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Contribution to the Symposium: '*Fishery-Dependent Information*'

Original Article

Electronic monitoring trials on in the tropical tuna purse-seine fishery

J. Ruiz[1]*, A. Batty[2], P. Chavance[3], H. McElderry[2], V. Restrepo[4], P. Sharples[5], J. Santos[6], and A. Urtizberea[1]

[1]*AZTI Tecnalia, Txatxarramendi ugartea z/g, Sukarrieta E-48395, Spain*
[2]*Archipelago Marine Research, Victoria, BC, Canada*
[3]*Institut de Recherche pour le Développement (IRD), SETE, France*
[4]*International Sustainable Seafood Foundation (ISSF), Washington, DC, USA*
[5]*Secretariat of the Pacific Community (SPC), Noumea Cedex, France*
[6]*University of Tromsø (UIT), Tromso, Norway*

**Corresponding author: tel: +34 667174375; e-mail: jruiz@azti.es*

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The difficulty of ensuring adequate statistical coverage of whole fleets is a challenge for the implementation of observer programmes and may reduce the usefulness of the data they obtain for management purposes. This makes it necessary to find cost-effective alternatives. Electronic monitoring (EM) systems are being used in some fisheries as an alternative or a complement to human observers. The objective of this study was to test the use and reliability of EM on the tropical tuna purse-seine fishery. To achieve this objective, seven trips of tuna purse seiners operating in the three Oceans were closely monitored to compare the information provided by EM and on-board observers to determine if EM can reliably document fishing effort, set type, tuna catch, and bycatch. Total tuna catch per set was not significantly different between EM and observer datasets; however, regarding species composition, only main species matched between EM and observers. Success on set-type identification using EM varied between 98.3 and 56.3%, depending on the camera placement. Overall, bycatch species were underestimated by EM, but large bodied species, such as billfishes, were well documented. The analyses in this study showed that EM can be used to determine the fishing effort (number of sets) and total tuna catch as reliably as observers can. Set-type identification also had very promising results, but indicated that refinement of the methods is still needed. To be fully comparable with observer data, improvements for accurately estimating the bycatch will need to be developed in the application and use of the EM system. Operational aspects that need to be improved for an EM programme to be implemented include standardizing installation and on-board catch handling methodology as well as improvements in video technology deployment.

Keywords: bycatch, catch composition, data collection, electronic monitoring system, observers, purse seining, tropical tuna.

Introduction

Fisheries managers need to understand the dynamics of the fish stocks and fleets to set policy and manage fisheries. Collecting and analysing fisheries data is one of the first steps during this process, and it is essential for informed decision-making (FAO, 1999).

Autonomous observer programmes are a key component of effective fisheries management. Data collected by independent observers during fishing operations are commonly used to complement data from port sampling or skippers' logbooks. For some types of data, such as discards, observer programmes can be the most reliable and sometimes the only source of information available for management of the fishery. Autonomous observer programmes are also valuable for monitoring, control, and surveillance (MCS). Research has shown that the presence of observers on-board commercial fishing vessels can improve compliance with regulations and that if violations do occur, they are more likely to be recorded on a vessel with an observer on-board.

Observer programmes are becoming an increasingly important tool to monitor tropical tuna fisheries. The IATTC (Inter American Tropical Tuna Commission) and WCPFC (Western and Central Pacific Fisheries Commission) regulations require 100% observer coverage of large-scale purse seiners. The ICCAT (International Commission for the Conservation of the Atlantic Tunas) and IOTC (Indian Ocean Tuna Commission) regulations recommend 5% coverage for large fishing vessels (ICCAT, 2010a,b; IOTC, 2010). The ICCAT requirement increases to 100% for purse seiners during a 2-month prohibition of fish aggregating devices (FADs) fishing in an area off western Africa (ICCAT, 2011).

There are, however, several difficulties involved in placing observers on fishing vessels, including the high costs of observer placement, the need for timely debriefing and data handling and limited space on vessels to accommodate observers. In some areas, such as the western equatorial Indian Ocean, piracy makes it extremely difficult and dangerous to place human observers on-board.

A remarkable range of technology is now being applied to monitor and collect fishery data. It includes vessel monitoring system (VMS) that record and transmit in real-time fishing activities in time and space; electronic logbooks that store traditional catch and effort information as entered by the captain or crew and electronic monitoring (EM) techniques that use video surveillance of the fishing deck in combination with other sensor data. These technologies provide traditional and new information at fine spatial scales and with near real-time availability in support of multiple objectives, from scientific research to compliance monitoring.

EM systems are being used in some fisheries as an alternative and/or a complement to human observers on-board (Stanley *et al*., 2009, 2011). The EM systems consist of a central computer combined with several sensors and cameras that record key aspects of fishing operations, such as vessel location, vessel speed, catch, fishing methods, and protected species interactions (McElderry, 2008). This technology is quickly gaining popularity with management agencies. However, as EM becomes more widespread, some questions about its use have been raised and study cases have identified different strengths and weaknesses (McElderry, 2008; Blass, 2013).

Archipelago Marine Research Ltd. (Archipelago) has developed an EM system that has been used in a wide variety of applications for monitoring fishing and collecting fisheries related data. Over the past decade, pilot studies have been carried out in more than 25 fisheries in several countries with different gear and target species to test the efficacy of this technology (McElderry *et al*., 2005a,b,c; Dalskov and Kindt-Larsen, 2009; Dalskov, 2010; McElderry *et al*., 2011; Piasente *et al*., 2012).

In some places EM systems have been fully integrated as a fishery monitoring tool. Such is the case on the west coast of Canada and the USA, where there is a significant level of EM acceptance by fishers and fishing management agencies.

McElderry (2008) surveyed a list of pilot studies conducted between 2002 and 2008 and concluded that the efficacy of EM for monitoring issues varies according to fishing methods and other factors. In general, EM has a number of advantages over traditional observer programmes, including suitability across a broad range of vessels, the ability to create of a permanent data record, lower cost and the ability to engage industry in self-reporting processes. Observer programmes are more suited as a tool for industry outreach, complex catch handling operations, and collecting biological samples.

The utility of EM systems to monitor catch depends on the fishing method, working well with fishing methods such as gillnet and longline gear where catch is retrieved serially. EM is not well suited for catch monitoring in high-volume fishing gear such as trawl and seine (McElderry, 2008).

Before this study, the EM technology had not been tested on the high seas in the tropical tuna purse-seine fishery.

The main objective of this study was to compare the data collected using EM with that collected by observers to determine whether EM systems can be used to reliably collect unbiased data with respect to; (a) monitoring fishing effort, understood as operations including set type, (b) monitoring of tuna catches (total catch and by species) for the retained and for the discarded components, and (c) monitoring bycatch, such as sharks, billfishes, turtles, and other bony fish.

Tropical tuna purse-seine fishery

Tuna and tuna-like species are important socio-economic resources as well as a significant source of protein. Three species abundant in tropical waters, bigeye (*Thunnus obesus*, BET), skipjack (*Katsuwonus pelamis*, SKJ), and yellowfin (*Thunnus albacares*, YFT) are among the most commercially important. Skipjack and yellowfin live in shallower habitats and warmer waters than bigeye tunas. These species are caught by several industrial fleets of different countries as well as by artisanal fleets of coastal states. Purse seine is the surface gear that contributes most to the catch of yellowfin and skipjack globally (Majkowski *et al*., 2011).

The eastern and western Pacific, the eastern Atlantic and the western Indian Oceans are the major fishing grounds for the tropical purse-seine tuna fishery. Purse-seine fishing vessels catch nearly 62% of the 4.2 million tons of tuna caught globally every year. There are an estimated 1664 purse-seine vessels authorized to fish for tuna around the world; however, only 678 are considered large-scale tropical tuna purse seiners with the capacity to hold about 637 000 tons of fish (Restrepo and Forrestal, 2012).

