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Precision in bycatch estimates: the case of tuna purse-seine fisheries in the Indian Ocean

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Estimating bycatch, i.e. the incidental catch of non-target marine animals and undersized individuals of target species, by raising observer data to the whole fishery is routine practice. The annual bycatch of the European tropical tuna purse-seine fishery over the period 2003–2009 was estimated at 11 590 t [95% confidence interval: (8165–15 818 t)], corresponding to 4.7% of the tuna landings. An analysis of the variability in the precision of this estimate, based on generalized linear models and Monte Carlo simulations, showed that the current sampling coverage of the tropical tuna fishery observer programme, which is 4.6% of the fishing trips, resulted in large uncertainties in bycatch estimates by species, i.e. none of the estimates have a relative root mean square error smaller than 50%. Although the overall magnitude of bycatch of the fishery appeared to be small, the current sampling coverage was insufficient to give any reliable estimate for low-occurring species, such as marine turtles, some oceanic pelagic sharks, and some billfishes. Increasing the sampling coverage would likely improve bycatch estimates. Simulation outputs were produced to help define (i) trade-offs between the priority species to be monitored, (ii) the estimation precision, (iii) expected accuracy, and (iv) the associated sampling costs.

Keywords: Bycatch, fishery observer programme, precision, purse-seine, tropical tuna.

Introduction

In addition to its direct impact on the abundance and productivity of targeted fish stocks, fishing has been shown to affect marine ecosystems through modifications in community structure and diversity, changes in trophic interactions, degradation of benthic habitat, and increasing mortality of unwanted bycatch species (Jennings and Kaiser, 1998). The ecosystem approach to fishery management (EAFM), initiated with the 1995 FAO code of conduct for responsible fisheries and promoted by several international agreements and frameworks, calls for ecosystem considerations to be consistently included in fishery management policy (Pikitch *et al.*, 2004). One of the major operational objectives of EAFM is to reduce bycatch, i.e. the incidental catch of non-target marine animals and undersized individuals of target species (Crowder and Murawski, 1998; Garcia *et al.*, 2003; Davies *et al.*, 2009). However, several major difficulties are associated with the assessment of global levels of commercial fisheries bycatch and discards, mainly due to the lack of available information for most fisheries. The average overall annual discards (i.e. bycatch discarded at sea) during the 1990s have been tentatively estimated at 7.3 million t (Kelleher, 2005), while few attempts have been undertaken for global fisheries bycatch, with the notable exception of the highly discussed study of Alverson *et al.*, (1994). Overall, levels of bycatch and discards have been shown to be fishery-specific, to display strong variations in space and time, and are explained by several compound factors, including technical, economic, environmental, and management measures (Stratoudakis *et al.*, 1999; Hall *et al.*, 2000; Kelleher, 2005; Rochet and Trenkel, 2005). Bycatch and discard issues have received increasing attention in recent decades (Ye *et al.*, 2000; Soykan *et al.*, 2008), particularly since regional fisheries management organizations (RFMOs) have established subcommittees and working groups for analyzing the overall ecosystem effects of fishing, and since regional observer programmes have been developed to monitor the magnitude of fisheries bycatch and discards (Gilman, 2011).

During the late 2000s, tuna fisheries have represented more than 4.1 million t of the global fisheries catches and have been dominated by three fishing gears, i.e. purse-seine, longline, and pole and line, accounting for about 60, 15, and 11% of the world tuna catches respectively (FAO, 2012). The European tuna purse-seine fishery has been operating in the Indian Ocean to target yellowfin (*Thunnus albacares*), skipjack (*Katsuwonus pelamis*), and bigeye (*Thunnus obesus*) tuna since the early 1980s. Over the last decade, the total catches of the principal market tuna species of the European purse-seine fishery reached a maximum of about 400 000 t in 2003 and have fluctuated around 250 000 t in recent years (Pianet *et al.*, 2010).

Tuna purse-seine bycatch rates have been shown to be low (Amandè *et al.*, 2010) in comparison to other fishing gears, such as longlines, that can result in substantial levels of bycatch (Liu *et al.*, 2009). For example, shark discards relative to tuna landings have been estimated to be 60–90% for some longline pelagic fisheries (Harrington *et al.*, 2005). Nevertheless, bycatch in tuna purse-seines is comprised of a large variety of species, including sea turtles, rays, sharks, and marine mammals, which indicates the need for careful monitoring (Romanov, 2002; Lennert-Cody *et al.*, 2004; Amandè *et al.*, 2010; Gilman, 2011). The magnitude and species composition of bycatch depend on the fishing practice used by tuna purse-seiners. Fish-aggregated-device (FAD)-associated sets lead to a higher (about 90% of the total) bycatch and discard occurrence than free-swimming school sets (Fonteneau *et al.*, 2000; Sánchez *et al.*, 2007; Amandè *et al.*, 2010). Since 2001, the European Union (EU) has established a mandatory observer programme within the Data Collection Framework [DCF, Reg (EC) 1543/2000 and 199/2008] to monitor the impacts of fishing. A target sampling coverage rate of 10% of the fishing trips has been recommended to estimate the magnitude of bycatch by tuna RFMOs (T-RFMOs), namely by the ICCAT (International Commission for the Conservation of Atlantic Tunas) and IOTC (Indian Ocean Tuna Commission), on the basis of previous work showing that a minimum of 20% is needed to obtain acceptable levels of bycatch estimation (Lennert-Cody, 2001). Without the notable exception of Sánchez *et al.*, (2007), who focused on shark bycatch estimation in the EU tuna purse-seine fishery, no study has been conducted to date to assess the efficiency and limits of this observer programme. Precision and accuracy of bycatch estimates based on the current observer sampling design might, however, depend on several biological, ecological, and environmental factors that might affect our perception of fishing effects on open-sea ecosystems.

