Evaluating stock structure hypotheses for swordfish (*Xiphias gladius*) in the Pacific Ocean using size composition statistics of Taiwanese distant water longliners

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Abstract

Delineating the stock structure of a harvested fish species is a major pre-requisite for conducting reliable stock assessments and providing effective management. Although the current stock assessment for the North Pacific swordfish was based on a two-stock working hypothesis, there is no consensus on Pacific swordfish population stock structure according to observations from genetic studies, life history, and fishery characteristics (CPUE). In this study, we evaluated the stock structure hypotheses for swordfish (*Xiphias gladius*) in the Pacific Ocean by using size composition statistics from the Taiwanese distant water longliners. There was a substantial spatial and temporal variability of swordfish size based on the examination of fishery statistics and the spatially explicit nonlinear models. Furthermore, several stock structure hypotheses were evaluated by using model selection of generalized linear models.

Keywords: swordfish, stock structure, size composition, stock assessment

Introduction

Swordfish (*Xiphias gladius*), a.k.a. broadbill swordfish, inhabit a wide region of the Pacific between the latitudes of 50˚N and 50˚S (Ward et al., 2000). Swordfish is a highly migratory species with high economic value in both commercial and recreational fisheries. In the North Pacific, the majority of catch has been taken by longline fishing vessels from Japan, Taiwan and the United States, which accounted for 95% of the total harvest in the North Pacific in 2010s, with the remaining catch taken by China, Korea, Mexico, and Spain.

ISC (2014) conducted the stock assessment of swordfish in the North Pacific Ocean by using the Bayesian surplus production models based the two- stock structure hypothesis (Jon's paper), e.g., the two-stock scenario with Western and Central North Pacific Ocean (WCNPO) and Eastern Pacific Ocean (EPO) stocks (Figure 1). The assessment result suggested that the WCNPO swordfish stock does not appear to have been overfished or to have experienced overfishing throughout most of the assessment time horizon of 1951-2012, but the EPO stock showed that overfishing likely occurred in only a few years (Chang et al., 2014; Yau et al., 2014).

Delineating the stock structure of a harvested fish species is a major pre-requisite for understanding its population dynamics, conducting reliable stock assessments, and providing effective management. The assumption of an incorrect stock structure can lead to severe bias in the estimation of stock assessment parameters and consequently, in the derived management benchmarks (Arrizabalaga et al., 2007; Brooks and Apostolaki, 2007).

Stock structure delineation is especially difficult for large migratory species such as tunas and billfishes (Graves and McDowell, 2003). For example, the stock structure of the Pacific swordfish, which inhabit wide ranges of ocean, have been issues that need long discussion for purely ecological interests as well as for practical stock assessment and stock management. Although the current stock assessment for the North Pacific swordfish was based on the two-stock hypothesis, there is no consensus on Pacific swordfish population structure. Kimoto et al (2014) found that there was a rapid increasing trends of the swordfish nominal CPUEs in the WCNPO area where close to the stock boundary and within the EPO, but not in WCNPO, and suggested the temporal change of the stock boundary.

Genetic studies have been conducted to test the hypothesis of panmixia in Pacific swordfish; yielding conflicting results (see Table 4 of Lu et al., 2016). Recently, a complex genetic differentiation of the Pacific swordfish (temperate areas were differed from most tropical areas, but genetic heterogeneity was also detected among several tropical areas) was suggested by Lu et al. (2016).

Genetic studies are usually time-consuming and in many cases require sampling protocols that are cost prohibitive. Furthermore, genetic studies face the problem that the spatial coverage and temporal replication of biological samples is limited.
In contrast to genetic data, the types of non-genetic data that pertains to stock structure includes physical barriers or transition zones, life-history characteristics (growth, maturity, etc.), age and size compositions, trends in population abundance, morphometric and meristic data, mark-recapture data, and "natural" tags such as otolith microchemistry and parasites (Spencer et al., 2010). The possibility of different stocks among swordfish populations in the Pacific has been suggested by CPUE analysis from fisheries data (Hinton, 2003; Ichinokawa and Brodziak, 2008). Differences in age and size composition could potentially be an indicator of differences in recruitment and thus reflect the demographic independence and reproductive isolation between areas.