In the purse-seine fishery, three main fishing strategies (set types) are used to capture tunas: (1) targeting fish swimming in free schools, (2) targeting fish swimming around drifting objects, and (3) targeting fish associated with dolphins (only in the eastern Pacific Ocean) and in some isolated cases associated with whales or whale sharks. In the first approach, called a free-school set, a school of fish is identified from the surface and is encircled with a net. In the second approach, a drifting object where fish have aggregated is encircled with the net. Within this second strategy, there are a subset of techniques including sets on encountered "natural" floating objects ("log sets") and sets on fish aggregating devices (FADs). FADs are floating objects that have been modified and placed by the fishers to attract fish and to facilitate their aggregation and capture. FADs are often outfitted with a locator buoy. The strategy of using FADs was developed in the 1980s but greatly increased during the 1990s and the technique is currently responsible for a major portion of the purse-seine bycatch and discards (Dagorn and Restrepo, 2011). The ability to classify the set type is a crucial element of the tropical tuna purse-seine fishery monitoring programme and helps to define the fishing effort of the fleet.

Different studies show that tuna purse seining generates low levels of bycatch relative to the total catch (Romanov, 2002; Amandè *et al*., 2008, 2010). Recently, Hall and Roman (2013) carried out a review of the available data of the bycatches from the tropical tuna purse-seine fisheries of the world. The total discards amount to 1–5% of the total tonnage captured and tunas of the species targeted and other tuna-like species amount to over 90–95% of those bycatches. The silky shark (*Carcharhinus falciformis*) is the most common shark species by far, followed by the oceanic whitetip sharks (*Carcharhinus longimanus*). Marlins and sailfishes are also taken but in reduced numbers. Olive ridley sea turtles (*Lepidochelys olivacea*) are the most common turtle captured, but the majority of them are released alive and unharmed. In relation with other bony fishes, more than 97% of this group bycatch is caught during FAD sets and the dominant bycatch species are triggerfish (*Balistidae*), rainbow runner (*Elegatis bipinnulata*), mahi-mahis (*Coryphaena hippurus*), wahoos (*Acanthocybium solandri*), and amberjack yellowtail (*Seriola lalandi*) are the major pelagic bony fishes taken with the tunas.

Material and methods

Data collection

Three studies were carried out from December 2011 to August 2012 to examine the ability of EM to collect unbiased and precise catch and bycatch data in the tuna purse-seine fishery. EM and observers were deployed simultaneously on seven trips with over 130 fishing events on three purse-seine fishing boats in the Indian, Atlantic, and west Pacific Oceans (Table 1).

The Archipelago EM Observe™ system was used. It has a system control centre, up to four closed circuit television cameras, a GPS receiver, a hydraulic pressure sensor, rotational sensor, and a satellite modem transceiver (Figure 1). The EM system collects high-frequency sensor data throughout the trip and records imagery only when triggered by fishing activity. Imagery and sensor data are stored digitally on a removable hard drive that can be exchanged when it is full. Two four-analog camera EM systems were used to record all fishing activities on each of the vessels during the study period. A system installed on the main deck was set to record the capture of fish and general fishing activity, including setting, pursing, brailing, and some discarding. A system installed in the fish-processing deck was set to capture movement of fish along the sorting conveyor belt of the vessels in the Atlantic and Indian Oceans.

The data collected using the EM systems were reviewed in the lab using the Archipelago EM Interpret™ software. EM Interpret™ is a software package that integrates and displays EM sensor and imagery data for review.

For comparison with EM data, observers for this study used the standard methods used in the EU and WCPFC observer programme. During these trips, observers filled in five different data sheets (Delgado de Molina *et al.*, 1997) with information about tuna species, bycatch species, and Fish Aggregating Devices (FADs). Observer data were assumed to be the baseline data (-independent sample) for the purposes of this study.

Table 1. Number (N°) of fishing operations during the seven sampled trips.

Vessel	Trip	Port	Total sets
Playa de Bakio	1	Abidjan	26
Playa de Bakio	2	Abidjan	13
Playa de Bakio	3	Abidjan	22
Torre Guilia	1	Seychelles	22
Cape Finisterre	1	Pago Pago	19
Cape Finisterre	2	Pago Pago	12
Cape Finisterre	3	Pago Pago	25
Total	7		139

Observer and EMs data comparison

Classification of set types

Differences in set-type classification made by the observer and by the EMs were analysed first. This is a crucial element of the tropical tuna purse-seine fishery monitoring programme and helps to define the fishing effort of the fleet. The set classification made by the observer (free-school set or FAD set) was considered as the correct one and the degree of sets correctly classified during the EM data review process was calculated. An exact binomial test (Conover, 1971) was used to calculate the probability of success during the set classification. The classification of EMs was based on imagery review. Additionally, sensor data (i.e. speed, location, hydraulic pressure) were also examined to determine whether it is possible to determine the set type from the sensor data alone.

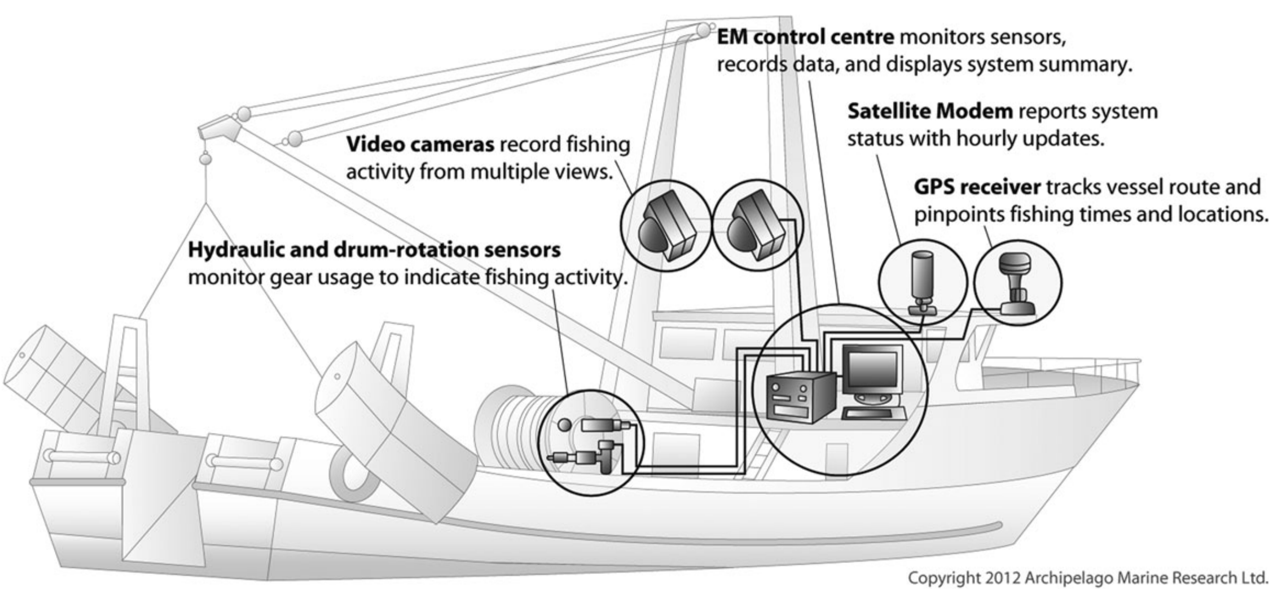

Figure 1. Schematic of a standard EM system.

Catch comparison

Three main categories of data collected by both observers and EM were compared: (1) tuna catch, (2) bycatch of larger species, and (3) bycatch of other bony fish. In the case of tunas, discarded and retained fractions of catch were analysed separately. For the bycatch, the retained and discarded fractions were combined and analysed jointly. Statistical analyses were conducted in a similar fashion for the three categories of data.

First, the total retained tuna catch in biomass per set was compared between EM and observer records using in a generalized linear model (GLM). The GLM was applied as a summarizing model of the match between the two estimates, rather than a prediction or causation model (Freedman, 1997). We applied the model assuming that the observer record was the independent variable and estimates by EM the dependent variable with which statistical error is associated (Piñeiro *et al*., 2008). As the catch data are continuous and positive, and their variance increased with the mean, the error was assumed to be gamma distributed (McCullagh and Nelder, 1989). The EM and the observer data were expected to follow a 1:1 relationship, expressed as a slope of 1 in a regression model (Piñeiro *et al*., 2008). Thus, we utilized an identity link and examined whether the 95% confidence intervals of the estimated intercept encompassed 0 and the confidence intervals of the estimated slope embraced 1. When that occurred, the hypothesis that EM catch estimates were as reliable as observer recordings could not be rejected. Skunk (failed) sets were omitted and only sets with more than 0.1 metric tons of catch were included in the analyses. The same GLM approach was used in a second step to compare the tuna catch data, discriminated by species, registered by EM and observers.

