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Wen-Pei Tsai
Institute of Oceanography, National Taiwan University, Taipei, Taiwan Department of Fisheries Production and Management, National Kaohsiung Marine University, Kaohsiung, Taiwan

Chi-Lu Sun
Institute of Oceanography, National Taiwan University, Taipei, Taiwan

Kwang-Ming Liu
Institute of Marine Affairs and Resource Management, National Taiwan Ocean University, Keelung, Taiwan George Chen Shark Research Center, National Taiwan Ocean University, Keelung, Taiwan, kmliu@mail.ntou.edu.tw

Shyh-Bin Wang
Institute of Marine Affairs and Resource Management, National Taiwan Ocean University, Keelung, Taiwan

Nancy C. H. Lo
2575 Ardath Road La Jolla, California, USA.

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Wen-Pei Tsai[1, 2], Chi-Lu Sun[1], Kwang-Ming Liu[3, 4], Shyh-Bin Wang[3], and Nancy C. H. Lo[5]

Key words: blue shark, North Pacific Ocean, catch per unit effort (CPUE), delta-lognormal model.

ABSTRACT

The blue shark, *Prionace glauca*, is a pelagic species with a circum-global distribution in tropical to temperate waters. It is the top by-catch shark species for the Taiwanese large-scale tuna longline (LTLL) fishery. However, its population status in the North Pacific Ocean is still little known. In the present study, the blue shark catch and effort data from observers' records of Taiwanese LTLL fishing vessels operating in the North Pacific Ocean from 2004 to 2012 were analyzed. Due to the large percentage of zero blue shark catch, the catch per unit effort (CPUE) of blue shark, as the number of fish caught per 1,000 hooks, was standardized using a delta-lognormal model. The standardized CPUE of blue sharks, as an estimate of relative abundance of blue shark, decreased from 2005 to 2009 and showed an increasing trend thereafter. Back-estimated historical blue shark by-catch of Taiwanese LTLL fishery in the North Pacific Ocean ranged from 0.4 MT in 1973 to 1,447 MT in 2002. The results obtained in this study can be improved if longer time series observers' data are available and environmental factors are included in the model.

Paper submitted 04/11/14; revised 09/17/14; accepted 12/30/14. Author for correspondence: Kwang-Ming Liu (e-mail: kmliu@mail.ntou.edu.tw).
[1] *Institute of Oceanography, National Taiwan University, Taipei, Taiwan, R.O.C.*
[2] *Current address: Department of Fisheries Production and Management, National Kaohsiung Marine University, Kaohsiung, Taiwan, R.O.C.*
[3] *Institute of Marine Affairs and Resource Management, National Taiwan Ocean University, Keelung, Taiwan, R.O.C.*
[4] *George Chen Shark Research Center, National Taiwan Ocean University, Keelung, Taiwan, R.O.C.*
[5] *2575 Ardath Road La Jolla, California, USA.*

I. INTRODUCTION

Shark conservation and management attracted great concern in recent years due to the decline of shark populations in many areas (Baum et al., 2003; Baum and Myers, 2004; Burgess et al., 2005). International organizations and regional fisheries management organizations (RFMO's) therefore, have made various management measures on sharks. For example, two large shark species (whale shark, *Rhincodon typus*, and basking shark, *Cetorhinus maximus*) were listed in the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) Appendix II in 2002 (CITES Animals Committee, 2002), followed by great white shark (*Carcharodon carcharias*) in 2004 (CITES Animals Committee, 2004). The International Commission for the Conservation of Atlantic Tunas (ICCAT) prohibited the retaining of bigeye thresher shark, *Alopias superciliosus*, oceanic whitetip shark, *Carcharhinus longimanus*, and hammerhead sharks (family *Sphyrnidae* except for *Sphyrna tiburo*) on board in 2010 (ICCAT Compliance Committee, 2010) and silky shark, *Carcharhinus falciformis*, in 2011 (ICCAT Compliance Committee, 2011). The Indian Ocean Tuna Commission (IOTC) also prohibited the retaining of thresher sharks (family Alopiidae) on board in 2010 (IOTC WPEB, 2010). The prohibition of retaining oceanic whitetip shark was also adopted by the Western and Central Pacific Fisheries Commission (WCPFC) in 2012 (WCPFC TCC, 2012). More recently, oceanic whitetip, scalloped hammerhead shark, *S. lewini*, smooth hammerhead, *S. zygaena*, great hammerhead, *S. mokarran*, and porbeagle shark, *Lamna nasus*, have been put on the Appendix II list of CITES in 2013 (CITES Animals Committee, 2013). All of these management measures highlighted the importance of shark conservation and management.

