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Original Article

Quantifying bycatch risk factors for the Chinese distant water fishery

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Mitigating bycatch of non-target fish species is a common objective in fisheries management that may be supported by the gathering of data from fishery observer programs and quantitative analysis of bycatch risk factors. We build three GLM models based on Chinese tuna longline fishery observer data in terms of analysis of total bycatch rate (TB rate), total bycatch ratio (TB ratio), and species-specific bycatch rate, respectively. The positive log-linear models assumed a Gaussian observation error model and a linear combination of categorical independent variables, including area, year, month, depth, and bycatch species. Results show that distributions of TB rate and TB ratio followed different trends and a latitudinal decrease was observed from both the northern and southern hemisphere of the equator. Comprehensively, the Pacific is a better place to fish compared to the Indian and Atlantic Oceans in terms of relatively lower TB rate and TB ratio. Fishing in open oceans can somehow avoid a high TB ratio than fishing in coastal waters. As a result, we recommend area 2SW, 2SE, 2 NW, 14SW, 14SE, and 14 NW as appropriate fishing ground for Albacore (*Thunnus alalunga*) while area 11N, 11S, 18SW, and 18SE to be appropriate fishing ground for fishing bigeye tuna (*Thunnus obesus*). Setting fishing gears deeper than 500 m would also help to get a low TB rate and TB ratio.

Keywords: bycatch, Chinese tuna fishery, high seas fishing, observer program, pelagic longline.

Introduction

More than one-third of the wild global fisheries production comes from less than 1% of the world's fish stocks (FAO, 2018). In the pursuit of larger target stocks, a larger number of smaller bycatch population can be subject to incidental fishing mortality: by some estimates, the discard levels represent between 10 and 20% of total reconstructed catches per year until 2000 and then decrease account for less than 10% (Zeller *et al.*, 2018). These dynamics are prevalent in high-seas tuna fisheries whose vessels generally target between 2 and 4 species of relatively large population size but catch more than 50 others, many of which are of conservation concern such as sharks and sea turtles (Lewison *et al.*, 2014).

The Chinese distant water fishery (CDF) began in the 1980s arising from a joint venture with the Indian Ocean longline fishery for deep-frozen tuna (Zhang *et al.*, 2009). The CDF subsequently expanded to include longline fisheries sourcing fresh tuna from the Western and Central Pacific and deep-frozen tuna from the high seas of the Atlantic and Eastern Pacific (Zhang *et al.*, 2009). Early in 1994, the CDF reached its maximum capacity with 457 vessels operating in the Western and Centre Pacific, where is still the most important fishing ground of Chinese tuna longline fishery. Due to various factors including declining catch rates and disputes over fishing grounds, the number of vessels decreased markedly to just 204 at the end of 1998, with 120, 18, and 66 operating in the Indian, Atlantic and Pacific Oceans, respectively. That year the CDF caught 6770 metric tons, around half the 1994 catch of 12885 metric tons (Zhang *et al.*, 2009). The number of fishing vessels declined to 46 in 2008 and declined further after November 2008 when pirates took a longline vessel hostage in the Indian Ocean (Xu *et al.*, 2010).

An extensive observer program for the CDF was designed and implemented in 2003 (referred to herein as the CDFOP) to provide 5% trip coverage of global CDF fishing operations (Chen *et al.*, 2007). Alongside China, several other countries implemented observer programs to meet RFMO requirements such as the Japanese longline observer program (Matsumoto *et al.*, 2005; ICCAT, 2016) and the U.S. Pelagic Observer Program of the National Marine Fisheries Service that follows the U.S. Atlantic pelagic longline vessels operating in the Atlantic (Diaz *et al.*, 2008; Beerkircher *et al.*, 2009).Observer programs such as the CDFOP provides detailed data on bycatch species that are often missing from commercial logbooks, which are subject to less strict reporting standards.

In this first publication using the CDFOP dataset, our principal aim and motivation are to conduct a post-hoc analysis to identify and quantify the main critical risk factors determining bycatch rates in the CDF. Additionally, "bycatch" in this study is defined as the non-targeted species caught in tuna longline fisheries excluding the three target species, which are bluefin tuna (*Thunnus Thynnus*), bigeye tuna (*Thunnus obesus*) and albacore (*Thunnus alalunga*). Similarly to the definition of "bycatch" in Zeller *et al.* (2018), bycatch here may or may not be discarded but will be well recorded by observers. As a fact, due to similarities between fleets in the Chinese tuna longline fishery and the stochastic arrangement of setting observers on fishing vessels, we assumed here that data collected from the observer program can well represent China's tuna longline fishery.

Material and methods

All types of data, including catch data, spatial information, and set conditions were taken from CDFOP. From 2010 to 2017 the CDFOP measured and identified 246700 animals from 6400 longlines with complete data on fishery location and gear type, providing an extensive global fishery dataset. From a conservational perspective, the geographical location, depth, size, and catch rates of bycatch species present critical information gaps. In the Pacific, at least 650 species of other bony fishes may be caught in association with pelagic longline fisheries many of which are only reported in observer programs. Amongst the most commonly encountered are dolphinfish, opah, oilfish, escolar, and ocean sunfish all of which have poorly understood population status. The elasmobranchs (sharks, skates, and rays) occupy a unique position somewhere along the spectrum between explicit target species and undesirable bycatch species. Amongst the 14 bycatch species of sharks listed by WCPFC in need of data collection, nine were recorded in the CDFOP complete with detailed information of depth, location, and gear configuration. Likewise, the CDFOP obtained detailed data for five species of sea turtles (except hawksbill turtle) listed by the WCPFC in need of data collection; also listed as under threat of extinction (Clarke *et al.*, 2014, 2015; Williams *et al.*, 2016). For detailed data collection methods, see WCPFC (2018).

In this study, yellowfin tuna (*Thunnus albacares*), wahoo (*Acanthocybium solandri*), swordfish (*Xiphias gladius*), skipjack tuna (*Katsuwonus pelamis*), escolar (*Lepidocybium flavobrunneum*), blue shark (*Prionace glauca*), and long snouted lancetfish (*Alepisaurus ferox*) were chosen to investigate bycatch risk factors in tuna longline fishery, on account of ranking the first seven abundant bycatch species through CDFOP record from 2010 to 2017. Given the geographically varying composition of target species, and prevailing oceanographic conditions affecting species habitats, data used here were separated per ocean. Data recorded for each ocean were assigned a categorical area definition to ease localizing oceanographic conditions, fishing behaviour, and species composition. Similarly, gear set depth was categorized into the same levels, and fishing time during the year was summarized as months. Additional categorical covariates were included such as year, month, gear, and vessel ID. Based on these categorical independent variables, three generalized linear models were built to evaluate their correlation with the following response variables: total bycatch numbers of all species combined per unit effort (total bycatch rate, Equation (1)), total bycatch numbers of all species per total target species catch in numbers (total bycatch ratio, Equation (2)), and bycatch in numbers of each species per unit effort (species-specific bycatch rate, Equation (3)). The first analysis summarizes this overall bycatch species. The second analysis aims to identify the most bycatch-efficient means of obtaining a given catch limit for target species. The third analysis was used to identify possible species-specific drivers of bycatch for a standard unit of fishing.

