Estimation of annual catch rates and catches for shortfin mako (*Isurus Oxyrinchus*) caught by Japanese longline fishery operated in the Indian Ocean from 1993 to 2018

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Abstract

Annual catch rates and catches are important fishery data to assess fish population dynamics. However, these data of sharks have an issue of under-reporting. To solve the issue, we standardized nominal CPUEs of shortfin mako caught by Japanese longline fisheries in the Indian Ocean from 1993 to 2018 using three observation error models (zero-inflated Poisson model: ZIP, negative binomial model: NB, and Poisson model: PO) with logbook data after filtering the data. The NB with full explanatory variables was selected by AIC as the most parsimonious model. The estimated annual catch rates (standardized CPUE) showed a decreasing trends with large fluctuations from the beginning of 1990s until 2009, and then they showed a slight increase trends. We also estimated the annual catches from 1993 to 2018 using the estimated annual catch rates and total fishing effort of Japanese longline fisheries operated in the Indian Ocean. The estimated catches increased in the beginning of 1990s and reached at peak in 1996 due to high fishing effort and catch rates. The estimated catches therefore gradually decreased due to the decrease in the fishing effort and lower catch rates. These annual catch rates and catches would be useful for the next stock assessment of shortfin mako in the Indian Ocean.

Key words

Shortfin mako, Standardized CPUE, Longline fishery, *Isurus oxyrinchus*, Negative binomial model

Introduction

Shortfin mako, *Isurus oxyrinchus*, is widely distributed in the tropical and warm-temperate oceans worldwide (**Compagno, 2001**). It is one of the popular and important bycatch shark species for Japanese tuna longline fishery in the Indian Ocean. Japanese longline fishery in the Indian Ocean is largely divided into operations targeting southern bluefin tuna (*Thunnus maccoyii*) and those targeting other tuna species (**Semba *et al.*, 2015**). Although the area and season of operation targeting *T. maccoyii* is limited, operation area of Japanese fleet in the Indian Ocean is generally overlapped with distribution area of shortfin mako.

In the past, **Kimoto *et al.* (2011)** estimated the abundance index of shortfin mako caught by Japanese longliners in the Indian Ocean, using filtering method (**Nakano and Clarke, 2006**) for log-book data of Japanese commercial longline fishery. Although they evaluated the impact of reporting rates on the abundance index, there is some improvement left to be done, such as the consideration of zero-catch with appropriate statistical models. In addition, catch has been only available via landing data at present and has not been estimated based on abundance index.

To provide the abundance indices of shortfin mako in the Indian Ocean, we standardize the nominal CPUE of shortfin mako shark caught by Japanese longline fisheries in the Indian Ocean from 1993 to 2018 using logbook data after we filtered set-by-set data with under-reporting. We also estimate annual catches of shortfin mako using the estimates of annual catch rates (standardized CPUE) and total fishing efforts of longline fisheries operated in the Indian Ocean (obtained from logbook data before filtering).

Material and Method

1) Data sources

Since spatial coverages of Japanese observer data collected in the Indian Ocean are limited (see Fig.A1 in **Kai, 2019**), we used Japanese longline logbook data in Indian Ocean from 1993 to 2018 collected by National Research Institute of Far Seas Fisheries in Japan. We used a newly developed statistical filtering method (**Hoyle *et al*., 2017**; **Kai, 2019a**) to remove set-by-set data with under-reporting. The details of the logbook data as well as the filtering method are summarized in a document working paper submitted simultaneously to the IOTC secretariat (**Kai, 2019b**). The preliminary filtering for logbook data reduced the number of records for this analysis from 603,427 sets to 595,784 sets. The follow-up filtering for logbook data reduced the number of records for this analysis from 595,784 sets representing 27,795 trips to 95,914 sets representing 4,696 trips. Although the large number of records were removed by these filtering, the number of records remained is much larger than those for observer data (13,764 sets).

Gear configuration of the number of branch lines between floats (HBF) was simply classified into shallower sets (number of lines between floats; 4~10) and deeper sets (number of lines between floats; 11~28). Four seasons (quarters 1 to 4) were defined as follows: quarter 1 was spring from January to March; quarter 2 was summer from April to June; quarter 3 was fall from July to September; and quarter 4 was winter from October to December. The details of area separation in Indian Ocean are described in **Appendix A**.

2) Model description

Since the set-by-set logbook data for shortfin mako indicated high zero-catch ratio (74.6%) with overdispersion (variance/mean = 16.8), we attempted to use zero-inflated negative binomial model. However, the model had a convergence issue, so that we used zero-inflated Poisson model (ZIP), Negative binomial model (NB), and Poisson model (PO) (**Zuur, 2009**) to standardize the nominal

CPUE of shortfin mako in the Indian Ocean. The ZIP can be written as follows:

$$\begin{aligned}\Pr(y_i = 0) &= \pi_i + (1 - \pi_i) \times \ Poisson\ (\mu_i) \\ \Pr(Y_i = y_i | y_{i_i} > 0) &= (1 - \pi) \times \ Poisson\ (\mu_i)\end{aligned} \quad (1)$$

where $\Pr()$ stands for probability, y_i is a catch number for observation i, π is a probability of false zero, and μ_i is a mean of Poisson distribution. It was assumed that the encounter probability: $p = (1 - \pi)$, which follows a binomial distribution with a logit link function for the binary response variable:

$$\mathrm{y} \sim Binomial(1, p)$$

$$\mathrm{logit}\ (p) = \log \frac{p}{1-p} = \beta_0 + \beta_1 year + \beta_2 qt + \beta_3 area + \beta_4 hbf, \quad (2)$$

where y is a response variable, $Binomial(1, p)$ is a binomial distribution with one trial and the encounter probability p, "*year*" represents year-effect (signifying each year from 1993 to 2018), "*qt*" represents quarter-effect (signifying each quarter from quarter 1 to quarter 4), "*area*" represents area-effect (signifying each subareas from 1 to 3, see **Fig. 1**), and "*hbf*" represents gear-effect (signifying shallow and deep sets from 1 to 2). The interaction terms such as a year and quarter (year:quarter) were not included in the binomial model due to convergence issues. The Poisson model and the NB with a log-link function for the count data can be written as follows:

$$Y_i^{NB} \sim \ NegBin\ (\mu_i, k),$$

$$Y_i \sim \ Poisson\ (\mu_i),$$

$$\log\ (\mu_i) = \beta_0 + \beta_1 year + \beta_2 qt + \beta_3 area + \beta_4 hbf + \beta_4 year{:}\,area + \beta_5 year{:}\,qt + \beta_6 area{:}\,qt + \beta_7 year{:}\,hbf + \beta_8 qt{:}\,hbf + \beta_9 area{:}\,hbf + \mathrm{offset}(\log(hooks)), \quad (3)$$

where Y_i^{NB} is negative binomial distributed with mean μ_i and parameter *k*, and "$hooks$" represents a fishing effort (number of hooks) given as an offset term. For the zero-inflated model, the expected total catch is calculated by multiplying the expected catch y by the encounter probability p (i.e. $1 - \pi$).

3) Model diagnostics

To select the most parsimonious model from the three candidate models (ZIP, NB, PO), we used a full model including all explanatory variable and the interaction terms and compared the AIC among them. Then, we conducted a stepwise-AIC for the selected model to choose the most parsimonious model from multiple candidates of explanatory variables. We removed each explanatory variable and the interaction terms one by one from the full model and compared the AICs to select the best model. We also evaluated the fitting of the model to the data using the person residuals, QQ-plot and type-II analysis. The residuals were calculated using a randomized quantile (**Dunn and Smyth, 1996**) to produce continuous normal residuals.

To evaluate the uncertainties in the estimates of annual catch rates (i.e. standardized CPUE), we estimated the 95 % confidence intervals using a bootstrapping method for the selected model.

4) Estimation of annual catches

To estimate annual catches of shortfin mako caught by Japanese longline fisheries in the Indian Ocean from 1993 to 2018, we multiply the catch rates (standardized CPUE) by total fishing effort (total number of hooks before filtering) of Japanese fleets operated in the Indian Ocean. Specifically, we estimated catch number using the catch rates and fishing effort by year, quarter, and area. We then convert the catch number to catch weight using the average weight by area and season of shortfin mako caught by Japanese longline fisheries in the Indian Ocean from 1994 to 2018 (**Table 1**).

Results

The negative binomial model (NB) with full explanatory variables (year, quarter, area, hbf, and the two ways of interaction terms for each combinations of factors) was selected by AIC as the most parsimonious model in comparisons with ZIP and PO (**Tables 2 and 3**). All factors of the deviance table for the selected NB were statistically significant (**Table 4**). The fittings of the best model to the data were also pretty good (**Figs. 2 and 3**).