The blue shark, *Prionace glauca*, is a pelagic species with a circum-global distribution in tropical to temperate seas (Compagno, 1984). It is the major by-catch shark species for Taiwanese tuna longline fisheries in the three Oceans and has been concerned by the RFMOs such as the WCPFC, IOTC, and ICCAT because large amount of this species have been caught. Recent shark stock assessment meeting of ICCAT suggested that the blue shark populations in the Atlantic Ocean (both North and South) are in healthy condition (ICCAT, 2012). However, the stock status of blue shark in the North Pacific Ocean is still little known apart from a recent stock assessment by the Shark Working Group of International Science Committee (ISC). As blue shark is the top by-catch shark species of Taiwanese large-scale tuna longline (LTLL, fishing vessels > 100 Gross Registered Tonnage, GRT) fishery in the North Pacific Ocean, it is necessary to examine its recent abundance trend by using the logbook data of tuna fisheries. However, catch-per-unit-effort (CPUE) standardization of sharks caught by Taiwanese fleets is not straightforward because the logbook data have been confounded with many factors, such as under-reporting, no-recording of sharks and target-shifting effects. On the other hand, the shark by-catch and effort data collected by observers provide an alternate way to achieve this goal. An increased coverage rate of observations of Taiwanese LTLL fleets in recent years enabled us to get a better estimation of shark by-catch.

CPUE is often the main piece of information used in fisheries stock assessments and usually assumed to be proportional to the fish abundance and is used as a relative index of abundance (Maunder, 2001; Campbell, 2004). Consequently, it is essential to remove possible factors that may influence the representation of CPUE index. The process of reducing the influence of these factors on CPUE is commonly referred to as CPUE standardization (Dunn et al., 2000; Harley et al., 2001; Hinton and Maunder, 2003). The most common method to standardize the CPUE series is the application of generalized linear models (GLM).

The GLM has been commonly used in CPUE standardization of tunas (McCULLAG and Nelder, 1989; Nishida and Chen, 2004). Catch and effort data, however, often include high proportion of zero-catch records, particularly for non-target species and for by-catch species even though effort is recorded to be non-zero. To deal with the zero catch, nominal CPUE is usually added a small value and then taken a logarithm based on a normal or log-normal distribution when using a GLM approach, so that CPUE is always greater than zero. Unfortunately, adding a constant value may cause some bias in the estimated year effect (Hinton and Maunder, 2003).

Apparently, the GLM approach is improper for the CPUE standardization of by-catch species (Hinton and Maunder, 2003) such as sharks as a large proportion of zero values is commonly found in the catch data. The delta-lognormal modeling, on the other hand, accounts for a large proportion of zero values, is considered to be a more appropriate approach to model zero-heavy data (Pennington, 1983; Lo et al., 1992; Pennington, 1996). This model has been widely used to construct abundance indices for the northern anchovy, *Engraulis mordax* (Lo et al., 1992), tunas (Soto et al., 2004) and billfishes (Hazin et al., 2007; Hazin et al., 2011). As blue shark is a common by-catch species in the tuna longline fishery, the

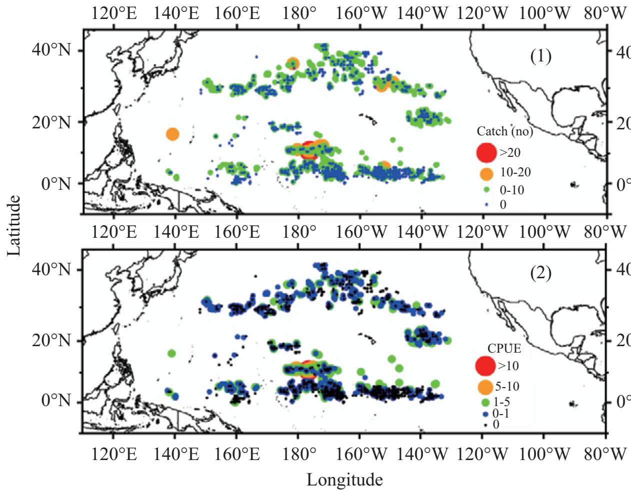

Fig. 1. Observed catch (top figure) and CPUE (bottom figure) of blue sharks of Taiwanese large-scale tuna longline fisheries in the North Pacific from 2004 to 2012.