The positive log-linear models assumed a Gaussian observation error model and a linear combination of categorical independent variables:

$$ln\left(\frac{B}{E}\right) = a + m + d + y + s + \varepsilon. \quad (1)$$

$$ln\left(\frac{B}{T}\right) = a + m + d + y + s + \varepsilon. \quad (2)$$

$$ln\left(\frac{B_s}{E}\right) = a + m + d + y + \varepsilon. \quad (3)$$

As it was defined above, Equation (1) is for total bycatch rate (TB rate), Equation (2) is for total bycatch ratio (TB ratio), and Equation (3) is for species-specific bycatch rate (SBR). All parameters are set-specific summarized using the China tuna longline observer data. Where, depending on the analysis, B is the total number of captured bycatch species (retained and discarded on observer record), B_S is the catch in numbers of a specific bycatch species, E is the fishing effort (number of hook) and T is the catch number of target species (retained and discarded on observer record). The categorical independent variables represent: area a, month m, depth d, year y, and species s. The term ε represents a normal observation error term. Models (1), (2), and (3) are final models based on interaction result (Supplementary Tables S1, S2-1, and S2-2) as interactions do not improve model fit effectively.

Based on set numbers in each area and geographical distribution, only a few sets operated in some areas, and massive sets occurred in one area. So, we recategorized some of the original areas assigned by latitude and longitude, areas with less than 20 sets were not concerned in the analysis, and secondary strata were assigned in areas with a large number of sets (e.g. Area 2, 14, and 18). We also combined some areas for the convenience of the analysis and make it more reasonable (areas 7 and 8). The final set numbers and geographical distribution are presented in Figure 1. The model with the most appropriate and explanatory Bayesian Information Criterion (BIC) value (Schwarz 1978) was chosen as the final model.

To test for overparameterization, we conducted a set of cross-validation exercises wherein multiple instances the final model was fitted to randomized samples of 80% of the data to evaluate the predictive ability for the remaining 20%. A total of two indices were used to measure the performance of the final model used in this analysis [Root Mean Square Error (RMSE) and R Squares (RS)]. These indices were used to quantify the accuracy and precision of values estimated by the model.

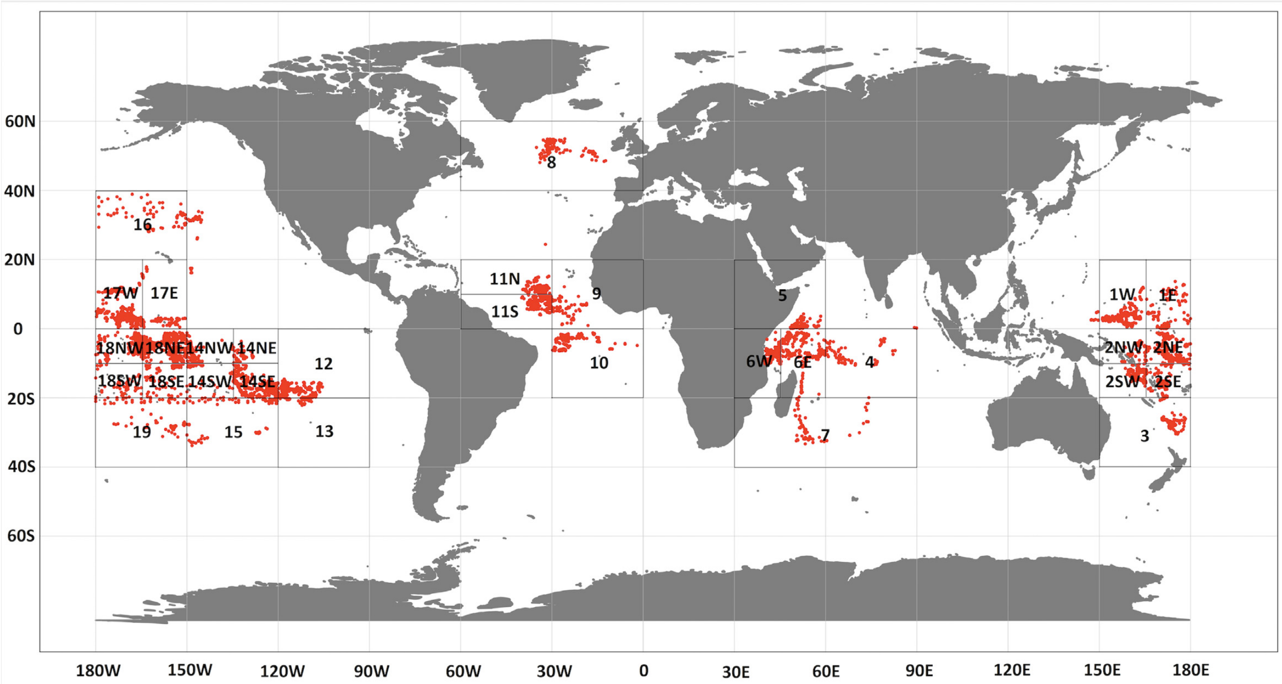

Figure 1. Set distribution with strata names over oceans. Each red point represents a single set. There were 19 main strata with sub-strata of areas with a large number of sets operated.

Table 1. Cross-validation result of positive log-linear models. Values of parameters come with 95% *CI*.

Cases	Models	RMSE	RS	a	b
TB rate	ln(B/E)	0.81 (0.797, 0.829)	0.16 (0.140, 0.178)	0.98 (0.903, 1.092)	− 0.01 (−0.041, 0.042)
TB ratio	ln(B/T)	1.06 (1.017, 1.133)	0.35 (0.323, 0.373)	0.99 (0.940, 1.062)	− 0.06 (−0.393, 0.388)
SBR_ALX	$\ln(B_S/E)$	0.80 (0.763, 0.858)	0.37 (0.296, 0.424)	0.97 (0.854, 1.081)	0.01 (−0.079, 0.072)
SBR_BSH	$\ln(B_S/E)$	0.87 (0.831, 0.915)	0.07 (0.035, 0.106)	0.92 (0.616, 1.219)	− 0.02 (−0.135, 0.085)
SBR_LEC	$\ln(B_S/E)$	0.68 (0.649, 0.721)	0.12 (0.068, 0.179)	0.93 (0.638, 1.260)	− 0.03 (−0.221, 0.147)
SBR_SKJ	$\ln(B_S/E)$	0.82 (0.767, 0.872)	0.11 (0.056, 0.161)	0.92 (0.581, 1.195)	− 0.01 (−0.131, 0.086)
SBR_SWO	$\ln(B_S/E)$	0.58 (0.551, 0.607)	0.13 (0.081, 0.180)	0.95 (0.730, 1.182)	− 0.03 (−0.165, 0.141)
SBR_WAH	$\ln(B_S/E)$	0.58 (0.547, 0.601)	0.11 (0.061, 0.173)	0.91 (0.667, 1.189)	− 0.04 (−0.202, 0.116)
SBR_YFT	$\ln(B_S/E)$	0.92 (0.888, 0.951)	0.11 (0.079, 0.158)	0.95 (0.771, 1.186)	0.01 (−0.079, 0.079)

TB rate: total bycatch rate; TB ratio: total bycatch ratio; SBR: species-specific bycatch rate; RMSE: root mean square error; RS: root square; a and b are linear regression parameters between observed and predicted values. Parameters are listed with point estimate and 95% *CI*.

All analyses were carried out in R software using the GLM function; the package "ggplot2" was also used for mapping and spatial analyses.

