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Silky shark (*Carcharhinus falciformis*) bycatch in the French tuna purse-seine fishery of the Indian Ocean

by

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Summary

Data collected through 20 observer fishing trips were used to quantify the number of silky sharks taken as bycatch by the French tuna purse seine fishery of the Western Indian Ocean. 1,385 immature silky sharks of which 85% was discarded at sea and 15% retained aboard, were observed as bycatch during 685 fishing sets observed from October 2005 to April 2008. Zero-inflated regression models fitted with Bayesian methods were used to explain silky shark bycatch as a function of fishing mode (free vs. fishing aggregating device-associated (FAD) schools), area, and season. Model results showed that silky sharks occurred in 24% of the fishing sets with an expected number of sharks per set estimated to be 2.02 ± 0.05. The 3 covariates were found to significantly explain both the presence and number of silky sharks caught by the French purse seiners. FAD was shown to have a strong positive effect on the number of silky sharks caught, an expected value of 4.3 sharks being taken in FAD-associated schools versus 0.3 shark in free schools. There were significant differences in silky shark bycatch between seasons and areas with higher bycatch than average in July-September and in the South-East Seychelles area while fewer sharks were expected to be caught in the North Somali area. Results are discussed within the context of the ecosystem approach to fisheries for the analysis of ecosystem effects of fishing.

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1. Introduction

In the recent years, the European tuna purse seine fishery catches annually about 250,000 t of major commercial tunas, i.e. more than 75% of the annual total catch of tuna and tuna-like species caught by purse seiners in the Indian Ocean. Species primarily targeted by the European tuna purse-seine fishery of the Indian Ocean include yellowfin tuna *Thunnus albacares* (Bonnaterre 1788) and skipjack tuna *Katsuwonus pelamis* (Linnaeus 1758); albacore *Thunnus alalunga* (Linnaeus 1758) and bigeye tunas *Thunnus obesus* (Lowe 1839) being caught as secondary target species, mostly as juveniles under fishing aggregating devices (FADs). More than fifty non-targeted marine species including billfishes, selaceans, turtles, cetaceans, and several finfishes can be taken as incidental bycatch in the tuna purse-seine fisheries of the Indian Ocean (Amandè 2007; Gonzalez *et al*. 2007; Romanov 2002). Bycatches are either discarded at sea because they have no commercial value, retained aboard fishing vessels for consumption by the fishing crew, or sold on local fish markets because they can not be processed by tuna canneries.

Incidental bycatch and associated discarding is often difficult to quantify because it is generally not or poorly recorded in logbooks by fishing masters. The issues raised by bycatch and discarding are however of increasing concern because such practices are responsible for economic loss, juvenile mortality, ecological effects on key species which are relevant to the overall ecosystem structure and functioning, and added threat to endangered or high ethical value species (Pascoe 1997; Garcia and Cochrane 2005). In addition, catches of juvenile tunas that are discarded or sold on local fish markets are generally absent of official statistics whereas they should be included in stock assessment models in use for providing scientific advice to fisheries managers and stakeholders (Clucas 1997). There has been a growing interest about bycatch and discards in the world fisheries in the last decades (Alverson *et al*. 1994; Harrington *et al*. 2005; Rosenberg 2005; Kelleher 2005) and the importance of monitoring and reducing bycatch and discards has been emphasized as a key for an ecosystem-based fishery management (Garcia and Cochrane 2005; Pikitch *et al*. 2004).

While several studies have been conducted in the Pacific Ocean based on observer data (Edwards and Perkins 1996; Lawson 1997; Perkins and Edwards 1998; Olson *et al*. 2006) bycatch remain poorly studied in the tropical purse-seine fisheries of the Atlantic and Indian Oceans (Gaertner *et al*. 2002; Romanov 2002). In the Western Indian Ocean (WIO), the only studies published in scientific journals concern the Soviet/Russian/Liberian-flag purse seiners based on about 500 fishing sets observed during the mid-1980s and early 1990s (Romanov 2008). Recently, analyses based on observers aboard French and

Spanish fishing vessels and scientific surveys have described the composition and spatial distribution of bycatch in the western and eastern parts of the Indian Ocean (Delgado de Molina *et al.* 2005; Rajruchithong *et al.* 2005, Viera and Pianet 2006, Gonzalez *et al.* 2007). Despite these analyses, few information is currently available about quantitative estimates of bycatch and discards of the European purse-seine fishery (Amandè *et al.* 2008).

In the present analysis, we focused on silky shark *Carcharhinus falciformis* (Müller and Henle 1839), the most frequent species of shark taken as bycatch in the tuna purse-seine fisheries of the Indian Ocean (Amandè 2007; Delgado de Molina e*t al.* 2005; Gonzalez *et al.* 2007). The objective was to estimate the amount of silky sharks per set taken as bycatch in the French tuna purse-seine fishery of the WIO. Silky shark's catch generally has many zero-valued observations and also includes high values (Fig. 1). Perkins and Edwards (1996) examined such types of data in the purse-seine fishery of the eastern tropical Pacific Ocean using a delta method that may also be applicable to the estimation of non-target species. Statistical models based on a large dataset of observer data were used to predict the amount of silky shark caught per fishing set. A zero-inflated Poisson regression model fitted with Bayesian methods was used to quantify the expected number of silky sharks taken by the French tropical tuna purse-seiners.

2. Materials and methods

Data

Data were collected within the framework of the European program of data acquisition 'Data Collection Regulation' (DCR). Information about sets was collected by observers placed aboard French tuna purse-seiners during fishing trips from October 2005 to April 2008. A total of 685 fishing sets were observed from 20 observer trips made during this period, corresponding to 613 fishing days. The coverage rate has evolved from about 2% of total fishing days in 2005 to reach 8% in 2007. The data consist in visual estimates of the commercial catch because weighting total catch is not feasible aboard purse-seiners for logistical reasons. For each fishing set, the observer records the quantity in weight or number and average estimate of the bycatch and discards in weight or length for each species. Information about the fishing sets and environmental conditions is also recorded, i.e. fishing time, sea surface temperature, fishing mode, geographic position, etc.