delta-lognormal model (DLN) was applied to handle these excessive zero catch of blue sharks in CPUE standardization. The objective of this study is to conduct CPUE standardization of blue sharks by using DLN model and to back-estimate historical blue shark by-catch of Taiwanese LTLL fishery in the North Pacific Ocean based on observers' records.

II. MATERIAL AND METHODS

1. Source of Data

The observers' records of Taiwanese LTLL fishery in the North Pacific Ocean from 2004 to 2012 provided by the Overseas Fisheries Development Council (OFDC), Republic of China, were used in CPUE (number of fish per 1000 hooks) standardization of blue sharks. These data include the information of fishing time, area, number of hooks, hook per basket, and the catches, lengths (fork length, FL in cm), and weights (in kg) of 31 major tuna, billfish and shark species. In addition, the logbook data of Taiwanese LTLL vessels operating in the North Pacific Ocean from 1971 to 2012 were also provided by the OFDC. These data were used to back-estimate the historical blue shark by-catch.

Blue sharks caught by Taiwanese LTLL fishery in the North Pacific Ocean were mainly observed in the equatorial waters where bigeye tuna, *Thunnus obesus*, was the targeting species and in the subtropical and temperate waters where albacore tuna, *Thunnus alalunga*, was the targeting species (Fig. 1). Based on this fishing pattern, the North Pacific Ocean was stratified as area A (north of 25°N; the proportion of albacore catch was about 94% of total catch in observers' records) and area B (0°N-25°N; the bigeye tuna catch was about 84% of total catch in observers' records) (Fig. 2), where total catch includes bigeye tuna, albacore tuna, swordfish (*Xiphias gladius*), shortfin mako shark (*Isurus oxyrinchus*), and blue shark.

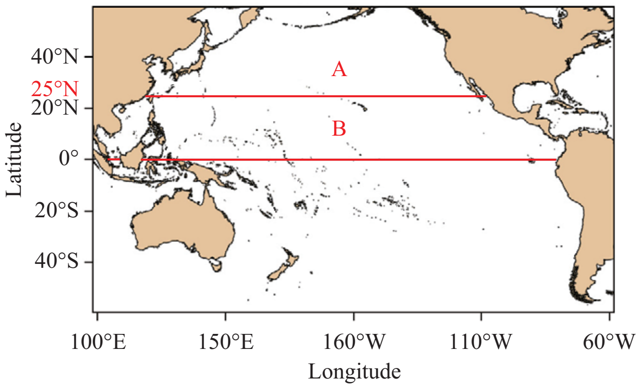

Fig. 2. Area stratification used for the estimate of blue shark by-catch of Taiwanese large-scale tuna longline fishery in the North Pacific Ocean.

CPUE standardization was estimated based on the set by set catch data from observers' records during the period of 2004-2012.

2. CPUE Standardization

A large proportion of zero blue shark catch (~50%) was found in observers' records. Hence, to address these excessive zeros, the delta-lognormal model (DLN) (Lo et al., 1992) was applied to the blue shark CPUE standardization. The DLN is a mixture of two GLM models, one model is used to estimate the proportion of positive catches and a separate model is to estimate the positive catch rate. The model was fit using the GLM function of statistical computing language R (R Development Core Team, 2013) to eliminate the temporal, spatial, and targeting effects.

The CPUE standardization of blue shark was constructed including the main effects and interaction terms. The main effects considered in the DLN model were the year (Y), quarter (Q), area (A), latitude (LAT), longitude (LON) and the number of hooks per basket (HPB). The effect of gear configuration of HPB was used to account for the shift of targeting species. The following multiplicative models were applied to the data in this study.