Results

Cross-validation and predictive capacity of the model

The BIC values, model fits, and residual patterns of all initially constructed models are presented in Supplementary Table S1. For each analysis, the model with the appropriate BIC value was selected for subsequent analysis. Cross-validations were conducted on all three final GLMs and results are presented as shown in Table 1.

The RMSE values of TB rate and the SBR models were similar, however, the RMSE value was slightly higher in the bycatch ratio (TB ratio) model than in the other two models (Table 1). RS values ranged from 0.14 to 0.43, the lowest recorded in TB rate case and the highest in SBR case. The predictive capacity of all three models was acceptable when looking through *a* and *b* values as they asymptotically approach the expected values 1 and 0, respectively.

Even though RS values were not relatively perfect, especially the RS of the bycatch rate model. Given the uncertainties and characteristics of commercial fisheries, we think the models explained the data well because the range of RMSE was far tighter than the range of the corresponding variables; and the values of *a* and *b* had reasonable ranges. Model fit is showed in Supplementary Table S6 and Figures S1, S2, and S3.

Summary of target species

Nominal CPUE (inds/hook) of the three target species including albacore, bigeye tuna, and bluefin tuna are summarized in Figure 2. CPUE of albacore was mainly concentrated in the Pacific Ocean,

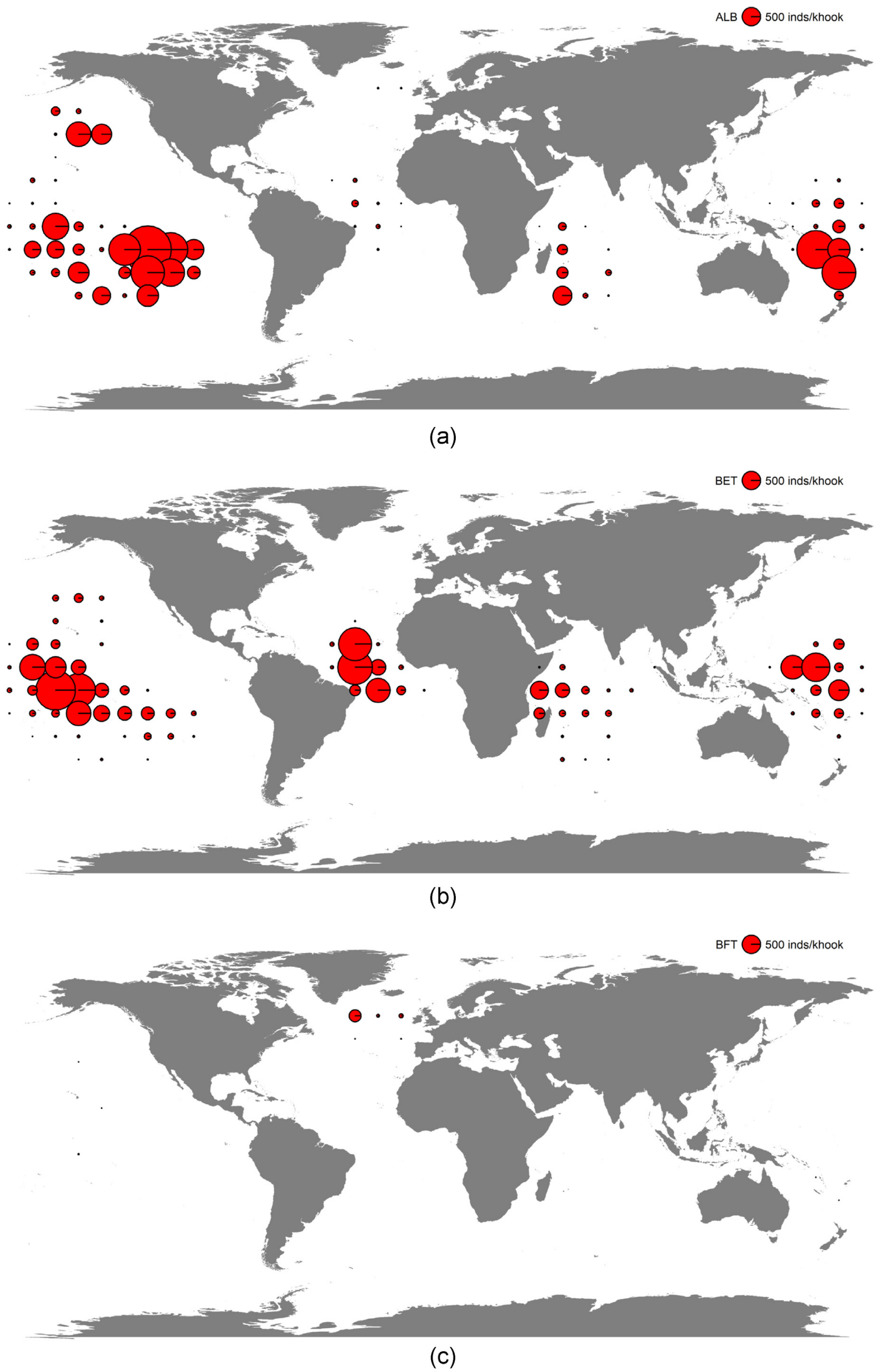

Figure 2. Nominal CPUE distribution of the three target species. (a) albacore (ALB), (b) bigeye tuna (BET), and (c) bluefin tuna (BFT).

particularly the West and East Pacific. A small concentration of the CPUE occurred in the Indian Ocean for albacore, as well as the bigeye tuna. A large amount of CPUE was observed in the central Atlantic Ocean for bigeye tuna, meanwhile, in the Pacific, high concentrations of the CPUE were observed in the west and central Pacific and decreased rapidly when moving towards the east. The CPUE of bluefin tuna was abundant only in the north Atlantic as a result of quota control imposed by ICCAT on this species.

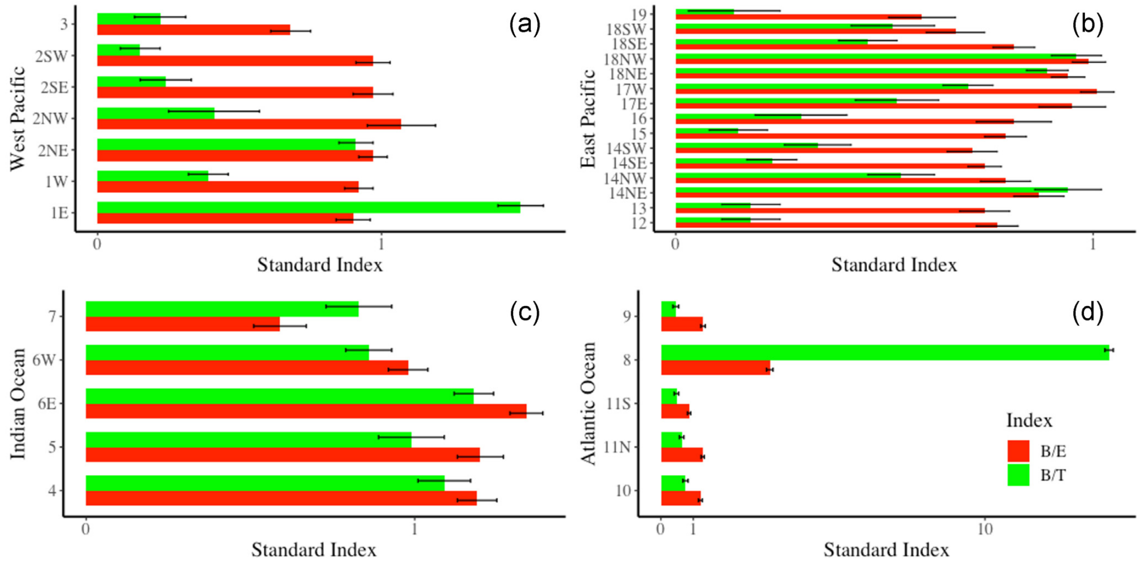

Figure 3. TB rate (B/E) and TB ratio (B/T) over oceans with 95% *CI*. B/T: TB ratio, B/E: TB rate.