One may distinguish between several types of biases. The "purely statistical" biases are a result of the statistical distributions of bycatch and of the survey schemes. These biases are the focus of the present paper. But there are other sources of potential biases not considered in this paper, because they are more difficult to handle quantitatively. For example, biases could be introduced by changes in fishing practices of vessels when an observer is on board and/or by the inexperience, negligence, or intentional actions of some observers. Many of these biases result from the difficulty or impossibility of following a solid statistical design, so the observer programmes "adapt" to the deficiencies.

The present analysis focuses on the European purse-seine fishery in the Indian Ocean (IO) to address the major issue of estimating fishery removals of non-target, associated, and dependent species. As well as providing insights into the precision and accuracy of bycatch estimates for the European purse-seine fishery in the IO, the study examines an applied ecology problem of immediate policy concern for the IOTC as it offers a flexible methodological framework for assessing the expected results of its regional observer scheme adopted in July 2010 for the monitoring of IO bycatch species (IOTC, 2010). Data collected during the European observer programme since 2003 were used to (i) estimate the annual bycatch for marine pelagic taxonomic groups and species of the European purse-seine fishery in the IO, based on simple raising procedures; (ii) analyse the relative error and bias of the bycatch estimates as a function of sampling coverage and of two indices describing the species bycatch statistical distribution; and finally (iii) provide guidelines into the levels of observer coverage required to accurately and precisely estimate species bycatch so as to reconcile current sampling strategies with the sustainable management and conservation objectives promoted by tuna RFMOs.

Material and methods

Fishery observer data

The collection of observer data aboard European purse-seiners targeting tropical tunas in the IO has been conducted on Spanish vessels since 2003 by the Instituto Español de Oceanografía (IEO) and the AZTI-Tecnalia (AZTI) following similar protocols, and since 2005 on French vessels by the Institut de Recherche pour le Développement (IRD).

The tropical tuna purse-seine fishery is characterized by two types of fishing operations: (i) sets performed on free-swimming tuna schools (FSC), and (ii) sets made on tuna aggregations encountered around floating objects. Originally, all objects were of natural origin, and the sets were called log sets, but nowadays a majority of sets are made on objects deployed by the fishermen called fish aggregating devices (FADs). The acronym FAD is here generic and embraces both natural objects (e.g. logs, palm branches) and anthropogenic floating objects, such as man-made bamboo rafts equipped with radio-range beacons, satellite transmitters, or scanning sonars (Dempster and Taquet, 2004). A very small proportion of the sets are made on live whales, here classified as FSC sets, whereas sets on whale sharks (*Rhincodon typus*) and dead whales were classified as FAD sets (Gaertner *et al.*, 2002). Bycatch is defined as all non-targeted species plus juveniles of targeted tuna species (Figure 1). The bycatch component rejected dead or alive at sea is termed "discard". The fraction of bycatch kept on board for utilization, i.e. for consumption on board or selling at local markets, is termed "by-product". The principal market for tropical tuna species primarily targeted by the EU purse-seine fishery, i.e. yellowfin, skipjack, and bigeye that are landed and mostly marketed through canneries, represent the "landings".

Data were collected by observers aboard tuna purse-seiners during 115 trips and 4020 days-at-sea involving a total of 3052 sets in the IO during 2003–2009. The overall coverage rate was 4.6% of the total number of trips, and increased from 1.7% in 2003 to 9% in 2007, before decreasing to 4% in 2009 due to Somali piracy acts that prevented the boarding of observers for security reasons (Chassot *et al.*, 2010). The fishing sets were

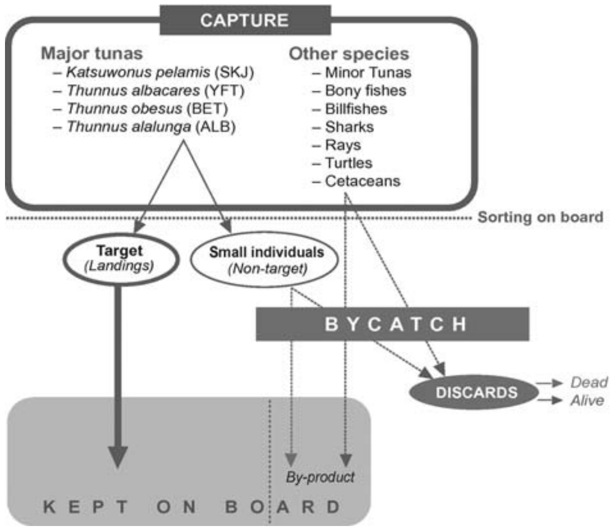

Figure 1. Conceptual scheme defining the terms used in the present study and describing the origin and fate of organisms caught aboard fishing vessels.

categorized into FAD and FSC sets on the basis of direct information reported by observers. The overall observer data included 1548 FSC and 1504 FAD sets, corresponding to an observed tuna catch of 30 626 and 42 551 t, respectively. Species caught were identified and sorted whenever possible. Genus or family names were used when organisms could not be identified at the species level. Observers generally reported numbers of individuals and average length or weight by species in each fishing set, or estimated total weights of each bycatch species when marine animals were too numerous. Species-specific length–weight parameters were applied to convert numbers of individuals into weights. The parameters used here came generally from FishBase (Froese and Pauly, 2012) when available and also from past observer programmes conducted in the European tropical tuna fishery. The overall bycatch species composition in weight by fishing mode (FSC and FAD) was derived from all observed sets pooled together over the entire period (see Table 1).