For the DLN modeling, the catch rates of the positive catch events (sets with positive blue shark catch) were modeled assuming a lognormal error distribution:

Part 1: Lognormal model

$$\ln(\mathrm{CPUE}) = \mu + \mathrm{Y} + \mathrm{Q} + \mathrm{A} + \mathrm{HPB} + \mathrm{LAT} + \mathrm{LON} + \mathrm{Q*A} + \mathrm{Q*HPB} + \mathrm{A*HPB} + \varepsilon_1 \qquad (1)$$

where μ is the mean, Q*A, Q*HPB, A*HPB are interaction terms, ε_1 is a normal random error term. The effect of gear configuration, HPB, was categorized into two classes: shallow set (HPB $\leqq$ 15), and deep set (HPB > 15) (Walsh, 2011), and quarter was categorized into 4 classes: the 1st quarter (Jan-Mar), the 2nd quarter (Apr-Jun), the 3rd quarter (Jul-Sep), and the 4th quarter (Oct-Dec). The area strata used for the analysis were shown in Fig. 2. To estimate the proportion of positive blue shark catch (P), we used a model assuming a binomial error distribution (ε_2):

Part 2: Binomial model

$$\mathrm{P} = \mu + \mathrm{Y} + \mathrm{Q} + \mathrm{A} + \mathrm{HPB} + \mathrm{LAT} + \mathrm{LON} + \mathrm{Q*A} + \mathrm{Q*HPB} + \mathrm{A*HPB} + \varepsilon_2 \qquad (2)$$

The best model for both Lognormal and Binominal models were selected using the stepwise AIC method (Venables and Ripley, 2002). For model diagnostics, the Cook's distance (Cook and Weisberg, 1982) 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 lognormal distribution of the positive catches. These diagnostic plots were used to evaluate the fitness of the models. In addition, deviance analysis tables for the proportion of positive observations and for the positive catch rates were also provided. The final estimate of relative annual abundance index was obtained by the product of the main annual effect of the Lognormal and Binomial components (Lo et al., 1992):

$$\text{Standardized CPUE} = \text{CPUE*P} \qquad (3)$$

Empirical confidence interval of standardized CPUE was estimated by using a bootstrap resampling method (Efron and Tibshirani, 1993). 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. Estimate of Blue Shark Catch

Annual blue shark by-catch in number (C_y) from 2004 to 2012 was estimated by the following equation:

$$C_y = \sum_{i}^{2} \frac{\text{Nominal } CPUE_{i,y} \times Logbook\ effort_{i,y}}{Coverage\ rate_y}. \qquad (4)$$

where y is year, i = 1 is area A and i = 2 is area B. Coverage rate is the total catch (bigeye tuna, albacore tuna, yellowfin tuna, and swordfish) in logbook to that in Task 1 (Nominal annual catch). Annual blue shark by-catch in number before 2004 was back-estimated using the same equation but annual nominal CPUE was replaced by the mean of nominal CPUE in the period of 2004-2012 because no observers' records were available before 2004.

The upper and lower bounds of the 95% confidence intervals (estimated from bootstrap resampling) of annual nominal CPUE were used to calculate 95% C.I. of the back-estimated blue shark catch. The 95% C.I. of blue shark catch for years before 2004 can also be calculated using the averaged upper