TB rate and TB ratio

The TB rate and TB ratio are shown in Figure 3 through spatial analysis in the Pacific Ocean, Indian Ocean, and the Atlantic Ocean based on the strata we created from the sets distribution. p-values for parameter-area are listed in Supplementary Tables S3 and S4 for Model (1) on TB rate and Model (2) on TB ratio, respectively. The TB rate and TB ratio have different tendencies among the strata.

TB rate

The TB rate in the Pacific looks like a normal distribution, even in some sub strata such as 18NE with a large number of sets as well as strata with dispersive distributed sets such as area 16, which means TB rates in the Pacific are similar among areas where commercial fisheries operate.

In the Indian Ocean, the TB rate appeared to be slightly higher than in the Pacific. The relatively lower value in area 7 might be influenced by only a few sets conducted over the large geographical area.

Interestingly in the Atlantic Ocean, the TB rate in area 8 was higher than those in other areas in the Atlantic. The bycatch rate reached 13.83 in area 8, which is over 23 times the average rate of the mean value of 0.59 in the other four areas. When looking into area 8, more than 87% of the bycatch were blue sharks, with the vessels targeting bluefin tuna fishery in this zone of the Atlantic Ocean. The catch compositions in this area were simpler to distinguish than those in other areas such as the Pacific, Indian, and South Atlantic Oceans.

TB ratio

The TB ratio is the factor fisheries scientists, companies, and managers pay the most attention to. Fishermen have great interest in areas where the target catch rate is high but with a low bycatch rate. The results of the TB ratio in our analysis showed varying distributions different from that of the TB rate.

In the Pacific, the TB ratio had various values for different areas. The highest value was over 1.5 while the lowest was less than 0.25 (Figure 3). In some strata, such as area 1, the bycatch ratio was completely different in the two sub-areas. Similar situations also happened in areas 2 and 14 alongside their sub-areas. Area 18, which contains massive sets in four sub-areas, the bycatch ratio of sub-strata close to the equator was much higher than those away from the equator. This situation was also observed in area 2 and 14 within their sub-strata.

In the Indian Ocean, we could easily find that the bycatch ratio in each stratum was relatively higher than those in the Pacific (Figure 3). Similar results were observed in areas with large number of sets such as area 6E than in areas with much fewer sets and wider distribution like area 7. Meanwhile in the Atlantic Ocean, a supremely large bycatch ratio was observed in area 8, located in the Northern Atlantic Ocean (Figure 3).

SBRs

The most abundant seven bycatch species in total catch were chosen to conduct the SBR analyses (Figure 4). The p-values of different species coefficients by areas are listed in Supplementary Table S5. The bycatch rates of the seven species appeared completely different in distributions as well as SBRs, which equally differed a lot in different areas for the same species. Blue shark is a species with a large amount of data and has an obvious ocean-specific distribution. The bycatch rate of the blue shark in the Pacific and Indian Oceans was mostly lower than 1, while in the Atlantic Ocean, the bycatch rate had extremely high values of up to 4.81 in area 8 in the Northern Atlantic Ocean. There were also some high catch rates of long-snouted lancetfish in some areas such as areas 3, 12, and 13 in the Pacific, and 4 and 6E in the Indian Ocean. Catch rates of other bycatch species, including the skipjack tuna, escolar, swordfish, yellowfin tuna, and wahoo could also be observed in the three oceans but had lower abundance as compared to the blue shark and long-snouted lancetfish.

Spatial patterns

As expected, there were obvious spatial characteristics of both bycatch rate and bycatch ratio, especially in terms of latitudes. The TB rate was stable all over the three oceans except in the Atlantic. In

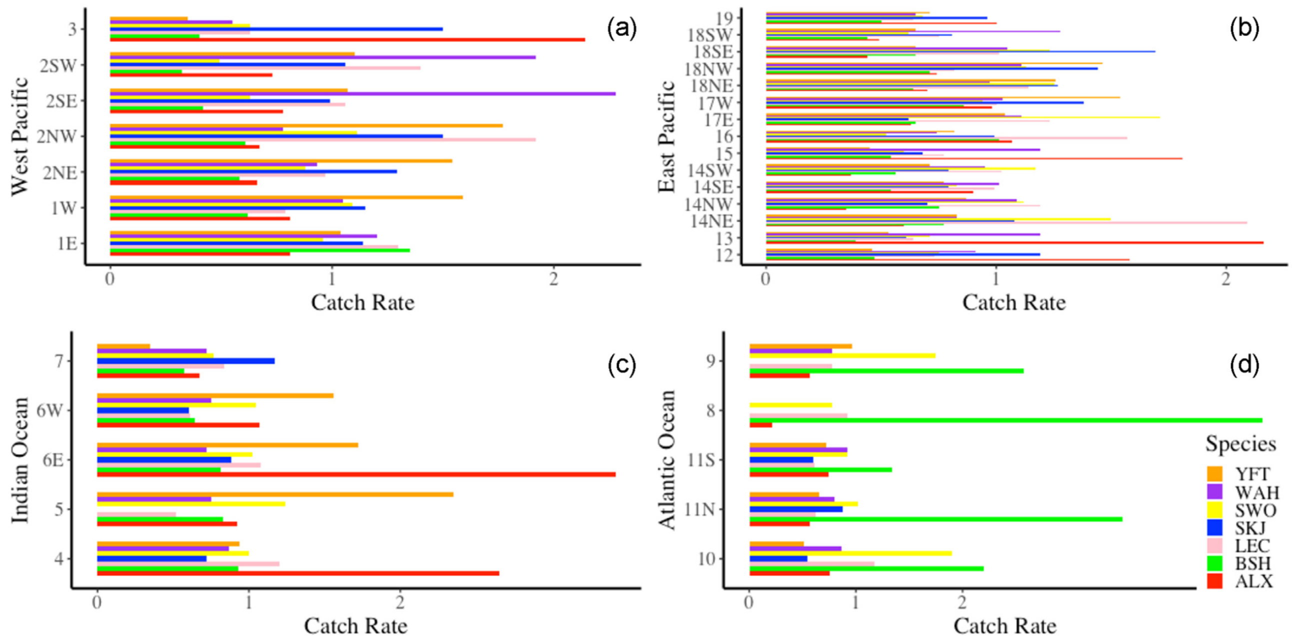

Figure 4. SBR over Oceans. Top seven abundant bycatch species in catch were included in the analysis. They are: yellowfin tuna (YFT), wahoo (WAH), swordfish (SWO), skipjack tuna (SKJ), escolar (LEC), blue shark (BSH), and long-snouted lancetfish (ALX).

the Atlantic Ocean, the TB rate was high in the north. Looking into the vessels and fisheries conditions in the Northern Atlantic, target species and limited bycatch species may probably be the reason.