The number of silky sharks caught per set during the fishing trips was not always available because observers sometimes only recorded a total and/or an average weight of sharks caught. In such cases, data were converted into numbers using the published Length-Weight relationship $W = 2.10^3 * L^{3.23}$ (Froese and Pauly 2008).

Factors affecting bycatch

Several factors have been shown to influence levels of discarding and bycatch, including the fishing methods and technical characteristics of the fishing vessel (gear selectivity, size, fishing mode, holding capacity, etc.), the spatio-temporal variability of the resource, the environmental conditions that can affect both resource availability and catchability, and the market incentives (Rochet and Trenkel 2005). In the present analysis, we focused on the effect of the fishing mode that has been shown to be of major importance for tuna purse seine fisheries (Gaertner *et al.* 2002). Tuna purse-seine sets are generally categorized into 3 types of fishing mode but only 2 were considered in the present analysis: tuna concentrations associated with FADs and free schools (FSC). Here, FAD includes any type of floating object, i.e. natural logs, palm branches, anthropogenic flotsam, and specially constructed FADs equipped or not with relocation equipment such as satellite transmitters.

To increase sample size, all years available were pooled in the present analyis, i.e. no year effect was considered. The spatial variability in silky shark bycatch was investigated by considering large spatial areas of the WIO (Fig. 2). The fishing area of the Indian Ocean has been stratified into ten strata said “ET areas” based on differences in catch composition (Pianet *et al*. 1998). These areas were considered here as factors to represent also different habitats for silky shark. Seasonal variations can be very high in the Indian Ocean and related to monsoon and El Nino-Southern Oscillation (ENSO) events (Krishnamurthy and Kirtman 2003). To account for seasonal changes in silky shark bycatch, the quarter corresponding to the period of fishing was included as a covariate into the model. The sampling design was quite unbalanced and there were some confounding effects between area and season due to the spatial reallocation of the fishing fleets throughout the year in the WIO (Table I)

Statistical model

A mixture distribution with added zeros was used to model the number of silky sharks caught per set. Mixture models have been used in different contexts by several authors and are appropriate for modelling skewed data. By contrast, regression models with commonly used discrete distributions such as Poisson or Negative Binomial may not fit such data well, i.e. they do not relate well covariates to the large percentage of zeros and the few occurrences of high values (Perkins and Edwards 1996; Wang and Alba 2006; Martin *et al.* 2005; Lord *et al*. 2005; Ghosh *et al.* 2006). Thus, the zero-inflated distribution is more appropriate for modelling real-life data that display overdispersion and excess zeros in the case of the silky shark bycatch (Minami *et al*. 2007). In the present analysis, a zero-inflated Poisson (ZIP) regression model that is a modification of the Poisson model with added zeros was used. This model allows for "excess zeros" in count models under the assumption that the silky shark bycatch is characterized by 2 regimes due to 2 distinct processes: one where data always have zero counts, and one where data have zero or positive counts. The likelihood of being in either state is estimated using a Bernoulli trial while the number of sharks in the second state are estimated using a Poisson distribution.

Let y_i be the observed catch of silky shark in the i^{th} fishing set. The observation is choosen from the first process (the perfect state) with probability 1- p_i and from the second process (the imperfect state) with probability p_i. The perfect state generates only zero values and the imperfect state is able to produce any possible value of the Poisson distribution (Minami *et al*. 2007).

$$y_i = \begin{cases} 0 & with \quad probability & 1-p_i \\ g(y_i|x_i,\lambda)=\lambda^{x_i} e^{\frac{-\lambda}{x_i!}} & with \quad probability & p_i \end{cases} \qquad (1)$$

where λ is the mean parameter of the Poisson distribution.

The distributional assumption of the silky shark bycatch yields a probability model with two parameters: $\theta = \{p, \lambda\}$. Thus, the probability function for the ZIP regression model is expressed as:

$$f(y_i|z_i,x_i,\beta,\gamma,\lambda,p) = \begin{cases} 1-p_i + g(0|x_i,\mu_i,\theta) & for \quad y_i = 0 \\ p_i g(y_i|x_i,\mu_i,\theta) & for \quad y_i \in \mathbb{N}^+ \end{cases} \qquad (2)$$

where g(y_i | x_i, μ_i) is the Poisson density function given by equation (1). The probability of being in the imperfect state (p_i) and the mean in this state (μ_i) were modelled via logistic and log-linear regressions respectively:

$$logit(p_i) = \gamma_o + \sum_{k=1}^{K} \gamma_k z_{ik} \qquad (3)$$

$$\log(\mu_i) = \beta_o + \sum_{k=1}^{K} \beta_k x_{ik} \qquad (4)$$

where the kth covariate values for the ith observation are z_{ik} and x_{ik}. No interaction effect was considered in the present analysis. Estimated coefficients of the model (γ and β) were derived from Bayesian methods considering non informative prior distribution. The model was fitted using the R statistical modelling freeware with the BRugs and coda packages (R Development Core Team 2008).

Posterior distributions of the parameters were obtained through Markov chain Monte Carlo methods that are implemented in BRugs in the form of a Metropolis-Hastings within Gibbs algorithm. We used the Gelman and Rubin approach for monitoring convergence of MCMC by launching 3 parallel chains with starting overdispersed values.