For discarded tuna, no regression analyses were performed due to the limitations in the data, and only a comparative summary of the discards recorded by EM and the observer is presented.

For bycatch, a GLM with the same model structure and procedures as in the tuna catch was also used to compare the total number of captured individuals estimated by both monitoring methods. The difference between the two cases was the applied error distribution. In the case of bycatch the measured variable was counts, as both observer and EM reviewer estimated the number of sharks, billfishes, and other bony fishes caught instead of their biomass. For this type of data, a GLM with identity link and Poisson error distribution is recommended (McCullagh and Nelder, 1989). The validation of the model fit and the adequacy of the error structure were checked by residual diagnostics. Sets where bycatch was detected by neither sampling methods were omitted from the regression analysis because they were considered to be structural zeros.

The same analytical approach was used for both large size bycatch species (sharks and billfishes) and small size bycatch species. First, groups of species (total sharks, total billfishes, and total small bony fishes) were analysed. In a second step, more detail was introduced by analysing, when possible, individual species.

Model fits were performed using the statistical software R (http://www.r-project.org/), including the packages stats and glm2 (Marschner, 2011).

Results

Determining set type using EM

Both EM and observer records allowed identification of 100% of the fishing operations that occurred during the seven trips. Both EM and observer records also allowed classification of a set type for all

Table 2. Probability of success determining set type by ocean, and 95% confidence intervals.

Ocean	Probability of success (%)	*p*-value	Lower 95% CI	Upper 95% CI
Atlantic Ocean	98.36	$<2.2e-16$	91.2	99.9
Pacific Ocean	56.33	$<2.2e-16$	44.04	68.08
Indian Ocean	72.72	$<2.2e-16$	49.2	89.6

fishing events, but the probability of successfully determining a set type was highly variable among oceans (Table 2) and ranged from 56.33% in the Pacific Ocean to 98.36% in the Atlantic Ocean trial.

In the Atlantic Ocean, EM was successful at determining a set type in most events; however, the EM reviewer identified one set during the first trip as an FAD set based on imagery review, while the observer classified it as a free-school set. In the Indian Ocean, due to some problems with the camera angles, only the sensor data were used for the set type assessment. The observer recorded 21 FAD sets and 1 free-school set during the trip. However, only 16 FADs were detected within the EM data. Moreover, the unique free-school set was identified as an FAD set by EM. In the Pacific Ocean, none of the fishing events had an FAD recorded in the EM data so all were identified as free-school fishing.

In general terms, it was expected that for FAD sets, the imagery commonly would show the FAD being towed by the speedboat within camera view, however, it would be very easy for this to take place outside of the camera view or for the EM reviewer to miss it with a minor change in vessel behaviour. On the other hand, during free-school sets, the imagery show both the skiff and the speedboat moving in circles until the rings were up to avoid fish escaping while the net is not completely closed.

The EM sensor data were not used as the main method of determining a set type (except in the Indian Ocean) and video data were mainly used for this purpose. However, a coarse qualitative assessment suggested that sensor data are good indicators of set type. There is a difference in fishing behaviour between free-school and non-free-school sets that can be inferred from the combination of speed and hydraulic pressure records. During the documented FAD sets, the vessel tended to approach the fishing area with constant speed, then slow down, then return to full speed immediately before the shooting operation (Figure 2a). Alternatively, during free-school sets (as confirmed by the observer data), the EM data showed that the speed before setting was more variable while the vessel followed the school and did not drop as low as during FAD sets (Figure 2b).

Tuna catch estimation

Retained tuna

There were good indications that EM and observer data were equally reliable methods for estimating total catch per set (Figure 3) and this was corroborated by the GLM (Table 3). The solid line in the figure shows the fitted linear regression and the dashed line indicates the expected 1:1 relationship. In the three Oceans, the 95% confidence intervals of the intercept encompass or are close to 0, and 1 is enclosed by the 95% confidence intervals of the slope.

The EM also allowed a successful identification of the main tuna species in the catch. Six tuna species (or genus) were identified using observer and EM methods: Skipjack (SKJ), yellowfin tuna (YFT), albacore (*Thunnus alalunga*) (ALB), bigeye tuna (BET), *Auxis* spp. (AUX) and *Euthynus* spp. (LTA).

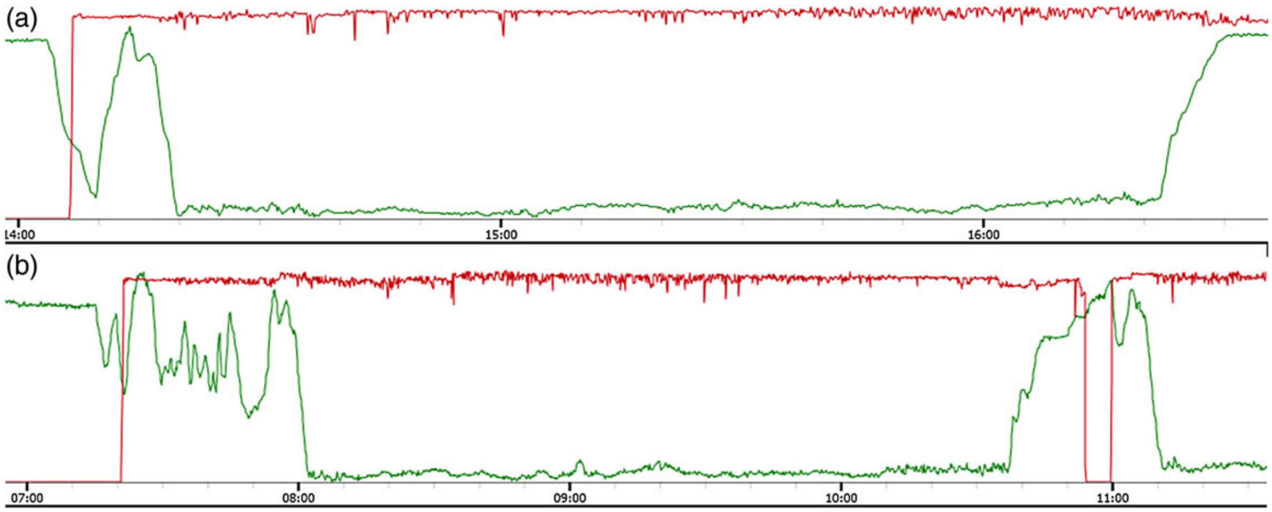

Figure 2. (a) Examples of typical sensor dataset for FAD fishing on the *Playa de Bakio*. (b) Example of typical sensor dataset for free-school fishing on the Playa de Bakio.

