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Updated standardized CPUE and historical catch estimate of the shortfin mako shark caught by Taiwanese large-scale tuna longline fishery in the North Pacific Ocean [1]

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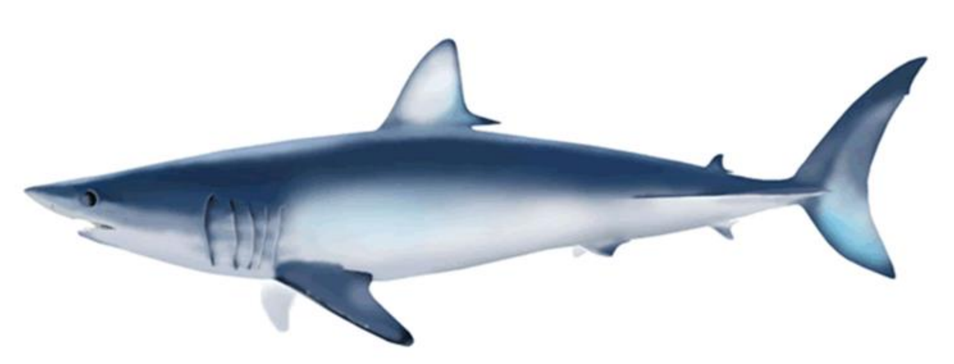

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ABSTRACT

In this study, we analyzed catch and effort data of shortfin mako sharks from the logbook records of Taiwanese large-scale tuna longline fishing vessels operating in the North Pacific Ocean from 2005 to 2022. Due to a significant percentage of zero shortfin mako shark catch, we standardized the catch per unit effort (CPUE) using a zero-inflated negative binomial model, presenting the number of fish caught per 1,000 hooks. Both nominal and standardized CPUE of shortfin mako sharks exhibited inter-annual fluctuations with two peaks in 2014 and 2020. The CPUE of north of 25°N showed a decline from 2006 to 2008, followed by an upward trend from 2010 to 2013. Except for a sudden increase in 2020, the trend remained relatively stable from 2013 to 2022. In the 0-25°N range, there was significant fluctuation of CPUE from 2005 to 2011, while those in the years from 2012 to 2022 exhibited a more stable pattern. The estimated shortfin mako shark catch in weight from the Taiwanese large-scale tuna longline fishery in the North Pacific ranged from 0 metric tons (MT) in 1973 to 156 MT in 2015, decreasing thereafter, increasing to 183 MT in 2020, and subsequently decreasing in 2021 and 2022.

1. Introduction

The shortfin mako shark is a frequently caught species in Taiwanese commercial offshore longline fisheries and is a major by-catch in tuna longline fisheries in distant waters. As a large apex predator with slow growth, low fecundity, and late maturity, the shortfin mako is particularly vulnerable to exploitation due to its life-history characteristics (Campana et al., 2005). Clarke et al. (2006) reported the utilization of approximately half a million shortfin mako sharks in the global shark fin trade in 2000. Given the high fishing pressure and declining population trends, the shortfin mako was classified as "Endangered" on the IUCN Red List of Threatened Species (Rigby et al., 2019) and was included in CITES Appendix II List (CITES, 2019). With growing concerns from international organizations and regional fisheries management organizations (RFMOs) regarding elasmobranch conservation, it becomes imperative to assess recent trends in shark species by examining tuna fisheries logbooks. The Taiwanese large-scale tuna longline (LTLL) fisheries primarily bycatch two major shark species: the blue shark (*Prionace glauca*) and the shortfin mako. This study aims to update CPUE standardization and estimate shortfin mako shark catches by the Taiwanese LTLL in the North Pacific based on logbook data.

2. Material and Methods

2.1. Source of Data

We utilized logbook data from the Taiwanese large-scale tuna longline fishery from 1971 to 2022, provided by the Overseas Fisheries Development Council, Taiwan. These logbook records encompass essential information on fishing time, area, number of hooks, and catches of 18 species (14 species before

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2005), including major tunas, billfishes, and sharks. The shark by-catch in the logbook was first recorded in 1981, with the category "sharks" further divided into four sub-categories namely the blue shark, *Prionace glauca*, mako shark, *Isurus* spp., silky shark, *Carcharihnus falciformis*, and others since 2005. As the Taiwanese longline fishery extensively covers the North Pacific Ocean, the fishery statistics derived from these logbooks are valuable for describing the population status of pelagic sharks. Species-specific catch and effort data from 2005 to 2022 (Figure 1) were used to standardize the CPUE of shortfin mako sharks in the Taiwanese large-scale longline fishery in the North Pacific Ocean. Additionally, nominal CPUE was applied to back-estimate historical shortfin mako catch before 2005.

2.2. CPUE Standardization

Shortfin mako sharks caught by the Taiwanese LTLL fishery were primarily observed in equatorial waters targeting bigeye tuna (*Thunnus obesus*) and in subtropical and temperate waters targeting albacore tuna (*T. alalunga*). The North Pacific Ocean was stratified into four areas based on the distributions of effort from the logbook, namely, A (north of 25°N, east of 175°E), B (north of 25°N, 175°E-160°W), C (north of 25°N, 160°W-135°W), D (0°N-25°N, east of 180°W), E (0°N-25°N, 180°W-140°W), and F (0°N-25°N, west of 140°W) (Figure 2**)**. CPUE standardization was carried out using a Zero-Inflated Negative Binomial model (ZINB) to address the high proportion of sets with zero shortfin mako shark catch (84%). The ZINB model, comprising both count models (Negative Binomial) and a Binomial model, was employed to eliminate biases caused by changes in targeting species, fishing grounds, and seasons. The model included year (Y), quarter (Q), area (A), latitude (LAT), longitude (LON), and number of hooks per basket (HPB) as main variables. The standardized CPUE series for shortfin mako sharks was constructed without interaction effects. The model is described as:

Catch= Year + Quarter + Area + HPB + LAT + LON

For the Zero Inflated Negative Binomial:
(Part 1: count models- Negative Binomial; Part 2: Binomial, link = logit)

The probability distribution of a zero-inflated negative binomial random variable Y is given by

$$\Pr(Y = y) = \begin{cases} \omega + (1-\omega)(1+k\lambda)^{1/k} & \text{for } y = 0 \\ (1-\omega)\frac{\Gamma(y+1/k)}{\Gamma(y+1)\Gamma(1/k)}\frac{(k\mu)^y}{(1+k\lambda)^{y+1/k}} & \text{for } y = 1,2,\ldots \end{cases}$$

where k is the negative binomial dispersion parameter.

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The effect of gear configuration, HPB, was categorized into two classes: shallow set (HPB $\leqq$ 15), and deep set (HPB > 15) (Walsh, 2011), and 4 quarters were categorized: the 1st quarter (Jan-Mar), the 2nd quarter (Apr-Jun), the 3rd quarter (Jul-Sep), and the 4th quarter (Oct-Dec). Continuous variables tested were the LAT and LON. The area strata used for the analysis are shown in Figure 2.

The best model for ZINB models were selected using the stepwise AIC method (Venables and Ripley, 2002). For model diagnostics, the rootograms function in R countreg package (Kleiber and Zeileis, 2016) was used to assess the influence of observations that exert on the model. The distribution of residuals was used to verify the assumption of the ZINB models. These diagnostic plots were used to evaluate the fitness of the models.