Predicting silky shark bycatch

Posterior distributions for the significant coefficients were used to calculate the mean and 95% confidence interval (CI) of the probability (p) and the average number of silky sharks (μ). For visualisation purpose, the expected number of silky sharks predicted by the ZIP regression model was predicted considering each covariate individually, i.e. averaging the effects of other covariates.

3. Results

For the 685 fishing sets observed aboard French purse seiners from October 2005 to April 2008, the percentage of null sets was about 40% and 10% for FSCs and FADs, respectively. A total of 1,385 silky sharks corresponding to a total weight of about 30 t were recorded as bycatch through the observer programme. The silky sharks appeared in 24% of the total sets, 15% and 28% on FSCs and FADs, respectively. 1,183 silky sharks caught by the purse-seiners during this period were discarded at sea (790 dead and 393 alive) and 202 conserved aboard for later use (for sale or self consumption). The length frequency of the silky sharks fluctuates between 50-250 cm, dominated by the 100 cm individuals corresponding to immature individuals (Oshitani *et al.* 2003). The figure 3 shows no difference in bycatch length of male comparing to female.

The expected number of silky shark per set estimated with the ZIP model was 2.02 ± 0.05 (Table 2). The probability of an observation to be in the imperfect state, i.e. the state in which sharks can occur but not certain, was 0.24 ± 0.01 (Table 2). A significant effect of the 3 covariates on the probability p of being in the imperfect state was shown with the ZIP regression model (Table 2). The fishing mode was shown to affect p, with a strong positive effect of FAD on the value of p (coefficient = 1.56). The probability p was also shown to vary with season throughout the year, with the highest probability of catching silky sharks during the months of July-September (coefficient = 0.69). There was a significant difference between spatial areas of the Western Indian Ocean, with lower values of p in North Somali and higher values of p in South Somali (Table 2).

In the imperfect state, the average value estimated with the ZIP regression model was 7.42 ± 0.37 sharks. Under the assumption of a Poisson distribution, such a high value of μ equal to 7.42 implies that the probability of observing zero shark in the imperfect state is quasi null, i.e. the probability of being in state 1 and that of the zero values are quasi identical (0.76). The 3 covariates were found to significantly explain the mean number of silky shark μ in the imperfect state (Table 2). There was a positive significant effect of FAD on the number of silky sharks caught (coefficient = 1.15). There were significant differences between seasons with more silky sharks caught during the first quarter of the year. The number of sharks caught as bycatch was significantly higher than average in the Mozambique Channel (coefficient = 0.84) and South Somali (coefficient = 0.28).

Model predictions

The ZIP model predicts a few number of silky sharks per set caught on free school sets (0.29) associated with a small variability whereas the number of sharks caught is about 15 times more important on FAD-associated sets (Fig. 4). Predictive values indicate a seasonal profile with silky shark bycatch higher during the third quarter compared to the rest of the year (Fig. 5). The variability appears however high during this time period and this could be due to the rather low sample size during the July-September period while the purse seiners are mainly located in the North West of the Seychelles and South Somali areas. The catch of silky sharks appears higher than average in the South East of the Seychelles (3.5 individuals per set) compared to the other areas and lower in the North Somali (Fig. 6).

4. Discussion

Observer data recently acquired through the DCR European program provide a unique opportunity to assess the amount of sharks and other associated species taken as bycatch in the purse-seine fisheries of the Indian Ocean, silky shark being the main shark species taken by the European purse seiners in the Indian Ocean (Amandè *et al.* 2008). Our findings show that silky sharks, most of them being immature, were caught in 24% of the fishing sets, in about 40% of FAD-associated school sets and in less than 15% for free school sets. In the WIO, the French tuna purse seine fishery generates few silky shark bycatch that are al-most exclusively caught under FADs. Considering the whole French tuna purse seine fishery, about 2 silky sharks were estimated to be caught per fishing set with major differences between areas and seasons.

Explaining silky shark bycatch

The regression models used to explain both the presence and number of silky sharks caught included fishing mode, area, and season. The estimates of probability of presence and mean number of silky sharks have shown significant spatio-temporal patterns in silky shark bycatch in addition to the strong effect of the fishing mode. Although only 24% of all fishing sets contained silky sharks, the results showed that the FADs substantially increased the probability of silky shark presence (> 40%) while the free schools decreased them (15%). This could be mainly due to the gregarious behaviour of juvenile silky sharks that tend to gather in schools under FADs for feeding and appear then more vulnerable to the purse seine fishing gear.

FAD-associated fishing sets showed a larger amount of silky sharks compared to free schools with quite a high variability, indicating the number of silky sharks could strongly vary from one concentration to another. This could be due to local oceanographic conditions, prey availability, or differences in the tuna school composition or size. Including environmental covariates such as sea surface temperature or chlorophyll-a concentration and covariates describing the composition of tuna concentration in regression models could improve our understanding of the processes explaining silky shark bycatch.

Zero-inflated models

Zero-inflated models have been used in many ecological cases including fishery data analysis with excess zeros (Fletcher *et al.* 2005). The main objective is to determine the origin of the zeros: the 'false' zeros coming from the perfect state and the 'true' zeros coming from the imperfect state. The potential sources of zeros in ecological data are developed in Martin et *al.* (2005). Such models appear particularly appropriate for bycatch analysis in purse seine fisheries that are characterized by many zero values and some occurrences of extreme values (Minami *et al.* 2007).

Our results indicate a high value for the mean parameter of the Poisson distribution, suggesting that the ZIP is not fully adapted and a zero inflated negative Binomial (ZINB) distribution might fit better the data and be more consistent with underlying dynamics. Such a ZINB has been shown to lead to better statistical fittings than ZIP models but can also lead to poorer fits when data are dominated by zero values such as silky shark in the case of free schools

(Minami *et al.* 2007). Using both approaches in parallel to compare model outputs might help assessing the robustness of the results. Including other observation data of silky shark bycatch as from the Spanish fleet in the analysis would increase the bearing and consistency of our findings. Including a year effect could allow tracking temporal trends in silky shark abundance following Minami et *al.* (2007) who have shown a significant decrease in the percentage of sets with no reported silky shark bycatch during 1994-2004. Such methods could be applied to other bycatch species when the dataset size is sufficient.