When looking at the TB ratio in Figure 2, we found that it looked very different from the TB rate. Bycatch ratio still stayed high in the Northern Atlantic probably due to the same reason mentioned above. In the Indian Ocean, we could easily observe that the TB ratio was proportional to the TB rate. There was an obvious difference in the TB ratio in terms of latitude, and this trend was more obvious in the TB ratio than in the TB rate. The TB ratio in the south of the main strata was lower than those in the northern areas. For instance, the bycatch ratio of areas 18SW and 18SE was lower than that in areas 18NW and 18NE. Similarly, the bycatch ratio in areas 14SW and 14SE was much lower than that in the Northern sub-strata of areas 14NW and 14NE. Generally in the Pacific, the TB ratio was higher when fishing was done closer to the equator.

SBRs appeared to be a bit cluttered when distribution was plotted spatially (Figure 4). The catch rate of the long-snouted lancetfish was high in coastal areas than in open oceans, and was much lower in the Atlantic than in the Pacific and Indian Oceans. As indicated above, blue shark was the main reason why the TB rate and ratio increased in the Northern Atlantic Ocean. Also, blue shark catch rate was higher in the Atlantic than in the other two oceans, which could be attributed to fishing vessels targeting bluefin tuna, consequently increasing bycatch rates in the Northern Pacific. The catch rate of yellowfin tuna in areas 1, 2, 5, 6, 17, and 18 were significantly higher than in the other areas. Skipjack tuna was not frequently caught all over the oceans compared to the other species. A low catch rate of this species was observed in the Indian Ocean and was barely caught in the Atlantic. Swordfish's catch rate in the Atlantic was slightly higher than in the Indian and Pacific Oceans. The catch rate of wahoo was significantly high in areas 2SW and 2SE compared to other areas while the catch rate of escolar in the Pacific was slightly higher when compared to the other two oceans.

Depth patterns

A large number of sets operated in the Pacific Ocean, with hooks depths ranging from 100 to over 700 m (Figure 5a). The TB rate and TB ratio from 100 to 500 m were higher than those in deeper waters over 500 m as observed in Figure 5 . Both values of the TB rate and TB ratio peaked at water columns 400–500 m, representing 1.14 and 1.29, respectively.

As for the Indian Ocean (Figure 5b), only four water column depths were reached in the fishery. Slight differences were observed in the TB rate in terms of depths, meanwhile, the TB ratio peaked at 1.32.

The number of water column depths in the Atlantic Ocean was the same as in the Indian Ocean but the situation was completely different (Figure 5c). Both the TB rate and TB ratio peaked at 1.45 and 1.24, respectively, in the deepest water column 400–500 m.

Discussion

A large amount of information is provided throughout quantifying bycatch risk factors, and the information reflected from the China Tuna Longline Observer Program might provide fundamental guidelines for mitigating bycatches in commercial fisheries. In this study, a tendency was observed related to the TB rate and TB ratio in terms of latitude. In the three oceans analysed in the present work, the depth patterns showed significant characteristics but differed by oceans. There exists impact on bycatch from the time factor year and month, whereas we believe this is caused by observer dispatching situation, which is also an aspect to be improved in future studies. Consequently, we mostly focused on spatial and depth patterns in this study. As a possible solution to problems faced in commercial fisheries, the information presented in this study could contribute to means of mitigating bycatches by exploring fishing grounds with an equilibrium target–bycatch relationship.

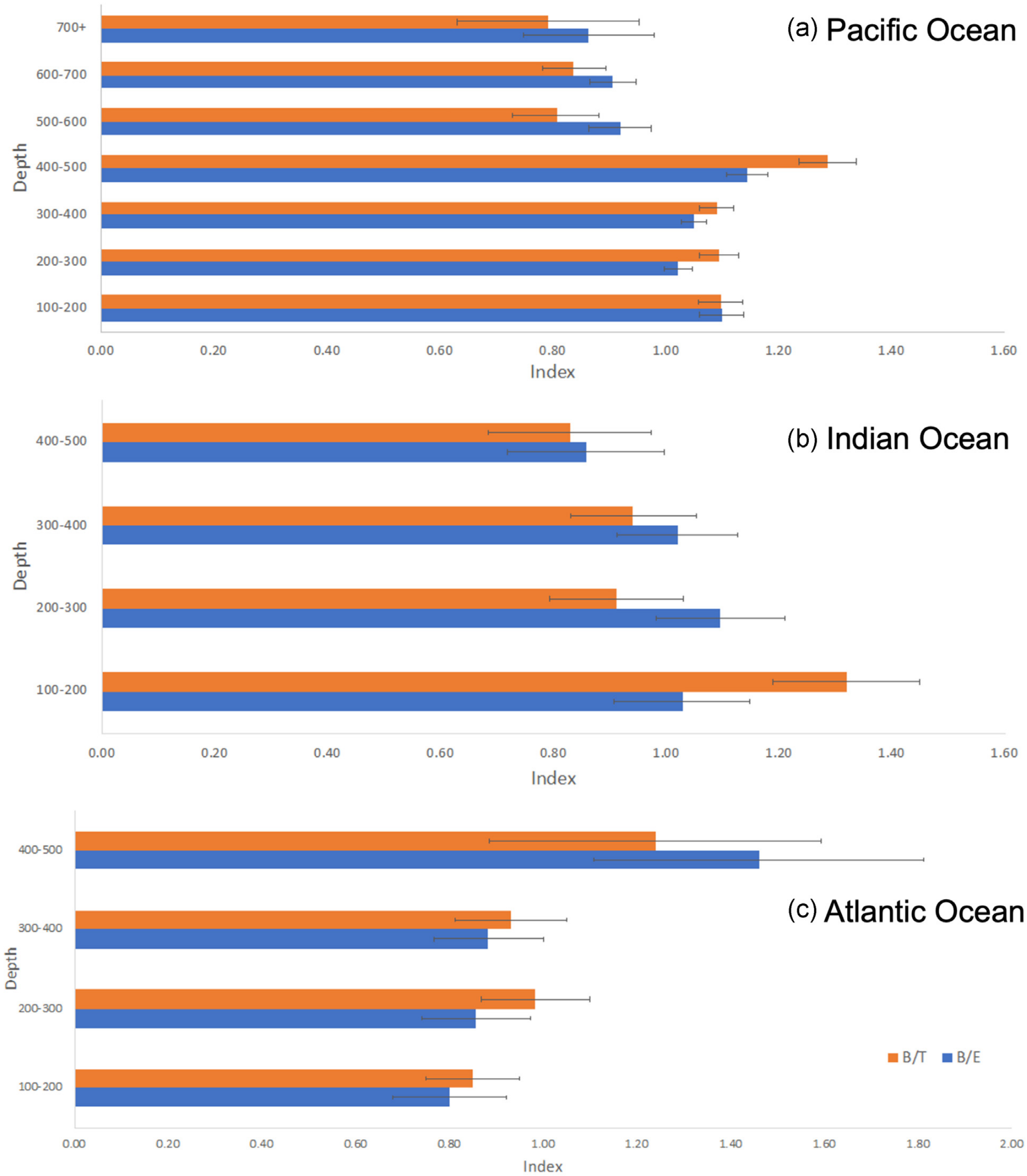

Figure 5. TB rate and TB ratio with 95% *CI* over oceans. B/T: TB ratio, B/E: TB rate.

Spatial distribution

Based on the fishery operations, there were 11 main strata located in the Pacific, accounting for more than half of the total number of areas. These numerous areas had the lowest average bycatch ratio observed in the Pacific Ocean indicating a better fishing area than those from the Atlantic and Indian Oceans. Theoretically, when we harvest the same amount of target species, we might get fewer bycatches in the Pacific Ocean than in the other two oceans.

