dolphins were encircled (Fig. 6). Predictive models could be developed to estimate spatial distributions of dolphin mortality, encircled herd size and tuna captures. Results of these models could be used to assess the tradeoffs between dolphin mortality and tuna catch at varying levels of fishing effort in areas where large herds are typically targeted by fishermen and to develop strategies for reallocation of fishing effort to dolphin sets in other areas or to sets on unassociated schools of tunas, which are sometimes made in similar areas as dolphin sets (Hall *et al.*, 1999; Watters, 1999).

Because of the goal of this analysis, we believe that addressing the extra zeros through a zero-inflated model accounts for the largest relative departure of the data from a classical Poisson model (Fig. 3). However, lack of fit of the ZIP model to the positive mortalities suggests that the ZIP model, as well as other zero-inflated (or zero-truncated) models (e.g. Mullahy, 1986; Ridout *et al.*, 2001) and over-dispersed Poisson alternatives (e.g. the negative binomial) are not good candidates for predictive models with this type of data. Although these models have been shown to be useful for prediction in other situations where data with excessive zeros arise (Mullahy, 1986; Lo *et al.*, 1992; Stefánsson, 1996; Hall, 2000), lack of fit in our case likely arises because of efforts on the part of fishermen to actively reduce mortality, which may evolve over the course of the set. Had prediction of mortality been our goal, algorithmic models (e.g. Breiman, 2001 and references therein) might yield superior performance; results of algorithmic models are generally more difficult to interpret and thus were not used in this analysis.

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REFERENCES

Akaike, H. 1974. A new look at the statistical model identification. *IEEE Transactions on Automatic Control* 19(6):716-23.

Allen, R.L. 1985. Dolphins and the purse-seine fishery for yellowfin tuna. pp. 236-52. *In:* J.R. Beddington, R.J.H. Beverton and D.M. Lavigne (eds.) *Marine Mammals and Fisheries*. George Allen & Unwin, London. 354pp.

Archer, F., Gerrodette, T., Dizon, A., Abella, K. and Southern, S. 2001. Unobserved kill of nursing dolphin calves in a tuna purse-seine fishery. *Mar. Mammal Sci.* 17:540-54.

Bayliff, W.H. 2001. *Organization, functions and achievements of the Inter-American Tropical Tuna Commission. Special Report 13*. Inter-American Tropical Tuna Commission, La Jolla, California. 122pp. [Available from: *http://www.iattc.org*].

Breiman, L. 2001. Statistical Modeling: The two cultures. *Stat. Sci.* 16:199-231.

Burnham, K.P. and Anderson, D.R. 1998. *Model Selection and Inference. A Practical Information-Theoretic Approach*. Springer-Verlag, New York. 353pp.

Everett, J., Powers, J., McNeely, R., Coe, J. and Butler, R. 1976. The use of speedboats in reducing incidental porpoise mortality in tuna purse seining. Southwest Fisheries Center Administrative Report No. LJ-76-35. Southwest Fisheries Science Center, NOAA, NMFS, La Jolla, California 92038, USA.

Fox, W.W. and Lenarz, W. 1975. Progress of research on porpoise mortality incidental to tuna purse-seine fishing for fiscal year 1975. Southwest Fisheries Center Administrative Report LJ-75-68. Southwest Fisheries Science Center, NOAA, NMFS, La Jolla, California 92038, USA.

Gosliner, M.L. 1999. The tuna-dolphin controversy. pp. 120-55. *In:* J.R. Twiss Jr. and R.R. Reeves (eds.) *Conservation and Management of Marine Mammals*. Smithsonian Institute, Washington, DC. 471pp.

Grogger, J.T. and Carson, R.T. 1991. Models for truncated counts. *Journal of Applied Econometrics* 6:225-38.

Hall, D.B. 2000. Zero-inflated Poisson and binomial regression with random effects: A case study. *Biometrics* 56:1030-9.

Hall, M.A. 1998. An ecological view of the tuna dolphin problem: impacts and trade-offs. *Rev. Fish Biol. Fish.* 8:1-34.

Hall, M.A., García, M., Lennert-Cody, C., Arenas, P. and Miller, F. 1999. *The association of tunas with floating objects and dolphins in the eastern Pacific Ocean: A review of the current purse-seine fishery.* pp.87-194. *In: Special Report 11*. Inter-American Tropical Tuna Commission, La Jolla, California. [Available from: *http://www.iattc.org*].

Hastie, T. 1987. A closer look at the deviance. *Am. Stat.* 41:16-20.

Heckel, G., Murphy, K.E. and Compéan Jiménez, G.A. 2000. Evasive behavior of spotted and spinner dolphins (*Stenella attenuata* and *S. longirostris*) during fishing for yellowfin tuna (*Thunnus albacares*) in the eastern Pacific Ocean. *Fish. Bull.* 98:692-703.