5. Conclusion

Modelling observations of associated-fauna species caught with tuna during a fishing set is a major prerequisite to identify the major factors explaining bycatch and to quantify their level at ecosystem scale. Such analyses are a first step to propose potential measures to mitigate the adverse ecosystem effects of fishing. For instance, our findings indicate that a reduction in FAD-fishing in the South East of the Seychelles would result in a substantial reduction in silky shark bycatch. Evaluating the impact on tuna catch and economic consequences for the fishing fleets of such measures is however crucial to address their usefulness and justification. In addition, mitigation measures for the purse seine fishery should be considered in a context where longline fishing gears have been shown to result in higher levels of shark bycatch but where observer data remain generally poorly available.

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Figure captions

Fig. 1. (a) Fishing set histogram of null and positive values of silky shark bycatch (b) Frequency histogram (in number) of positive bycatch values per fishing set

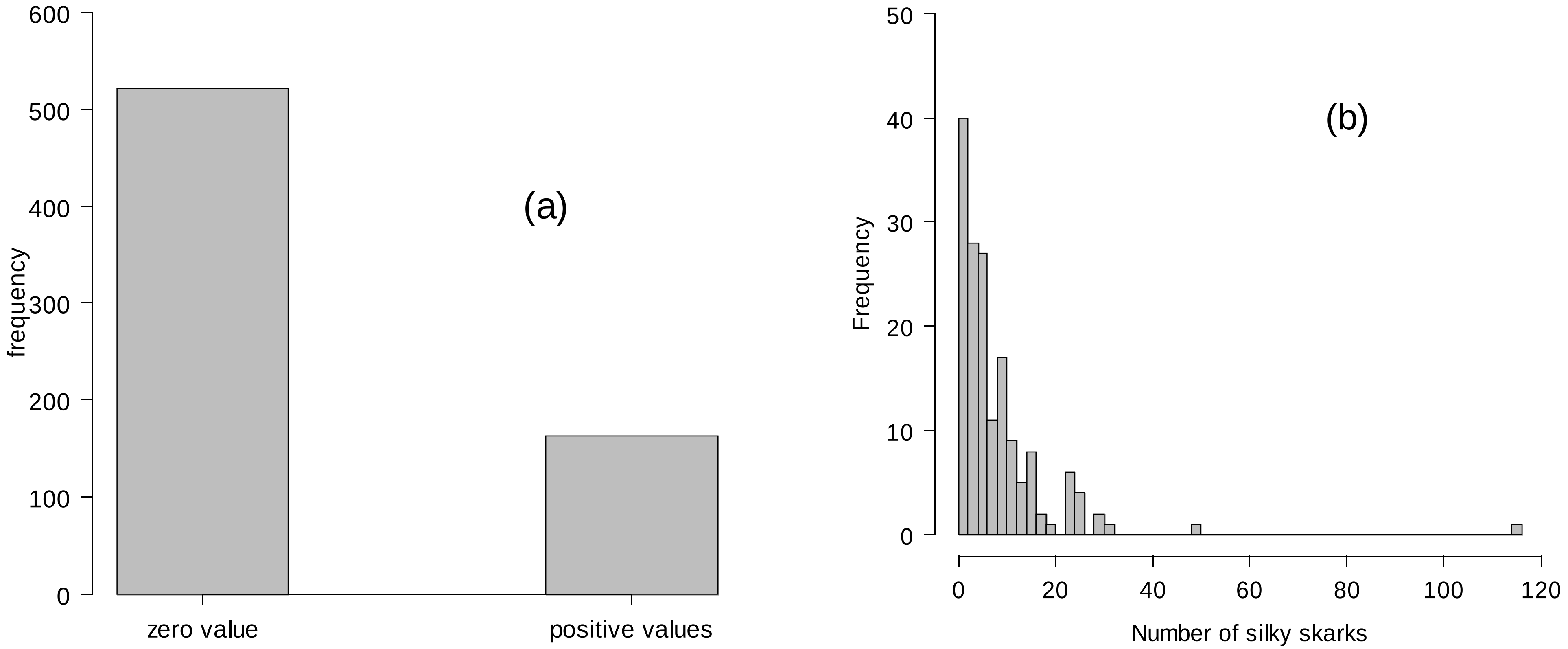
Fig. 2. Size frequency histogram by sex for silky shark (a) males and (b) females

Fig. 3. Spatial distribution of observed fishing sets per statistical rectangle of 1° latitude and 1° longitude in the Western Indian Ocean, FSC = Free school (lightgrey), FAD = Fishing aggregating device- associated school (darkgrey). Solid lines define “ET” areas

Fig. 4. Predicted number of silky sharks per set for each fishing mode considered in the study. FSC = free school; FAD = fishing aggregating device-associated school. Solid line indicates the 95% confidence interval

Fig. 5. Predicted number of silky sharks per set for each season of the year. Solid line indicates the 95% confidence interval

Fig. 6. Predicted number of silky sharks per set for each Western Indian Ocean area considered in the study. Solid line indicates the 95% confidence interval