The estimated annual catch rates (standardized CPUE) showed a decreasing trends with high fluctuations from the beginning of 1990s until 2009, and then the trends of the catch rates slightly increased (**Fig. 4**). Compared to other models (ZIP and PO), the NB decreased significantly the catch rates from 1993 to 1996, while the NB increased significantly the catch rates in 1999 and 2001 (**Fig. 4**). The differences in the model structure largely changed the magnitude of catch rates in 1996 and 1999 (**Fig. 5**). Complicated model tended to decreased the catch rate in 1996, while the complicated model tended to increase the catch rate in 1999 (**Fig. 5**). The 95 % confidence intervals for the best model were narrow through the periods (**Fig. 6**) and the coefficient of variation (CV) for the best model was small (the mean value of CV from 1993 to 2018 was 0.096).

Estimated annual catches increased in the beginning of 1990s and reached at peak in 1996 (**Fig. 7**) due to the increase in the fishing effort as well as the high catch rates of shortfin mako. Thereafter, the estimated annual catches decreased gradually due to the decrease in the fishing effort as well as the lower catch rates of shortfin mako (**Figs, 6 and 7**).

The annual changes of main quantities are summarized in **Table 5**.

Discussions

This working document paper provided annual catch rates and annual catches of shortfin mako caught by Japanese longline fishery operated in the Indian Ocean from 1993 to 2018 (**Table 5**).

The annual catch rates estimated by negative binomial model suggested that the abundance of shortfin mako in the Indian Ocean had decreased from 1993 to 2009 and increased slightly since then (**Fig. 6**). However, the large fluctuations of annual abundance of shortfin mako in 1990s is unrealistic due to the nature of low productivity species (**Semba *et al.*, 2019; Yokoi *et al.*, 2017**). The high values of scaled CPUE in 1996 and 1999 were caused by high catch rates of subareas1 and 2 (**Fig. 8**). Particularly, the high catch rates of shortfin mako appeared in the coastal water off South Africa and Mozambique **(Fig. 8)**. It is high possibility that the Japanese fleets caught smaller sized shortfin mako in the waters of these subareas because the average weight of shortfin mako in subareas 1 and 2 are smaller than that in subareas 3 (**Table 1**). The small sized shortfin mako caught in the limited areas near coastal water off South Africa and Mozambique might have increased the catch rates in 1996 and 1999. In future work, further investigation of the spatial-temporal changes in the size data for shortfin mako in the Indian Ocean might help to clear the reasons. In addition, a spatio-temporal generalized linear mixed model (spatio-temporal GLMM or geostatistical GLMM; **Thorson *et al*., 2015**; **Kai *et al*., 2017a, b**; **Kai, 2019**) would be useful to improve precision for estimated abundance indices of shortfin mako in the Indian Ocean because the spatio-temporal model can consider the spatial temporal correlation in the estimation of catch rates. Meanwhile, the generalized linear model such as a negative binomial model has a limitation to treat the spatio-temporal effects on the annual catch rates (e.g., we used only three subareas to treat the interaction terms between area and year).

The annual catches of shortfin mako were estimated using the catch rates of shortfin mako and total fishing effort (number of hooks) of Japanese fleets operated in the Indian Ocean. The catch records of pelagic sharks in the Japanese logbook data are commonly under-reporting. It is therefore reasonable to use the logbook data after follow-up filtering and it is believed that most of the set-by-set data with low-reporting rates were removed from the logbook data through the data filtering method (**Kai, 2019a**).

It is considered that the high values of estimated catches in 1996 and 1999 were caused by the high catch rates in those years, so that these catch estimates must be overestimation. However, the trends in the estimated catches (i.e., higher catches in 1990s and lower catches since 1999) and the average catches for each time periods (i.e., average catches: 2924 tons for 1993-1999; 880 tons for 2000-2009; 255 tons for 2010-2018) are reasonable because fishing efforts in 1990s were higher than those in 2000s and the catch rate in 2000s had gradually decreased. These results suggested that the abundance of shortfin mako had decreased due to higher catch rates and fishing effort in 1990s and at the beginning of 2000s, and then the abundance of shortfin mako had slightly increased due to the reduction of catch in conjunction with the reduction of fishing effort.

These annual catch rates and catches would be useful for the full stock assessment of shortfin mako in the Indian Ocean scheduled in 2020. If the annual catch rates estimated from Japanese data are representative of the abundance for shortfin mako in the Indian Ocean, it would be possible to estimate the annual catches of shortfin mako caught by longline fishery of all fleets in the Indian Ocean using the same methods. The essential points of the annual catch estimates of shortfin mako are to contemplate the spatial-temporal changes in the fishing efforts (e.g., **Fig.9**) and the precision of CPUE standardization. In the preliminary stock assessment for shortfin mako in the Indian Ocean (**Burnell**

***et al.*, 2018**), the three one-way increasing trends in the catches since 1975 (inconsistent trends with our results) were shown in their working document paper. We need to discuss these points at the upcoming meeting to solve the controversial issue.

Conclusions

Annual catch rates and annual catches of shortfin mako caught by Japanese longline fishery in the Indian Ocean from 1993 to 2018 were estimated using a generalized linear model with negative binomial error distribution based on the filtered logbook data. Although the estimated catch rates and catches have an issue of large fluctuation in 1990s, the historical trends in the catch rates as well as catches are reasonable from the perspective of their magnitude and historical trends. We therefore propose to use these estimates in the next stock assessment as well as in the indicator analysis.

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Table 1. Average weight of shortfin mako caught in the Indian Ocean from 1994 to 2018.

	Qt1	Qt2	Qt3	Qt4
Area1	23.1	45.5	38.6	27.9
Area2	64.0	56.0	46.1	58.0
Area3	67.2	73.8	66.4	70.3

Table 2. AIC values for three different models

Model	AIC
Zero-inflated Poisson	195,791
Neagtive binomial	169,040
Poisson	259,139

Table 3. Summary of model selection information for shortfin mako from multiple models ΔAIC denotes the reduction in AIC from the best-fitting model.

No	Structure of Negative binomial model	ΔAIC*	Deviance	Number of parameters
1	year+qt+area+hbf+year:qt+year:area+area:qt+hbf:qt+area:hbf+year:hbf	0	168652	194
2	year+qt+area+hbf+year:qt+year:area+area:qt+hbf:qt+area:hbf	1265	169967	169
3	year+qt+area+hbf+year:qt+area:qt+hbf:qt+area:hbf+year:hbf	1672	170424	144
4	year+qt+area+hbf+year:area+area:qt+hbf:qt+area:hbf+year:hbf	1371	170173	119
5	year+qt+area+hbf+year:qt+year:area+area:qt+hbf:qt	1639	170345	167
6	year+qt+area+hbf+year:qt+area:qt+hbf:qt+area:hbf	2990	171792	119
7	year+qt+area+hbf+year:qt+hbf:qt+area:hbf+year:hbf	2175	170939	138
8	year+qt+area+hbf+year:area+area:qt+hbf:qt+area:hbf	2784	171636	94
9	year+qt+area+hbf+year:area+hbf:qt+area:hbf+year:hbf	1932	170747	113
10	year+qt+area+hbf+area:qt+hbf:qt+area:hbf+year:hbf	3841	172743	69
11	year+qt+area+hbf+year:qt+year:area+area:qt	1691	170404	164
12	year+qt+area+hbf+year:qt+area:qt+hbf:qt	3700	172507	117
13	year+qt+area+hbf+year:qt+hbf:qt+area:hbf	3441	172256	113
14	year+qt+area+hbf+year:qt+area:hbf+year:hbf	2256	171026	135
15	year+qt+area+hbf+year:area+area:qt+hbf:qt	3118	171975	92
16	year+qt+area+hbf+year:area+hbf:qt+area:hbf	3290	172155	88
17	year+qt+area+hbf+year:area+area:hbf+year:hbf	2212	171032	110
18	year+qt+area+hbf+area:qt+hbf:qt+area:hbf	5514	174466	44
19	year+qt+area+hbf+area:qt+area:hbf+year:hbf	4098	173007	66
20	year+qt+area+hbf+hbf:qt+area:hbf++year:hbf	4387	173301	63
21	year+qt+area+hbf+year:qt+year:area	2102	170826	158
22	year+qt+area+hbf+year:qt+area:qt	3741	172553	114
23	year+qt+area+hbf+year:qt+hbf:qt	4188	173006	111
24	year+qt+area+hbf+year:qt+area:hbf	3520	172341	110
25	year+qt+area+hbf+year:qt+year:hbf	2841	171615	133
26	year+qt+area+hbf+year:area+area:qt	3276	172138	89
27	year+qt+area+hbf+year:area+hbf:qt	3620	172489	86
28	year+qt+area+hbf+year:area+area:hbf	3545	172415	85
29	year+qt+area+hbf+year:area+year:hbf	2423	171248	108
30	year+qt+area+hbf+area:qt+hbf:qt	6196	175152	42
31	year+qt+area+hbf+area:qt+area:hbf	5762	174721	41
32	year+qt+area+hbf+area:qt+year:hbf	4632	173545	64
33	year+qt+area+hbf+hbf:qt+area:hbf	5993	174957	38
34	year+qt+area+hbf+hbf:qt+year:hbf	5017	173935	61
35	year+qt+area+hbf+area:hbf+year:hbf	4712	173633	60
36	year+qt+area+hbf+year:qt	4235	173059	108
37	year+qt+area+hbf+year:area	3846	172721	83
38	year+qt+area+hbf+area:qt	6417	175380	39
39	year+qt+area+hbf+hbf:qt	6743	175711	36
40	year+qt+area+hbf+area:hbf	6325	175296	35
41	year+qt+area+hbf+year:hbf	5270	174195	58
42	year+qt+area+hbf	7018	175993	33
43	year+qt+area	7147	176123	32
44	year+area	8271	177253	29
45	year+qt	14843	183824	30
46	year	17489	186475	27
47	null	24155	193192	2