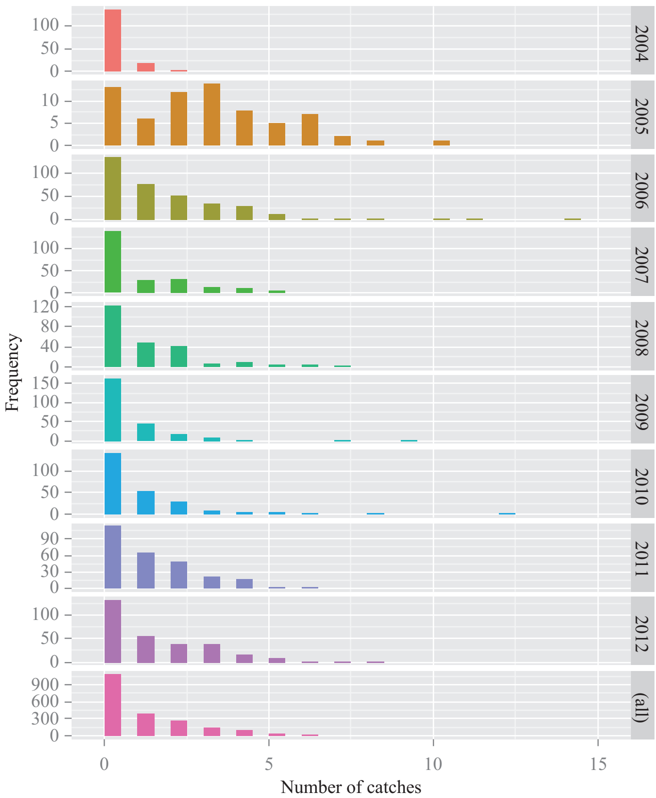

Fig. 3. Frequency distribution of blue shark by-catch per set, 2004-2012.

and lower bounds of nominal blue shark CPUE in 2004-2012. As the weight records from observers were inconsistent (often recorded as processed weight instead of whole weight) and might be biased, the catch in weight of blue shark was estimated using the multiplication of mean weight (assumed to be constant) and estimated or back-estimated catch in number. The mean FL of blue sharks was calculated from observers' data and the mean weight was obtained by substituting the mean FL into the W-FL relationship as following: $W = 5.009 \times 10^{-6}\ FL^{3.054}$ (Kohin and Wraith, 2010).

III. RESULTS

The mean length of blue sharks reported by observers was 212 cm FL (n = 3,281) and the estimated mean weight was 63.74 kg. The frequency distributions of blue shark by-catch per set are characterized by many zero values and a right-skew tail (Fig. 3). Overall, 51.17% of total sets had zero blue shark by-catch (Table 1).

The best models for Lognormal and Binomial models chosen by AIC were " $\ln(CPUE) = \mu + Y + Q + A + HPB + LAT + Q*HPB$ " and " $P = \mu + Y + Q + A + HPB + LAT + LON + Q*HPB$ ", respectively. The best models were then used for the later analyses.

The nominal CPUE of blue shark showed a strong inter-annual fluctuation. However, this variability was reduced in the standardized CPUE series (Fig. 4). This indicated that the

Table 1. Estimated annual blue shark (BSH) zero-catch percentage of Taiwanese large-scale tuna longline fishery in the North Pacific Ocean.

Year	BSH Zero %
2004	83.33%
2005	18.84%
2006	38.33%
2007	59.91%
2008	50.61%
2009	68.78%
2010	53.18%
2011	42.64%
2012	44.86%
Average	51.17%

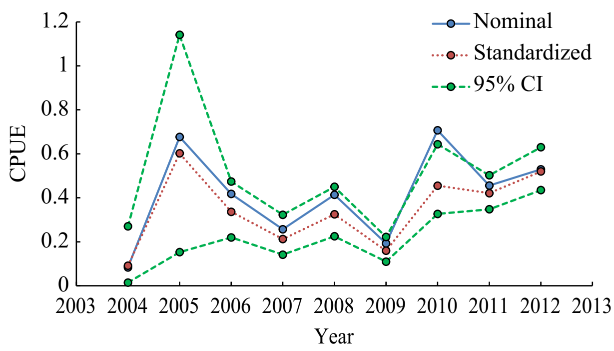

Fig. 4. Nominal and standardized CPUE with 95% CI of blue shark by Taiwanese large-scale tuna longline fisheries from 2004 to 2012.

standardization process removed certain variability attributes to the explanatory variables. The standardized CPUE series for blue shark using the DLN model was shown in Fig. 4. The standardized CPUE series contains the combined effects from two models, one that calculates the probability of a zero observation and the other one estimates the count per year. In general, the standardized CPUE series of the blue sharks caught by Taiwanese LTLL fishery decreased from 2005 to 2009 and showed a slightly increasing trend thereafter (Fig. 4).