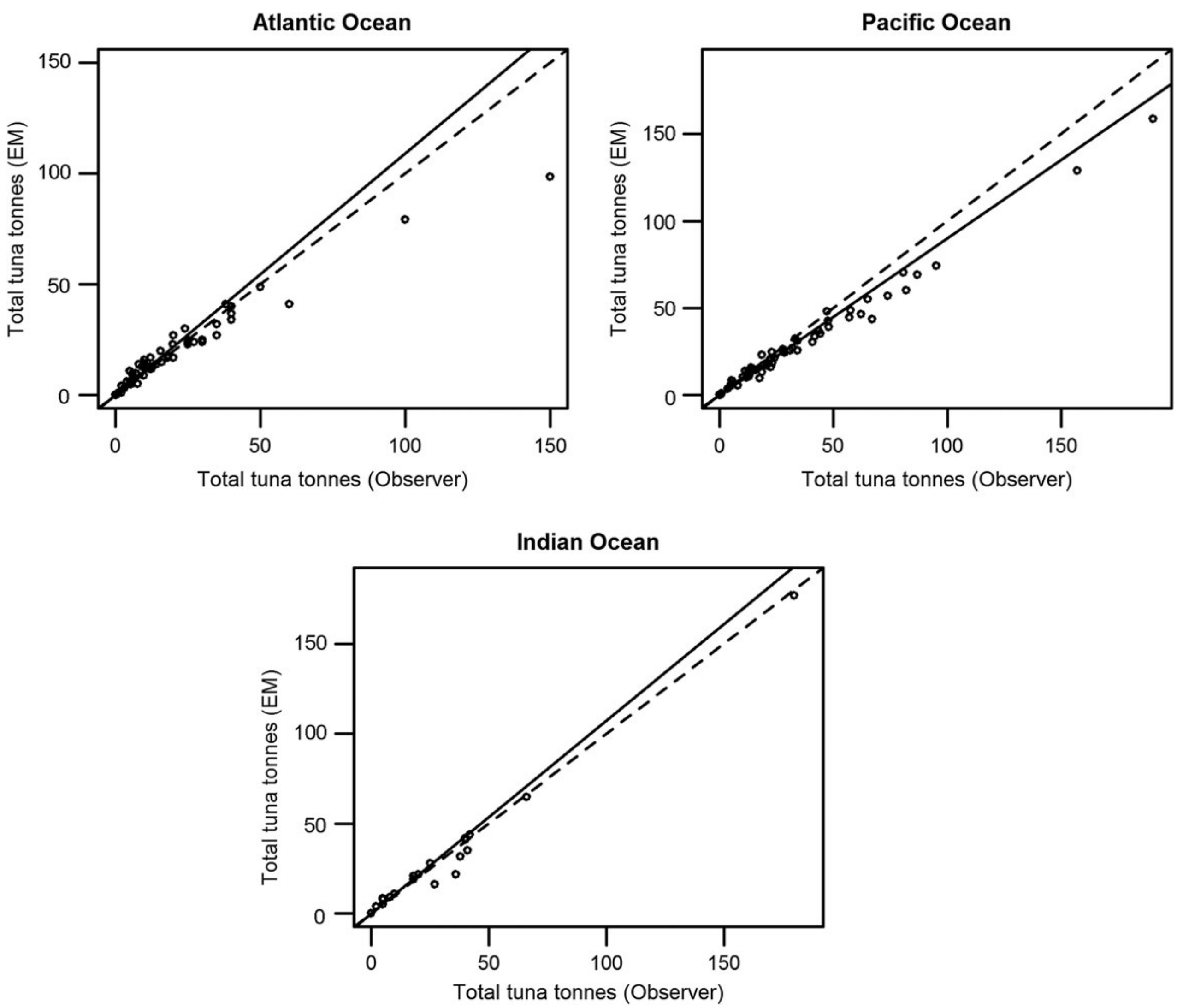

Figure 3. Estimated regression (solid line) and expected 1:1 relationship (dashed line) between observer and EM records of total tuna catch in all valid fishing sets in the Atlantic, West Pacific, and Indian Oceans. The GLM estimates are given in Table 3.

Table 3. Summary output of the GLM of the relationship between EM estimates and observer records in the determination of the total tuna catch.

Ocean	Coefficient estimate	Confidence intervals		*p*-value
		2.5%	97.5%	
Atlantic Ocean				
Intercept	0.119	−0.083	0.543	0.355
Observer tuna catch	1.089	0.993	1.193	<2e−16***
Pacific Ocean				
Intercept	0.06	0.052	0.092	4.97e−09**
Observer tuna catch	0.899	0.853	0.949	<2e−16***
Indian Ocean				
Intercept	0.12	0.075	0.24	0.0018**
Observer tuna catch	1.07	0.95	1.21	1.74e−12***

The GLM model assumed an identity link and gamma error.

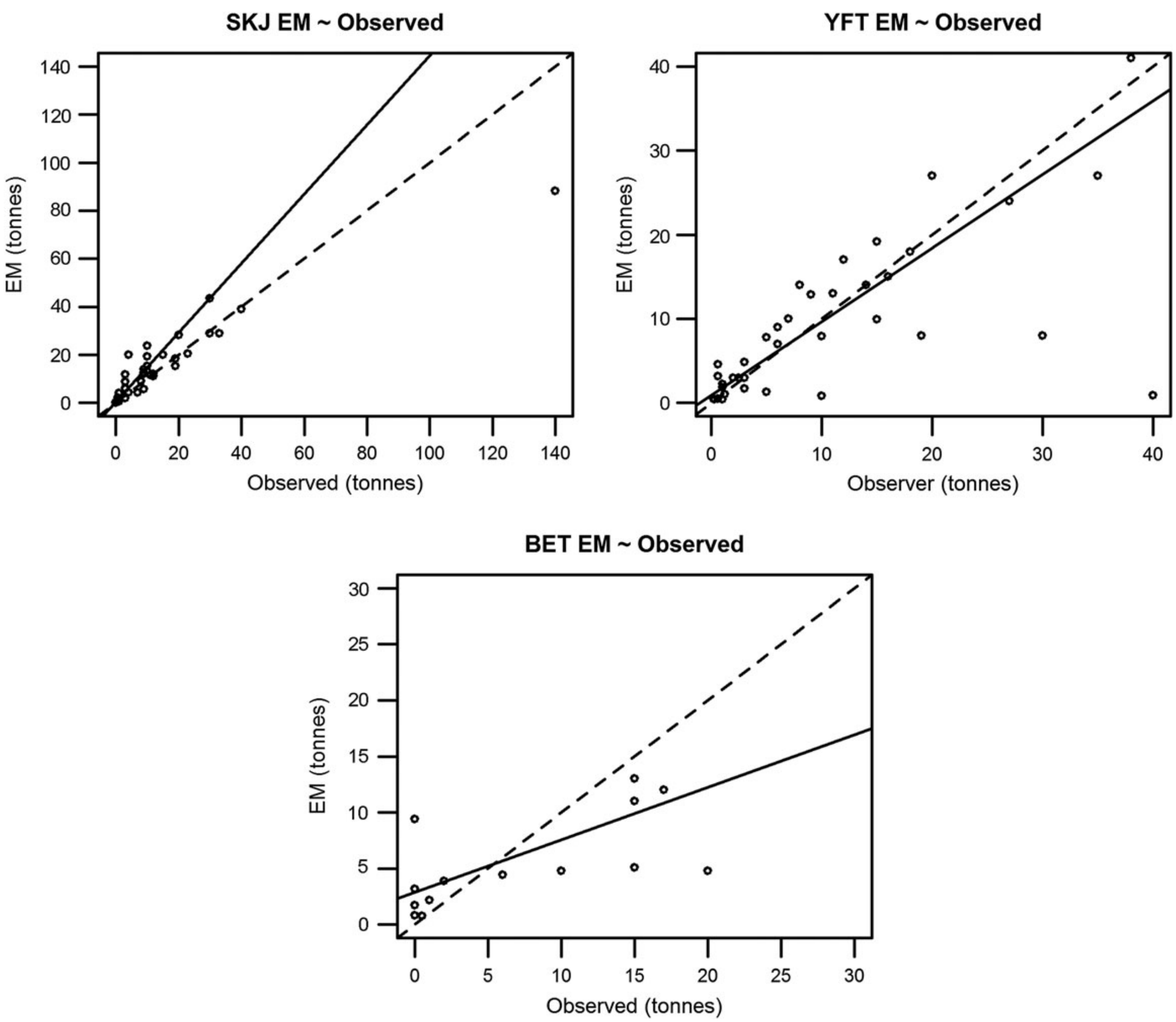

Figure 4. Estimated regression (solid line) and expected 1:1 relationship (dashed line) between observer and EM records of tuna catch by species in all valid fishing sets in the Atlantic Ocean. Skipjack (SKJ), yellowfin tuna (YFT), and bigeye tuna (BET). The GLM estimates are given in Table 4.

Results differed by ocean, but in general terms the EM and observer data were not equally reliable methods for estimating tuna catches discriminated by species, at least for some of the species. However, for the main species in volume within a set, yellowfin and skipjack, the EM estimates were reasonably close to the observed catch.