Empirical confidence interval of standardized CPUE was estimated by using a bootstrap resampling method. The number of bootstrapped sub-samples was generated based on the sample size of CPUE in each year. The 95% confidence intervals were then constructed based on bias corrected percentile method with 10,000 replicates (Efron and Tibshirani, 1993).

2.3. Estimate of Historical Shortfin Mako Shark Catch

Annual shortfin mako by-catch in number (Cy) was obtained by dividing logbook catch by coverage rate for 2005-2022. The shortfin mako by-catch in number before 2005 was back-estimated using the following equation:

$$C_y = \sum_{i}^{4} \frac{\text{Nominal } CPUE_{\text{i,}} \times Logbook\ effort_i}{Coverage\ rate}$$

where y is year, i = 1 is area A, i = 2 is B, i = 3 is area C, i = 4 is area D, i = 5 is area E, and i = 6 is area F. Coverage rate is the total catch (bigeye tuna, albacore tuna, yellowfin tuna, and swordfish) in logbook to that in Task 1. The nominal CPUE before 2005 was represented by the average of nominal CPUE in the period of 2005-2007 because there were no species-specific shark catch data in logbook before 2005. The catch in number from 2005 to 2022 was estimated by using the logbook SMA catch divided by coverage rate. The catch in weight of shortfin mako sharks was estimated using annual mean weight multiplied by the estimated/back-estimated catch in number. Incomplete weight records before 2015 were addressed by assuming a constant average value for 1971-2004. Size data not recorded in PCL (Fork Length recorded in logbook data) were converted to PCL based on the equations by Joung and Hsu (2005). The annual mean PCL of shortfin mako sharks was calculated based on logbook length data from 2005-2022, and the mean weight was obtained using the W-PCL relationship (sexes combined) as follows: $W = 2.28\times10^{-5}\ PCL^{2.88}$ (Su et al., 2017).

3. Results and Discussion

A total of 82,618 sets with 263 million hooks and 26,890 SMA catch were recorded from 2005 to 2022. Of which, 26,189 sets with 104 million hooks and 22,303 SMA catch were recorded in the waters north of 25°N. While, 56,429 sets with 159 million hooks and 4,587 SMA catch were recorded in the waters between 0° to 25°N (Table 1). The frequency distributions of shortfin mako shark by-catch per set revealed a high occurrence of zero values and a long right tail (Figure 3), with 84.11% of total sets reporting zero shortfin mako shark by-catch (Table 2). The best model of ZINB for the north was CPUE ~ Year + Quarter + Area + HPB, while the best model of ZINB was CPUE ~ Year + Quarter + Area + HPB for the south stock () based on the AIC. The best model of ZINB for the North Pacific selected based on AIC, was "CPUE ~ Year + Quarter + Area + HPB + LAT + LON". Detailed values for nominal and standardized CPUE are presented in Tables 3-5.

Both nominal and standardized CPUE of shortfin mako sharks exhibited inter-annual fluctuations. The CPUE of north of 25°N showed a decline from 2006 to 2008, followed by an upward trend from 2010 to 2013. Except for a sudden increase in 2020, the trend remained relatively stable from 2013 to 2022 (Figure 4a). In the 0-25°N range, there was significant fluctuation of CPUE from 2005 to 2011, while those in the years from 2012 to 2022 exhibited a more stable pattern (Figure 4b).The standardized CPUE series, combining effects from two models, decreased from 2006 to 2010, peaked in 2014, decreased thereafter, increased again in 2018 to 2020, and decreased in 2021-2022 (Figure 4c). Diagnostic results from the ZINB model did not indicate severe departures from model assumptions (Figures 5-6). Q-Q normal plots for ZINB models demonstrated error distributions close to normal (Figure 5), and no wave-like patterns in residuals indicated appropriate model capture. Additional residual plots for each factor were provided in Figure 6. ANOVA tables for each model are given in Tables 4-6, with all main effects tested being significant (mostly $P < 0.01$) and included in the final model.

The annual mean PCL of shortfin mako sharks recorded in the logbook is listed in Table 7. The average PCL was 133.46 cm (n=4,941), and the estimated mean weight was 38.06 kg. Back-estimated shortfin mako shark by-catch in number ranged from 0 in 1973 to 3,742 in 2020, while back-estimated by-catch in weight ranged from almost 0 MT in 1971 to 183 MT in 2020 (Table 8).

Many factors may affect the standardization of CPUE trend. In addition to the temporal and spatial effects, environmental factors are important which may affect the representation of standardized CPUE of pelagic fish, i.e. swordfish and blue shark in the North Pacific (Bigelow *et al.*, 1999), and big-eye tuna in the Indian Ocean (Okamoto *et al.*, 2001). Although shortfin mako sharks are homeotherm, the behavior of sharks with these characteristic is also triggered by the environmental temperature (Weng *et al.*, 2007). Environmental effects should be included in the future standardization models. In addition, the change of logbook reporting system is another possible factor influencing the CPUE. The paper logbook has been

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replaced by e-logbook since 2017. Despite of the transition year of 2017, the 100% coverage rate of 2018 to 2022 may lead to the increase of CPUE in these years.

4. Conclusion

In conclusion, this study provides valuable insights into the dynamics of shortfin mako shark catches in the North Pacific Ocean by the Taiwanese LTLL fishery. The observed fluctuations in CPUE highlight the complex interplay of environmental factors, fishing practices, and species biology. Continued monitoring and adaptive management strategies are crucial for the conservation of shortfin mako sharks, especially considering their endangered status. Future research should consider incorporating environmental effects into standardization models and accounting for changes in reporting systems for comprehensive assessments.