The residuals distribution and Q-Q normal plots (the left hand panel) for lognormal model showed that the error distributions approximate to normal (Figs. 5 and 6). The right hand panel showed the standard diagnostics of residuals *vs.* fitted and Cook's distance plot (Fig. 6). Overall, the diagnostic results and additional residuals plots (Figs. 6 and 7) indicated that lognormal model do not have severe departure from the model assumptions. The ANOVA tables for each model indicated that the main effects were significant (mostly $P < 0.01$) and were selected in the final model (Table 2). Estimated blue shark by-catch in number ranged from 6 in 1973 to 22,617 in 2002. The back-estimated blue shark by-catch in weight of Taiwanese LTLL fishery ranged from 0.4 metric tons (MT) in 1973 to 1,447 MT in 2002, with a mean of 370

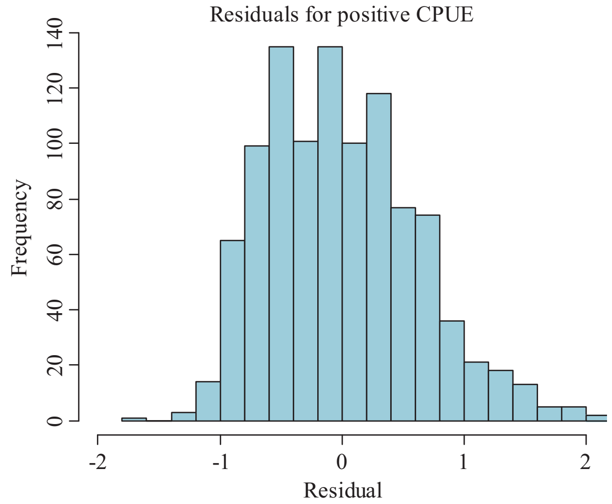

Fig. 5. Histogram of residuals plot for the lognormal model fit to the blue shark by-catch data.

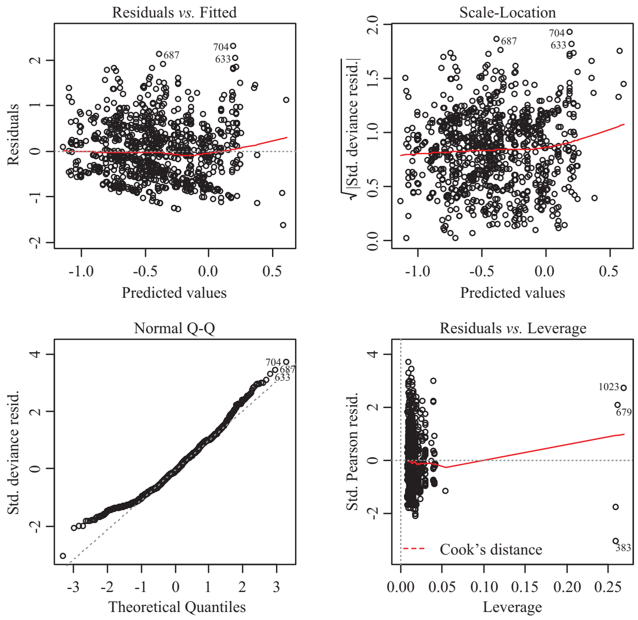

Fig. 6. Residual plots for the lognormal model fit to the blue shark by-catch data.

MT and 5,779 individuals in the North Pacific Ocean (Table 3). The estimated catch was relative low before 1995 and increased to more than 500 MT and fluctuated thereafter and peaked at 1,447 MT and 1,218 MT in 2002 and 2012, respectively (Table 3).

IV. DISCUSSION

Standardization of CPUE to develop an index of relative abundance of a fish stock assumes that the explanatory variables are sufficient to remove most of the variation in the data that is not attributable to the changes in abundance (Dunn et al., 2000; Harley et al., 2001; Hinton and Maunder, 2003; Maunder and Punt, 2004). However, there is still no guarantee that the resultant index of abundance is linearly proportional to the abundance (Maunder and Punt, 2004). In the present study, we have only used the DLN model in analyzing the observers' data on blue shark in the North Pacific Ocean. In addition to

Table 2. Deviance table for final GLM results of delta-lognormal model.