Figure 4 shows the comparison of the estimated weight of retained tuna per set from EM and observer in the Atlantic Ocean, by species and Table 4 shows the result of the GLM for the different species. In general, the EM tended to slightly overestimate the catch of the different species. The exception was bigeye tuna. They were clearly underestimated by nearly half when catch volumes were high (about 10–15 tons). For the main species by volume within a set, yellowfin and skipjack, however, the EM estimates were close to the observed catch. Their estimated slope coefficients had narrow limits and encompassed or were close to the expected value of 1.0. Moreover, if we analyse the results separately by set type, we see that the differences between the estimates made by EM and observer for main species decrease, that is, differences in estimates for yellowfin decrease when we only take into account the free-school sets and differences in estimates for skipjack decrease when we only take into account FAD sets (Figure 5 and Table 5).

Less commercially important species like *Auxis* spp. and *Euthynnus* spp. failed to provide strong regressions, because either the number of observations was too low or the EM estimates too variable. Although their regression coefficients were close to the expected 1:1 relationship their variance was too high (Table 4).

Table 4. Summary statistics of the slopes of the GLM applied to EM and observer data of the different tuna species in the Atlantic Ocean.

		Confidence intervals		
	Coefficient estimate	**2.5%**	**97.5%**	***p*-value**
SKJ	1.44	1.061	1.823	2.15e − 10**
BET	0.468	0.18	1.004	0.03841*
LTA	1.053	−3.308	5.414	0.201
YFT	0.8762	0.639	1.192	6.87 e − 8**
AUX	1.36	−0.0656	2.786	0.0583

Skipjack (SKJ), yellowfin tuna (YFT), bigeye tuna (BET), *Auxis* spp. (AUX), *Euthynnus* spp. (LTA).

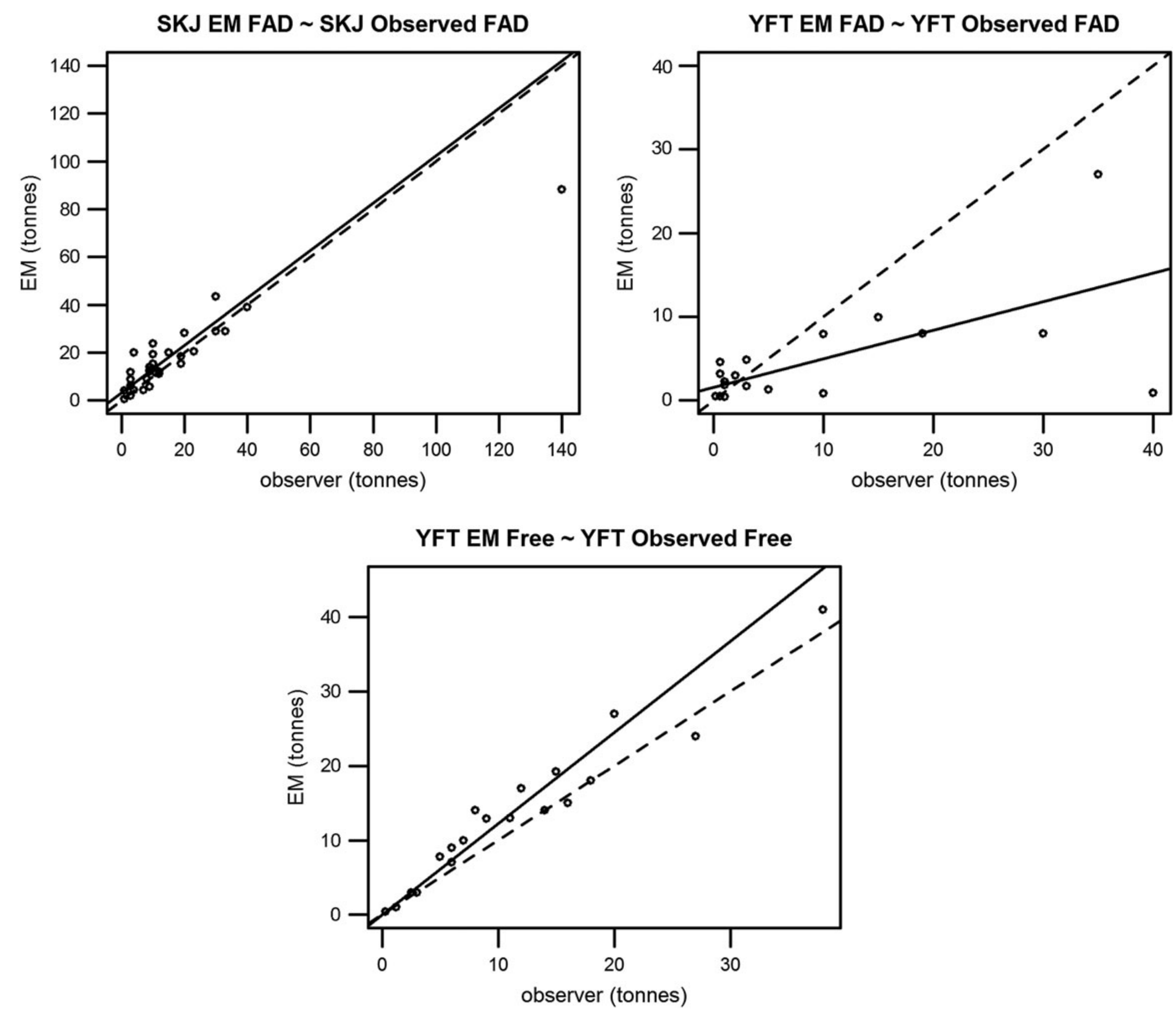

Figure 5. Estimated regression (solid line) and expected 1:1 relationship (dashed line) between observer and EM records, separated by set type (FAD and Free school sets), of tuna catch by species in all valid fishing sets in the Atlantic Ocean. Skipjack (SKJ); yellowfin tuna (YFT). The GLM estimates are given in Table 5.

In the Indian Ocean case, for the main species, yellowfin and skipjack (with maximum set catches of about 36 and 145 tons), the EM estimates were also close to the observed catch. Their estimated slope coefficients encompassed the expected value of 1.0 (Figure 6; Table 6).

On the other hand, less important species in volume—albacore, *Auxis* spp., and bigeye tuna—were only detected by EM in very few sets. Moreover, when these species were detected, they were consistently underestimated by the EM.

In the west Pacific Ocean, although some individuals of main tuna species were identified in some sets, EM was not able to distinguish between species and more than 70% of the total catch was only classified to family level (scombridae).

Discarded tuna

Discarded tuna quantities were low during the sampled trips. In general terms, discarded tuna catch was limited to some gilled and damaged small-size fish. In the seven trips, there were only three sets where discarded tuna weight was larger than one tonne; two sets in the west Pacific Ocean and one in the Atlantic Ocean. In all cases, the discarded catch was underestimated by EM (Table 7).

Bycatch estimation

Bycatch of large size species

Results show differences among oceans, but in general terms, EM and observer were not equally reliable methods for estimating bycatch of shark species. For most shark species the EM estimates were significantly lower than the observer estimates. However, in the case of billfishes, EM detected similar or larger numbers. In the Atlantic Ocean, while the observer registered 109 sharks and 29 billfishes in the bycatch, the EM data only contained records of 58 sharks and 20 billfishes. In the west Pacific Ocean while the observer registered 234 sharks and 7 billfishes in the bycatch, the EM data contained records of 184 sharks and 17 billfishes. In the Indian Ocean, the observer registered 116 shark and 4 billfishes, while the EM detected 114 sharks and the same 4 billfishes.

Figure 7 shows the comparison of the estimated numbers of the bycatch estimates per set from EM and observer for the total sharks and total billfishes. The summary of the statistical GLM fits for the different oceans is shown in Table 8. EM tended to underestimate consistently the catch of the different shark species both in the Atlantic Ocean and west Pacific Ocean. The estimated slope coefficients had narrow limits but they were below the expected value of 1.0. In the Indian Ocean the underestimation is not so clear and the slope is close to the expected value of 1.0. Billfishes provided a weaker regression because of the small number of observations. The variance was too high and the power of the regression was thereby low. In the Atlantic Ocean the estimated slope coefficients for billfishes were also clearly below the expected value. However, EM detected exactly the same number of billfishes as observer in the Indian Ocean and clearly larger number in the west Pacific Ocean.