The objectives of this study are 1) to explore the spatial and temporal patterns of swordfish length (lower jaw-to-fork length, LJFL; cm) and weight (kg) composition in the North Pacific Ocean caught by the Taiwanese distant water longline (TDWL) fisheries during 1983-2016; 2) to examine the two-stock hypothesis proposed by Ichinokawa and Brodziak (2008) for the above dataset based on a spatially explicit nonlinear model; 3) to evaluate alternative hypotheses of swordfish stock structures based on the swordfish weight caught by the TDWL fisheries during 2014-2016 by using generalized linear models.

Materials and methods

Data

Swordfish length (1983-2013) and weight (2014-2016) data were obtained for the Taiwanese distant-water longline fishery in the Pacific Ocean from the Overseas Fisheries Development Council (OFDC) of the Republic of China. More specifically, Length and weight data of striped marlin were collected through on-board sampling that the measurement is carried out by fishermen on the initial 30 fishes caught from each operation. The data were compiled by year, month, day, and 5◦×5◦ grid cell. In addition to length and weight information, each 5◦×5◦ record was merged with the monthly average sea surface temperature (SST). The SST data for 1983–2016 (0.25◦×0.25◦ daily resolution) were obtained from the NOAA-OI-SST-V2 High Resolution Dataset (https://www.esrl.noaa.gov/psd/cgi-bin/db_search/DBListFiles.pl?did=132&tid=59061&vid=2423).

Spatial and temporal patterns of length and weight composition

Spatial distribution average length and weight was visually examined on map for ten-year interval. Length and weight composition was examined by histogram (5-cm bin interval) for five-year interval. Box-plot in combination with the violin plot (a combination of a boxplot and a kernel density plot) was used to examine possible trend of length and weight composition by factors of year, latitude, longitude, quarter, and stock area. We also examine the pattern of Length and weight composition against tw0 crossed factors (stock factor cross with all other factors).

Examination of the two-stock hypothesis

We related mean length and weight of swordfish to various predictor variables using a spatially explicit, variable-coefficient, generalized additive model (GAM) (Bacheler and Ballenger, 2015). GAM is a nonlinear, nonparametric, regression model that does not require a priori specification of the functional relationship between the response and predictor variables (Venables and Dichmont, 2004; Wood, 2008).

We developed two broad classes of spatially explicit GAMs to understand more about the spatial and temporal patterns of swordfish in the Pacific Ocean. The first model used mean swordfish LJFL in each 5◦×5◦ cells as the response variable for the GAM (hereafter, "length model"). The second model type used mean swordfish weight as the response variable (hereafter, "weight model").

We examined the influence of various predictor variables on the mean length and weight of swordfish. Six primary variables were considered for inclusion based on our hypotheses and previous knowledge: year, quarter, and stock area were included as factor variables, and latitude, longitude, and SST were included in the model as smoothed variables. The length and weight model were based on the assumptions of normal and lognormal distributions, respectively.

The base length and weight model were formulated as:

$$\text{Length} \sim \text{Year} + \text{Quarter} + \text{Stock} + s(\text{Latitude}) + s(\text{Longitude}) + s(\text{SST}) \quad (1)$$

$$\ln(\text{Weight}) \sim \text{Year} + \text{Quarter} + \text{Stock} + s(\text{Latitude}) + s(\text{Longitude}) + s(\text{SST}) \quad (2)$$

where $s(x)$ denotes a spline smoother (with three degrees of freedom) function of the covariate x.

Evaluation of hypotheses of stock structures

Other than the Ichinokawa and Brodziak (2008)'s two-stock hypothesis, several models varying in number from a single panmictic population to four subpopulations have been proposed (Figure 2). Evaluation of alternative hypotheses of swordfish stock structures was carried out by model selection using Akaike information criterion (AIC) calculated from generalized linear models (GLMs) for the mean weight, on the basis different assumptions of stock boundaries. The analysis only focused on the mean weight because of the better data quality of weight in comparison to the length data (OFDC, personal communication, April 13, 2017). Furthermore, we only focused on the recent weight data to eliminate the potential temporal changes of fishery practice.