Log-normal Positive Catch rate

Source	Df	Deviance	Resid. Df	Resid. deviance	*P* value
Intercept			1022	500.70	
yy	8	59.133	1014	441.57	<0.001
Q	3	17.18	1011	424.39	<0.001
A	1	6.185	1010	418.21	<0.001
HPB	1	1.458	1009	416.75	<0.05
LAT	1	13.43	1008	403.32	<0.001
Q:HPB	3	10.971	1005	392.35	<0.001

Binomial Model

Source	Df	Deviance	Resid. Df	Resid. deviance	*P* value
Intercept			2115	2931.1	
yy	8	177.646	2107	2753.4	<0.001
Q	3	10.115	2104	2743.3	<0.05
A	1	28.503	2103	2714.8	<0.001
HPB	1	4.062	2102	2710.8	<0.05
LAT	1	98.149	2101	2612.6	<0.001
LON	1	8.565	2100	2604.0	<0.05
Q:HPB	3	19.868	2097	2584.2	<0.001

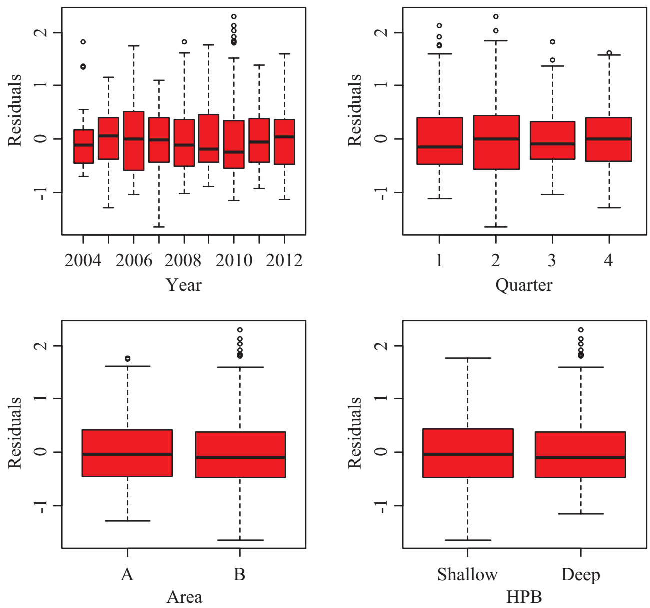

Fig. 7. Partial dependence plots for the lognormal model fit to the blue shark by-catch data.

Table 3. Estimated annual blue shark by-catch in number and weight (MT) of Taiwanese large-scale tuna longline fishery in the North Pacific Ocean.

Year	No. of hooks	EstBSH (N)	95% CI (N)	EstBSH (MT)	95% CI (MT)
1971	37300	80	(68,91)	5	(4,6)
1972	30480	76	(65,86)	5	(4,6)
1973	2400	6	(5,7)	0.4	(0.2,0.6)
1974	266558	2225	(1907,2543)	142	(122,163)
1975	343696	3331	(2855,3808)	213	(183,244)
1976	200272	132	(113,151)	8	(7,10)
1977	323517	803	(688,918)	51	(44,59)
1978	344360	993	(851,1135)	64	(54,73)
1979	365203	241	(207,276)	15	(13,18)
1980	635256	757	(649,865)	48	(42,55)
1981	988497	662	(567,756)	42	(36,48)
1982	129552	86	(73,98)	6	(5,6)
1983	58000	82	(70,93)	5	(4,6)
1984	1900	8	(5,10)	0.5	(0.3,0.8)
1985	466920	1912	(1639,2185)	122	(105,140)
1986	466920	2292	(1964,2619)	147	(126,168)
1987	931940	937	(803,1071)	60	(51,69)
1988	39000	172	(147,196)	11	(9,13)
1989	1355680	895	(767,1023)	57	(49,65)
1990	659765	3592	(3079,4106)	230	(197,263)
1991	581555	3841	(3292,4390)	246	(211,281)
1992	285000	1255	(1076,1434)	80	(69,92)
1993	495550	992	(850,1134)	63	(54,73)
1994	96000	205	(175,234)	13	(11,15)
1995	3382600	10639	(9119,12160)	681	(584,778)
1996	3120800	4581	(3926,5235)	293	(251,335)
1997	3477000	5341	(4578,6104)	342	(293,391)
1998	1868286	5609	(4808,6411)	359	(308,410)
1999	5032112	10387	(8902,11871)	665	(570,760)
2000	6038027	11395	(9766,13023)	729	(625,833)
2001	12411650	16396	(14053,18739)	1049	(899,1199)
2002	14723756	22617	(19385,25849)	1447	(1241,1654)
2003	8820760	12947	(11097,14797)	829	(710,947)
2004	24905230	19819	(16987,22652)	1268	(1087,1450)
2005	20321919	15253	(13073,17433)	976	(837,1116)
2006	22532898	14736	(12630,16842)	943	(808,1078)
2007	19617707	13640	(11690,15589)	873	(748,998)
2008	15946129	11325	(9707,12944)	725	(621,828)
2009	11098971	7968	(6830,9107)	510	(437,583)
2010	7505780	5570	(4774,6366)	356	(306,407)
2011	10793917	9902	(8487,11317)	634	(543,724)
2012*	8236364	19027	(16179,22266)	1218	(1035,1425)