*ΔAIC denotes a diffference between AIC and a minimum value of AIC

Table 4. Type-II analysis of deviance table for model components produced by the negative binomial model (best model). LR Chisq denotes Likelihood Ratio Chi-Square statistics, DF is degree of freedom, and Pr is significant probability for each factor.

Factor	LR Chisq	DF	Pr(>Chisq)
Year	8286	25	< 0.001
Quarter	1231	3	< 0.001
Area	9451	2	< 0.001
HBF	216	1	< 0.001
Year:Quarter	1555	75	< 0.001
Year:Area	1824	50	< 0.001
Quarter:Area	482	6	< 0.001
Year:HBF	1340	25	< 0.001
Quarter:HBF	87	3	< 0.001
Area:HBF	308	2	< 0.001

Table 5. Summary of outputs.

Year	Nominal CPUE	Standardized CPUE	Scaled standardized CPUE	Estimated catch weight (tons)	Estimated catch number	Total Landings (number)	Total landing (number) for filterd data	Total number of hooks (one millions)	Coefficient of variations	Lower value (scaled CPUE) of 95% CI	Upper value (scaled CPUE) of 95% CI
1993	0.63	0.37	1.41	487	12,356	4,322	2,849	39.6	0.095	1.19	1.73
1994	0.64	0.40	1.52	1768	31,516	7,136	4,175	72.2	0.079	1.33	1.81
1995	0.31	0.41	1.58	1965	36,330	5,623	2,731	87.7	0.107	1.29	1.95
1996	1.16	0.80	3.07	5217	100,623	13,487	10,557	104.7	0.044	2.84	3.38
1997	0.61	0.58	2.24	3593	93,034	11,555	7,629	118.5	0.065	1.98	2.55
1998	0.19	0.33	1.27	2358	38,990	4,691	1,768	111.5	0.086	1.11	1.56
1999	0.51	0.87	3.34	5082	76,290	6,180	2,871	98.1	0.097	2.87	4.12
2000	0.32	0.24	0.92	983	15,546	5,697	2,306	95.3	0.085	0.81	1.13
2001	0.17	0.37	1.43	1260	23,279	4,232	1,569	104.7	0.113	1.18	1.84
2002	0.10	0.16	0.60	893	13,431	3,100	590	95.6	0.139	0.49	0.81
2003	0.05	0.07	0.28	333	4,811	1,725	169	72.3	0.137	0.22	0.38
2004	0.34	0.35	1.33	1702	31,647	5,598	2,336	91.9	0.059	1.19	1.49
2005	0.15	0.15	0.57	1150	20,675	4,985	1,271	104.7	0.068	0.51	0.67
2006	0.13	0.17	0.64	1203	20,292	3,720	1,221	107.2	0.081	0.55	0.75
2007	0.10	0.12	0.45	647	11,109	2,808	806	98.1	0.104	0.37	0.55
2008	0.14	0.10	0.38	403	7,466	5,357	3,897	82.4	0.084	0.33	0.46
2009	0.12	0.07	0.28	229	4,062	4,707	3,495	66.1	0.055	0.26	0.32
2010	0.17	0.13	0.50	328	5,352	4,473	3,550	40.2	0.060	0.44	0.56
2011	0.20	0.13	0.50	184	3,712	4,876	4,143	32.1	0.074	0.44	0.59
2012	0.15	0.13	0.49	256	4,576	3,648	2,926	34.1	0.054	0.44	0.55
2013	0.17	0.13	0.52	261	4,233	3,002	2,327	32.0	0.091	0.43	0.61
2014	0.14	0.18	0.68	379	6,178	2,531	1,918	33.0	0.105	0.56	0.84
2015	0.14	0.13	0.50	250	3,894	2,255	1,619	29.9	0.122	0.39	0.63
2016	0.12	0.09	0.33	161	2,607	1,816	957	27.7	0.255	0.19	0.52
2017	0.10	0.10	0.39	189	2,706	1,646	1,020	24.2	0.113	0.31	0.49
2018	0.14	0.20	0.77	285	4,256	1,682	1,033	22.5	0.134	0.57	0.96

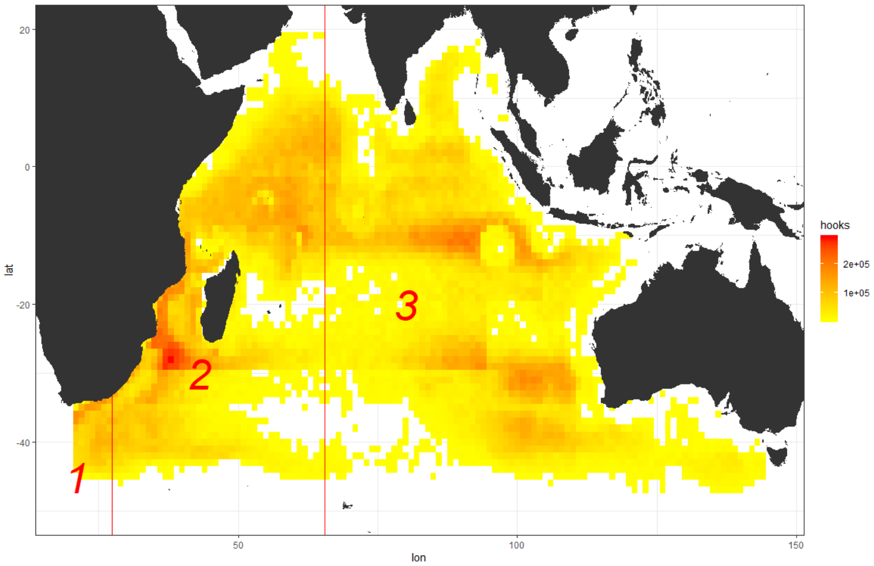

Fig.1 Overall spatial distribution of fishing effort (number of hooks) for Japanese longline fleets operated in the Indian Ocean from 1993 to 2018 with three subareas separated by GLM-tree.

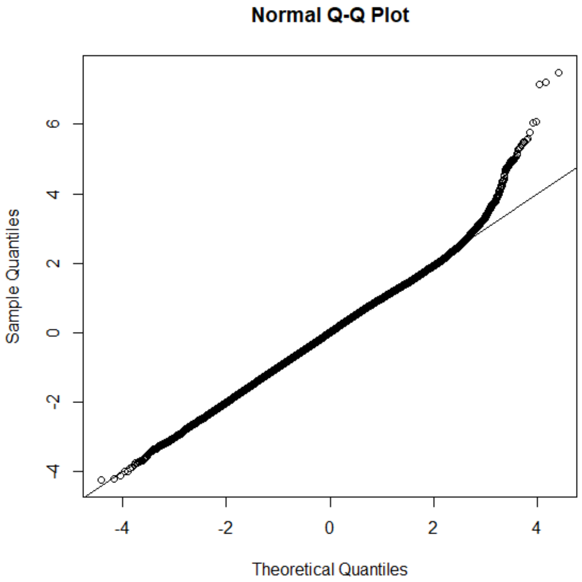

Fig. 2 Diagnostic plots of goodness-of-fit for the negative binomial model (best model).