The GLM includes explanatory variables of year (Y), quarter (Q), area (A), and some interaction terms:

$$\ln(\text{Weight}) \sim \text{Year} + \text{Quarter} + \text{Stock} + \text{Year*Stock} + \text{Quarter*Stock} \quad (3)$$

The AIC was calculated from model deviance (D) evaluated at the maximum likelihood estimation and a parameter penalty term which depends on the number of parameters (p): AIC = D + 2p.

Results and discussion

Spatial and temporal patterns of length and weight composition

The analyses are based on 159,630 and 49148 records for length and weight, respectively, detail information of length and weight records by year and stock area were shown in table 1 and 2.

Swordfish size (1981-2016) and weight (2014-2016) composition by 5-years intervals were shown in Figure 3. The plot indicated some patterns of temporal variation of mean length and weight, and sample size. In the early period (1981-2000), the samples size was small and the data were scattered (Table 1 and Figure 3a-d). With the increase of sample size (2001-2013) (Figure 3e-g), the weight compositions showed a similar normal distribution pattern (Figure 3h). Weight data from 2014 to 2016 indicated a lognormal distribution pattern. The average lengths of swordfish in1991-1995 and 1996-2000 (136.96 and 117.72 cm) were relative smaller than that of other years.

Box-violin plot of annual variation of length and weight composition were shown in Figure 4. The size range in the early period (1981-2000) was smaller than other time periods, presumably due to the smaller sample size. The length composition in 1995-2001 was apparently different than other years. The size composition from 2005-2013 showed the larger size ranges compared to the early period and indicted a stable pattern overtime. The weight composition also indicted a stable pattern during 2014-2016 with few larger individuals in 2016. Seasonal pattern of length composition was not observed (Figure 5), but in the weight composition. Relative smaller mean weight was found in the quarter 3.

Overall length compositions were similar among stock areas (Figure 6). However, the weight composition in the WCNPO area was different (with larger mean weight) than other areas. Length compositions for the cells from higher north latitude (≥ 27.5 latitude) were different than the other cells (Figure 7). For the weight compositions, both temperate areas of northern and southern hemisphere were different than the topical area. Length compositions of the cells of offshore area in the west Pacific region and east Pacific region were different than the distant water region (172.5–227.5 longitude) (Figure 8a). Similar pattern was found for the weight composition (Figure 8b). However, the east Pacific region tend to have the weight composition consisted of much smaller fish (>=232.5 longitude) compared to distant water region.

We also examine the pattern of length and weight composition against two crossed factors (stock factor cross with all other factors). The temporal patterns of length compositions were similar between WCNPO and EPO stock areas (Figure 9a-b). There is not length record before 1989. The temporal patterns of length compositions in the "others" area was similar the length compositions in the North Pacific Ocean. Similar pattern was found in the weight composition among stock areas (Figure 9d-f).

Length and weight composition by quarter and stock area were shown in figure 10. The length composition from quarter 4 in the WCNPO area was different than others (Figure 10a). Quarterly weight compositions were not consistent between the WCNPO area and EPO area (Figure 10d-e). Quarter 1 in the WCNPO area consisted of much smaller fish than other quarters, but Quarter 3 had much smaller fish in the EPO area. Length and weight composition by latitude and stock area were shown in figure 11. Length and weight composition by longitude and stock area were shown in figure 12.

The spatial distribution of average body length by 10-year interval was shown in figure 13. The distribution of average length is quite patchy, and there is no obvious spatial pattern. However, the average length of swordfish is relatively small in 1991-200 (except the eastern coast off Australia) (Figure 13b); the average body length is relative higher in the overlap stock areas of EPO and SWPO (except 1991-2000). The spatial distribution of average weight in 2014-2016 was shown in figure 13e, and the spatial distribution of mean weight is quite patchy and there is no obvious spatial trend.