Bycatch estimation

Bycatch in the European purse-seine fishery was estimated for the major taxonomic groups and species based on the ratio estimator method (Cochran, 1977; Thompson, 2002) that has been used in many fisheries and in many RFMOs as a simple, robust, and practical method to estimate bycatch (Hall and Boyer, 1986; Ye *et al.*, 2000; Borges *et al.*, 2005). The bycatch–over-landings ratio was used because (i) the major tuna landings are available in the logbook data, and (ii) this ratio offers the advantage of being comparable across fisheries regardless of the fishing method. Data were post-stratified according to fishing mode, as this has been shown to strongly affect bycatch magnitude and composition (Romanov, 2002; Dempster and Taquet, 2004; Amandè *et al.*, 2010). Bycatch values were recorded along with associated landings values in observer data. The ratio was calculated as follows:

$$R_{h,i} = \frac{x_{h,i}}{y_{h,i}} \qquad (1)$$

where $x_{h,i}$ is the total bycatch and $y_{h,i}$ the total tuna landings for the h^{th} fishing mode (i.e. FSC or FAD) and the i^{th} species or group of species. Assuming a linear relationship between total bycatch and total landings, the ratio estimate of the population total of the i^{th} bycatch species or group of species is then given by:

$$\hat{X}_i = \sum_{h=1}^{2} R_{h,i}.Y_h \qquad (2)$$

where Y_h is the total tuna landings conditionally to the fishing mode h. Confidence intervals for each species group were calculated using a non-parametric bootstrap procedure (Efron and Tibshirani, 1993) using the R statistical software (R Development Core Team, 2009).

Uncertainty and bias in bycatch estimates

Non-parametric bootstrap was used to assess precision and bias of bycatch estimates as a function of the coverage rate. Considering the observer dataset as the fishery universe, pseudo observer data were generated by uniform random sampling of trips without replacement to mimic the real sampling process for various coverage rates j, going from 3 to 90%. For each pair of species i, and sampling coverage level j, the procedure was repeated 10 000 times to obtain a sufficient number of independent samples. For the k^{th} pseudo observer dataset, the estimate of total bycatch was calculated according to Equations (1) and (2) and denoted $\hat{X}_{ijk}$. Precision of the bycatch estimate was assessed through the mean square error MSE. The relative root mean square error (RRMSE), obtained by dividing the root of the MSE by the true value of the total bycatch, is a normalized indicator that enables comparison of the accuracy of the total bycatch estimates. The RRMSE for species i and coverage level j was computed as follows:

$$RRMSE_{i,j} = \frac{\sqrt{MSE_{i,j}}}{X_i} = \frac{\sqrt{\frac{1}{10000}\sum_{k=1}^{10000}(\hat{X}_{ijk} - X_i)^2}}{X_i} \qquad (3)$$

In the same way, the relative bias (RBIAS), obtained by dividing the bias by the true value of the total bycatch, was computed for species i and coverage level j as:

$$RBIAS_{i,j} = \frac{E[\hat{X}_{ijk}] - X_i}{X_i} \qquad (4)$$

where $E[\hat{X}_{ijk}]$ is the expectation of the estimates resulting from the bootstrap procedure.

Several technical (e.g. gear selectivity) and ecological (e.g. schooling behaviour) factors are likely to affect the nature and levels of fishery bycatch (Rochet and Trenkel, 2005). Non-target species catch distributions have many zero-valued observations, but their positive count distributions are generally different from one species to another, depending on species ecology and aggregative behavior (e.g. Minami *et al.*, 2007). For example, some gregarious species, such as silky sharks (*Carcharhinus falciformis*) or dolphin fishes (*Coryphaena hippurus*), can sometimes occur in fishing sets in high abundance (Ward and Myers, 2005), while solitary species, such as oceanic whitetip sharks (*Carcharhinus longimanus*), occur in fishing sets with no more than two or three individuals. To generalize our modelling approach, two simple and generic indices were used as proxies of the characteristics of each bycatch species distribution: the proportion of fishing sets

Table 1. Observed bycatch composition in weight according to fishing mode.

Species group	Scientific name	Species code	FSC[b] Weight[a] (in tonnes)	FSC[b] % within group	FAD[c] Weight[a] (in tonnes)	FAD[c] % within group	Total Weight[a] (in tonnes)	Total % within group
Tunas	*Katsuwonus pelamis*	SKJ	98.58	29.94	693.44	42.39	792.02	40.31
	Auxis thazard	FRI	122.17	37.11	558.52	34.14	680.69	34.64
	Auxis rochei	BLT	64.14	19.48	149.10	9.12	213.24	10.85
	Thunnus albacares	YFT	18.28	5.55	124.25	7.60	142.52	7.25
	Auxis sp.	FRZ	3.23	0.98	68.45	4.18	71.68	3.65
	Thunnus obesus	BET	8.69	2.64	33.04	2.02	41.73	2.12
	Euthynnus affinis	KAW	13.69	4.16	8.78	0.54	22.47	1.14
	Thunnus alalunga	GER	0.46	0.14	0.00	0.00	0.46	0.02
	Euthynnus alletteratus	LTA	0.00	0.00	0.15	0.01	0.15	0.01
	Total tunas		**329.24**	**100.00**	**1 635.73**	**100.00**	**1 964.96**	**100.00**
Bony fishes	*Elagatis bipinnulata*	ELP	45.62	41.72	273.83	31.27	319.45	32.43
	Coryphaena hippurus	COH	16.66	15.24	259.58	29.64	276.24	28.04
	Canthidermis maculatus	BCM	16.45	15.04	122.19	13.95	138.64	14.07
	Acanthocybium solandri	WAH	5.63	5.15	61.56	7.03	67.19	6.82
	Others	–	24.98	22.84	158.65	18.12	183.63	18.64
	Total bony fishes		**109.33**	**100.00**	**875.81**	**100.00**	**985.15**	**100.00**
Sharks	*Carcharhinus falciformis*	CFA	25.50	55.38	156.77	68.09	182.28	65.97
	Requin non identifié	REX	15.75	34.20	34.60	15.03	50.35	18.22
	Carcharhinidae	FCA	1.86	4.04	27.40	11.90	29.26	10.59
	Carcharhinus longimanus	CLO	1.76	3.82	5.59	2.43	7.35	2.66
	Others	–	1.18	2.56	5.88	2.55	7.06	2.55
	Total sharks		**46.05**	**100.00**	**230.24**	**100.00**	**276.30**	**100.00**
Billfishes	*Makaira indica*	BLM	6.17	31.23	16.49	33.09	22.66	32.56
	Tetrapturus audax	STM	6.70	33.92	12.51	25.10	19.21	27.60
	Istiophoridae	FIS	2.30	11.66	8.89	17.83	11.19	16.08
	Xiphias gladius	SWO	1.46	7.40	7.69	15.43	9.15	13.15
	Makaira nigricans	BUM	2.79	14.09	4.19	8.41	6.97	10.02
	Tetrapturus angustirostris	SHS	0.33	1.69	0.07	0.14	0.41	0.58
	Total billfishes		**19.76**	**100.00**	**49.83**	**100.00**	**69.59**	**100.00**
Rays	*Manta birostris*	MBA	3.50	31.93	3.60	51.76	7.09	39.62
	Mobula mobular	MOM	3.85	35.13	0.75	10.80	4.60	25.69
	Mobula coilloti	MCO	1.50	13.69	1.65	23.75	3.15	17.59
	Mobula rancurelli	MRA	1.05	9.58	0.35	5.04	1.40	7.82
	Others	xxx	1.06	9.68	0.60	8.65	1.66	9.28
	Total rays		**10.96**	**100.00**	**6.95**	**100.00**	**17.91**	**100.00**
Turtles	*Lepidochelys olivacea*	LOL	0.07	57.57	0.00	0.00	0.07	50.04
	Chelonia mydas	CMM	0.03	22.29	0.00	0.00	0.03	19.37
	Caretta caretta	CCC	0.02	20.15	0.00	0.00	0.02	17.51
	Lepidochelis kempii	LKE	0.00	0.00	0.02	100.00	0.02	13.08
	Total turtles		**0.12**	**100.00**	**0.02**	**100.00**	**0.14**	**100.00**
TOTAL			**515.46**	–	**2 798.58**	–	**3 314.04**	–
% of total bycatch			**15.55**	–	**84.45**	–	**100.00**	–