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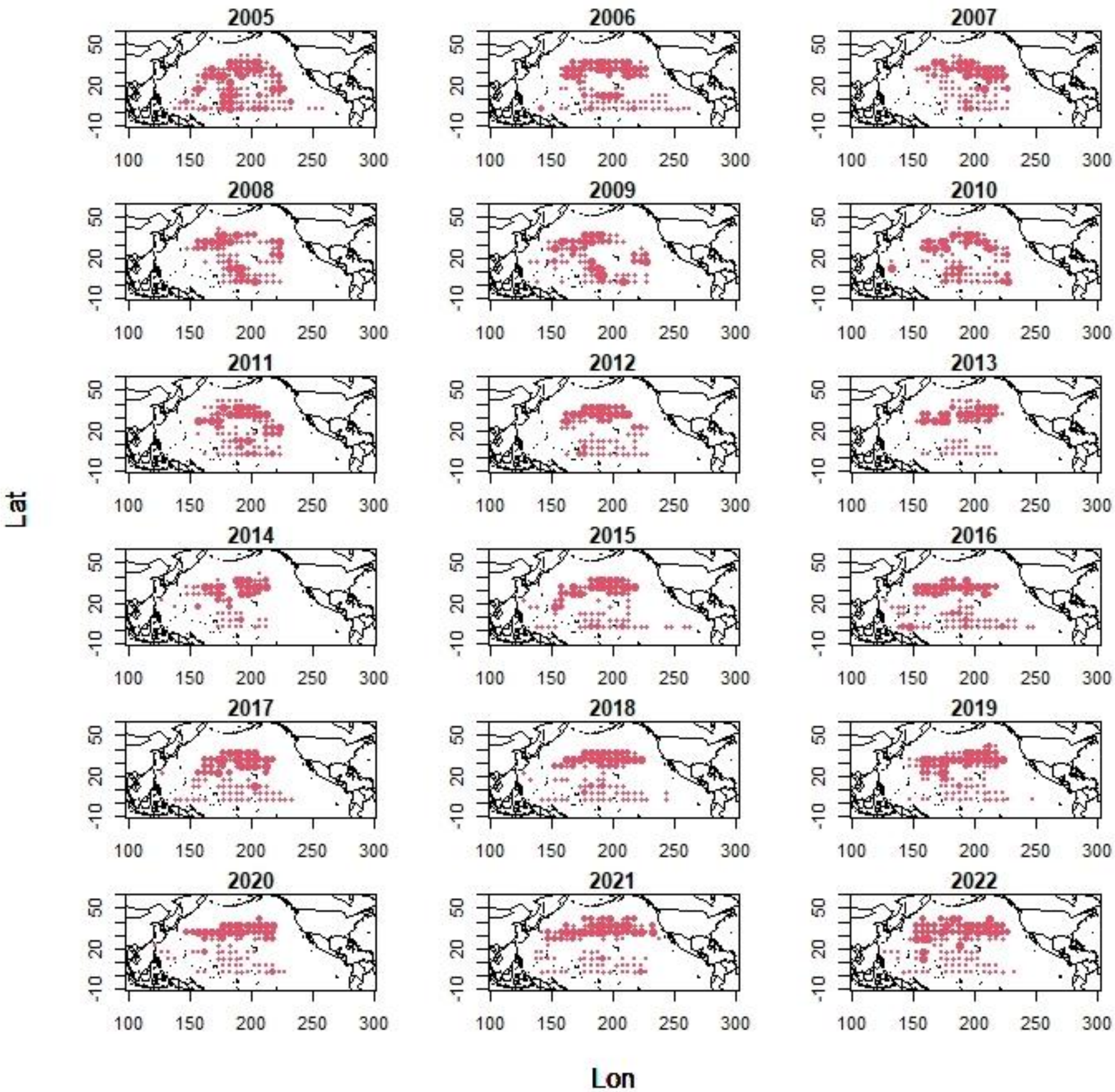

Figure 1. Nominal CPUE distribution of shortfin mako sharks caught by the Taiwanese large-scale tuna longline fishery in the North Pacific Ocean from 2005-2022.

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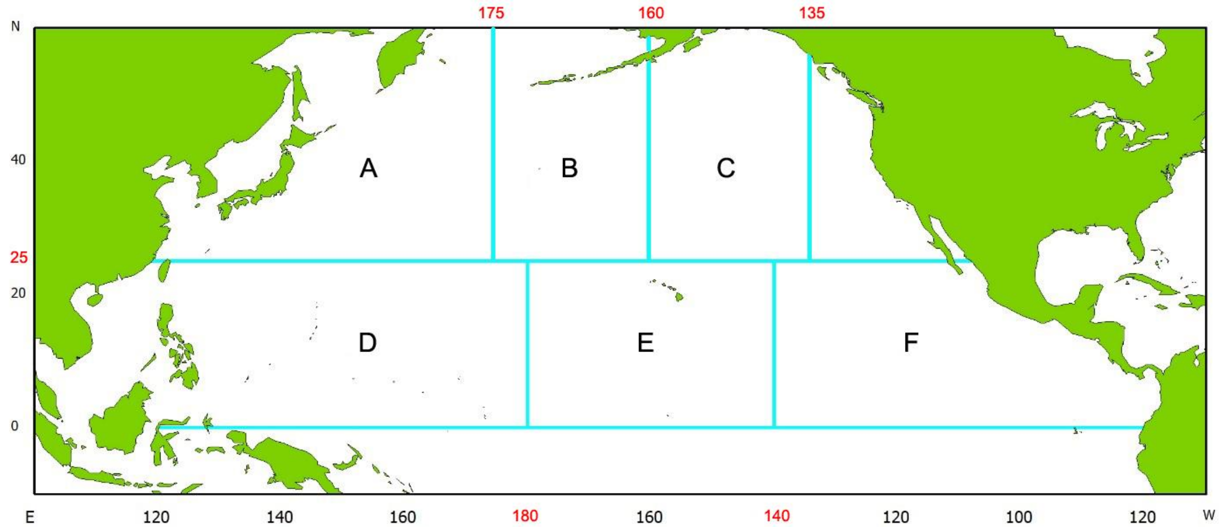

Figure 2. Area stratification used for the estimate of shortfin mako shark by-catch of the Taiwanese large-scale tuna longline fishery in North Pacific Ocean.

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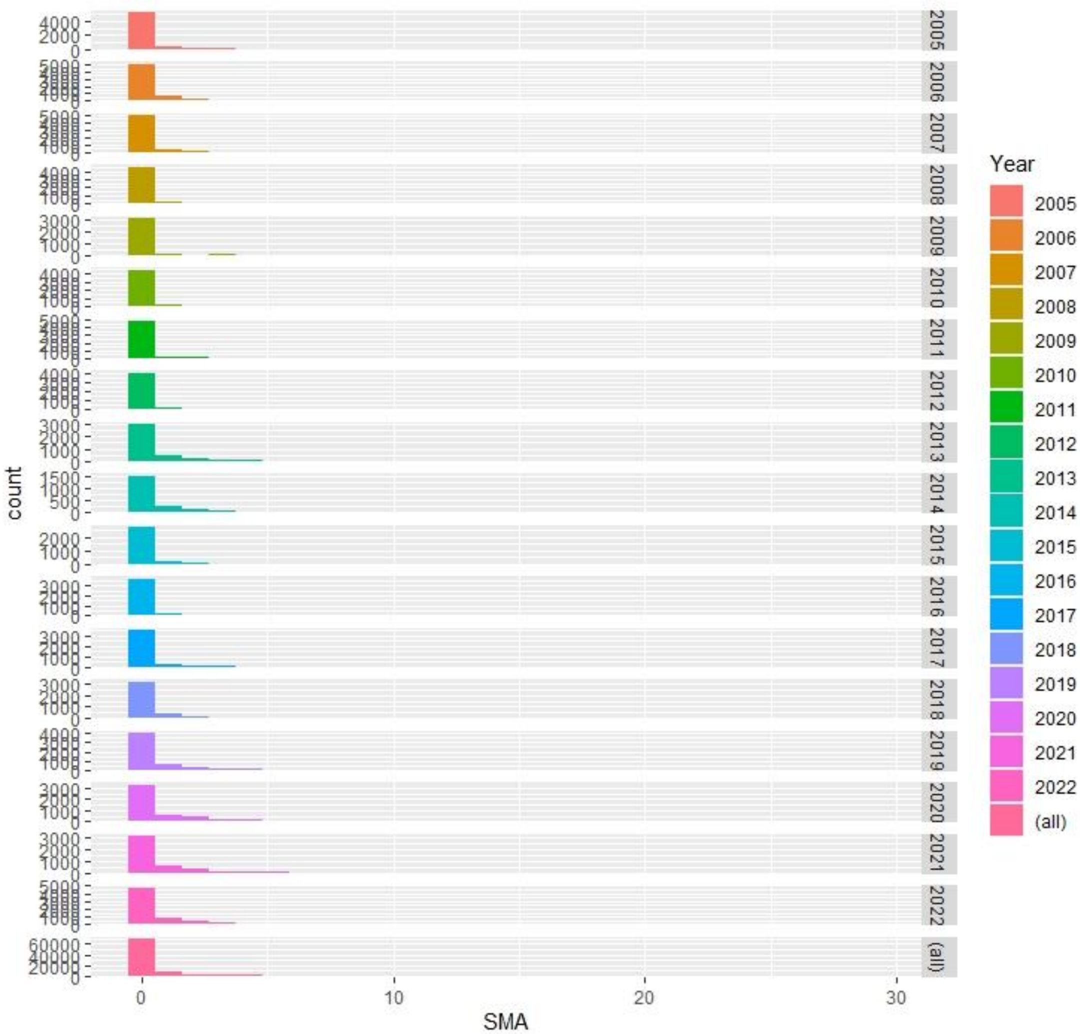