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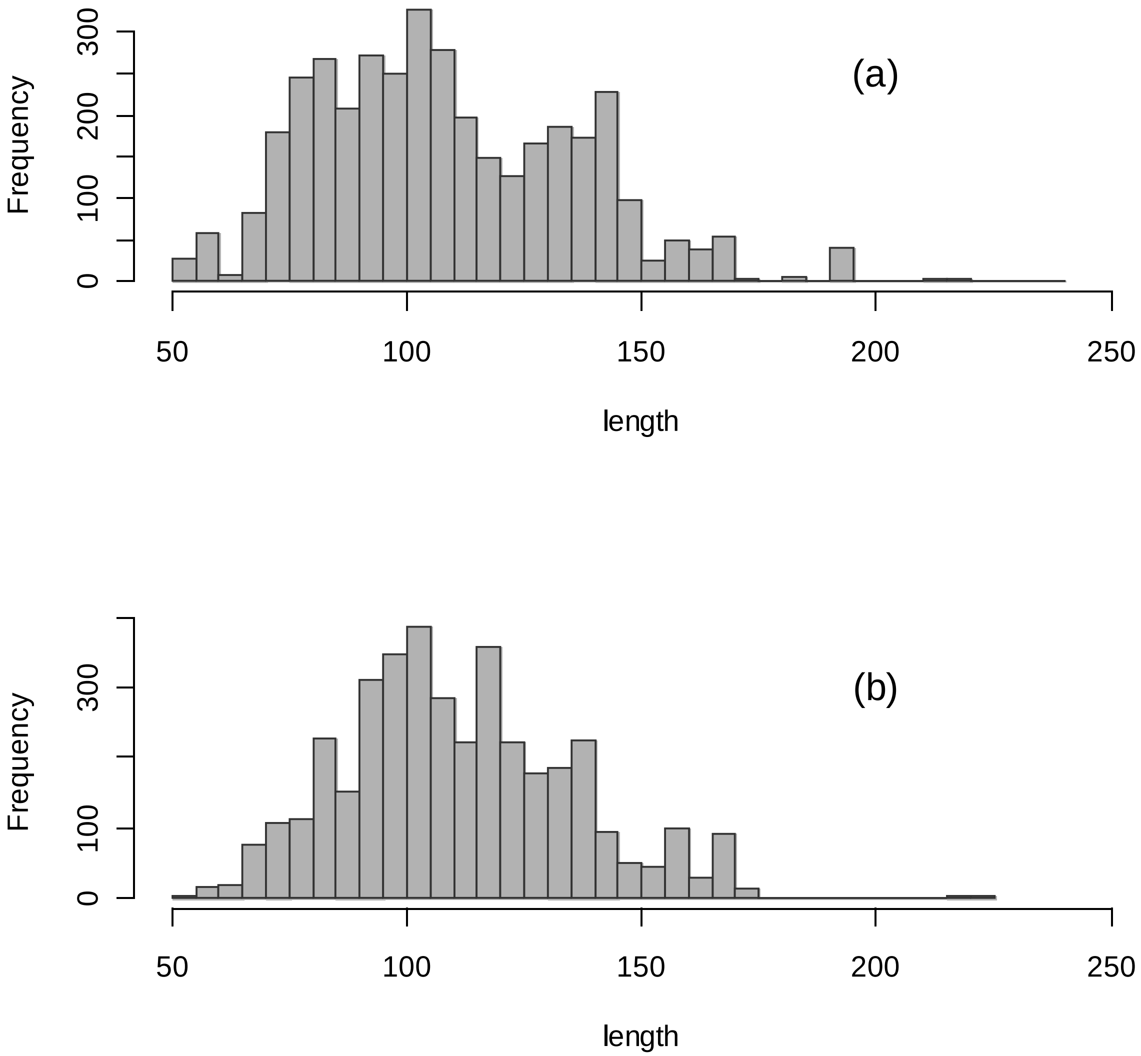