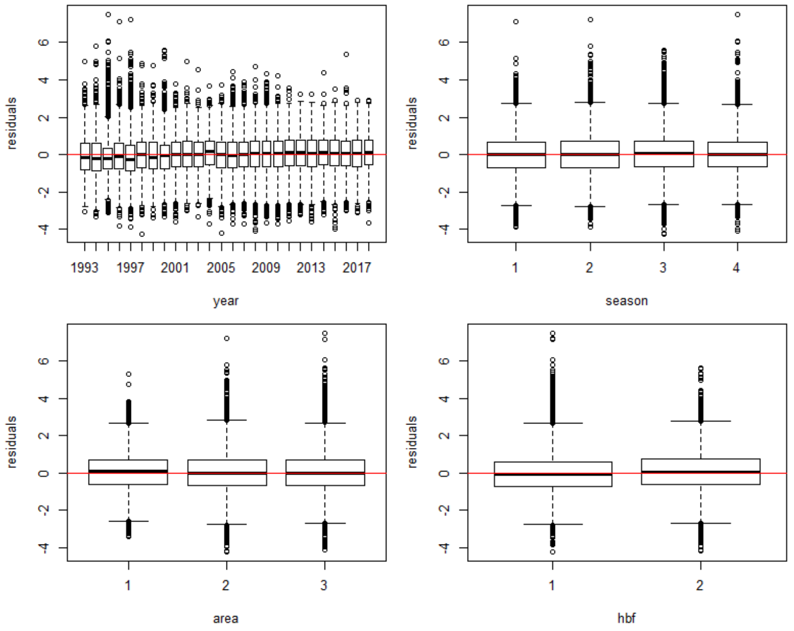

Fig. 3 Residual plots of the negative binomial model (best model) for each explanatory variable.

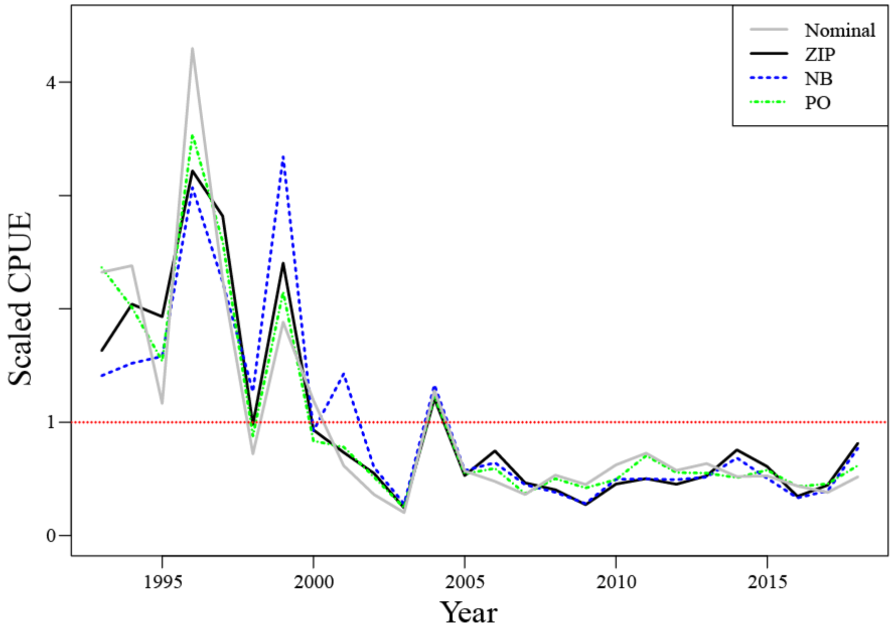

Fig.4 Comparisons of standardized CPUEs (scaled by a mean value) among different error structures. ZIP, NB, and PO represents Zero-inflated Poisson model, Negative binomial model, and Poisson model, respectively. Nominal represents nominal CPUE.

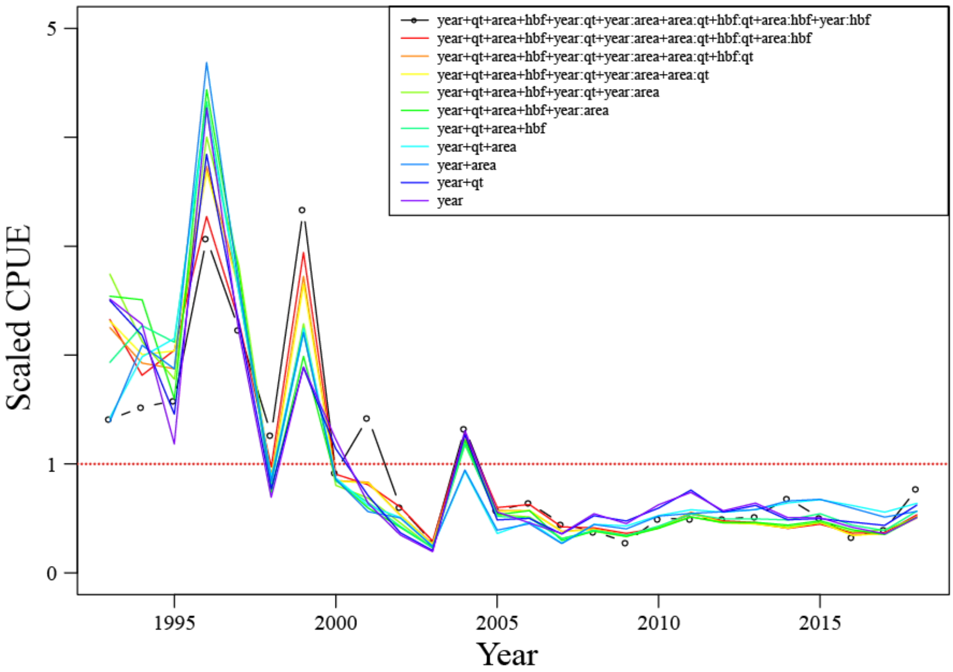

Fig.5 Comparisons of standardized CPUEs (scaled by a mean value) among the different model structures.

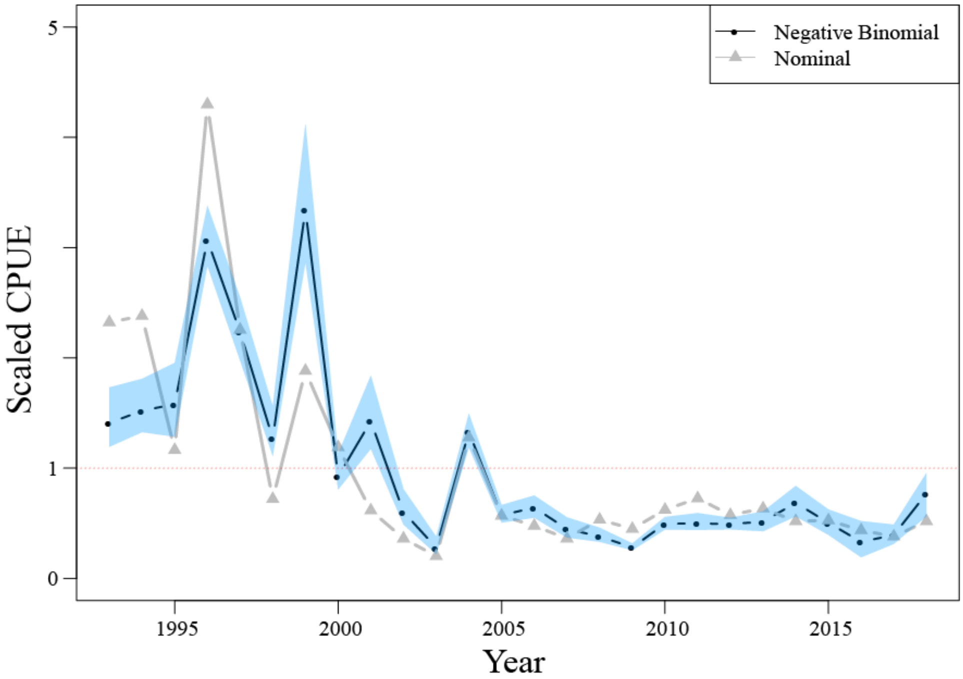

Fig.6 Sstandardized CPUEs (best model) of shortfin mako and its 95% confidence intervals (ranges of light blue) estimated from 1000 bootstrapping.