Figure 3. Frequency distribution of the shortfin mako shark by-catch per set, 2005–2022.

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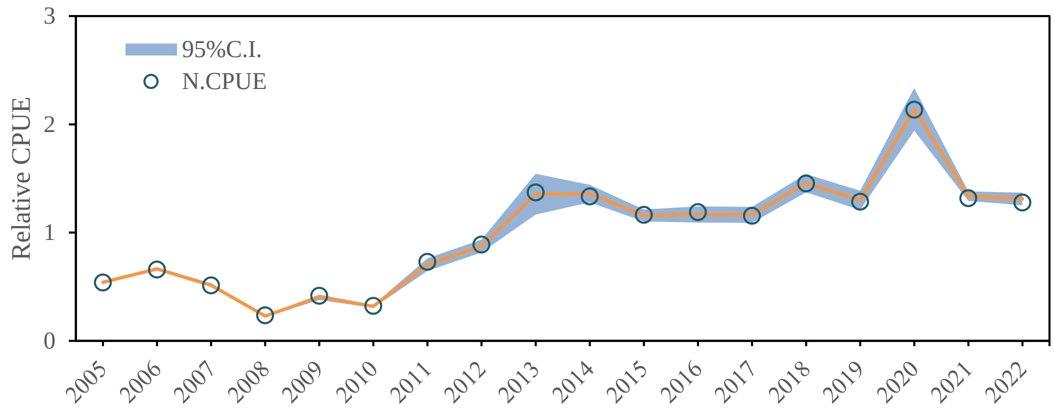
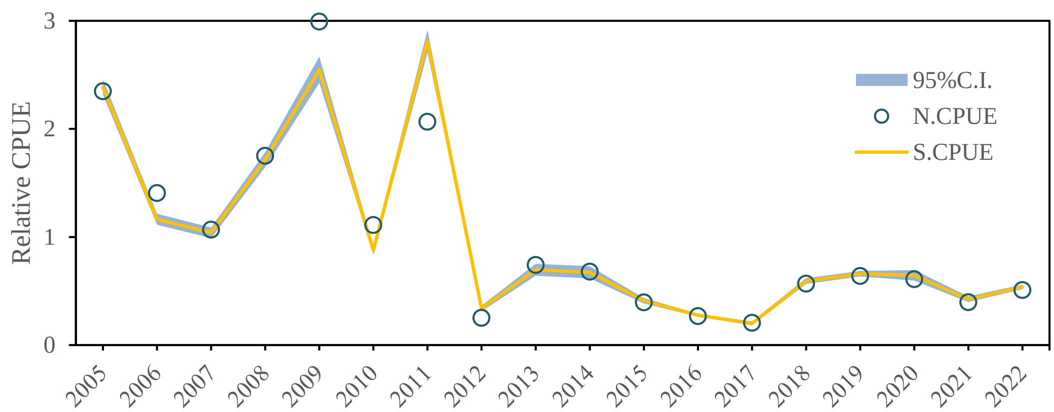
(a) north of 25°N



(b) 0°-25°N



(c) North Pacific

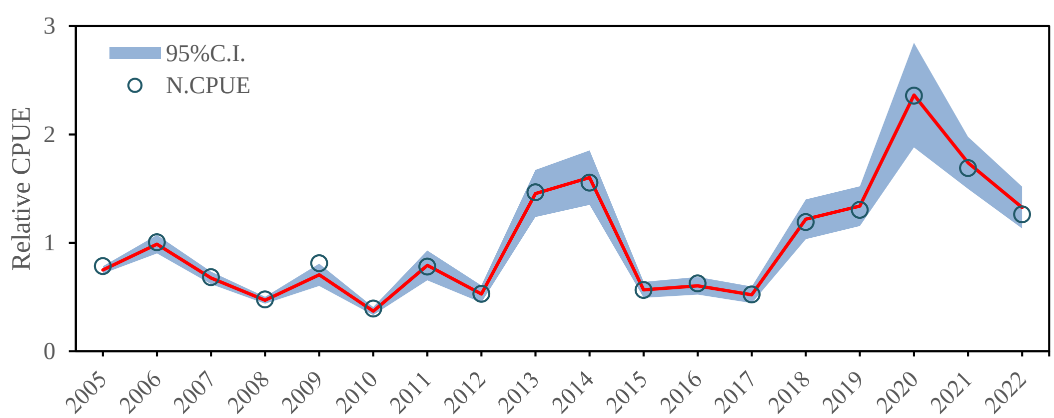


Figure 4. Relative nominal (open circle) and standardized CPUE with 95% C.I. of shortfin mako shark by the Taiwanese large-scale tuna longline fishery in the North Pacific Ocean from 2005 to 2022.

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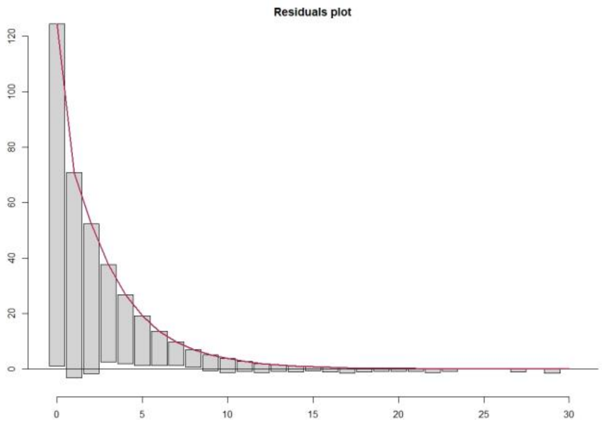
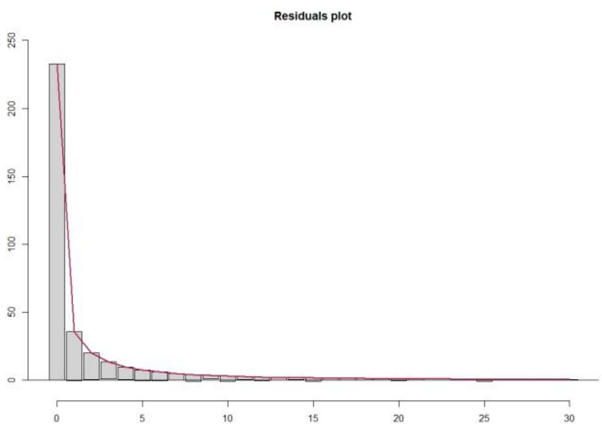
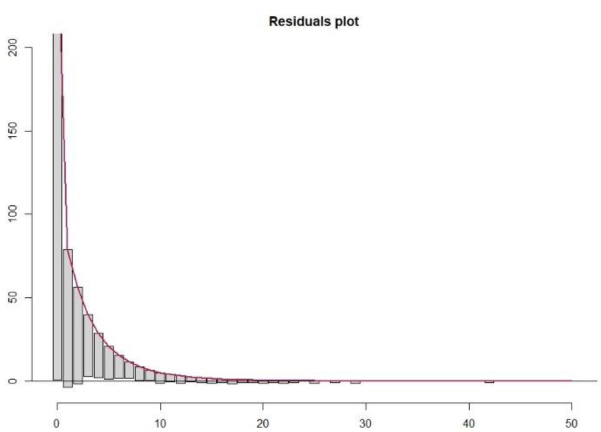