Comprehensively, the spatial characteristics of distribution are easy to find when we look at the TB ratio over oceans. As observed, the bycatch ratio increased when fishing was done closer to the equator. In the Pacific, the TB ratio in areas away from the equator, including areas 3, 13, 15, 16, and 19 were much lower than those in areas located on the equator. However, this was not obvious in the Indian and Atlantic Oceans. We think this difference might be caused by both data size and geographical coverage of the fishery analysed in the present study. We also think there might be some differences between coastal areas and areas in the open oceans, probably because of the limited coverage of our data distribution, this was not obvious in our analysis.

In the Indian Ocean, there were not huge differences in the TB rate and TB ratio between areas. The main observed difference was that the TB rate in area 7, which is a combined area in the Southern Indian Ocean, was slightly lower than those in other areas. We guess it is caused by the geography distribution of bycatch species. Most bycatch species aggregate in equator waters, which means there could be fewer bycatches stay or caught in areas away from the equator such as area 7.

In the southern Atlantic, the TB ratio was moderate compared to the Pacific and was almost half of that observed in the Indian

Ocean. Furthermore, this ratio attained 13.83 in the Northern Atlantic. Not surprisingly, bluefin tuna fishing was probably the main reason causing this increase. Most vessels fishing in the northern Atlantic targeted bluefin tuna and only a few of them targeted bigeye tuna before or after bluefin fishing because it only takes few days to finish the allocated quota. In the Northern Atlantic, bycatch species composition differed greatly as blue shark was the most numerous bycatch species in this region, meanwhile, other bycatch species found in other areas were scarce in this region. Hence, we noticed that the high captures of blue shark species led to the increase of the TB rate and ratio. When looking at the other two oceans, the comparability of blue shark catch rate among oceans was very weak caused by the variation between stocks in different oceans. Furthermore, the target catch is also an important impact issue on the bycatch rate and ratio as it was emphasized in the content above, e.g. the simple component of catch species in the Atlantic results in the significant bycatch rate and ratio. Standing at the point of the global fishery, our study aims to provide scientific evidence to managers on decision making progress in fisheries on high seas, thus we focused on oceans when comparing species-specific indices.

Given data from the commercial fishery, this result can only represent the condition in the open ocean and also a few coastal and water areas around islands. We are still lacking data on coastal areas. Thus, providing room for improving data coverage to determine bycatch issues all over different oceans.

Depth

The depth of 500 m seemed to be the boundary in both the total catch rate and ratio analysis. In the Pacific, both TB rate and TB ratio below 500 m water are significantly higher than those above 500 m. A low TB rate with a low TB ratio meant we had more harvest on target species with fewer bycatches. This reflects important information in the Pacific, with a water column below 500 m as a better choice to reduce bycatch than putting hooks deeper than 500 m. Biologically, this might be caused by the behaviours of both target and bycatch species. Based on our results, we think that most of the bycatch species fed in depths above 500 m. Thus, it will be a good choice to increase the depth of fishing gear appropriately, for instance between 500 and 700 m, and try to reduce hook numbers for water columns below 500 m. However, based on the studies conducted by other researchers (Gamblin *et al*., 2007; Xu *et al*., 2012; Campbell and Young 2012), longline fisheries targeting tuna and tuna-like species usually set hooks around 0–500 m water column, where TB rate and ratio are critically higher than in deeper waters. As a result, for commercial fisheries, deeper hook sets would probably not be an ideal method to mitigate bycatches as they might affect target catch and increase effort input.

In the Atlantic, the TB ratio was much higher in water columns above 200 m than those below 200 m. But when observing the TB rate, it was not proportional to the TB ratio. So combining these two signals, we think that shallow water columns above 200 m would not be a good choice for tuna longline fishery as more bycatches would be observed, particularly blue sharks in the Northern Atlantic.

Regarding the Indian Ocean, interestingly, both TB rate and ratio reached peak values at 400–500 m water columns. This reminds fishermen to pay more attention when fishing in the Indian Ocean. Conversely, fishing gears should be set at shallower depths in the Indian Ocean, above 400 m from our analysis.

Fishing hot spots

As mentioned above, TB ratio analysis indicates the catch rate correlation between bycatch and target species. Here, we only discussed the fishing hot spots within each ocean without comparing them among the three oceans because this study aims to provide management advice to RFMOs. Therefore, inter-ocean comparison on TB rate and TB ratio is less meaningful than analysis on strata characteristics within oceans. The Atlantic Ocean is an interesting region to take a look at, especially in the North Atlantic with the actively controlled bluefin tuna fishing operations. The significantly high TB ratio observed in this study was mostly due to the high catches of the blue shark, which probably made it simple to reduce the bycatch ratio. Since the catch rate of blue sharks slightly dropped above the 500 m water column, we suggest trying proper implementation of deeper hook depths when fishing bluefin tuna in the northern Atlantic. However, the catch rate of target species such as bluefin tuna might affect the bycatch ratio given that in the north Atlantic, the main bycatch species observed was the blue shark (about 90% of total bycatch in the North Atlantic). Block *et al.* (2001) pointed that Atlantic bluefin tuna can dive to water depths of over 1000 m, thus, we believe that there will be a slight influence on target catch when hooks are applied at higher depths.

As regarding the Indian Ocean, the distribution of bycatch species mainly varied with respect to latitudes. The TB rate was higher in the northern Indian Ocean as compared to the south; contrarily, the TB ratio dropped, respectively. Unfortunately, we do not have data from the eastern Indian Ocean. For proper comprehension of how bycatch species are distributed in the Indian Ocean, we encourage the collection of more data to help in future bycatch ratio analysis in the entire Indian Ocean.

There were 11 strata in the Pacific, which is more than half of the total strata of the three oceans. Based on the Chinese tuna longline fishing history, the Pacific Ocean has always been the main fishing ground for commercial fishing when compared to the Indian and Atlantic Oceans. The Western and Central Pacific Ocean is the main fishing ground for the Chinese tuna longline fishery. The average TB ratio in the Pacific was the lowest among the three oceans and there was a significant trend in terms of latitudes. Areas with obviously low bycatch ratio were mostly located between 20°S–40°S and 20°N–40°N. Based on the results of the TB rate and TB ratio in our study, fishing areas around the equator were not ideal fishing grounds for tuna longline fishery since more bycatch species were observed in these areas. However, from the set distribution map (Figure 1) and the nominal CPUE distribution of the three target species (Figure 2), fishing seemed to have been more concentrated in areas close to the equator to fish tunas, which might solely be because of the distribution of target species. Consequently, for longline fishery targeting albacore, our suggestion would be to fish in areas 2 and 14 as this balances the target species CPUE and the TB ratio.

The central Pacific Ocean might not be a good fishing ground as albacore CPUE was very low and the TB ratio was high as well. For the fishery targeting bigeye tuna, we suggest to fish in the southern Area 18 and move more effort to the Atlantic Ocean if possible as we got high bigeye CPUE and relatively low TB ratio in that area. We encourage to fish in relatively high latitude areas, for instance, higher than 20°S and 20°N, meanwhile, try to put fishing gears appropriately deeper. We think this might be very helpful in tuna longline fishery, particularly in the Pacific Ocean.