The most frequent species of sharks and billfishes were observed by both monitoring methods, at least in some sets. The main species identified by both methods were: *Makaira nigricans*, *Carcharhinus falciformis*, *Carcharhinus longimanus*, *Istiophorus albicans*, and *Sphyrna lewini*. Nevertheless, in most cases, with the EM method, the taxonomic identification only reached the family level or, in the case of unidentified sharks, the order level. Observers reached species level in most of the cases and some less captured species like *Isurus oxyrinchus* and *Xiphias gladius* were only recorded by observers. On the other hand, the EM data contained one *Mobula* spp. that was not found in the observer data. Two *Tetrapterus albidus* individuals were also identified using EM only, but cross-checking with observer data indicated that they were *Istiophorus albicans* individuals. They were, therefore, likely misidentified by EM.

Table 5. Summary statistics of the slopes of the GLM applied to EM and observer data, separated by set type, of the different tuna species in the Atlantic Ocean.

	Coefficient estimate	Confidence intervals		
		2.5%	97.5%	*p*-value
SKJ (only FAD sets)	0.9906	0.6376807	1.408979	1.53e−06***
YFT (only FAD sets)	0.3421	0.1496045	0.7223678	0.01516*
YFT (only free sets)	1.225073	1.1051476	1.3607348	8.73e−13***

SKJ, Skipjack; YFT, yellowfin tuna.

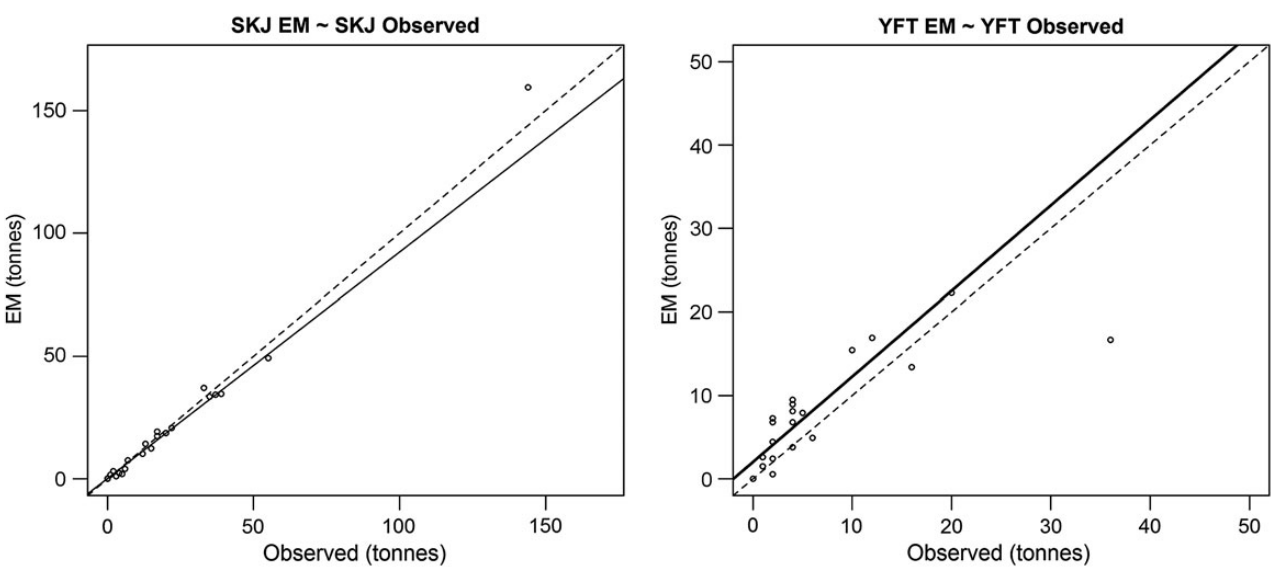

Figure 6. Estimated regression (solid line) and expected 1:1 relationship (dashed line) between observer and EM records of tuna catch by species in all valid fishing sets in the Indian Ocean. Skipjack (SKJ), yellowfin tuna (YFT). The GLM estimates are given in Table 6.

Table 6. Summary statistics of the slopes of the GLM applied to EM and observer data of the different tuna species in the Indian Ocean.

	Coefficient estimate	Confidence intervals 2.5%	97.5%	*p*-value
SJK	0.91	0.80	1.06	1.52e − 11***
YFT	1.02	0.54	1.68	0.00048**

SKJ, Skipjack; YFT, yellowfin tuna.

Table 7. Discarded tuna estimates made by EM and observers.

		EM system estimates				Observer estimate				
Trip	Ocean	SKJ	YFT	AUX	Total	SKJ	YFT	AUX	BET	Total
2	Atl. Oc.	0.50			0.50	2.00		0.50		2.50
1	Pac. Oc.				0.00	1.3	0.35			1.65
2	Pac. Oc.				0.00	4	1.8			5.8
2	Pac. Oc.				0.00	10.5	7.2		3.00	20.7

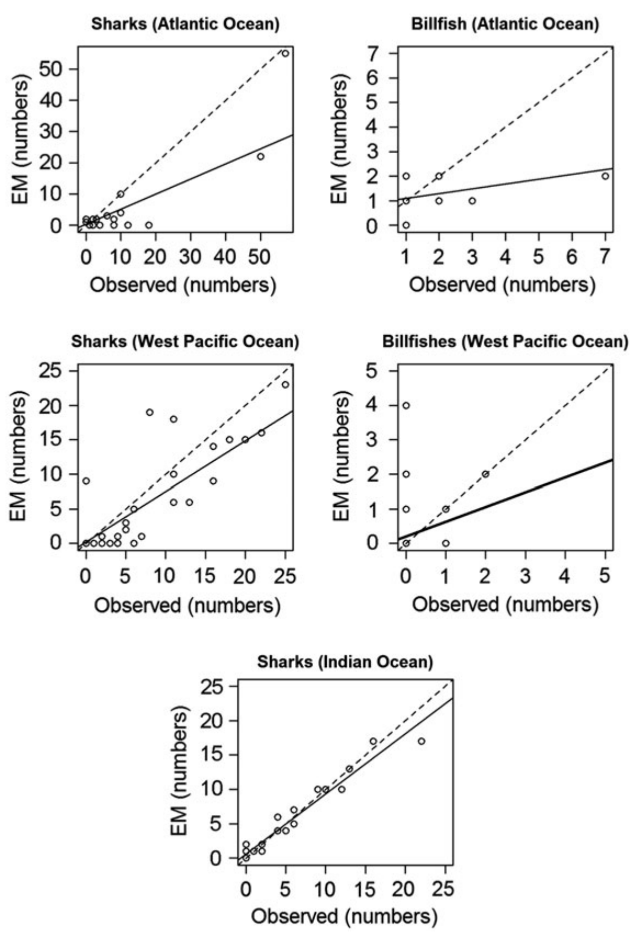

Figure 7. Estimated regression (solid line) and expected 1:1 relationship (dashed line) between observer and EM records of total shark and total billfish bycatch (numbers); Atlantic Ocean, West Pacific Ocean and Indian Ocean. The GLM estimates are given in Table 8.

The lack of effectiveness of EMs when identifying species does not allow the realization of a robust comparison of the catch estimates by species made by both methods.

Table 8. Summary statistics of the slopes of the GLM relationship between EM and observer data of the different large size bycatch species in the Atlantic Ocean.

	Estimate	Confidence intervals 2.5%	97.5%	*p*-value
Total shark (Atl. O.)	0.482	0.389	0.501	<2e − 16***
Total billfish (Atl. O.)	0.195	− 0.116	0.823	0.409
Total shark (Pac. O.)	0.73	0.627	0.849	<2e − 16***
Total billfish (Pac. O.)	0.42	− 0.16	1.01	0.00033**
Total shark (Ind. O.)	0.876	0.695	1.072	<2e − 16***

Bycatch of small size Species (other bony fishes)

Although rare bony fish species were never detected or identified using EM, the more common species in these trips were observed by both methods. The main species include the following: *Canthidermis maculatus*, *Caranx crysos*, *Elegatis bipinnulata*, *Acanthocybium solandri*, *Coryphaena hippurus*, *Kyphosus spectator*, *Lobotes surinamensis*, *Seriola rivoleana*, Balistidae, *Mola mola* and *Sphyraena barracuda*.