(a) north of 25ºN



(b) 0º-25ºN



(c) north Pacific

Figure 5. Diagnostic results from the ZINB model fit to the shortfin mako shark caught by the Taiwan large-scale tuna longline fishery.

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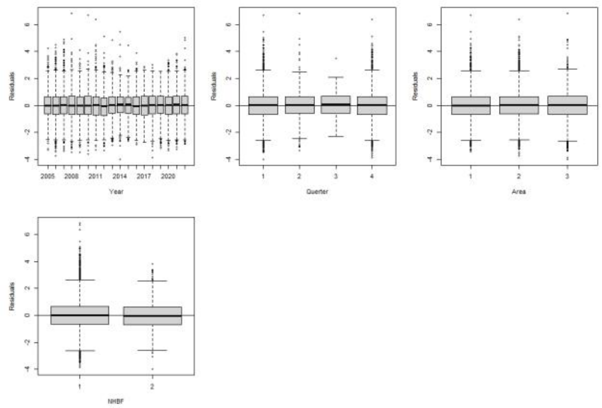
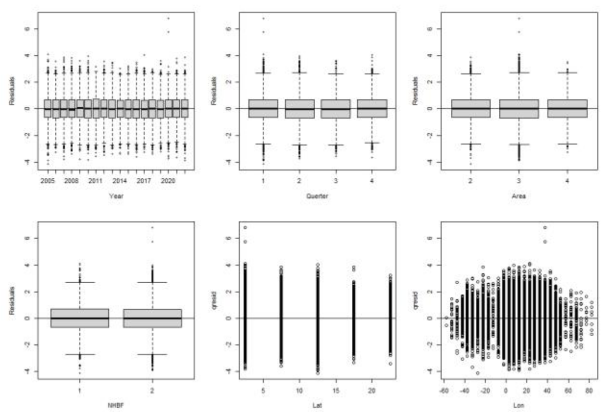
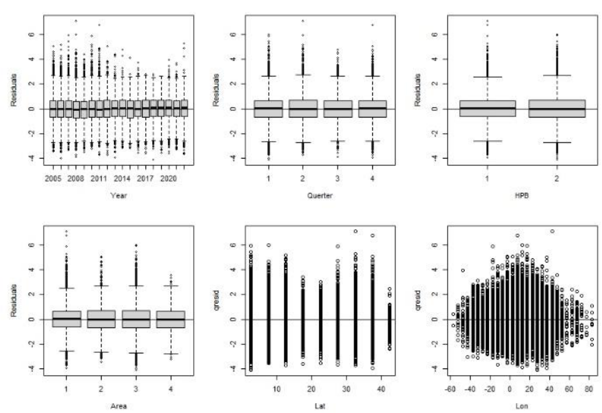


(a) North of 25ºN



(b) 0º-25ºN



(c) North Pacific

Figure 6. Box plots of the Pearson residuals vs. the covariates for the variables Year, Quarter, Area, NHBF, Lat and Lon.

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Table 1. The logbook data by set, hooks and catch in number of SMA of from 2005 to 2022

Area	north of 25ºN			0º-25ºN			Total		
Year	Set	Hooks (thousand)	SMA	Set	Hooks (thousand)	SMA	Set	Hooks (thousand)	SMA
2005	1,661	6,840	761	4,462	13,482	812	6,123	20,322	1,573
2006	3,046	13,092	1,704	3,191	9,441	348	6,237	22,533	2,052
2007	2,230	9,497	972	3,359	10,120	278	5,589	19,618	1,250
2008	1,541	6,231	309	3,359	10,086	456	4,900	16,317	765
2009	942	3,662	334	2,470	7,574	573	3,412	11,236	907
2010	1,069	4,180	294	3,659	10,728	315	4,728	14,907	609
2011	1,104	4,343	685	4,234	12,520	678	5,338	16,863	1,363
2012	919	3,641	695	3,489	10,047	68	4,408	13,688	763
2013	1,514	5,816	1,764	2,455	6,743	141	3,969	12,559	1,905
2014	861	3,313	976	1,177	3,275	62	2,038	6,588	1,038
2015	494	1,909	489	2,576	6,753	79	3,070	8,662	568
2016	772	2,893	780	3,378	8,827	70	4,150	11,720	850
2017	624	2,389	613	3,255	8,868	52	3,879	11,257	665
2018	1,154	4,532	1,426	2,819	7,381	124	3,973	11,913	1,550
2019	1,925	7,485	2,103	3,393	8,987	168	5,318	16,472	2,271
2020	1,988	7,740	3,607	2,860	7,442	135	4,848	15,182	3,742
2021	2,132	8,214	2,387	2,310	6,424	71	4,442	14,638	2,458
2022	2,213	8,366	2,404	3,983	10,895	157	6,196	19,261	2,561
Total	26,189	104,142	22,303	56,429	159,592	4,587	82,618	263,735	26,890

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Table 2. Estimated annual shortfin mako shark (SMA) zero-catch percentage of the Taiwanese large-scale tuna longline fishery in the North Pacific Ocean.

Year	SMA Zero%
2005	86.38
2006	82.43
2007	87.73
2008	92.84
2009	92.41
2010	94.54
2011	90.80
2012	92.97
2013	76.19
2014	74.73
2015	89.25
2016	89.71
2017	90.56
2018	79.66
2019	76.04
2020	68.69
2021	71.61
2022	77.49
Average	84.11

Table 3. Estimated nominal and standardized CPUE values for shortfin mako shark of the Taiwanese tuna longline fishery in the north of 25°N Pacific Ocean.