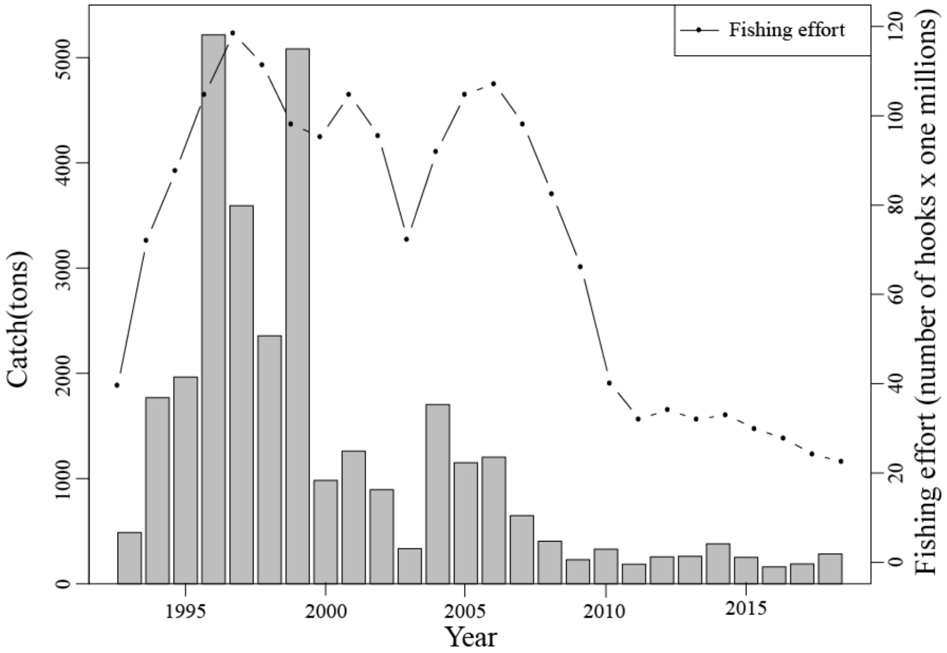

Fig.7 Estimated catch weight (tons) of shortfin mako and total fishing effort before filtering (number of hooks x one millions) operated in the Indian Ocean by Japanese fleets from 1993 to 2018.

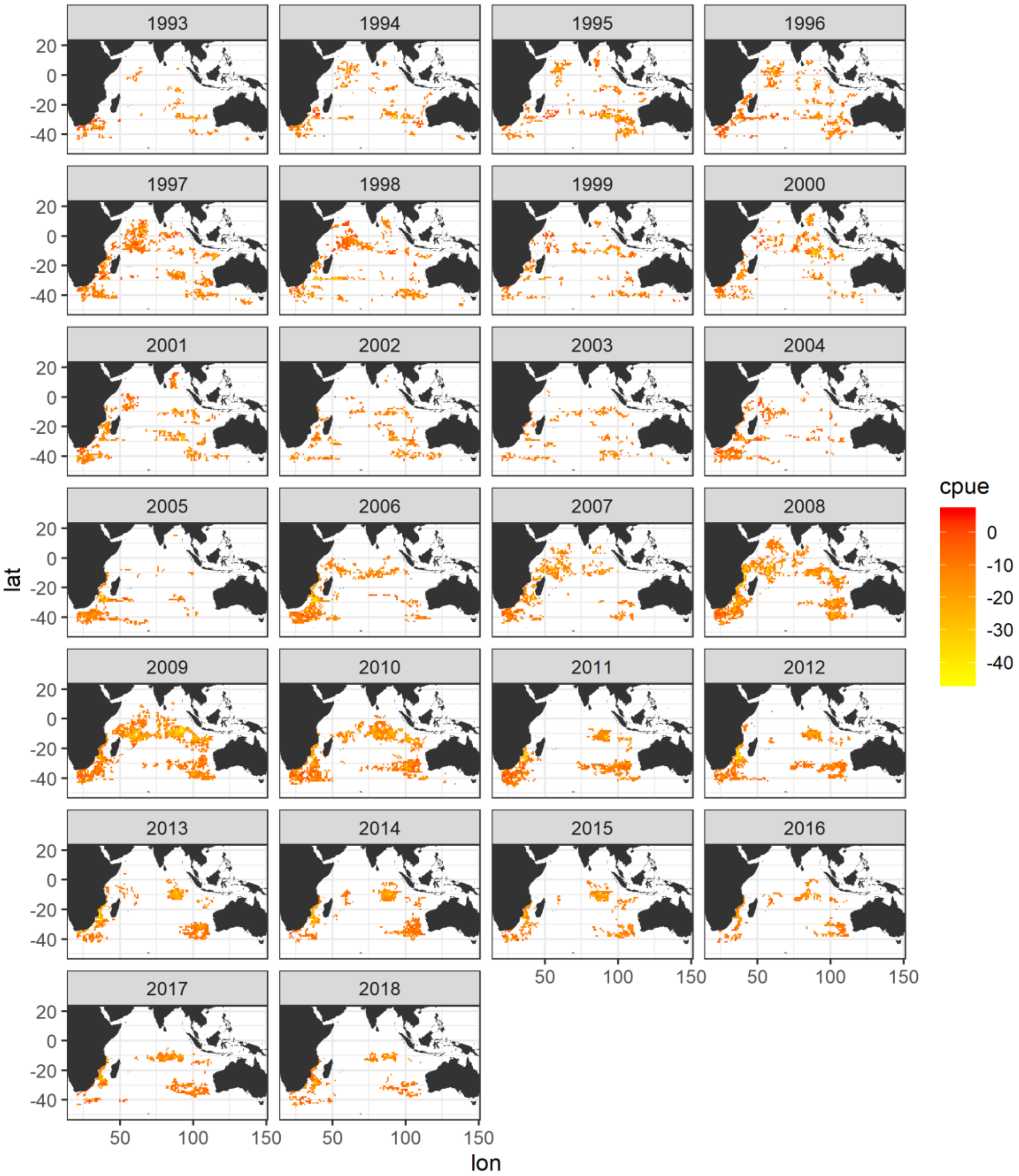

Fig. 8 Year-specific spatial distribution of nominal CPUE (log-cpue) for shortfin mako caught by Japanese longline fishery in the Indian Ocean from 1993 to 2018.

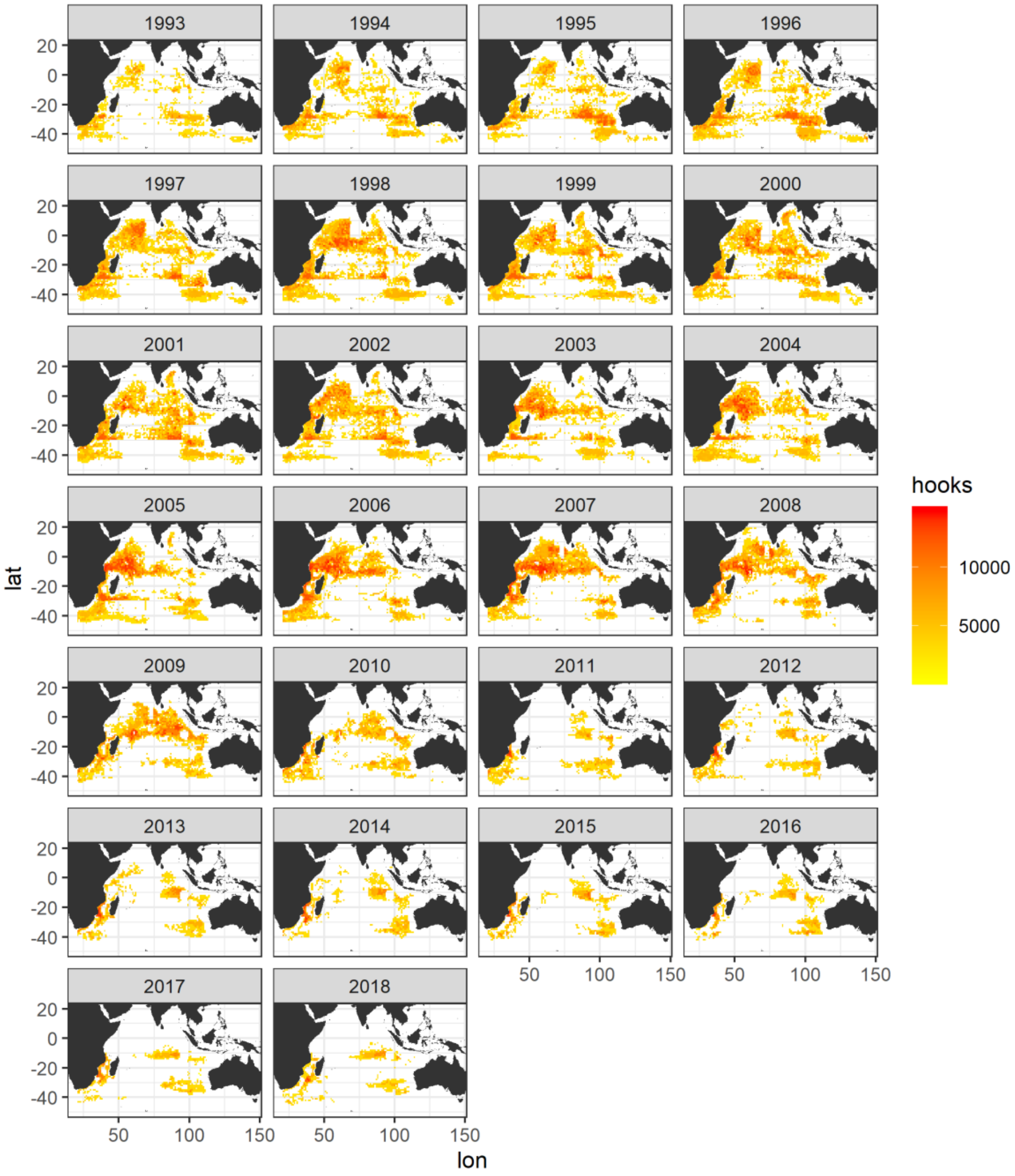

Fig. 9 Year-specific spatial distribution of fishing effort (no filtering) of Japanese longline fleets in the Indian Ocean from 1993 to 2018.