Overall EM underestimated the total bycatch of small fish species. In total, in the Atlantic Ocean, the observer estimated the capture of 15 007 small bony fish during the three trips. Only 3801 (25.3%) individuals were estimated using EM. In the Pacific Ocean, the observer estimated the capture of 734 small bony fish during the three trips, and only 272 (27.03%) individuals were estimated using EM. In the Indian Ocean the observer estimated the capture of 11 714 individuals while the EM estimated 15 236 (130%). This last result leads us to believe that the EMs overestimate small fish bycatch in the Indian Ocean, but if we make the same comparison by species, we found that the difference comes from the overestimation of a single species, triggerfish (*Canthidermis maculatus*); the most numerous captured species. The remaining species are underestimated, as occurs in the other oceans.

The difference in the estimated numbers in the bycatch from EM and observer data for the total small bycatch species by ocean is illustrated in Figure 8. The estimated slope coefficients were clearly below the expected value of 1.0. The summary of the GLM model fit for the different species is given in Table 9; total small bony fishes in a first place and by species later. These findings suggest that EM consistently underestimated bycatch for all the small size species, thus, EM and observer data were not equally reliable methods for counting the bycatch of small size bony fish.

Discussion

Set type classification

Species composition and mean individual length are very different between free-school and FAD sets (see for example: Amandè *et al*., 2008; Amandè *et al*., 2010). The type of sets used to capture tunas is a major factor to determine the catches and the bycatches (Hall and Roman, 2013). This information is used for stratification in most computation on tropical tuna purse-seine fishery statistics. It is therefore important to be able to discriminate between the two types of sets. The approach used in this research to identify set types from imagery and sensor data signatures appears effective for the fishing techniques of the *Playa de Bakio* (a Spanish vessel operating in the Atlantic Ocean). Results in the Pacific Ocean failed to achieve such high performance in classifying the set type. The main

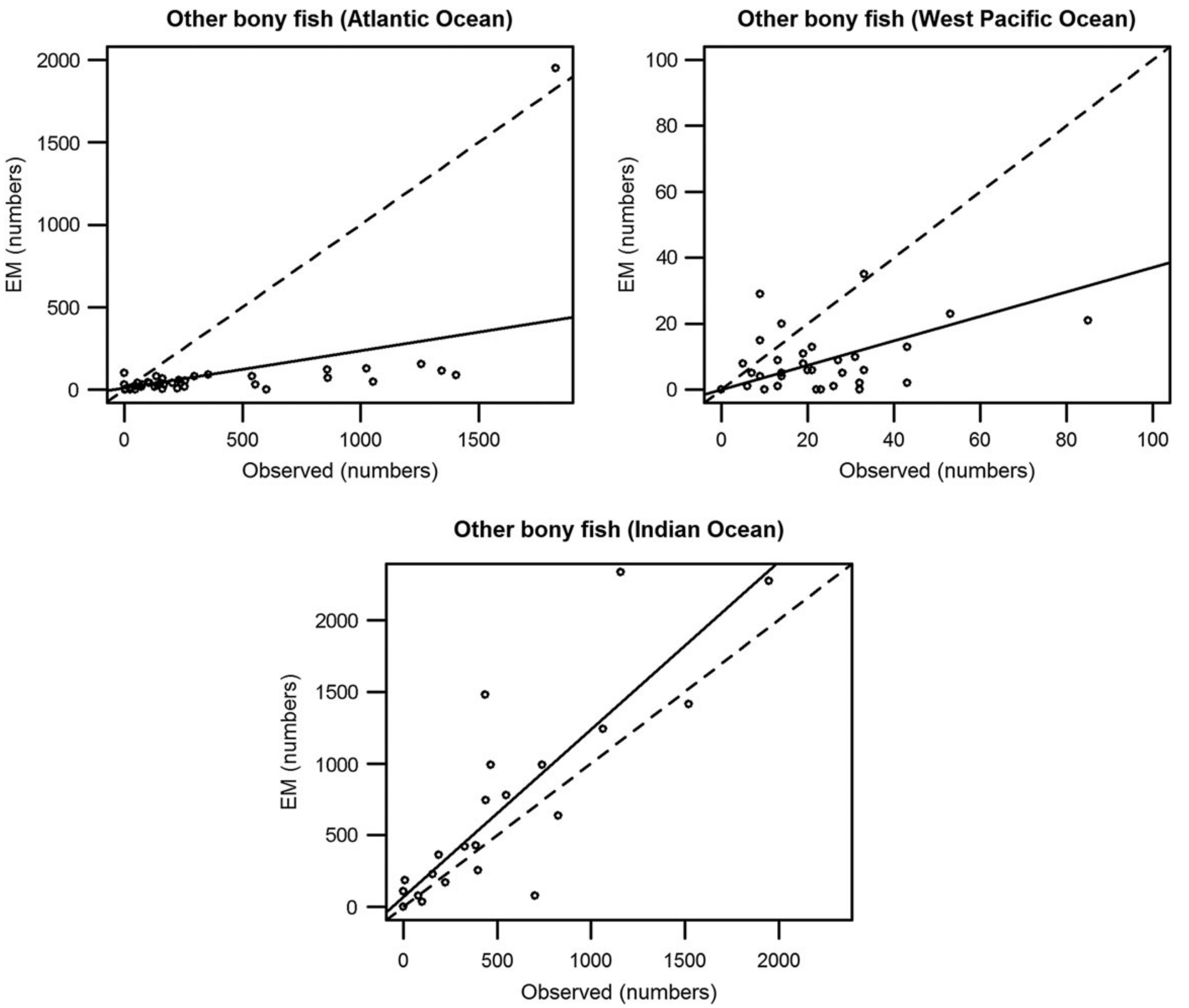

Figure 8. Estimated regression (solid line) and expected 1:1 relationship (dashed line) between observer and EM records of bycatch (numbers) of the total small size bony fish species; Atlantic Ocean, West Pacific Ocean and Indian Ocean. The GLM estimates are given in Table 9.

Table 9. Summary statistics of the slopes of the GLM applied to EM and observer data of the main small size bycatch species.

		Confidence intervals		
	Estimate	**2.5%**	**97.5%**	***p*-value**
Total small bony fishes (Atl. O.)	0.226	0.212	0.234	<2e−16***
Total small bony fishes (Pac. O.)	0.376	0.310	0.415	<2e−16***
Total small bony fishes (Ind. O.)	1.166	1.142	1.190	<2e−16***
Elegatis bipinnulata (Atl. O.)	0.351	0.330	0.372	<2e−16***
Elegatis bipinnulata (Pac. O.)	0.183	0.088	0.295	0.000549***
Elegatis bipinnulata (Ind. O.)	0.851	0.773	0.931	<2e−16***
Caranx crysos (Atl. O.)	0.005	−0.002	0.013	0.181
Canthidermis maculatus (Atl. O.)	0.334	0.323	0.355	<2e−16***
Canthidermis maculatus (Ind. O.)	1.457	1.429	1.484	<2e-16***
Coryphaena hippurus (Atl. O.)	0.473	0.368	0.586	2.92e−15**
Coryphaena hippurus (Pac. O.)	0.252	0.187	0.317	9.49e−15***
Coryphaena hippurus (Ind. O.)	0.404	0.353	0.458	<2e−16***
Acanthocybium solandri (Atl. O.)	0.259	0.170	0.356	9.18−e8**
Acanthocybium solandri (Pac. O.)	0.266	0.204	0.338	3.10e−14***
Acanthocybium solandri (In. O.)	0.361	0.32	0.404	<2e−16***

difference among vessels was the placement of camera views relative to the area of FAD handling. This suggests that proper alignment between camera views and fishing practices is a crucial element for the usefulness of the EM methodology. Future research should focus on the validation and development of the EM methods for identification of set type without previous disclosure of the observer and fishing logbooks.