Year	nominal	standardized	Std_CV	relative	Rel_CV
2005	0.1113	0.4579	5.90	0.5407	5.91
2006	0.1302	0.5626	3.88	0.6644	3.65
2007	0.1023	0.4352	5.47	0.5139	5.49
2008	0.0496	0.1941	12.10	0.2292	12.08
2009	0.0912	0.3412	11.52	0.4029	11.38
2010	0.0703	0.2701	13.02	0.3190	12.75
2011	0.1577	0.5969	12.43	0.7049	11.66
2012	0.1909	0.7420	8.06	0.8762	7.82
2013	0.3033	1.1478	2.96	1.3554	3.04
2014	0.2946	1.1520	5.11	1.3604	5.00
2015	0.2562	0.9814	5.60	1.1589	5.42
2016	0.2696	0.9889	5.07	1.1679	4.77
2017	0.2566	0.9859	5.60	1.1643	5.40
2018	0.3147	1.2335	3.43	1.4567	3.31
2019	0.2810	1.0995	2.75	1.2984	2.94
2020	0.4660	1.8109	2.67	2.1385	2.40
2021	0.2906	1.1321	2.91	1.3369	2.90
2022	0.2873	1.1105	2.81	1.3114	3.05
Average	0.2180	0.8468			

Table 4. Estimated nominal and standardized CPUE values for shortfin mako shark of the Taiwanese tuna longline fishery in the 0-25° North Pacific Ocean.

Year	nominal	standardized	Std_CV	relative	Rel_CV
2005	0.0602	0.1804	7.67	2.3854	7.20
2006	0.0369	0.0880	12.13	1.1634	11.20
2007	0.0275	0.0786	12.46	1.0391	11.74
2008	0.0452	0.1298	11.51	1.7158	10.45
2009	0.0757	0.1927	13.78	2.5473	11.82
2010	0.0294	0.0663	11.94	0.8770	11.72
2011	0.0542	0.2127	10.14	2.8117	10.13
2012	0.0068	0.0256	20.53	0.3391	20.05
2013	0.0209	0.0527	21.12	0.6971	20.17
2014	0.0189	0.0509	21.39	0.6733	20.88
2015	0.0117	0.0311	14.93	0.4112	15.25
2016	0.0079	0.0209	11.75	0.2769	12.21
2017	0.0059	0.0152	22.64	0.2008	23.23
2018	0.0168	0.0448	11.00	0.5921	11.63
2019	0.0187	0.0500	9.97	0.6609	9.84
2020	0.0181	0.0488	19.18	0.6452	19.05
2021	0.0111	0.0322	16.00	0.4251	15.51
2022	0.0144	0.0407	9.33	0.5386	9.93
Average	0.0267	0.0756			

[1] Working document submitted to the ISC Shark Working Group Workshop, 29-30 November- 1-2, 4-7 December 2023, Yokohama, Kanagawa, Japan. **Document not to be cited without author's permission.**

Table 3. Estimated nominal and standardized CPUE values for shortfin mako shark of the Taiwanese tuna longline fishery in the North Pacific Ocean.

Year	nominal	standardized	Std_CV	relative	Rel_CV
2005	0.0774	0.2458	3.80	0.7493	3.81
2006	0.0911	0.3238	3.48	0.9871	3.36
2007	0.0637	0.2216	5.07	0.6756	5.27
2008	0.0469	0.1542	8.73	0.4701	8.58
2009	0.0807	0.2310	9.76	0.7043	9.35
2010	0.0409	0.1213	9.58	0.3697	9.44
2011	0.0808	0.2595	8.12	0.7912	7.95
2012	0.0557	0.1729	7.56	0.5271	7.63
2013	0.1517	0.4772	3.55	1.4547	3.21
2014	0.1576	0.5252	5.96	1.6011	5.44
2015	0.0656	0.1856	6.84	0.5658	6.71
2016	0.0725	0.1979	5.41	0.6034	5.26
2017	0.0591	0.1706	5.69	0.5202	5.61
2018	0.1301	0.3992	4.06	1.2171	3.85
2019	0.1379	0.4389	3.23	1.3381	3.19
2020	0.2465	0.7750	2.71	2.3628	2.74
2021	0.1679	0.5699	2.98	1.7375	2.91
2022	0.1330	0.4346	3.39	1.3249	3.31
Average	0.1033	0.3280			

[1] Working document submitted to the ISC Shark Working Group Workshop, 29-30 November- 1-2, 4-7 December 2023, Yokohama, Kanagawa, Japan. **Document not to be cited without author's permission.**

Table 4. Analysis of Deviance Table of count model and Zero-inflated model in the north of 25°N Pacific Ocean.

```
Call:
zeroinfl(formula = SHK ~ Yr + Qtr + Area + NHBF, data = dat, offset = log(Hook), dist = "negbin")

Pearson residuals:
    Min      1Q  Median      3Q     Max 
-1.0052 -0.5672 -0.3300  0.3050 49.6451 

Count model coefficients (negbin with log link):
             Estimate Std. Error  z value Pr(>|z|)    
(Intercept) -8.215851   0.071095 -115.562  < 2e-16 ***
Yr2006      -0.015850   0.082004   -0.193   0.8467    
Yr2007      -0.099218   0.086489   -1.147   0.2513    
Yr2008      -0.209440   0.129790   -1.614   0.1066    
Yr2009       0.596509   0.117965    5.057 4.27e-07 ***
Yr2010       0.233674   0.126913    1.841   0.0656 .  
Yr2011       0.859121   0.095826    8.965  < 2e-16 ***
Yr2012       0.771568   0.093569    8.246  < 2e-16 ***
Yr2013       0.459947   0.074094    6.208 5.38e-10 ***
Yr2014       0.599299   0.083891    7.144 9.08e-13 ***
Yr2015       0.166665   0.093923    1.774   0.0760 .  
Yr2016       0.185156   0.087422    2.118   0.0342 *  
Yr2017       0.197402   0.090087    2.191   0.0284 *  
Yr2018       0.407488   0.075170    5.421 5.93e-08 ***
Yr2019       0.364819   0.074033    4.928 8.32e-07 ***
Yr2020       0.684634   0.071470    9.579  < 2e-16 ***
Yr2021       0.400674   0.073456    5.455 4.91e-08 ***
Yr2022       0.382037   0.073297    5.212 1.87e-07 ***
Qtr2         0.027081   0.096685    0.280   0.7794    
Qtr3        -0.275774   0.266603   -1.034   0.3010    
Qtr4        -0.101695   0.023822   -4.269 1.96e-05 ***
Area2        0.005257   0.031817    0.165   0.8688    
Area3       -0.337909   0.034846   -9.697  < 2e-16 ***
NHBF2       -0.849668   0.053965  -15.745  < 2e-16 ***
Log(theta)   0.584507   0.035407   16.508  < 2e-16 ***

Zero-inflation model coefficients (binomial with logit link):
              Estimate Std. Error z value Pr(>|z|)    
(Intercept)  1.306e+00  1.317e-01   9.912  < 2e-16 ***
Yr2006      -4.846e-01  1.561e-01  -3.104 0.001911 ** 
Yr2007      -1.988e-01  1.551e-01  -1.281 0.200065    
Yr2008       4.901e-01  1.860e-01   2.634 0.008428 ** 
Yr2009       1.001e+00  1.658e-01   6.035 1.59e-09 ***
Yr2010       1.010e+00  1.816e-01   5.562 2.67e-08 ***
Yr2011       7.198e-01  1.503e-01   4.788 1.68e-06 ***
Yr2012       3.098e-01  1.561e-01   1.984 0.047233 *  
Yr2013      -2.641e+01  3.420e+04  -0.001 0.999384    
Yr2014      -1.367e+00  1.907e-01  -7.169 7.57e-13 ***
Yr2015      -3.793e+00  1.126e+00  -3.368 0.000758 ***
Yr2016      -3.428e+00  6.002e-01  -5.711 1.12e-08 ***
Yr2017      -3.509e+00  9.981e-01  -3.515 0.000439 ***
Yr2018      -2.059e+01  3.035e+03  -0.007 0.994587    
Yr2019      -2.957e+00  3.330e-01  -8.882  < 2e-16 ***
Yr2020      -1.802e+01  6.630e+02  -0.027 0.978315    
Yr2021      -2.344e+00  1.922e-01 -12.198  < 2e-16 ***
Yr2022      -2.876e+00  2.424e-01 -11.867  < 2e-16 ***
Qtr2         6.116e-01  1.811e-01   3.377 0.000734 ***
Qtr3         1.390e+00  4.413e-01   3.150 0.001634 ** 
Qtr4        -4.099e-02  8.547e-02  -0.480 0.631495    
Area2       -1.265e+00  9.961e-02 -12.702  < 2e-16 ***
Area3       -1.817e+00  1.022e-01 -17.784  < 2e-16 ***
NHBF2       -1.443e+00  6.167e-01  -2.340 0.019278 *  
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1 

Theta = 1.7941 
Number of iterations in BFGS optimization: 88 
Log-likelihood: -3.056e+04 on 49 Df
```