[a]Weights refer to the cumulative bycatch over the period (2003–2009). Marine mammals and whale sharks are not included.
[b]FSC = free swimming school.
[c]FAD = fish aggregating device.

with at least one individual of species i (p_i) and the Gini index of positive values of species i (G_i). The Gini index measures distribution heterogeneity. The Gini index was preferred to the variance of bycatch distribution as it is normalized and, therefore, enables comparison of species characteristics. G_i was calculated on the basis of positive values of non-target catch as follows:

$$G_i = \frac{1}{n}\left(n + 1 - 2.\frac{\sum_{l=1}^{n}(n+1-l).x_{il}}{\sum_{l=1}^{n}x_{il}}\right) \quad (5)$$

where x_{il}, $l = \{1{:}n\}$ denotes the observed positive values of species i, indexed in increasing order, i.e $x_l \leq x_{l+1}$.

The relationship between the RRMSE and the covariates, i.e. the sampling coverage C_j and the bycatch statistical characteristics summarized by p_i and G_i indices, was assessed using a generalized linear model (GLM) with an inverse-gamma link seeming to be consistent with the distribution of the RRMSE. Second-order interactions were considered in the model. In a final step, a simple interpolation by inverse distance allowed mapping the predicted RRMSE at the 10% target level of observer coverage in the two-dimensional space defined by the vector (p, G). A principal component analysis allowed analysing the links between RBIAS and RRMSE and how both varied over the different taxa.

Four species, chosen from different taxonomic groups and characterized by contrasted ecological characteristics, namely silky shark (*Carcharhinus falciformis*), pelagic stingray (*Dasyatis*