Examination of the two-stock hypothesis

Table 3 and figure 14 summarize the results of applying GAM to the mean length and mean weight data. All of the main effects were significantly different from zero at $\alpha = 0.01$ for both length and weight models. In this study, the length and weight models only explained 5% and 4% of the deviances in mean length and mean weight, respectively.

Figure 14 showed the estimates of the year, quarter, and stock factors from the length model and the weight model, along with the smoothers for latitude, longitude and SST. The estimates of year factors showed a large variation before 2004. This may result from few samples were recorded before 2004. However, moderate annual variation for the year factors was also found during 2004-2013 (Figure 14a). The estimated year factor in 2016 is higher than 2014 and 2015 for the weight model (Figure 14b). The estimates of quarter factors indicated a clear seasonal cycle for both length and weight models.

The estimates of stock area factors indicated a pattern of smaller fish size in the “other” area for both length and weight models. However, the estimated value for the WCNPO factor was higher than EPO for the length model, but not shown in the weight model. The trends of smoothers for latitude and longitude were generally similar between the length model and the weight model. Neither the length model nor weight model had a clear nonlinear relationship between SST and mean size of swordfish. Examination of plots of standardized residuals and quantile–quantile plots provided slightly violation of normal assumption for the length model (Figure 15a), but no violation of lognormal assumption for the weight model (Figure 15b).

Evaluation of hypotheses of stock structures

For each of six stock area hypotheses, all of the main effects from the GLM were significantly different from zero at α = 0.01. AIC derived from the GLM were compared among different stock area hypotheses. The result suggested that the three-stock hypothesis of Nakano (1998) has the smallest AIC. The composite four-stock hypothesis of Sosa-Nishizaki and Shimizu (1991), Hinton and Deriso (1998); Hinton (2003) was the second supported model. Unexpectedly, the current three-stock hypothesis for the ISC (2014) was less supported.

In this study, we only compared the simple GLM for the recent mean weight data (2014-2106). AIC calculated from GLM with the assumed stock area hypotheses didn't compare among those from different complexity of the models. We expected including other interaction terms may increase the percentage of deviance explained.

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Table 1. Amount of swordfish length records by stock area (defined in figure 1) from 1981 to 2013 of Taiwanese distant water longliners in the Pacific Ocean.

	WCNPO	EPO	OTHERS
1981	15	195	677
1982	0	64	271
1983	1	19	228
1984	0	32	305
1985	0	19	122
1986	0	21	67
1987	0	27	36
1988	0	40	117
1989	23	144	23
1990	86	70	128
1991	7	51	21
1992	0	0	133
1993	166	15	192
1994	0	21	29
1995	117	5	96
1996	24	3	0
1997	6	0	0
1998	0	0	14
1999	13	0	178
2000	59	172	73
2001	52	571	74
2002	373	5926	1576
2003	435	1755	959
2004	2387	12504	6324
2005	1365	8529	3478
2006	741	7772	3710
2007	839	4820	4854
2008	1291	4263	8693
2009	1086	4762	7129
2010	2211	8951	5889
2011	2521	5886	6641
2012	2215	7823	5920
2013	1369	5821	3990

Table 2. Amount of swordfish weight records by stock area (defined in figure 1) from 1981 to 2013 of Taiwanese distant water longliners in the Pacific Ocean.

	WCNPO	EPO	OTHERS
2014	863	8652	5444
2015	1357	12120	3310
2016	2063	13654	1685

Table 3. Analysis of deviance table for the GAM to mean length (a) and weight (b) data for swordfish caught by the Taiwanese distant-water longline fishery in the Pacific Ocean.