Appendix A

Area separation

GLM-tree (Ichinokawa and Broziak 2010), which is a simulation method to objectively separate the area into some subareas, was used to separate an entire area in the Indian Ocean into several subareas. Since it was difficult to determine the optimal number of areas using GLM-tree algorithm based on the AIC criteria, which was one way decreasing trend (**Fig. A1**), we arbitrarily gave a small number of subareas to include the interaction terms of year and area (year:area) in the model. **Ichinokawa and Brodziak (2010)** suggested that strict optimization until AIC minimum may not always be needed to derive robust estimates of abundance indices, from a practical point of view. **Fig. A2** shows the increasing number of areas created by the boundaries selected by the GLM-tree algorithm. First, we chose four areas based on the GLM-tree, but we combined the subarea 1 and 3 to include the interaction term of year and area. The final map of area separation is shown in **Fig. 1.** The standardized CPUEs by subarea and year were weighted by the proportions of operated cell at each subarea (i.e., number of operated cells at each subarea/total number of operated cells) by year (**Table A1**).

Table A1. Proportions of subareas by year.

Year	Subarea		
	1	2	3
1993	0.16	0.40	0.45
1994	0.09	0.44	0.47
1995	0.07	0.33	0.60
1996	0.06	0.42	0.51
1997	0.06	0.46	0.48
1998	0.06	0.47	0.47
1999	0.10	0.36	0.53
2000	0.09	0.33	0.58
2001	0.12	0.38	0.51
2002	0.05	0.32	0.63
2003	0.07	0.36	0.56
2004	0.12	0.67	0.21
2005	0.14	0.68	0.18
2006	0.08	0.58	0.34
2007	0.11	0.58	0.31
2008	0.07	0.47	0.46
2009	0.06	0.38	0.56
2010	0.08	0.33	0.59
2011	0.13	0.30	0.57
2012	0.09	0.39	0.52
2013	0.08	0.40	0.52
2014	0.06	0.33	0.61
2015	0.08	0.32	0.60
2016	0.03	0.36	0.61
2017	0.05	0.27	0.68
2018	0.08	0.41	0.50

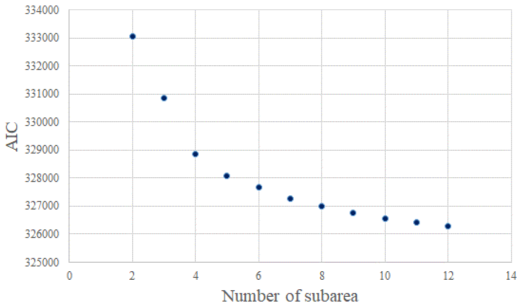

Fig. A1 Relationships between AIC and number of subareas obtained from GLM-tree.

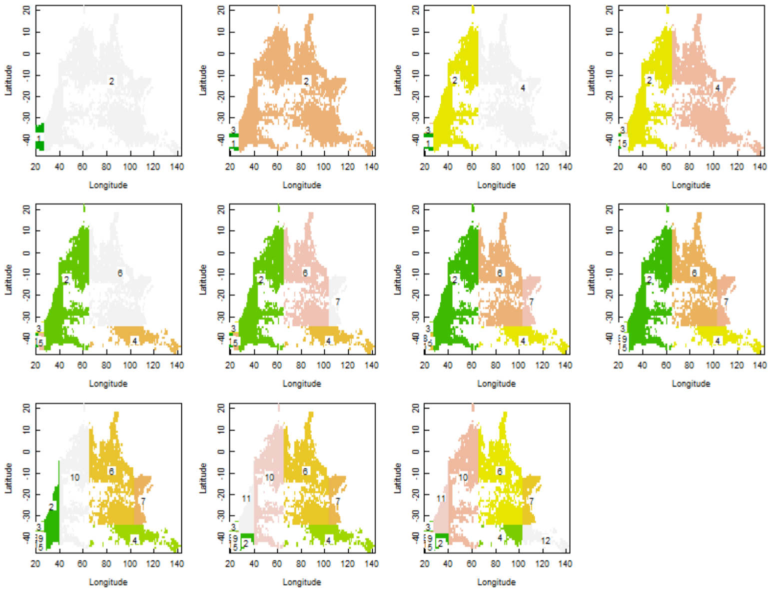

Fig. A2 Maps of subareas created by GLM-tree.

Appendix references

Ichinokawa, M. and J. Brodziak 2010. Using adaptive area stratification to standardize catch rates with application to North Pcific swordfith (*Xiphias gladius*). Fish. Res. 106: 249-260

Appendix B

Effects of SST

We attempted to examine the effect of sea surface temperature (SST) on the annual catch rates. The SST was added to the best model (full model) using a spline curve in the library of R “splines” and set ns (SST,df=5) . Consequently, the model was not converged due to the increase in the complexity of the model. In addition, the set-by-set data in Japanese logbook data has a basic issue that some set-by-set data (approximately 450 set-by-set data after filtering) have no information about SST.

Appendix C

Summary of outputs for negative binomial model (selected model)

```
Call:
glm.nb(formula = SFM ~ factor(YEAR) + factor(QT) + factor(AREA2) +
    factor(HBF2) + factor(YEAR):factor(QT) + factor(YEAR):factor(AREA2) +
    factor(QT):factor(AREA2) + factor(YEAR):factor(HBF2) + factor(QT):factor(HBF2) +
    factor(AREA2):factor(HBF2) + offset(log(HOOK)), data = LB0,
    init.theta = 0.3912472442, link = log)

Deviance Residuals:
    Min       1Q   Median       3Q      Max
-1.8139  -0.7711  -0.5512  -0.2699   7.2329

Coefficients:
                              Estimate Std. Error z value Pr(>|z|)
(Intercept)                   -5.94322    0.18361 -32.369  < 2e-16 ***
factor(YEAR)1994              -0.46267    0.23692  -1.953 0.050835 .
factor(YEAR)1995               0.70477    0.23080   3.054 0.002261 **
factor(YEAR)1996              -0.98183    0.24288  -4.042 5.29e-05 ***
factor(YEAR)1997              -1.75717    0.23662  -7.426 1.12e-13 ***
factor(YEAR)1998              -2.34371    0.27505  -8.521  < 2e-16 ***
factor(YEAR)1999              -0.23746    0.26091  -0.910 0.362758
factor(YEAR)2000              -0.74619    0.24832  -3.005 0.002656 **
factor(YEAR)2001              -1.20499    0.25559  -4.714 2.42e-06 ***
factor(YEAR)2002              -0.76537    0.32457  -2.358 0.018370 *
factor(YEAR)2003              -1.72689    0.41213  -4.190 2.79e-05 ***
factor(YEAR)2004              -1.41832    0.26780  -5.296 1.18e-07 ***
factor(YEAR)2005              -1.67223    0.28199  -5.930 3.03e-09 ***
factor(YEAR)2006              -1.81748    0.29448  -6.172 6.75e-10 ***
factor(YEAR)2007              -0.83336    0.29145  -2.859 0.004246 **
factor(YEAR)2008              -1.90592    0.27953  -6.818 9.21e-12 ***
factor(YEAR)2009              -2.55130    0.28133  -9.069  < 2e-16 ***
factor(YEAR)2010              -2.10238    0.26675  -7.881 3.24e-15 ***
factor(YEAR)2011              -1.93419    0.31526  -6.135 8.50e-10 ***
factor(YEAR)2012              -1.99178    0.26149  -7.617 2.60e-14 ***
```