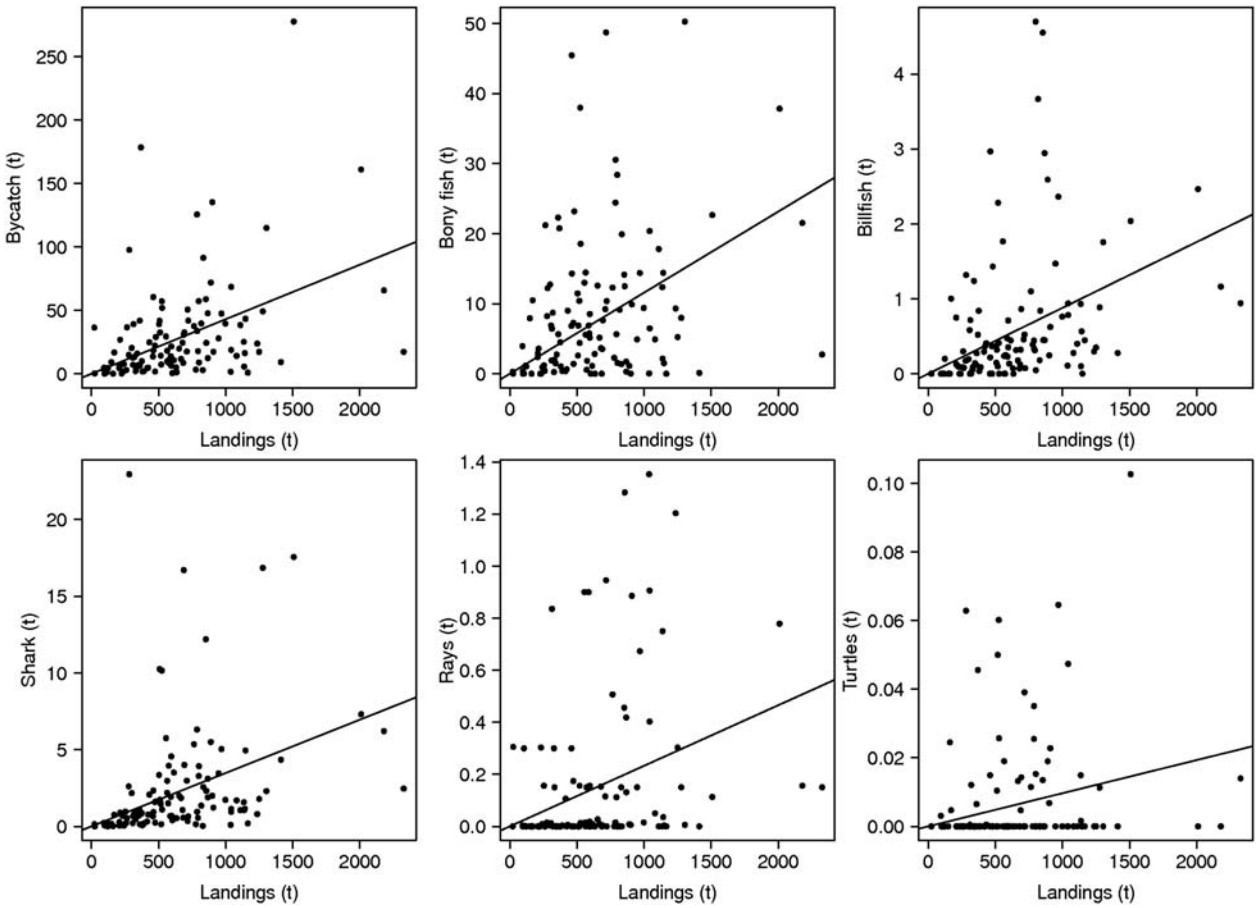

Figure 2. Relationship between total bycatch (all or by taxonomic groups) and total tuna landings in all observed trips.

violacea), Kemp's ridley sea turtle (*Lepidochelys kempii*), and white marlin (*Tetrapturus albidus*), were considered to relate the predicted values of RRMSE. These species were arbitrarily chosen to illustrate the trend of the RRMSE with regard to different sampling coverage rates and associated costs. We considered a cost of 200 € per day, which is the actual daily cost of the observer programme endorsed by IRD (P. Chavance, pers. comm.).

Results

Relationship between bycatch and tuna landings

At the trip level, all linear regressions between total tuna landings and bycatch separated into taxonomic groups were statistically different from zero with, however, low r^2 for rays and turtles (Figure 2 and Table 2). The simulation results indicated that biases were very low compared to the uncertainty in bycatch estimates (Figure 3).

Bycatch in the tuna purse-seine fishery

The European tuna purse-seine fishery total annual bycatch in the IO, over the period 2003–2009, was estimated at about 11 592 t [95% confidence interval: (8165–15 818 t)] corresponding to 47.3 t per 1000 t of tuna landed. Bycatch of marine species was mostly observed for FAD sets, which accounted for about 85% of the incidental catch. A similar pattern was observed for all taxonomic groups, except for rays, which were mostly caught on free-swimming school sets (Table 3). Regarding rays, this difference was due to *Mobula* spp. that were caught more frequently in FSC sets

Table 2. Summary of the linear regression models ($Y = aX + \varepsilon$) to analyse the relationship between the overall bycatch by taxonomic groups and the total tuna landings.

	a	s.d.	*t*-value	Pr(>|t|)	r^2
Bycatch	0.06423	0.00539	11.91	0.000	0.57
Bony fishes	0.01691	0.00158	10.68	0.000	0.51
Shark	0.00114	0.00013	9.07	0.000	0.43
Billfishes	0.00473	0.00050	9.48	0.000	0.45
Rays	0.00019	0.00003	6.14	0.000	0.26
Turtles	0.00002	0.00000	5.67	0.000	0.23

and constituted 73% of the total ray catch in weight, while the pelagic stingrays and manta rays (the most frequent species) were very common in FAD sets. Skipjack juveniles as well as frigate (*Auxis thazard*) and bullet (*Auxis rochei*) tunas predominated in the tuna bycatch and comprised about 59% of the total bycatch, corresponding to a mean annual value of 28 t per 1000 t of tuna landings (Tables 1 and 2). The remaining 41% of the bycatch was composed of different taxonomic groups, each being dominated by a few species. Bony fishes were dominated by rainbow runner (*Elagatis bipinnulata*) and dolphinfish (*Coryphaena hippurus*) and represented a total of about 30% of the bycatch, i.e. corresponding to 14.2 t per 1000 t of the landings. The silky shark represented more than 65% of the overall shark group and reached an average value of 8.3% of the total bycatch biomass. Bycatch of billfishes only represented about 1.0 t per

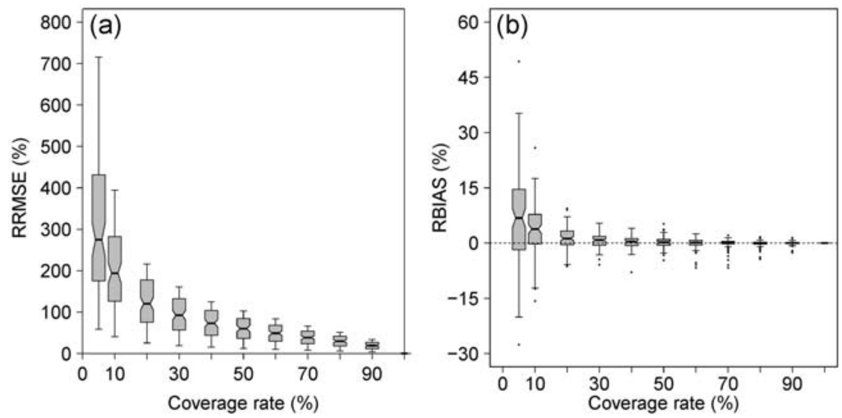

Figure 3. Distribution of the relative root mean square error (RRMSE) (a) and the relative bias (RBIAS) (b) of all bycatch species estimates conditionally to the observer sampling coverage.

Table 3. Annual landings and estimates of bycatch by species group for the European tuna purse-seine fishery of the Indian Ocean.