(a)

Predictor	Df	Deviance	Resid. Df	Resid. Dev	Pr(>Chi)
NULL			71501	55339625	
Year	30	2548204	71471	52791421	< 0.01
Quarter	3	198630	71468	52592791	< 0.01
Stock	2	47180	71466	52545612	< 0.01
s(Lat)	3	112609	71463	52433003	< 0.01
s(Lon)	3	66165	71460	52366837	< 0.01
s(SST)	3.0002	11037	71457	52355800	< 0.01

(b)

Predictor	Df	Deviance	Resid. Df	Resid. Dev	Pr(>Chi)
NULL			15125	3013.2	
Year	2	23.249	15123	2990	< 0.01
Quarter	3	33.032	15120	2956.9	< 0.01
Stock	2	10.543	15118	2946.4	< 0.01
s(Lat)	3.0002	25.234	15115	2921.2	< 0.01
s(Lon)	3	19.349	15112	2901.8	< 0.01
s(SST)	2.9998	8.247	15109	2893.6	< 0.01

Table 4. Summary statistics for the model selection of generalized linear models applied to various stock structure hypotheses (defined in figures).

Stock area hypothesis	Source	Null deviance	Null df.	Res. Deviance	Res. df.	AIC	Delta AIC
Two stocks	Nakano (1998)	13870	49147	13643	49136	76514.21	168.76
Three stocks	Bartoo and Coan (1988)	13870	49147	13703	49131	76737.96	392.51
Three stocks	Ichinokawa and Brodziak (2008)	13870	49147	13649	49130	76547.38	201.93
Three stocks	Nakano (1998)	13870	49147	13593	49130	76345.45	0
Four stocks	Sosa-Nishizaki and Shimizu (1991); Hinton and Deriso (1998); Hinton (2003)	13870	49147	13604	49124	76396.04	50.59

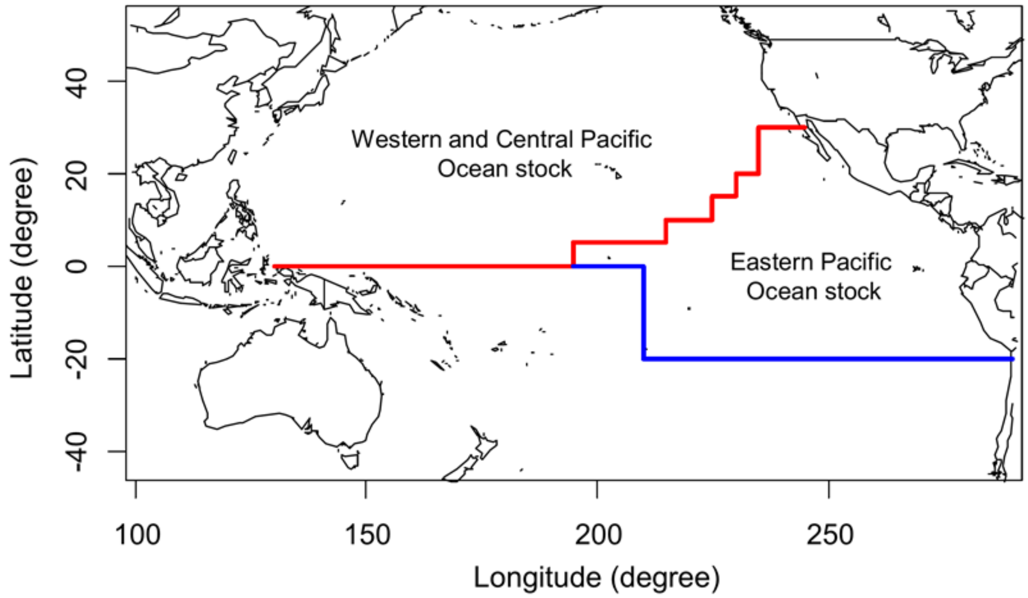


Figure 1. Spatial definition of management units for North Pacific swordfish stock assessments conducted by the ISC Billfish Working Group in 2014 with stocks in the Western and Central Pacific Ocean (WCNPO stock) and in the Eastern Pacific Ocean (EPO stock).