[1] Working document submitted to the ISC Shark Working Group Workshop, 29-30 November- 1-2, 4-7 December 2023, Yokohama, Kanagawa, Japan. **Document not to be cited without author's permission.**

Table 5. Analysis of Deviance Table of count model and Zero-inflated model in the 0-25° North Pacific Ocean.

```
Call:
zeroinfl(formula = SHK ~ Yr + Qtr + Area + NHBF + Lat + Lon, data = dat, offset = log(Hook), dist = "negbin")

Pearson residuals:
    Min      1Q  Median      3Q     Max
-0.3723 -0.1789 -0.1451 -0.1153 71.1913

Count model coefficients (negbin with log link):
             Estimate Std. Error z value Pr(>|z|)
(Intercept) -8.798407   0.192848 -45.623  < 2e-16 ***
Yr2006       0.222748   0.214859   1.037 0.299869
Yr2007       0.455949   0.199242   2.288 0.022113 *
Yr2008       0.340709   0.215300   1.582 0.113538
Yr2009       0.900865   0.192079   4.690 2.73e-06 ***
Yr2010       0.224935   0.196068   1.147 0.251285
Yr2011       1.235193   0.216693   5.700 1.20e-08 ***
Yr2012      -0.183254   0.322845  -0.568 0.570292
Yr2013       0.089706   0.275469   0.326 0.744691
Yr2014      -0.727958   0.314401  -2.315 0.020592 *
Yr2015      -1.263598   0.311530  -4.056 4.99e-05 ***
Yr2016      -2.108353   0.422721  -4.988 6.11e-07 ***
Yr2017      -0.775903   0.351157  -2.210 0.027135 *
Yr2018      -1.465086   0.315133  -4.649 3.33e-06 ***
Yr2019      -1.513753   0.261444  -5.790 7.04e-09 ***
Yr2020      -1.156620   0.283418  -4.081 4.48e-05 ***
Yr2021      -1.752727   0.394290  -4.445 8.78e-06 ***
Yr2022      -1.445964   0.257406  -5.617 1.94e-08 ***
Qtr2         0.289687   0.093106   3.111 0.001862 **
Qtr3        -0.569389   0.171371  -3.323 0.000892 ***
Qtr4        -0.745295   0.165072  -4.515 6.33e-06 ***
Area3        0.575321   0.165904   3.468 0.000525 ***
Area4        0.323268   0.309033   1.046 0.295531
NHBF2        0.055485   0.200823   0.276 0.782326
Lat         -0.002659   0.008752  -0.304 0.761240
Lon         -0.023045   0.004353  -5.294 1.20e-07 ***
Log(theta)  -1.071167   0.219099  -4.889 1.01e-06 ***

Zero-inflation model coefficients (binomial with logit link):
            Estimate Std. Error z value Pr(>|z|)
(Intercept)  1.33197    0.22931   5.809 6.30e-09 ***
Yr2006       1.17351    0.24468   4.796 1.62e-06 ***
Yr2007       1.66580    0.22366   7.448 9.48e-14 ***
Yr2008       1.10685    0.24722   4.477 7.56e-06 ***
Yr2009       1.48613    0.21963   6.767 1.32e-11 ***
Yr2010       1.64770    0.22229   7.412 1.24e-13 ***
Yr2011       1.80770    0.27542   6.563 5.26e-11 ***
Yr2012       2.71071    0.33230   8.158 3.42e-16 ***
Yr2013       2.01447    0.29095   6.924 4.39e-12 ***
Yr2014       1.16907    0.33127   3.529 0.000417 ***
Yr2015       0.62370    0.36678   1.700 0.089044 .
Yr2016       0.14802    0.58653   0.252 0.800751
Yr2017       2.24937    0.35199   6.391 1.65e-10 ***
Yr2018       0.13426    0.41177   0.326 0.744391
Yr2019      -0.26118    0.36585  -0.714 0.475292
Yr2020       0.31180    0.35657   0.874 0.381877
Yr2021       0.19415    0.58353   0.333 0.739352
Yr2022       0.27000    0.32684   0.826 0.408742
Qtr2         0.13660    0.09456   1.444 0.148599
Qtr3        -0.52664    0.21775  -2.419 0.015583 *
Qtr4        -0.76903    0.23363  -3.292 0.000996 ***
Area3        0.70818    0.17427   4.064 4.83e-05 ***
Area4        0.46170    0.38870   1.188 0.234910
NHBF2       -0.48981    0.21018  -2.330 0.019781 *
Lat         -0.08644    0.01150  -7.514 5.72e-14 ***
Lon         -0.02274    0.00476  -4.778 1.77e-06 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Theta = 0.3426
Number of iterations in BFGS optimization: 82
Log-likelihood: -1.142e+04 on 53 Df
```