	FSC		FAD		Total	
	T	t/ 1 000t	T	t/ 1 000t	T	t/ 1 000t
Total catch	94 378		162 472		256 849	
Production	92 812		152 446		245 257	
Total bycatch	1 566	16.9	10 026	65.8	11 592	47.3
Tunas	1 000	10.8	5 859	38.4	6 858	28.0
Bony fishes	333	3.6	3 137	20.6	3 469	14.2
Sharks	140	1.5	825	5.4	965	3.9
Billfishes	60	0.7	179	1.2	239	1.0
Rays	33	0.4	25	0.2	58	0.2
Turtles	0	0.0	2	0.0	3	0.01

Average year representing 2003–2009. FSC = free swimming school; FAD = fish aggregating device; t/1000t = bycatch in t per thousand t of tuna landings.

1000 t of the tuna landings, while the levels of bycatch of rays and turtles were small, i.e. about 0.2 t and <0.01 t per 1000 t of the landings, respectively. Marine mammals occurred in less than 1% of the observed sets and were always released alive without being brought on board the vessel, resulting in no direct mortality due to the impact of the purse-seine operations. Turtles were also generally discarded alive, but no specific action was conducted to collect information on the survival rates of the released animals.

Uncertainty and bias in bycatch estimates

Uncertainty in bycatch estimates was strongly dependent on observer coverage and the ecological characteristics of the pelagic species of interest. Almost 85% of the total variability in RRMSE was explained by the GLM (Table 4). The observer coverage rate and the percentage of positive bycatch in sets were the main significant factors affecting precision and accuracy in bycatch estimates, with about 70 and 10% of the total variability explained, respectively. The effect of the Gini index was also significant, but explained a small percentage of deviance (0.21%). The correlation between RRMSE and the sampling coverage rate was strong, significant, and negative: the higher the sampling coverage, the lower the error in bycatch estimates for a species. For each coverage rate, the RRMSEs were also highly different between species (Table 4 and Figure 4).

The simulation outputs showed that bias was 20-fold lower than RRMSE for the different taxa. Bias increased for smaller sample sizes and was generally positive; meaning that bycatch was overestimated, particularly when observer coverage was lower than 30% (Figure 3).

Considering a target sampling rate of 10%, the expected best estimates for one bycatch species would be characterized by a relative root mean error of about 40–50% (Figure 4). In addition, more than 90% of the species incidentally caught by purse-seiners would be poorly estimated with an RRMSE larger than 50% (Figure 5). A minimum of 90% sampling coverage would be required to estimate 50% of the bycatch species with a relative error less than 20%. If the observer programme targeted an RRMSE up to 50% for all bycatch species, almost all fishing trips would have to be observed. In contrast, only 40% of the bycatch species would be estimated with an RRMSE up to 50% if sampling coverage were limited to 50% (in the case of a financial constraint allowing only 1.75 M€ for observer data collection). Overall, our results show that the current 10% coverage rate targeted by the European purse-seine fishery is sufficient for estimating the bycatch of silky shark with an RRMSE lower than 50%. However, this coverage rate would yield larger RRMSEs for pelagic stingray, Kemp's ridley sea turtle, and white marlin, for which a respective minimum of 20, 70, and 80% coverage, respectively, would be necessary to comply with an RRMSE of 50% (Figure 5).

The first plane of the principal component analysis explained 74% of the total variability, with 48 and 26% for the first and second axes, respectively. The first axis contrasted species with higher RRMSE to those with lower RRMSE, higher occurrence, and higher Gini index. The second axis contrasted the species estimated with respectively large and low bias. The bias was not correlated either with the statistical characteristics of bycatch (occurrence, heterogeneity) or with the precision of the estimation (Figure 6).

Discussion

We used a large observer fishery dataset collected during the 2000s to provide a first estimate of the bycatch of pelagic taxonomic

Table 4. Regression coefficients and analysis of variance (ANOVA) of the generalized linear model explaining the RRMSE as a function of the coverage (*C*), the percentage of positive occurrence (*p*), the conditional Gini index (*G*) and their interaction factors (see text for details).

Regression coefficients				Analysis of variance						
	Estimate	s.e.	Pr(>|t|)		d.f	Deviance	Resid. d.f.	Resid. Dev	P(>|Chi|)	Explained variance (%)
(Intercept)	0.00099	0.00009	$<$0.001	Null	–	–	1 311	1 271.07	–	–
C	0.00023	0.00001	$<$0.001	*C*	1	901.47	1 310	369.65	0	70.92
p	0.08890	0.01259	$<$0.001	*p*	1	116.88	1 309	252.77	$<$ 0.001	9.20
G	0.00065	0.00025	0.008	*G*	1	2.66	1 308	250.17	$<$ 0.001	0.21
C : p	0.01674	0.00091	$<$0.001	*C : p*	1	39.50	1 307	210.67	$<$ 0.001	3.11
C : G	0.00016	0.00002	$<$ 0.001	*C : G*	1	2.58	1 306	208.06	$<$ 0.001	0.20

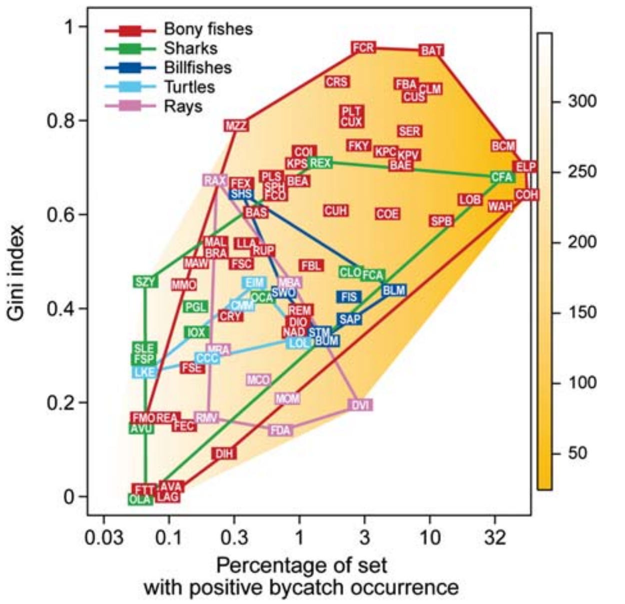

Figure 4. Relative root mean square error (RRMSE) of bycatch estimates as a function of positive occurrence (x-axis) and conditional Gini index (y-axis). The grey levels indicate the RRMSE at 10% sampling coverage. Colored straight lines delimit predator guilds (bony fishes, sharks, billfishes, turtles, and rays). Individual species are represented by their alphabetic codes (see Table 1 for species codes).