Fig. 2. Size frequency histogram by sex: (a) male and (b) female

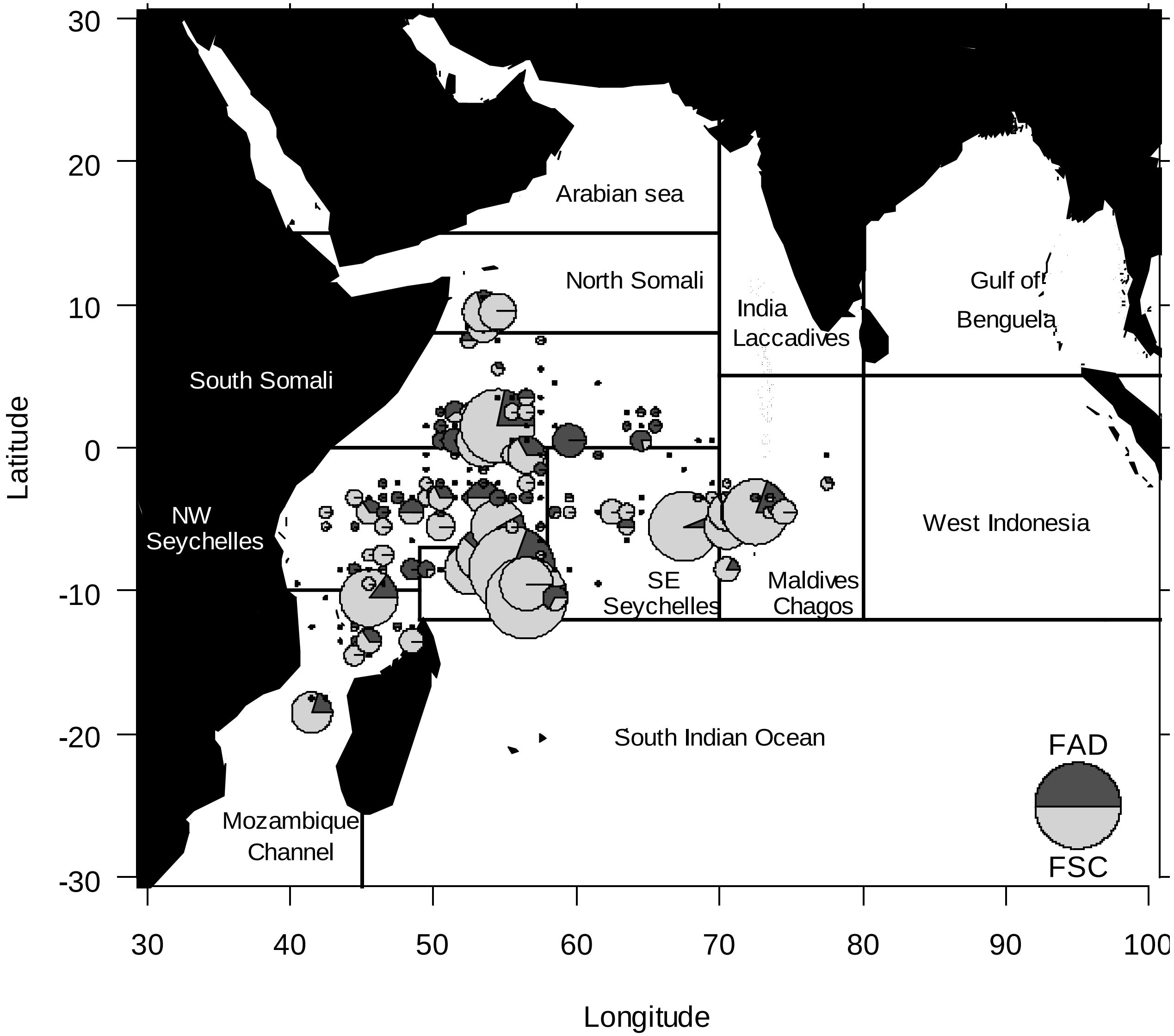
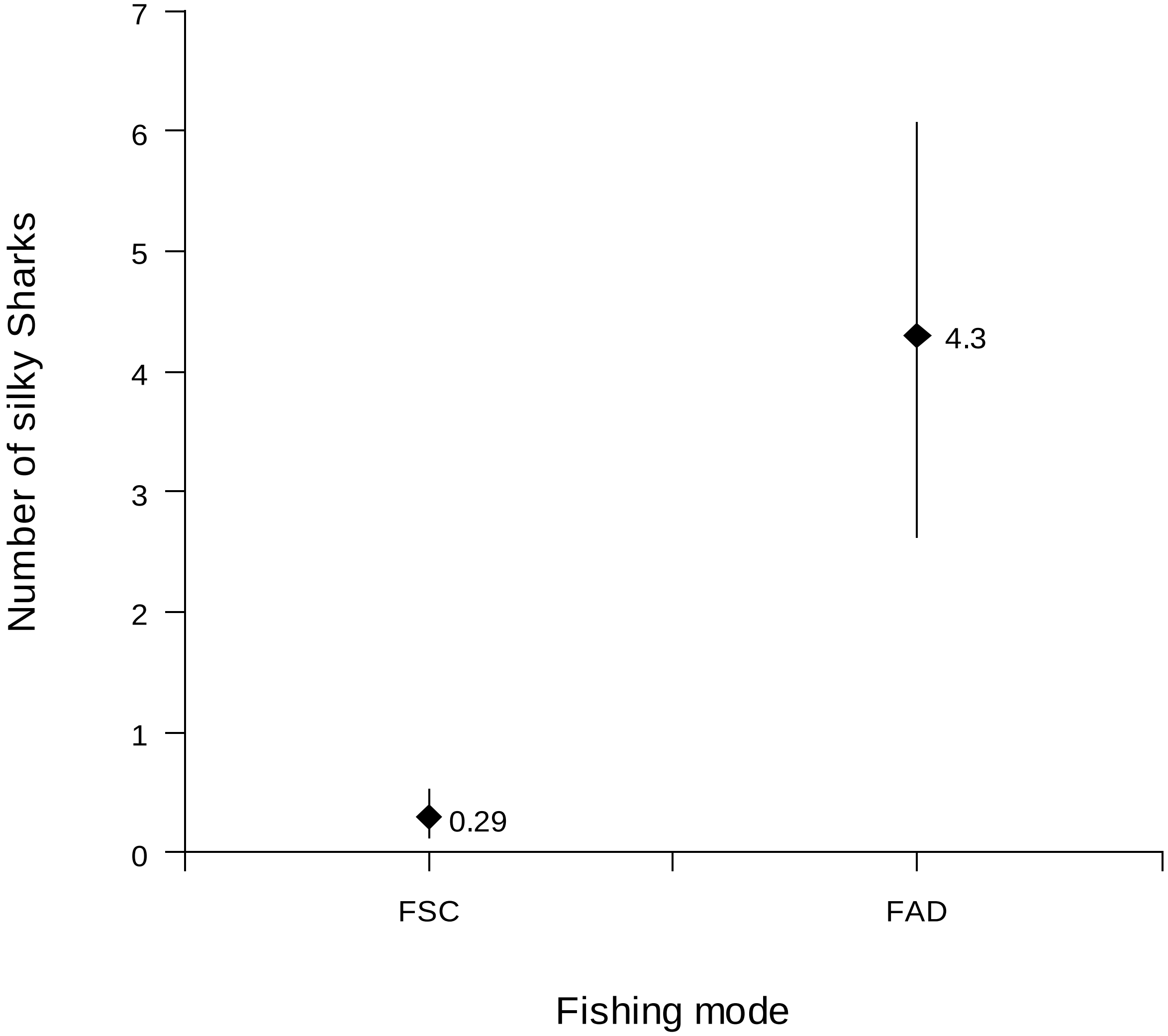


Fig. 3**.** Spatial distribution of observed fishing sets per statistical rectangle of 1° latitude and 1° longitude in the Western Indian Ocean, FSC = Free school (lightgrey), FAD = Fishing aggregating device- associated school (darkgrey). Solid lines define "ET" areas