Table 6. Analysis of Deviance Table of count model and Zero-inflated model in the North Pacific Ocean.

```
Call:
zeroinfl(formula = SHK ~ Yr + Qtr + Area + NHBF + Lat + Lon,
 data = dat, offset = log(Hook), dist = "negbin")

Pearson residuals:
     Min       1Q   Median       3Q      Max
-0.84515 -0.24020 -0.14991 -0.08718 79.99456

Count model coefficients (negbin with log link):
              Estimate Std. Error z value Pr(>|z|)
(Intercept) -7.6892924  0.0942365 -81.596  < 2e-16 ***
Yr2006       0.3214499  0.0565898   5.680 1.34e-08 ***
Yr2007       0.2816714  0.0652180   4.319 1.57e-05 ***
Yr2008       0.3340920  0.1224092   2.729  0.00635 **
Yr2009       1.2715756  0.0835240  15.224  < 2e-16 ***
Yr2010       0.6202644  0.0935591   6.630 3.36e-11 ***
Yr2011       1.1274678  0.0741895  15.197  < 2e-16 ***
Yr2012       1.0532753  0.0773367  13.619  < 2e-16 ***
Yr2013       0.9435216  0.0549501  17.171  < 2e-16 ***
Yr2014       0.9120452  0.0648102  14.073  < 2e-16 ***
Yr2015       0.6138051  0.0763807   8.036 9.27e-16 ***
Yr2016       0.6925139  0.0702167   9.863  < 2e-16 ***
Yr2017       0.7271578  0.0736668   9.871  < 2e-16 ***
Yr2018       0.8651928  0.0565893  15.289  < 2e-16 ***
Yr2019       0.8044745  0.0525203  15.317  < 2e-16 ***
Yr2020       1.1810004  0.0513797  22.986  < 2e-16 ***
Yr2021       0.8915812  0.0532442  16.745  < 2e-16 ***
Yr2022       0.8375162  0.0520698  16.084  < 2e-16 ***
Qtr2         0.3360896  0.0518525   6.482 9.07e-11 ***
Qtr3        -0.4264063  0.1064272  -4.007 6.16e-05 ***
Qtr4        -0.0238241  0.0267057  -0.892  0.37234
Area2       -0.0654720  0.0742350  -0.882  0.37780
NHBF2       -0.5465924  0.0463834 -11.784  < 2e-16 ***
Lat         -0.0320111  0.0030724 -10.419  < 2e-16 ***
Lon         -0.0078429  0.0007056 -11.115  < 2e-16 ***
Log(theta)   0.3740504  0.0375689   9.956  < 2e-16 ***


  -
Zero-inflation model coefficients (binomial with logit link):
             Estimate Std. Error z value Pr(>|z|)
(Intercept)  4.638895   0.152523  30.414  < 2e-16 ***
Yr2006       1.615679   0.128726  12.551  < 2e-16 ***
Yr2007       2.060576   0.131901  15.622  < 2e-16 ***
Yr2008       2.257248   0.205199  11.000  < 2e-16 ***
Yr2009       2.913366   0.135589  21.487  < 2e-16 ***
Yr2010       2.702145   0.149215  18.109  < 2e-16 ***
Yr2011       2.166833   0.132664  16.333  < 2e-16 ***
Yr2012       3.028368   0.137490  22.026  < 2e-16 ***
Yr2013       1.086867   0.118080   9.204  < 2e-16 ***
Yr2014       1.181219   0.136546   8.651  < 2e-16 ***
Yr2015       1.230537   0.133972   9.185  < 2e-16 ***
Yr2016       1.560346   0.124933  12.489  < 2e-16 ***
Yr2017       1.733454   0.130939  13.239  < 2e-16 ***
Yr2018       0.933119   0.117789   7.922 2.34e-15 ***
Yr2019       0.879711   0.110297   7.976 1.51e-15 ***
Yr2020       0.820227   0.108199   7.581 3.44e-14 ***
Yr2021       1.177095   0.119033   9.889  < 2e-16 ***
Yr2022       0.963930   0.108741   8.864  < 2e-16 ***
Qtr2         0.192487   0.065367   2.945 0.003232 **
Qtr3        -0.278266   0.129112  -2.155 0.031143 *
Qtr4         0.221430   0.062443   3.546 0.000391 ***
Area2       -1.544590   0.089248 -17.307  < 2e-16 ***
NHBF2       -0.627054   0.071775  -8.736  < 2e-16 ***
Lat         -0.220389   0.005491 -40.137  < 2e-16 ***
Lon         -0.018581   0.001405 -13.222  < 2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' '
 1

Theta = 1.4536
Number of iterations in BFGS optimization: 64
Log-likelihood: -4.371e+04 on 51 Df
>
```

[1] Working document submitted to the ISC Shark Working Group Workshop, 29-30 November- 1-2, 4-7 December 2023, Yokohama, Kanagawa, Japan. **Document not to be cited without author's permission.**

Table 7. Estimated annual shortfin mako shark (SMA) mean PCL and mean weight from the logbook data.

Year	SMA_n	Mean PCL	Mean W
2005	441	124.53	31.17
2006	260	139.74	43.44
2007	176	137.65	41.60
2008	325	118.65	27.12
2009	389	106.23	19.72
2010	234	119.03	27.37
2011	484	127.71	33.52
2012	66	149.77	53.04
2013	183	139.20	42.96
2014	182	121.29	28.89
2015	58	152.40	55.76
2016	198	146.05	49.33
2017	157	146.46	49.73
2018	401	142.40	45.86
2019	551	143.33	46.74
2020	344	145.47	48.77
2021	271	143.12	46.54
2022	221	141.76	45.28
Total	4,941	133.46	38.06

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Table 8. Estimated annual shortfin mako shark by-catch in number and weight (MT) of the Taiwanese large-scale tuna longline fishery in the North Pacific Ocean.

* For years before 2005 were estimated based on the average Area specific nominal CPUE of 2005-2007.

	north of 25°N		0°-25°N		North Pacific	
Year	EstSMA (n)	EstSMA (ton)	EstSMA (n)	EstSMA (ton)	EstSMA (n)	EstSMA (ton)
1971	3	0	4	0	7	0
1972	3	0	3	0	6	0
1973	0	0	0	0	0	0
1974	89	5	99	5	188	10
1975	133	7	149	8	282	15
1976	8	0	8	0	16	0
1977	44	2	49	3	93	5
1978	47	3	52	3	99	6
1979	9	0	11	1	20	1
1980	30	1	34	2	64	3
1981	27	1	31	2	58	3
1982	3	0	4	0	7	0
1983	3	0	4	0	7	0
1984	0	0	1	0	1	0
1985	76	4	86	4	162	8
1986	91	5	103	5	194	10
1987	37	2	42	2	79	4
1988	7	0	8	1	15	1
1989	36	2	40	2	76	4
1990	143	8	161	8	304	16
1991	153	8	172	9	325	17
1992	50	3	56	3	106	6
1993	40	2	44	2	84	4
1994	8	0	9	1	17	1
1995	819	43	920	48	1,739	91
1996	354	18	398	21	752	39
1997	320	17	359	19	679	36
1998	371	19	417	22	788	41
1999	776	40	871	45	1,647	85
2000	717	38	804	42	1,521	80
2001	754	39	847	44	1,601	83
2002	1,018	53	1,144	60	2,162	113
2003	660	34	742	39	1,402	73
2004	1,093	57	1,227	64	2,320	121

	north of 25°N		0°-25°N		North Pacific	
Year	EstSMA (n)	EstSMA (ton)	EstSMA (n)	EstSMA (ton)	EstSMA (n)	EstSMA (ton)
2005	602	25	1,186	50	1,788	75
2006	1,181	69	851	50	2,032	119
2007	637	35	679	38	1,316	73
2008	314	11	508	19	822	30
2009	321	8	665	18	986	26
2010	192	7	492	18	684	25
2011	405	18	1,167	53	1,572	71
2012	256	18	708	51	964	69
2013	1,007	58	1,167	67	2,174	125
2014	1,348	52	1,332	52	2,680	104
2015	511	34	1,809	122	2,320	156
2016	526	37	1,606	113	2,132	150
2017	141	8	524	32	665	40
2018	590	33	960	54	1,550	87
2019	1,032	65	1,239	77	2,271	142
2020	1,908	93	1,834	90	3,742	183
2021	1,379	64	1,079	50	2,458	114
2022	1,112	50	1,449	66	2,561	116

[1] Working document submitted to the ISC Shark Working Group Workshop, 29-30 November- 1-2, 4-7 December 2023, Yokohama, Kanagawa, Japan. **Document not to be cited without author's permission.**