IATTC. 1984. *Annual Report of the Inter-American Tropical Tuna Commission, 1983*. Inter-American Tropical Tuna Commission, La Jolla, California.

IATTC. 1986. *Annual Report of the Inter-American Tropical Tuna Commission, 1985*. Inter-American Tropical Tuna Commission, La Jolla, California.

IATTC. 1987. *Annual Report of the Inter-American Tropical Tuna Commission, 1986*. Inter-American Tropical Tuna Commission, La Jolla, California.

IATTC. 1989. *Annual Report of the Inter-American Tropical Tuna Commission, 1988*. Scripps Institution of Oceanography, La Jolla, CA. 288pp.

IATTC. 2002. *Annual Report of the Inter-American Tropical Tuna Commission, 2000*. Inter-American Tropical Tuna Commission, La Jolla, California.

Joseph, J. 1994. The tuna-dolphin controversy in the eastern Pacific ocean: biological, economic, and political impacts. *Ocean Dev. Int. Law* 25:1-30.

Lambert, D. 1992. Zero-inflated Poisson regression, with an application to defects in manufacturing. *Technometrics* 34:1-14.

Lennert-Cody, C.E. and Scott, M.D. In press. Spotted dolphin evasive response in relation to fishing effort. *Mar. Mammal Sci.*

Lo, N.C.H. and Smith, T.D. 1986. Incidental mortality of dolphins in the eastern tropical Pacific, 1959-1972. *Fish. Bull.* 84(1):27-34.

Lo, N.C.H., Jacobson, L.D. and Squire, J.L. 1992. Indices of relative abundance from fish spotter data based on delta-lognormal models. *Can. J. Fish. Aquat. Sci.* 49:2515-26.

McCullagh, P. and Nelder, J.A. 1989. *Monographs on Statistics and Applied Probability*. 37. *Generalized Linear Models*. 2nd Edn. Chapman & Hall, London. 511pp.

Mullahy, J. 1986. Specification and testing of some modified count data models. *Journal of Econometrics* 33:341-65.

National Research Council. 1992. *Dolphins and the Tuna Industry*. National Academy of Sciences, Washington. 176pp.

Powers, J.E., Lo, N.C.H. and Wahlen, B.E. 1979. A statistical analysis on effectiveness of porpoise rescue procedures in reducing incidental mortality. Southwest Fisheries Center Administrative Report No. LJ-79-7. Southwest Fisheries Science Center, NOAA, NMFS, La Jolla, California 92038, USA.

Pryor, K. and Shallenberger, I.K. 1991. Social structure in spotted dolphins (*Stenella attenuata*) in the tuna purse seine fishery in the Eastern Tropical Pacific. pp. 161-96. *In:* K. Pryor and K.N. Norris (eds.) *Dolphin Societies: Discoveries and Puzzles*. University of California Press, Oxford. 400pp.

Rice, J.A. 1988. *Mathematical Statistics and Data Analysis*. Wadsworth & Brooks/Cole, Pacific Grove, California. 595pp.

Ridout, M., Hinde, J. and Demétrio, C.G.B. 2001. A score test for testing a zero-inflated Poisson regression model against zero-inflated negative binomial alternatives. *Biometrics* 57:219-23.

Schramm, Y. 1997. Activity level of offshore spotted (*Stenella attenuata*) and eastern spinner dolphins (*S. longirostris*), during purse seining in the eastern Pacific Ocean. Master of Science Thesis, Universidad Autónoma de Baja California, Ensenada, Baja California, Mexico. 51pp.

Scott, M.D. and Cattanach, K.L. 1998. Diel patterns in aggregations of pelagic dolphins and tunas in the Eastern Pacific. *Mar. Mammal Sci.* 14(3):401-28.

Seber, G.A.F. 1984. *Multivariate Observations*. John Wiley and Sons, New York. 686pp.

Stefánsson, G. 1996. Analysis of groundfish survey abundance data: combining the GLM and delta approaches. *ICES J. Mar. Sci.* 53:577-88.

van den Broek, J. 1995. A score test for zero inflation in a Poisson distribution. *Biometrics* 51:738-43.

Wade, P.R. 1995. Revised estimates of incidental kill of dolphins (*Delphinidae*) by the purse-seine tuna fishery in the eastern tropical Pacific, 1959-1972. *Fish. Bull.* 93(2):345-54.

Watters, G.M. 1999. Geographical distributions of effort and catches of tunas by purse-seine vessels in the eastern Pacific Ocean during 1965-1998. IATTC data report 10. IATTC, La Jolla, California. [Available from: *http://www.iattc.org*].

Wilson, C. and Adamec, D. 2001. Correlations between surface chlorophyll and sea surface height in the tropical Pacific during the 1997-1999 El Niño-Southern Oscillation event. *J. Geophys. Res.* 106:31,175-88.