Consequently, on the purpose of providing a guidance for tuna longline fishery based on the Chinese tuna longline observer data, we suggest that fishing operations be carried in area 2SW, 2SE, 2 NW, 14SW, 14SE, and 14 NW, suitable fishing ground for capturing Albacore and area 11N, 11S, 18SW, and 18SE appropriate for fishing bigeye tuna.

Limitations

We only used positive index data in the analysis using GLM and assumed that results from areas with fewer data were less reliable. The unknown situation of areas without or only with few data will possibly bring problems in spatial analysis. A full-coverage dataset in the future would be very helpful to carry out a detailed analysis in terms of latitude and longitude over the whole ocean bodies.

RS coefficients indicated lower values implying that the model fits might not be that good; this might be due to the high uncertainty of the observer data. However, the uncertainties from our tuna longline observer program are difficult to remove or reduce due to the commercial fishing conditions. One suggestion is to enhance observer coverage on both geographical and seasonal coverage for further comprehensive analyses.

Another possible limitation was that of depth analysis presented in this paper where the use of the catenary equation was used to calculate the mean hook depth from recorded hooks per basket. There is evidence that this approach may be strongly biased and that hooks are deployed shallower than calculated results. For example, in the case of Chinese longline vessels operating in the Indian Ocean, using the catenary equation Xu *et al.* (2012), calculated that 59% of hooks were deployed in depths between 200 and 400 m. However, independent depth measurements obtained by Time Domain Reflectometry (TDR) suggested that 71% of hooks were deployed shallower than 200 m. Similarly, using the catenary equation, Song *et al.* (2007) calculated set specific maximum depths occurring between 310 and 350 m. When compared with independent measurements by TDR these could be as shallow as 90 m, indicating similar biases in the Indian and Pacific Oceans.

Future analyses

The observer data collected supports a wide range of new research directions to be further analysed including the calculation of abundance indices, quantification of Illegal, Unreported and Unregulated (IUU) fishing, derivation of standardized catch rate indices for stock assessment, and the development of spatial fishing strategies. A priority for subsequent research is to develop defensible standardization models to derive CDFOP abundance indices that may be submitted to RFMOs for their consideration, and where appropriate used to inform stock assessments. The spatial characterization of catch rates may also provide opportunities to develop spatial (including depth) strategies for maximizing the catch rate of target species while minimizing that of bycatch species (some of which may be endangered). For example, Figure 4 suggests that the geographical distribution of bigeye and yellowfin tunas is quite different from that of albacore providing scope for species-specific management strategies to achieve management objectives. Such management strategies may also benefit from the additional information that was collected regarding size at capture, by prioritizing the capture of juvenile or mature fish to address recruitment- or growth-overfishing, respectively (Matos-Caraballo, 1999; Diele *et al.*, 2005; Diekert, 2012).

For every trip that the CDFOP has detailed observer data, there are also standard log-book data. These paired data offer an opportunity to quantify the possible extent of IUU fishing and bycatch for the wider Chinese longline fleet (Walsh *et al.*, 2002). This could be extended to non-Chinese longline vessels by comparing reported catch rates by time–area–depth strata with those recorded by the CDFOP. Additionally, where effort data are available, the CDFOP catch rate data (target species and bycatch) could be used to assign catches of species of billfish, tuna, sharks, and sea turtles for similar gears that are fished at comparable times, areas, and depths. Release condition data for bycatch species could also be used to better characterize post-release mortality rate for principal bycatch species (Skomal, 2007; Campana *et al.*, 2009). Similarly, tag recovery data could be compared with those of the commercial fleet to quantify probabilistic estimates of tag reporting rates (Carruthers *et al.*, 2014).

In recent years, the Chinese government has worked together with Shanghai Ocean University to significantly improve the CDFOP and tailor it to the unique demands of the Chinese distant water fleet. Following experience gained from running the CDFOP and benefiting from the findings of other observer programs in the US and Japan, there are some areas where the CDFOP can be improved further. Although previously necessary for practical reasons, the incomplete seasonal coverage significantly lessens the scope of the potential post-hoc analyses that were listed above (e.g. quantification of IUU and catch rate standardization). For example, there was a lack of data from April to July throughout the 8 years of the CDFOP that may be a critical gap for species that migrate seasonally or whose seasonal distribution has changed over time. This is to be addressed by revision of the CDFOP to a year-round operation similar to the longline observer program of Japan (Matsumoto *et al.*, 2005; ICCAT, 2016), which will rely on more extensive communication and collaboration between government officials, stakeholders, and academic partners.

The CDFOP will continue to gather one of the richest and spatially extensive global fishery datasets. The principal challenge now is to analyse these data and disseminate results to maximize the value and impact of the program for the wider fishery management and scientific community. The Chinese government is committed to the long-term support of the CDFOP to meet the requirements of RFMOs but also to enhance collaboration and communication among RFMO partners. Bycatch analyses have previously focused on raw bycatch CPUE or spatial distribution of bycatch species (Sims *et al.*, 2008; Fossette *et al.*, 2014). For target fisheries controlled by TAC management, the most appropriate metric would be the bycatch ratio, target catch, which provides information of the best locations for implementing the TAC. Bycatch ratios are valuable and should be provided in these fisheries.

Global conservation blueprint

Bycatch-to-target species bycatch ratio is always a hot topic in international fisheries management. Stock *et al.* (2019) used the US west coast groundfish trawl survey data to evaluate the ratio estimator against the GAM and random forest methods where 15 bycatch species were applied representing a range of bycatch rates. Similar to what was observed in our study, stratified ratio estimators were implemented, therefore, the observed bycatch-to-target species catch ratio was multiplied by the target catch of the unobserved hauls in each stratum. As a result, a weak relationship between effort and bycatch was found. In another study, this time on global elasmobranch bycatches, Oliver *et al.* (2015) analysed the number and weight of captured elasmobranch bycatches relative to that of the target species. Their study corroborated with our findings, they pointed out that most of the current information on elasmobranch bycatch were mostly for the North Atlantic, which is not where the greatest fishing pressure is exerted. They also mentioned that the highest bycatch ratios observed in pelagic longline fisheries in the South Atlantic were mostly on shark species. Oliver *et al.* (2015) discovered that pelagic longline fisheries had the highest individual-based bycatch ratios, followed by pelagic trawls. Moreover, the size of the target species would have some influence on the individual- and weight-based bycatch ratio indicating that choices of management indicators could be based on apparent fisheries characteristics.

For species conservational purposes particularly for bycatch species, it is primordial to perform bycatch rate and ratio analyses with relation to target species to better understand the interaction that major bycatch species might have with main target species. This information would also assist managers or fishermen to identify fishing grounds susceptible to producing low bycatch-to-target species occurrences in order to better manage bycatch species and species of interest.

Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

1. Comparison of GLMs based on BIC.
2. Statistical significance of area effect in estimating TB rate, TB ratio, and SBR.
3. Deviance residuals and BIC for TB rate model, TB ratio model, and SBR models.
4. Residual patterns of TB rate model fit.
5. GLM residual plots for TB rate, TB ratio, and SBR.

Data availability statement

The data underlying this article will be shared on reasonable request to the corresponding authors.

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References

Beerkircher, L., Brown, C. A., and Restrepo, V. 2009. Pelagic observer program data summary, Gulf of Mexico bluefin tuna (*Thunnus thynnus*) spawning season 2007 and 2008; and analysis of observer coverage levels. NOAA Technical Memorandum NMFS-SEFSC-588, 33p.