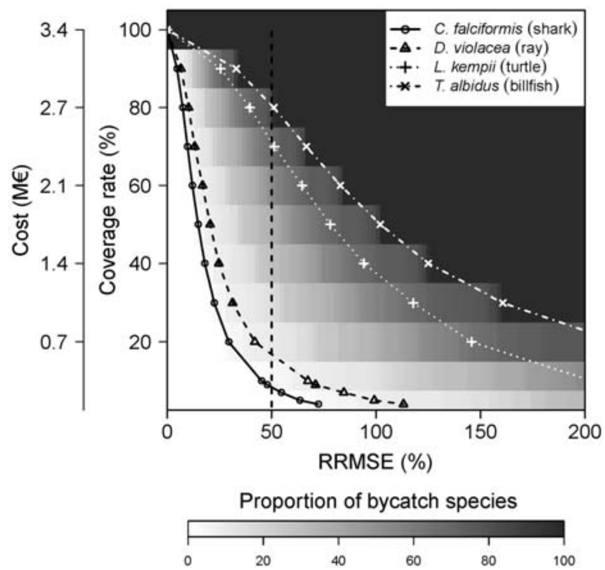

Figure 5. Proportion of bycatch species (color gradient) estimated with a given RRMSE (x-axis) according to the sampling costs (y-axis), considering constant marginal cost of the observer sampling coverage.

groups and species of the European tropical tuna purse-seine fishery in the IO. An overall ratio of bycatch vs. tuna landings was estimated to be 4.7% [95% confidence interval: (3.3–6.5%)] corresponding to a mean annual bycatch of about 11 592 t [95% confidence interval: (8165–15 818 t)] dominated by juveniles of skipjack tuna. The majority of non-target species is caught in fishing sets associated with FADs. Our findings also show that current target rates of observer coverage result in very large uncertainties around bycatch estimates for a large range of marine species, which might hinder a careful monitoring of open-sea pelagic communities. Precision and accuracy in bycatch estimates highly depend on observer sampling coverage and characteristics of the marine species. Bias was shown to be uncorrelated to the bycatch species and negligible in comparison to the RRMSE. At the scale of the taxonomic groups and overall pelagic community, very large coverage rates (i.e.$>$90%) are required to reach relative root mean square errors of about 20%. Overall, our results indicate that the current European fishery observer programme provides some information on bycatch of marine predators in the Indian Ocean, but is insufficient to accurately monitor the effects of fishing on pelagic communities associated with tuna schools. It is the role of managers and stakeholders to (i) better define management objectives with regard to bycatch (e.g. identify priority target species, set levels of precision in estimates and/or magnitude of authorized discards), and (ii) define the observer coverage rates required to fulfill such management objectives. This would certainly lead to increasing observer coverage rates and associated costs for the EU, and this is also necessary for the current observer programme to become fully useful in addressing the questions of biodiversity conservation and sustainable management of pelagic predators within an ecosystem perspective. However, the efficiency of any observer programme in open-sea ecosystems will ultimately depend on the involvement and compliance of all types of fishing vessels from contracting and non-contracting parties of T-RFMOs whose vessels targeting tropical tunas also affect populations of non-targeted pelagic predators.

The overall bycatch rate of 4.7% of the major tuna landed was found to be lower in the IO than in the eastern Atlantic Ocean, where it was estimated to be about 8%, for the purse-seine

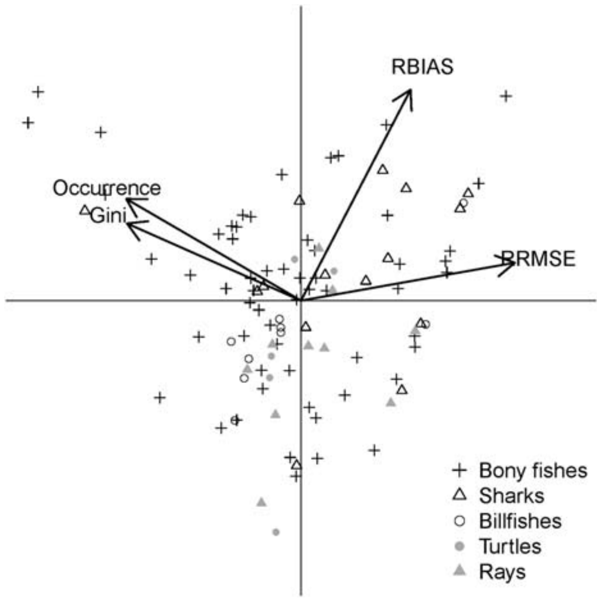

Figure 6. Principal component analysis of tropical tuna purse-seine fishery bycatch data.

fishery during the same period (Amandè *et al.*, 2010). Although the magnitude of bycatch in tropical tuna purse-seine fisheries is small, it can raise conservation issues because of the high diversity of non-target species that are incidentally caught, including some endangered and vulnerable species, such as turtles, sharks, and rays. Data collected from 2003 to 2009 by the French and Spanish observer programmes were pooled to increase the statistical material on which estimates were based. Neither temporal nor spatial stratifications were considered here, and data were only stratified according to fishing mode, on the basis of prior analyses for similar or comparable fisheries that showed quantitative differences in accidental catch between FAD and FSC sets (Gaertner *et al.*, 2002; Romanov, 2002; Amandè *et al.*, 2010). This post-stratification partially accounted for the difference between French and Spanish fishing strategies, the former predominantly seek FSC sets, while the latter extensively fish on FADs (Pianet *et al.*, 2010). Future work based on new datasets acquired through routine observer programmes will provide insights into the spatio–temporal variations in bycatch.