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factor(YEAR)2013                 -1.97620     0.31185   -6.337 2.34e-10 ***
factor(YEAR)2014                 -1.14873     0.32994   -3.482 0.000498 ***
factor(YEAR)2015                 -1.69895     0.38023   -4.468 7.89e-06 ***
factor(YEAR)2016                 -2.45255     0.71026   -3.453 0.000554 ***
factor(YEAR)2017                 -2.15277     0.48302   -4.457 8.32e-06 ***
factor(YEAR)2018                 -0.88645     0.42505   -2.086 0.037024 *
factor(QT)2                     -0.09345     0.20014   -0.467 0.640539
factor(QT)3                     -1.30315     0.20794   -6.267 3.68e-10 ***
factor(QT)4                     -0.73793     0.29865   -2.471 0.013477 *
factor(AREA2)2                   -1.43730     0.16639   -8.638   < 2e-16 ***
factor(AREA2)3                   -4.28235     0.22090 -19.386   < 2e-16 ***
factor(HBF2)2                   -1.12701     0.25262   -4.461 8.15e-06 ***
factor(YEAR)1994:factor(QT)2   -0.08343     0.24530   -0.340 0.733786
factor(YEAR)1995:factor(QT)2   -1.68391     0.23605   -7.134 9.78e-13 ***
factor(YEAR)1996:factor(QT)2   -0.33376     0.23312   -1.432 0.152230
factor(YEAR)1997:factor(QT)2   -0.29483     0.23482   -1.256 0.209278
factor(YEAR)1998:factor(QT)2   -1.09805     0.25194   -4.358 1.31e-05 ***
factor(YEAR)1999:factor(QT)2   -0.64778     0.25824   -2.508 0.012125 *
factor(YEAR)2000:factor(QT)2   -0.52566     0.26763   -1.964 0.049512 *
factor(YEAR)2001:factor(QT)2   -1.84254     0.26730   -6.893 5.46e-12 ***
factor(YEAR)2002:factor(QT)2   -1.02025     0.28199   -3.618 0.000297 ***
factor(YEAR)2003:factor(QT)2   -0.59296     0.35282   -1.681 0.092841 .
factor(YEAR)2004:factor(QT)2   -0.35777     0.26961   -1.327 0.184509
factor(YEAR)2005:factor(QT)2   -1.22250     0.28680   -4.262 2.02e-05 ***
factor(YEAR)2006:factor(QT)2   -0.65540     0.29097   -2.252 0.024294 *
factor(YEAR)2007:factor(QT)2   -1.62560     0.29166   -5.574 2.50e-08 ***
factor(YEAR)2008:factor(QT)2   -0.39277     0.25841   -1.520 0.128526
factor(YEAR)2009:factor(QT)2   -0.88597     0.24035   -3.686 0.000228 ***
factor(YEAR)2010:factor(QT)2   -0.25003     0.24416   -1.024 0.305805
factor(YEAR)2011:factor(QT)2   -0.57086     0.24110   -2.368 0.017897 *
factor(YEAR)2012:factor(QT)2   -0.49082     0.24197   -2.028 0.042513 *
factor(YEAR)2013:factor(QT)2   -0.13375     0.25158   -0.532 0.594968
factor(YEAR)2014:factor(QT)2   -0.10071     0.26125   -0.386 0.699864
factor(YEAR)2015:factor(QT)2   -0.32623     0.25348   -1.287 0.198105
factor(YEAR)2016:factor(QT)2   -0.36073     0.28442   -1.268 0.204683
factor(YEAR)2017:factor(QT)2   -0.16863     0.27500   -0.613 0.539727
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factor(YEAR)2018:factor(QT)2    -0.98981    0.26823   -3.690 0.000224 ***
factor(YEAR)1994:factor(QT)3    -0.32644    0.25995   -1.256 0.209202
factor(YEAR)1995:factor(QT)3    -0.45854    0.24468   -1.874 0.060929 .
factor(YEAR)1996:factor(QT)3     1.23341    0.23822    5.178 2.25e-07 ***
factor(YEAR)1997:factor(QT)3     1.39999    0.24062    5.818 5.95e-09 ***
factor(YEAR)1998:factor(QT)3     1.09002    0.25906    4.208 2.58e-05 ***
factor(YEAR)1999:factor(QT)3    -0.02450    0.26465   -0.093 0.926254
factor(YEAR)2000:factor(QT)3     1.31496    0.26287    5.002 5.67e-07 ***
factor(YEAR)2001:factor(QT)3     0.40398    0.26203    1.542 0.123135
factor(YEAR)2002:factor(QT)3     0.51849    0.28661    1.809 0.070441 .
factor(YEAR)2003:factor(QT)3     0.51950    0.37567    1.383 0.166707
factor(YEAR)2004:factor(QT)3     1.60232    0.26850    5.968 2.41e-09 ***
factor(YEAR)2005:factor(QT)3     0.78779    0.28767    2.738 0.006173 **
factor(YEAR)2006:factor(QT)3     1.26306    0.28612    4.414 1.01e-05 ***
factor(YEAR)2007:factor(QT)3     0.27979    0.29270    0.956 0.339129
factor(YEAR)2008:factor(QT)3     1.23926    0.26198    4.730 2.24e-06 ***
factor(YEAR)2009:factor(QT)3     1.37427    0.24443    5.622 1.88e-08 ***
factor(YEAR)2010:factor(QT)3     1.60654    0.24967    6.435 1.24e-10 ***
factor(YEAR)2011:factor(QT)3     1.06919    0.24484    4.367 1.26e-05 ***
factor(YEAR)2012:factor(QT)3     1.17640    0.24506    4.800 1.58e-06 ***
factor(YEAR)2013:factor(QT)3     1.56234    0.25926    6.026 1.68e-09 ***
factor(YEAR)2014:factor(QT)3     1.31764    0.26702    4.935 8.03e-07 ***
factor(YEAR)2015:factor(QT)3     1.24917    0.26156    4.776 1.79e-06 ***
factor(YEAR)2016:factor(QT)3     0.77719    0.29244    2.658 0.007870 **
factor(YEAR)2017:factor(QT)3     0.94903    0.26988    3.516 0.000437 ***
factor(YEAR)2018:factor(QT)3     0.48561    0.28298    1.716 0.086154 .
factor(YEAR)1994:factor(QT)4    -0.28054    0.34670   -0.809 0.418421
factor(YEAR)1995:factor(QT)4     0.72823    0.31939    2.280 0.022605 *
factor(YEAR)1996:factor(QT)4    -1.13838    0.34169   -3.332 0.000864 ***
factor(YEAR)1997:factor(QT)4     0.61869    0.31632    1.956 0.050478 .
factor(YEAR)1998:factor(QT)4     1.30192    0.34289    3.797 0.000147 ***
factor(YEAR)1999:factor(QT)4    -0.43649    0.33848   -1.290 0.197205
factor(YEAR)2000:factor(QT)4     0.66549    0.35496    1.875 0.060814 .
factor(YEAR)2001:factor(QT)4     0.46842    0.33503    1.398 0.162071
factor(YEAR)2002:factor(QT)4     1.16332    0.36400    3.196 0.001394 **
factor(YEAR)2003:factor(QT)4     0.38264    0.48321    0.792 0.428433
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factor(YEAR)2004:factor(QT)4        1.20396     0.34991    3.441 0.000580 ***
factor(YEAR)2005:factor(QT)4        0.30663     0.39188    0.782 0.433942
factor(YEAR)2006:factor(QT)4        2.12277     0.35101    6.048 1.47e-09 ***
factor(YEAR)2007:factor(QT)4       -0.04160     0.36679   -0.113 0.909709
factor(YEAR)2008:factor(QT)4        1.05900     0.33523    3.159 0.001583 **
factor(YEAR)2009:factor(QT)4        0.87037     0.32300    2.695 0.007047 **
factor(YEAR)2010:factor(QT)4        1.00895     0.32781    3.078 0.002085 **
factor(YEAR)2011:factor(QT)4        0.71483     0.32032    2.232 0.025639 *
factor(YEAR)2012:factor(QT)4        0.71120     0.32690    2.176 0.029585 *
factor(YEAR)2013:factor(QT)4        1.13560     0.33470    3.393 0.000692 ***
factor(YEAR)2014:factor(QT)4        0.68546     0.34043    2.014 0.044061 *
factor(YEAR)2015:factor(QT)4        0.45365     0.34756    1.305 0.191811
factor(YEAR)2016:factor(QT)4        1.10346     0.34863    3.165 0.001550 **
factor(YEAR)2017:factor(QT)4        0.75870     0.33599    2.258 0.023940 *
factor(YEAR)2018:factor(QT)4        0.21955     0.34167    0.643 0.520503
factor(YEAR)1994:factor(AREA2)2   0.84443     0.16692    5.059 4.21e-07 ***
factor(YEAR)1995:factor(AREA2)2 -0.56946     0.18007   -3.163 0.001564 **
factor(YEAR)1996:factor(AREA2)2   2.04056     0.18365   11.111   < 2e-16 ***