While this study used imagery to determine set type, the exclusive use of EM sensor data is a very promising method as well. In the Indian Ocean a 72% success rate was achieved based exclusively on sensor data. The differences in how vessels approach and initiate the fishing operation on either FAD or free-school sets seemed to be consistent for some vessels in the EM sensor data. Future examination of EM data collected on-board other vessels should emphasize the differences in sensor data between FAD and free-school operations.

Tuna catch estimation

It is a general requirement that catch should be accurately recorded (or within a determinate percentage of the true value), as measured in the landings. The total catch of tuna in the sets performed in the present study could generally be accurately estimated using EM. Given the combination of the camera views and a known brail volume or weight, it is feasible to accurately estimate the total catch using the number of brails and the fullness of each.

Although for the most important tuna species in volume within a set, such as the yellowfin and skipjack, the estimates made by the EM were accurate and statistically undistinguishable from the estimates made by observers, this was not the case for all tuna species. Free-school sets are normally mono-specific sets dominated by yellowfin tuna and the identification of the species is quite easy for the imagery reviewer. In contrast, FAD sets tend to be dominated by skipjack and the rest of the accompanying tuna species seems to be slightly underestimated at the expense of principal species. Clearly, sets with highly mixed species require greater attention from experienced EM reviewers and on-board methods that allow for species identification.

A major difficulty reported by EM reviewers with regard to identification of species in large mixed sets is the large volume of fish that enter the conveyor belt or shorting hopper at once. A large portion of the fish is covered by the top layer of fish in the EM footage. In an operational setting, it is necessary to ensure that fish are within camera view without slowing the movement to freezers as the elapsed time between brailing and freezing in the wells is critical to tuna product quality. The development of some mechanism to manage a high volume of fish without increasing the time before freezing would help to improve the EM-based estimate without compromising the quality of fish.

These results are consistent with other studies that have been conducted in other fisheries that have to deal with similar problems. McElderry (2008) concluded after several pilot studies that the determination of catch composition using EM is challenging in fishing gears such as seine and trawl, which bring catch aboard *en masse*.

Bycatch estimation

The EM technology utilized permitted a reliable identification and quantification of some billfish catches, but underestimated the bycatch for most other species. This result was due to catch handling methods on the participating vessels that allowed easy identification of large bycatch using EM, but made it very difficult to track and identify smaller fish, including some shark species.

Larger bycatch species (marlins, and some large size sharks) were well documented by EM, because the catch handling of the fish was easily visible to the reviewer. This type of bycatch is normally sorted from the brailer in the main deck area because they are too large to go directly through the hatch into the fish processing deck area. One benefit of EM is that it allows the simultaneous analysis of the deck and the factory. Such was the case in the Pacific Ocean, where EM detected clearly more billfishes.

Another challenge for the EM technology is the coarser grade of taxonomic identification of the catch. Precise taxonomic identification is critical when assessing the fishing effect on marine biodiversity (Vecchione *et al*., 2000). Although some bycatch was documented by the EM reviewers, in most of the cases, it was impossible to determine the species from the imagery. For species with small distinctive identifying characteristics the camera views may not allow clear enough images to discriminate bycatch to species level. The taxonomic performance with regard to large bycatch may also be improved with increased imagery resolution and frame rate.

The amount of bony fish and smaller bycatch species captured in the present experiment was generally underestimated by EM, but their presence was well documented. The high concentration of fish being processed on the conveyor belt represents the biggest challenge for the use of EM and complicates the estimation of bycatch on the processing deck. During the catch handling operation, these fish pass directly through the hatch in bulk with the rest of the catch, making their observation and identification very difficult. The catch handling methods that were used resulted in a large portion of the bony fishes and small sharks being missed in the EM review process. Usually bony fishes were retained in the wells together with tunas and they were not sorted by crew. In the case of the small sharks, sorting and discarding occurred at many different places. This catch handling method complicates the discrimination of the species bycatch using EM. These details highlight the importance of using standardized catch handling methods on-board in conjunction with EM to ensure complete data capture.

The challenge of aligning EM data collection with complex catch handling methods has been also identified by other authors as one of the main barriers for the identification of catches to species level (McElderry, 2008; Pria *et al*., 2008; Dalskov and Kindt-Larsen, 2009; McElderry *et al*., 2011; Piasente *et al*., 2012). These authors agree that working with the crew to develop and adopt a standardized approach to handling catch would improve the EM system's ability to accurately document events.

Conclusion and recommendations

Based on this research, EM is a viable tool for monitoring fishing effort, set type, and total tuna catch within the tropical tuna purse-seine fishery. To be useful, however, installation planning must be coordinated with the monitoring objectives and catch handling. Some limitations still exist for estimating species composition and monitoring bycatch.

The differences seen in this study between the two observation methods are the result of several factors related to the EM observations as well as the EM technology itself. These limitations appear similar to those found by other authors regardless of the type of vessel, gear or species (McElderry, 2008; Dalskov, 2010). In this type of study it must be emphasized to recognize that both observer and EM results are estimates; there is no precise benchmark from which to measure EM data accuracy. Since the accuracy of observer estimates are not known, it is difficult to estimate the absolute bias and precision of the EM technology. Despite the potential uncertainty of the observer estimates, these provide a more comprehensive assessment of catch than EM estimates.

Potentially one of the most influential factors for the difference between the EM-based and the observer estimates was the highly distributed catch handling on the vessels. The limited number of cameras and lack of control points hampers catch assessment. Improvements will be difficult to achieve without more cameras, more structured catch handling or both. The success of an EM programme requires that the vessel owners and crew understand the importance of standardized catch handling. This requires a good dialogue so that installation of the system does not hamper the operation of the crew, vessel and gear.

Furthermore, the EM-based catch assessment was also limited by the quality of imagery itself. The tested EM system uses analog CCTV cameras because they are economical, reliable and quite durable for at sea conditions. The lower resolution (about 0.33 megapixels per image) has generally been addressed by setting the field of view of each camera to the desired objective. When there are many activities occurring, more analog cameras are needed to cover the resolution needs properly. Digital cameras are the current standard for use with EM and there are models that are comparable to analog cameras in cost and durability. Digital cameras have much higher image resolution and frame rates and dramatically improve the ability to make catch assessments, but come with high data storage requirements. The challenge of balancing resolution needs with data storage duration becomes more difficult, especially for vessels on 6–8 week fishing trips. However, with image recording limited to setting of the net and catch processing time, significant improvements in imagery could be achieved without a burdensome addition to data storage.

Despite some of the limitations, the EM system, when used with port sampling for proper validation of taxonomic identification and catch volumes, will be valuable to gather catch statistics on target species in situations where these data are lacking or of poor quality. For bycatch investigation, the use of EM could be a complementary tool to observers during the data collection process. EM is a useful alternative that could significantly increase the sampling coverage, even if the EM data were limited to effort, location, set type and tuna catch. There are many cases where full monitoring coverage is required, mainly for fisheries control and enforcement. An example is the ICCAT requirement to increase observer-coverage to 100% for purse seiners during a two-month prohibition on FAD fishing in an area off western Africa (ICCAT Rec. 11-01). Another application would be for companies and vessels under "eco-label" certification schemes. These may require very close monitoring, including 100% observer coverage. In this case, EM could become a reliable tool for monitoring operations that the fishing industry would be happy to adopt because of its lower cost relative to other alternatives.

Finally, to be effective, any type of monitoring programme must have clear objectives, defined by the science and management data needs (Zollett *et al.*, 2011). EM shows promise as a monitoring tool for tuna purse seine, but it cannot be considered a "plug-and-play" alternative to observers. As such, industry, managers, and scientists will need to discuss how EM can fit into the overall monitoring programme, as a compliment to observers or fishing logbooks or as a tool for when observers are not an option. Each of these alternatives presents a variety of possible ways to use EM and should be considered fully. To that end, we have made recommendations to improve critical control points and video and image technology. If adopted, these recommendations could lead to significant improvements in the accuracy and precision of EM estimates.

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