*: preliminary estimate.

the delta-lognormal model, the zero-inflated negative binomial regression model (ZINB) (Lambert, 1992) has also been widely used to accommodate data with certain proportion of zero-valued observations (Hall, 2000; Minami et al., 2007). Both two models could produce similar results for CPUE standardizations. However, it has been suggested that for data dominated by zero-valued observations, the ZINB may not be appropriate or may need to be modified (Minami et al., 2007). The ZINB may overestimate model coefficients when fit to data with many zero-valued observations (Minami et al., 2007). As large proportion of zero blue shark catch (>50%) was found in observers' records, the DLN is believed to be a better method for CPUE standardization of this species.

Blue shark is by far the most numerous and wide-ranging shark species caught by tuna longline fishery (Huang, 2006), with a complex life history that includes migrations and ontogenetic and sexual segregation (Nakano and Stevens, 2008). In the present paper, only Taiwanese blue shark data were used in the delta-lognormal model analysis. However, highly migratory species such as blue sharks may migrate throughout large areas of the North Pacific Ocean and are harvested by several nations. Clearly, more data including those from Japan and the United States should be used in the analysis in the future before drawing any further conclusions on its population status. We also noted that the increasing trend in Taiwanese blue shark by-catch is consistent with the standardized CPUE series of Japanese longline fisheries, but conflicts with those of the Hawaii deep-set longline fisheries and the longline fisheries observed by the Secretariat of the Pacific Community (SPC) in the North Pacific Ocean (ISC, 2014). Different fishing practices, areas, target species, and gear types may result in these discrepancies. Further interpretation and inference for these different indices of the blue shark in the North Pacific Ocean would be helpful in evaluating the current population status.

Many factors may affect the standardization of CPUE series. In addition to the temporal and spatial effects, environmental factors may affect the representation of standardized CPUE of pelagic fish i.e., swordfish and blue shark in the North Pacific Ocean (Bigelow et al., 1999), and bigeye tuna in the Indian Ocean (Okamoto et al., 2001). In this study, despite of environmental effects not being included in the model for standardization, and short time-series on CPUE standardization, our study provides useful information for the North Pacific blue shark, because the analysis based on detailed observers' data which cover a wide range of the North Pacific Ocean. The results obtained in this study can be improved if longer time series observers' data are available and environmental factors were included in the model.

Sharks have not been recorded in the logbook of Taiwanese LTLL before 1980 and have not been identified to the species level until 2003. A back-estimate of historical shark by-catch based on observers' records is useful in reconstructing these catch data, although it would be inherently uncertain due to no observers' records being available before 2004. The major analytical concern is the under-reporting of shark catch in the logbook. Checks on blue shark catches in particular can be tedious and time-consuming. In addition to under-reporting, the most common source of bias in the logbook is the lacking of releasing and discarding data, which may result in an underestimation of shark catch.

The back-estimations of historical blue shark by-catch in this study were based on observers' records (including catch, release and discarded data) from 2004-2012, which reduced the under-reporting bias and contributed to more accurate catch estimates. However, some weakness still could not be fully addressed in this study, i.e., the assumption that the nominal CPUE before 2004 was constant as the average value of 2004-2012 obtained from observers' records. In addition, based on the logbook data, the majority of fishing efforts of Taiwanese LTLL fishing vessels were concentrated in the South Pacific Ocean before 1995. Thus, the lowest back-estimated blue shark catches in 1973 (0.4 MT) and 1984 (0.5 MT) were likely due to the particularly low efforts deployed in the North Pacific Ocean in these two years (Table 3). More effort needs to be taken on relieving these limitations in the future.

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