factor(YEAR)1997:factor(AREA2)2   1.98052     0.16942   11.690   < 2e-16 ***
factor(YEAR)1998:factor(AREA2)2   0.02900     0.19455    0.149 0.881513
factor(YEAR)1999:factor(AREA2)2 -0.16105     0.19103   -0.843 0.399217
factor(YEAR)2000:factor(AREA2)2 -0.97834     0.17978   -5.442 5.27e-08 ***
factor(YEAR)2001:factor(AREA2)2 -0.96801     0.18437   -5.250 1.52e-07 ***
factor(YEAR)2002:factor(AREA2)2 -0.50865     0.26427   -1.925 0.054261 .
factor(YEAR)2003:factor(AREA2)2 -0.52293     0.34179   -1.530 0.126019
factor(YEAR)2004:factor(AREA2)2 -0.51645     0.16920   -3.052 0.002270 **
factor(YEAR)2005:factor(AREA2)2   0.32739     0.16372    2.000 0.045524 *
factor(YEAR)2006:factor(AREA2)2 -0.38176     0.17820   -2.142 0.032168 *
factor(YEAR)2007:factor(AREA2)2 -0.40213     0.18907   -2.127 0.033432 *
factor(YEAR)2008:factor(AREA2)2 -0.35930     0.16198   -2.218 0.026546 *
factor(YEAR)2009:factor(AREA2)2   0.04604     0.16508    0.279 0.780332
factor(YEAR)2010:factor(AREA2)2   0.54780     0.16199    3.382 0.000720 ***
factor(YEAR)2011:factor(AREA2)2   0.29742     0.16303    1.824 0.068099 .
factor(YEAR)2012:factor(AREA2)2   0.41912     0.16671    2.514 0.011934 *
factor(YEAR)2013:factor(AREA2)2   0.21420     0.17152    1.249 0.211731
factor(YEAR)2014:factor(AREA2)2   0.28468     0.19233    1.480 0.138814
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factor(YEAR)2015:factor(AREA2)2   0.28345     0.19988     1.418 0.156154
factor(YEAR)2016:factor(AREA2)2   0.63294     0.24316     2.603 0.009241 **
factor(YEAR)2017:factor(AREA2)2   0.90682     0.28644     3.166 0.001546 **
factor(YEAR)2018:factor(AREA2)2   0.58273     0.22406     2.601 0.009303 **
factor(YEAR)1994:factor(AREA2)3   0.75194     0.23691     3.174 0.001504 **
factor(YEAR)1995:factor(AREA2)3   1.59912     0.22791     7.017 2.27e-12 ***
factor(YEAR)1996:factor(AREA2)3   1.48916     0.23615     6.306 2.87e-10 ***
factor(YEAR)1997:factor(AREA2)3   2.18722     0.21941     9.969   < 2e-16 ***
factor(YEAR)1998:factor(AREA2)3   1.46829     0.24421     6.012 1.83e-09 ***
factor(YEAR)1999:factor(AREA2)3   1.31649     0.22950     5.736 9.68e-09 ***
factor(YEAR)2000:factor(AREA2)3   0.31868     0.22285     1.430 0.152705
factor(YEAR)2001:factor(AREA2)3   0.27561     0.24053     1.146 0.251866
factor(YEAR)2002:factor(AREA2)3   0.47584     0.30713     1.549 0.121313
factor(YEAR)2003:factor(AREA2)3   1.11977     0.39752     2.817 0.004849 **
factor(YEAR)2004:factor(AREA2)3   1.67348     0.25887     6.464 1.02e-10 ***
factor(YEAR)2005:factor(AREA2)3   2.21711     0.27079     8.188 2.67e-16 ***
factor(YEAR)2006:factor(AREA2)3   2.11612     0.24940     8.485   < 2e-16 ***
factor(YEAR)2007:factor(AREA2)3   1.41909     0.25070     5.660 1.51e-08 ***
factor(YEAR)2008:factor(AREA2)3   0.19580     0.21499     0.911 0.362424
factor(YEAR)2009:factor(AREA2)3   0.48382     0.21408     2.260 0.023823 *
factor(YEAR)2010:factor(AREA2)3   1.55876     0.21290     7.322 2.45e-13 ***
factor(YEAR)2011:factor(AREA2)3   0.89005     0.21728     4.096 4.20e-05 ***
factor(YEAR)2012:factor(AREA2)3   1.50634     0.21664     6.953 3.58e-12 ***
factor(YEAR)2013:factor(AREA2)3   1.12455     0.22225     5.060 4.20e-07 ***
factor(YEAR)2014:factor(AREA2)3   1.21124     0.23118     5.239 1.61e-07 ***
factor(YEAR)2015:factor(AREA2)3   1.32336     0.23491     5.634 1.77e-08 ***
factor(YEAR)2016:factor(AREA2)3   1.29918     0.26728     4.861 1.17e-06 ***
factor(YEAR)2017:factor(AREA2)3   1.16664     0.31368     3.719 0.000200 ***
factor(YEAR)2018:factor(AREA2)3   1.28864     0.25485     5.057 4.27e-07 ***
factor(QT)2:factor(AREA2)2      0.79610     0.11339     7.021 2.20e-12 ***
factor(QT)3:factor(AREA2)2      0.84281     0.11477     7.344 2.08e-13 ***
factor(QT)4:factor(AREA2)2      0.41633     0.14169     2.938 0.003299 **
factor(QT)2:factor(AREA2)3      1.58297     0.11930    13.268   < 2e-16 ***
factor(QT)3:factor(AREA2)3      0.97865     0.11972     8.174 2.97e-16 ***
factor(QT)4:factor(AREA2)3      0.21476     0.14699     1.461 0.144021
factor(YEAR)1994:factor(HBF2)2    0.84335     0.26191     3.220 0.001282 **
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factor(YEAR)1995:factor(HBF2)2     0.32530     0.25597     1.271 0.203783
factor(YEAR)1996:factor(HBF2)2     1.05556     0.25000     4.222 2.42e-05 ***
factor(YEAR)1997:factor(HBF2)2     1.39082     0.24522     5.672 1.41e-08 ***
factor(YEAR)1998:factor(HBF2)2     3.59621     0.25612    14.041  < 2e-16 ***
factor(YEAR)1999:factor(HBF2)2     2.76314     0.25715    10.745  < 2e-16 ***
factor(YEAR)2000:factor(HBF2)2     1.68445     0.25703     6.553 5.62e-11 ***
factor(YEAR)2001:factor(HBF2)2     3.34070     0.25940    12.879  < 2e-16 ***
factor(YEAR)2002:factor(HBF2)2     1.51018     0.26698     5.657 1.54e-08 ***
factor(YEAR)2003:factor(HBF2)2     1.45866     0.32438     4.497 6.90e-06 ***
factor(YEAR)2004:factor(HBF2)2     2.03079     0.25459     7.977 1.50e-15 ***
factor(YEAR)2005:factor(HBF2)2     1.25084     0.25592     4.888 1.02e-06 ***
factor(YEAR)2006:factor(HBF2)2     0.98478     0.25367     3.882 0.000104 ***
factor(YEAR)2007:factor(HBF2)2     0.67250     0.26108     2.576 0.009998 **
factor(YEAR)2008:factor(HBF2)2     1.75681     0.27283     6.439 1.20e-10 ***
factor(YEAR)2009:factor(HBF2)2     2.28996     0.28454     8.048 8.42e-16 ***
factor(YEAR)2010:factor(HBF2)2     1.15376     0.26715     4.319 1.57e-05 ***
factor(YEAR)2011:factor(HBF2)2     1.73562     0.31670     5.480 4.25e-08 ***
factor(YEAR)2012:factor(HBF2)2     1.47315     0.26985     5.459 4.78e-08 ***
factor(YEAR)2013:factor(HBF2)2     1.32458     0.30065     4.406 1.05e-05 ***
factor(YEAR)2014:factor(HBF2)2     0.57194     0.29909     1.912 0.055846 .
factor(YEAR)2015:factor(HBF2)2     1.27575     0.35343     3.610 0.000307 ***
factor(YEAR)2016:factor(HBF2)2     1.78837     0.67990     2.630 0.008530 **
factor(YEAR)2017:factor(HBF2)2     1.41983     0.39976     3.552 0.000383 ***
factor(YEAR)2018:factor(HBF2)2     0.85830     0.37374     2.297 0.021645 *
factor(QT)2:factor(HBF2)2          0.51692     0.08041     6.429 1.29e-10 ***
factor(QT)3:factor(HBF2)2          0.21315     0.07998     2.665 0.007701 **
factor(QT)4:factor(HBF2)2         -0.19183     0.09251    -2.074 0.038111 *
factor(AREA2)2:factor(HBF2)2      -0.88738     0.06494   -13.665  < 2e-16 ***
factor(AREA2)3:factor(HBF2)2       0.07507     0.07095     1.058 0.290005
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

(Dispersion parameter for Negative Binomial(0.3912) family taken to be 1)

    Null deviance: 92854  on 95913  degrees of freedom
Residual deviance: 58304  on 95721  degrees of freedom
```

```
AIC: 169040

Number of Fisher Scoring iterations: 1


              Theta:  0.39125
          Std. Err.:  0.00451

 2 x log-likelihood:  -168652.30500
```