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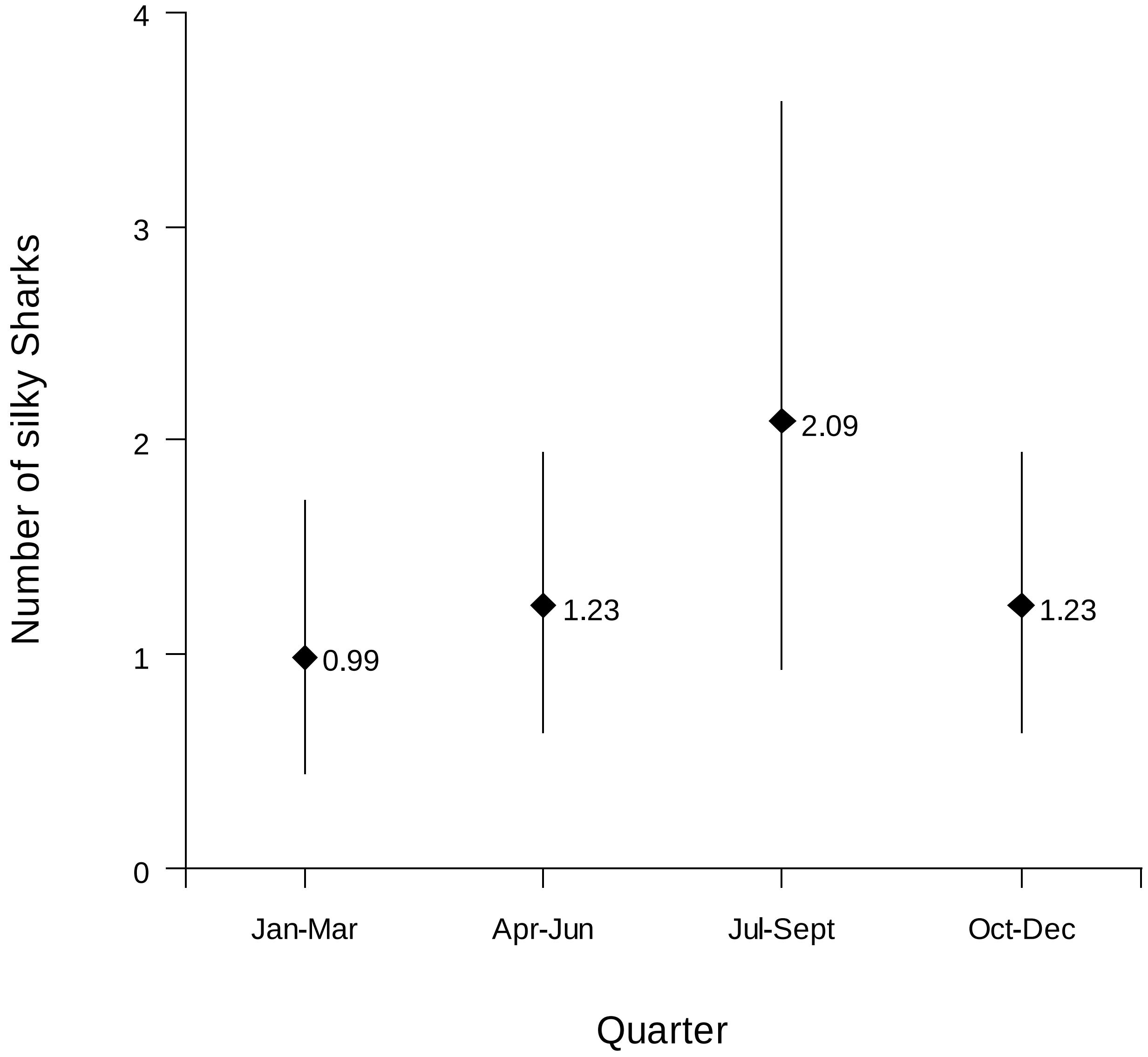

Fig. 5. Predicted number of silky sharks per set for each season of the year. Solid line indicates the 95% confidence interval