The ratio estimator method used to estimate overall bycatch is based on two main assumptions required for extrapolation. First, selected trips are supposed to be representative of the overall fishery data. Differences can, however, exist between observed and non-observed trips due to changes in fishers' strategies aimed at minimizing the impact of their activities on incidental catch when observers are on board (Hall, 1996, 1999; Benoît and Allard, 2009). For logistical reasons, the process of vessel selection for boarding observers was opportunistic and resulted in an over-representation of medium-size vessels (carrying capacity between 800 and 1200 t) in the observed trips over the total number of trips. This might not result in biased estimates in the analysis, since vessel size was shown not to affect the tuna species composition of the sets (Pallarés and Hallier, 1997). Second, the bycatch-over-landings ratio was assumed to be constant for each fishing mode (i.e. FSC sets vs. FAD sets), irrespective of all other factors amongst which time of day, season, area, vessel size, and/or vessel equipments are likely to play a role. The simulation study reported in this paper, however, indicated that bias was negligible in comparison to precision of the bycatch estimate that was strongly dependent on the sampling coverage rate. In this regard, the problem of the non-stationarity of the ratio used for the estimation appears to be secondary.

Because bycatch by species or taxonomic groups was not always highly correlated with total tuna landings, the ratio estimator is expected to be biased. However, the simulation results showed that biases were very low compared with uncertainty in bycatch estimates. The simulation outputs showed purely statistical biases that are the result of the ratio-estimator method, conditionally to the distributions of bycatch. These biases decreased when sampling coverage increased, but the bycatch data could be affected by other sources of biases due to the difficulty of a consistent statistical design for data collection. Detecting and removing the presence of these biases is, however, important for improving accuracy of bycatch estimates. Some operational biases may be detected by comparing trip characteristics (observed vs. unobserved) from landings or vessel-monitoring-system data. Differences in trip characteristics, such as duration, fishing grounds, species and size composition of observed and unobserved trips, could indicate some inaccuracy in the data and enable improvement in the current observer sampling design.

Precision in bycatch estimates depends on sampling coverage in the first instance. This is consistent with previous analyses that showed the impact of sampling coverage in the estimation of bycatch (Lennert-Cody, 2001; Babcock *et al.*, 2003; Sánchez *et al.*, 2007). However, uncertainty in bycatch estimates was also explained by the statistical characteristics of the distributions of each species taken as bycatch. With the objective to provide a generic approach, these distributions were summarized by the percentage of positive data values (p) and their homogeneity (G). In a management perspective, this means that setting a fixed value of sampling coverage for all bycatch species does not result in the same degree of confidence for all bycatch estimates. However, it is worth mentioning that, in the present case, the dominant bycatch species (e.g. *Elagatis bipinnulata*, *Coryphaena hippurus*, and *Carcharhinus falciformis*) are those that can be estimated with the highest precision. Our approach is transferable to other fisheries, particularly the eastern Atlantic Ocean purse-seine fishery, where almost all bycatch species are encountered with similar distributions.

Sampling coverage during the study period was about 4.6% of trips, i.e. less than half of the target rate of 10%. This coverage level is very low compared to the equivalent observer programmes in the eastern and western parts of the Pacific Ocean, which have been reaching almost 100 and 20% coverage, respectively (Hall, 1999; Lennert-Cody *et al.*, 2004). Consequently, almost all bycatch species are even more poorly estimated than expected. All the estimates were characterized by an RRMSE $>50\%$, which means that the true unknown quantities of bycatch can be somewhere between 0 and up to more than twice the estimate. This can have drastic consequences for pelagic groups, such as sharks, turtles, and rays, which have already been heavily impacted by fishing activities (Stevens *et al.*, 2000; Dulvy *et al.*, 2003; Lewison *et al.*, 2004).

We showed that the gain in precision (loss in RRMSE) associated with an increase in sampling coverage progressively increases as sampling coverage increases. Meanwhile, the cost of sampling increases linearly, so there is an optimal sampling coverage where costs induced by the increase in sampling coverage are balanced by gains in precision. However, the optimum value depends on the marginal willingness to pay associated with a unit of precision in estimates. It is the role of managers and stakeholders to set management objectives and their associated costs, and our approach mainly aimed to illustrate the expected outcomes of various potential management targets, i.e. levels of observer coverage or degree of precision in the overall or species-specific bycatch. Assessing the effects of changes in sampling coverage for a fleet-based observer programme might, however, be insufficient for adequately monitoring non-targeted pelagic species that can be harvested by various fishing gears across different spatio–temporal scales. Except for the notable exception of European purse-seiners, very little information on bycatch is currently available for most of the other tuna fisheries in the Indian Ocean, which, in turn, may jeopardize efforts to collect data consistently at the scale of the pelagic populations and communities needed to eventually implement spatial and technical measures to mitigate the adverse effects of fishing.

Another major challenging issue comes from developing countries with small-scale fisheries, which currently account for about 50% of the tuna catch in the IO, and which cannot implement observer programmes or increase sampling coverage due to financial or technical limitations. The implementation and compliance of regional observer programmes (e.g. those recently conducted at the ocean-basin scale by the IOTC, 2011) within T-RMFOs is then essential to improve data availability and accessibility for bycatch of marine species and for concurring with an ecosystem approach to fishery management. Meanwhile, the current level of the observer programme deployed in the IO can only provide a qualitative indication of the level of the bycatch-over-landings ratio. Beyond this baseline, an effort should be made to increase the current sampling coverage to improve the precision of bycatch estimates. The required level of coverage may be based on species of interest which are potentially vulnerable or endangered, knowing that rare and highly variable species can only be correctly estimated with a high level of coverage.

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