Block, B. A., Dewar, H., Blackwell, S. B., Williams, T. D., Prince, E. D., Farwell, C. J., Boustany, A. *et al.* 2001. Migratory movements, depth preferences, and thermal biology of Atlantic bluefin tuna. Science, 293: 1310–1314.

Campana, S. E., Joyce, W., and Manning, M. J. 2009. Bycatch and discard mortality in commercially caught blue sharks *Prionace glauca* assessed using archival satellite pop-up tags. Marine Ecology Progress Series, 387: 241–253.

Campbell, R. A., and Young, J. W. 2012. Monitoring the behaviour of longline gears and the depth and time of fish capture in the Australian eastern tuna and billfish fishery. Fisheries Research, 119-120: 48–65

Carruthers, T., Fonteneau, A., and Hallier, J. P. 2014. Estimating tag reporting rates for tropical tuna fleets of the Indian Ocean. Fisheries Research, 155: 20–32.

Chen, J.T., Dai, X.J., Xu, L.X., and Song, L.M. 2007. Report of the observer program for the Chinese longline fishery in the Atlantic Ocean in 2006. Col. Vol. Sci. Pap. ICCAT, 60: 1757–1760.

Clarke, S., Nicol, S., and Williams, P. 2015. Proposal for a bycatch data exchange protocol (BDEP) amongst the t-RFMOs. Working Paper EB-WP-06, Eleventh Meeting of the Scientific Committee, WCPFC, 5–13 August 2015. WCPFC, Pohnpei, Federated States of Micronesia. http://www.wcpfc.int/node/9139. Accessed 13 August, 2015.

Clarke, S., Sato, M., Small, C., Sullivan, B., Inoue, Y., and Ochi, D. 2014. Bycatch in longline fisheries for tuna and tuna-like species: a global review of status and mitigation measures. FAO Fisheries and Aquaculture Technical Paper, 588: 1–199.

Diaz, G. A., Beerkircher, L. R., and Restrepo, V. R. 2008. Description of the U.S. Pelagic Observer Program (POP). ICCAT, SCRS/2008/034, Collect. Volumes of Scientific Papers ICCAT, 64: 2415–2426

Diekert, F. K. 2012. Growth overfishing: the race to fish extends to the dimension of size. Environmental and Resource Economics, 52: 549–572.

Diele, K., Koch, V., and Saint-Paul, U. 2005. Population structure, catch composition and CPUE of the artisanally harvested mangrove crab Ucides cordatus (*Ocypodidae*) in the Caeté estuary, North Brazil: indications for overfishing? Aquatic Living Resources, 18: 169–178.

FAO, 2018. The State of World Fisheries and Aquaculture 2018 Meeting the sustainable development goals. Food and Agriculture Organization of the United Nations, Rome. Licence: CC BY-NC-SA 3.0 IGO.

Fossette, S., Witt, M. J., Miller, P., Nalovic, M. A., Albareda, D., Almeida, A. P., Broderick, A. C. *et al.* 2014. Pan-Atlantic analysis of the overlap of a highly migratory species, the leatherback turtle, with pelagic longline fisheries. Proceedings of the Royal Society B: Biological Sciences, 281: 20133065

Gamblin, C., Bach, P., and Lucas, V. 2007. Capture depths of longline targeted species (yellowfin, bigeye, swordfish): preliminary results obtained from experimental longline fishing carried out in Seychelles' oceanic waters. IOTC-2007-WPTT-28. http://www.fao.org/3/bj139e/bj139e.pdf, Accessed 16 July, 2007.

ICCAT 2016. Report of Japan's scientific observer program for tuna longline fishery in the Atlantic Ocean in the fishing years 2013 and 2014, working paper SCRS/2015/152, Collect. Volumes of Scientific Papers ICCAT, 72: 2328–2338.

Lewison, R. L., Crowder, L. B., Wallace, B. P., Moore, J. E., Cox, T., Zydelis, R., McDonald, S. *et al.* 2014. Global patterns of marine mammal, seabird, and sea turtle bycatch reveal taxa-specific and cumulative megafauna hotspots. Proceedings of the National Academy of Sciences, 111: 5271–5276.

Matos-Caraballo, D. 1999. Comparison of size of capture of the parrotfishes *Sparisoma viride* and *Sparisoma chrysopterum* in Puerto Rico using traps and entanglement nets during 1988-1992. Proceedings of the Gulf and Caribbean Fisheries Institute 46 299–308.

Matsumoto, T., Saito, H., and Miyabe, N. 2005. Report of observer program for Japanese tuna longline fishery in the Atlantic Ocean from August 2003 to January 2004. Collective Volumes of Scientific Papers ICCAT, 59: 663–681.

Oliver, S., Braccini, M., Newman, S. J., and Harvey, E. S. 2015. Global patterns in the bycatch of sharks and rays. Marine Policy, 54: 86–97.

Schwarz Gideon, E. 1978. Estimating the dimension of a model, Annals of Statistics, 6: 461–464.

Sims, M., Cox, T., and Lewinson, R. 2008. Modelling spatial patterns in fisheries bycatch: improving bycatch maps to aid fisheries management. Ecological Applications, 18: 649–661.

Skomal, G. B. 2007. Evaluating the physiological and physical consequences of capture on post-release survivorship in large pelagic fishes. Fisheries Management and Ecology, 14: 81–89.

Song, L. M., Zhou, J., Gao, P. F., and Xu, L. X. 2007. Modeling the hook depth of tuna longline in the tropical areas of the Indian Ocean. IOTC-2007-WPTT-13-rev1. IOTC.

Stock, B. C., Ward, E. J., Thorson, J. T., Jannot, J. E., and Semmens, B. X. 2019. The utility of spatial model-based estimators of unobserved bycatch. ICES Journal of Marine Science, 76: 255–267.

Walsh, W. A., Kleiber, P., and McCraken, M. 2002. Comparison of logbook reports of incidental blue shark catch rates by Hawaii-based longline vessels to fishery observer data by application of a generalized additive model. Fisheries Research, 58: 79–94.

WCPFC 2018. Conservation and Management Measure for the Regional Observer Programme, CMM 2018-05, https://www.wcpfc.int/doc/cmm-2018-05/conservation-and-management-measure-regional-observer-programme, Accessed 14 December, 2018.

Williams, P., Smith, N., Tuiloma, I., Falasi, C., and Clarke, S. 2016. Trial application of the BDEP template for summarizing bycatch data. SC12 EB-WP-03. Twelfth Regular Session of the Scientific Committee of the WCPFC (SC12). Bali, Indonesia, FSM. 3–11 August 2016. Annual catch estimates.

Xu, L. X., Zhu, G. P., and Song, L. M. 2012. Profile of Hook depth of Chinese Fresh tuna longline in the tropical Indian Ocean based on TDR data. IOTC-2006-WPTT-33. IOTC.

Xu , L. X., Dai, X. J., and Zhu, G. P. 2010. Chinese Tuna Longline Fishery in the Indian Ocean in 2008. IOTC IOTC–2010-S14-CoC19[E].

Zeller, D., Cashion, T., Palomares, M., and Pauly, D. 2018. Global marine fisheries discards: a synthesis of reconstructed data. Fish and Fisheries, 19: 30–39.

Zhang, Q., Wang, X. C., and Liu, Y. 2009. Status and development trend of tuna fishery in China. South China Fisheries Science, 5: 68–74.

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