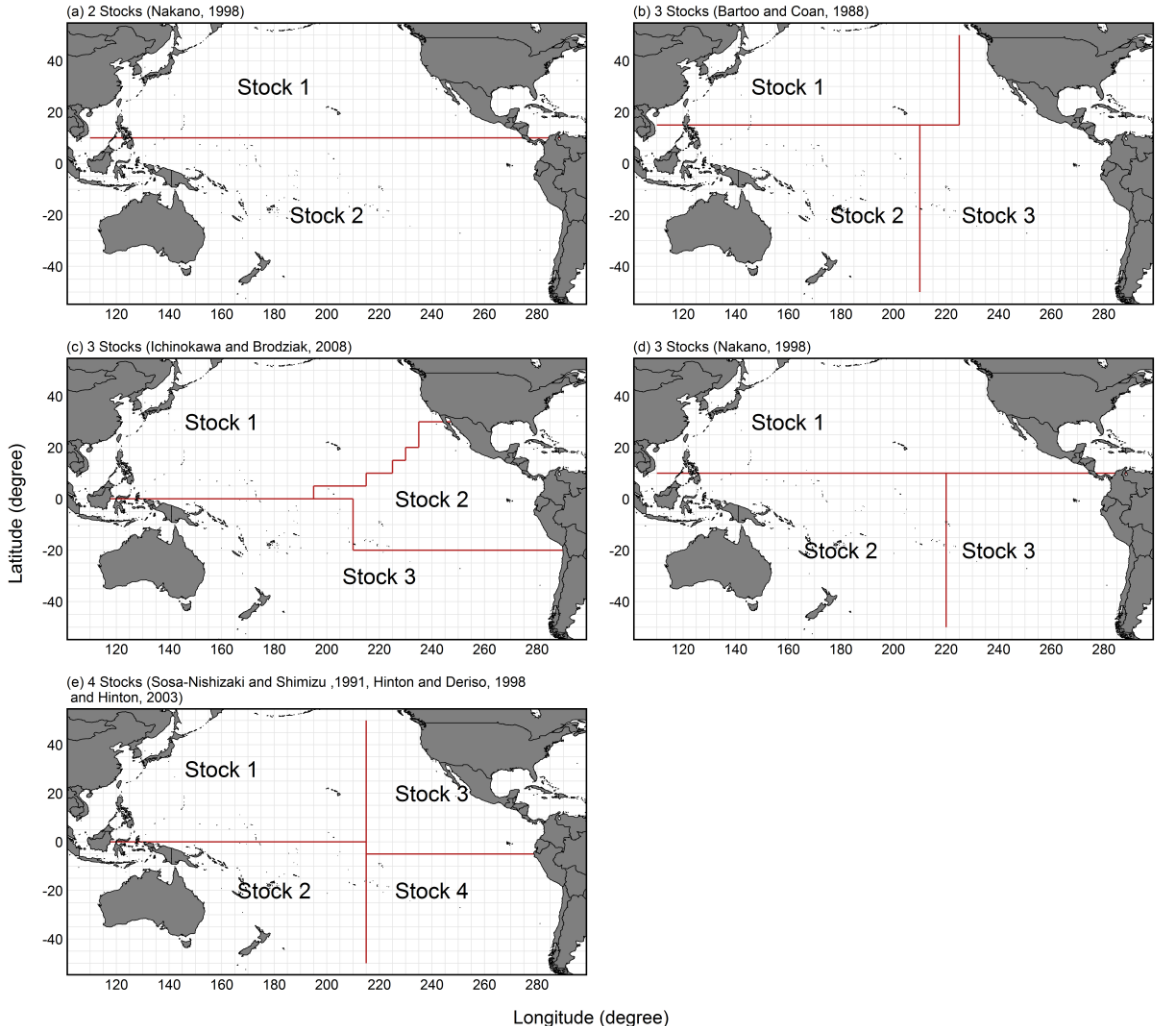


Figure 2. Spatial definitions of various stock boundaries hypotheses of swordfish in the Pacific Ocean. The hypothesis are based on (a) 2 stocks (Nakano, 1998); (b) 3 stocks (Bartoo and Coan, 1988); (c) 3 stocks (Ichinokawa and Brodziak, 2008); (d) 3 stocks (Nakano, 1998); (e) composite 4 stocks (please see the hypotheses of Sosa-Nishizaki and Shimizu (1991); Hinton and Deriso (1998); Hinton (2003)).