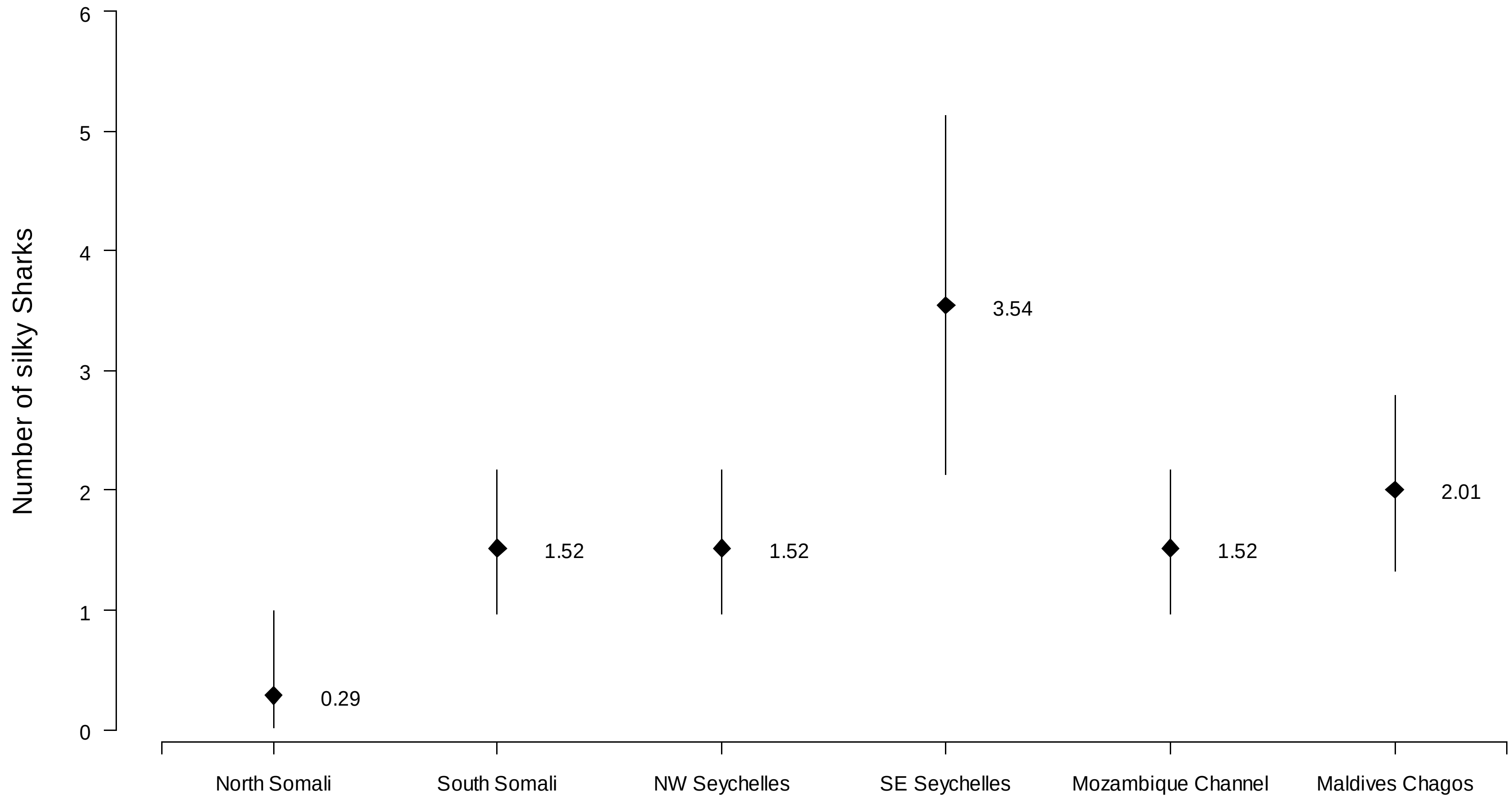

Fig. 6. Predicted number of silky sharks per set for each Western Indian Ocean area considered in the study. Solid line indicates the 95% confidence interval

Table I. Number of fishing sets per strata observed during 0ctober 2005 to January 2008

		ET Areas						
Fishing mode	Quarter	NW Seychelles	SE Seychelles	Mozambique Channel	Maldives Chagos	North Somali	South Somali	Total
FSC	Jan - Mar	8	42	6	35	26	18	135
	Apr - Jun	39	30	36	-	-	-	105
	Jul - Sept	30	-	-	-	-	23	53
	Oct - Dec	26	90	-	24	-	34	174
	Total FSC	103	162	42	59	26	75	467
FAD	Jan - Mar	18	9	3	7	6	6	49
	Apr - Jun	12	10	13	-	-	2	37
	Jul - Sept	9	-	-	-	-	19	28
	Oct - Dec	33	23	-	10	1	37	104
	Total FAD	72	42	16	17	7	64	218
Total		175	204	58	76	33	139	685

Table II. Estimates of coefficients, standard errors (se) and 95% confidence interval for the zero inflated regression model. Significant coefficients are marked by xxx

	Covariates		**Mean**	**se**	**2.5%**	**97.5%**	**Significance**
p	Intercept		-1.29	0.21	-1.72	-0.91	xxx
	Fishing mode	FSC	-1.56	0.12	-1.81	-1.33	xxx
		FAD	1.56	0.12	1.33	1.81	xxx
	Quarter	Jan - Mar	-0.61	0.23	-1.08	-0.17	xxx
		Apr - Jun	0.07	0.24	-0.40	0.53	-
		Jul - Sept	0.69	0.28	0.15	1.24	xxx
		Oct - Dec	-0.15	0.18	-0.51	0.21	-
	Area	North Somali	-1.35	0.71	-2.92	-0.14	xxx
		South Somali	0.46	0.30	-0.11	1.06	-
		NW Seychelles	0.30	0.26	-0.22	0.82	-
		SE Seychelles	0.29	0.28	-0.25	0.85	-
		Mozambique Channel	0.04	0.21	-0.54	0.36	-
		Arabian sea	0.27	0.34	-0.12	1.08	-
μ	Intercept		1.85	0.12	1.57	2.07	xxx
	Fishing mode	FSC	-0.15	0.04	-0.23	-0.07	xxx
		FAD	0.15	0.04	0.07	0.23	xxx
	Quarter	Jan - Mar	0.29	0.06	0.14	0.40	xxx
		Apr - Jun	-0.33	0.14	-0.49	0.20	-
		Jul - Sept	0.13	0.09	-0.12	0.26	-
		Oct - Dec	-0.09	0.06	-0.24	0.01	-
	Area	North Somali	-0.88	0.42	-1.75	-0.28	xxx
		South Somali	0.02	0.13	-0.21	0.29	-
		NW Seychelles	0.26	0.15	-0.10	0.55	-
		SE Seychelles	0.84	0.19	0.44	1.20	xxx
		Mozambique Channel	-0.16	0.16	-0.46	0.16	-
		Arabian sea	0.28	0.13	0.04	0.55	xxx
P (imperfect state)			0.24	0.01	0.21	0.26	xxx
Bycatch mean | imperfect state			7.42	0.37	6.67	8.13	xxx
ZIP mean			2.02	0.05	1.91	2.13	xxx
Probability of zero bycatch			0.76	0.01	0.74	0.79	xxx