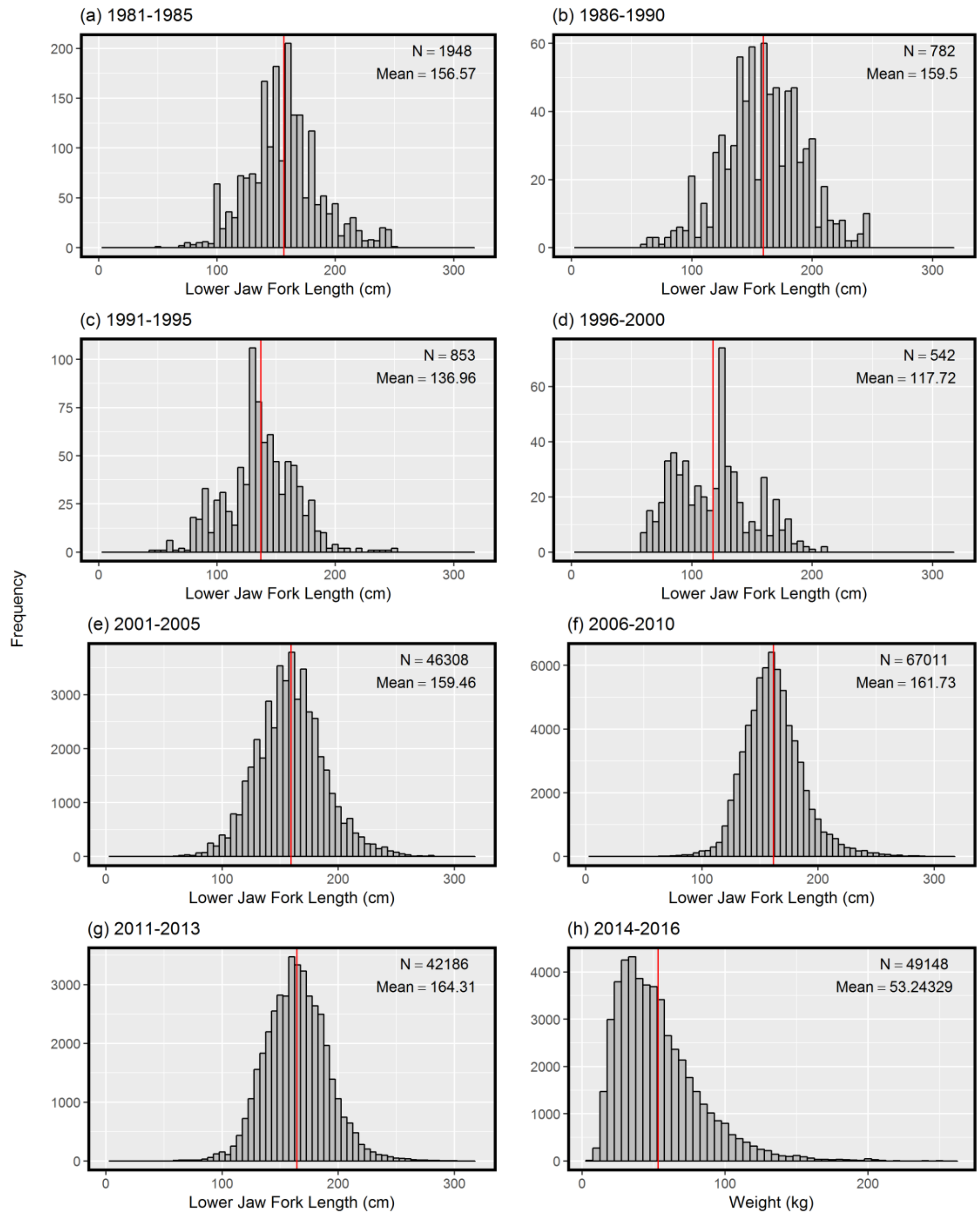


Figure 3. Length (lower jaw-to-fork length, cm) (a-g) and weight (kg) (h) frequency distribution for the swordfish caught by the Taiwanese distant-water longline fishery in the Pacific Ocean during 1981-2016.

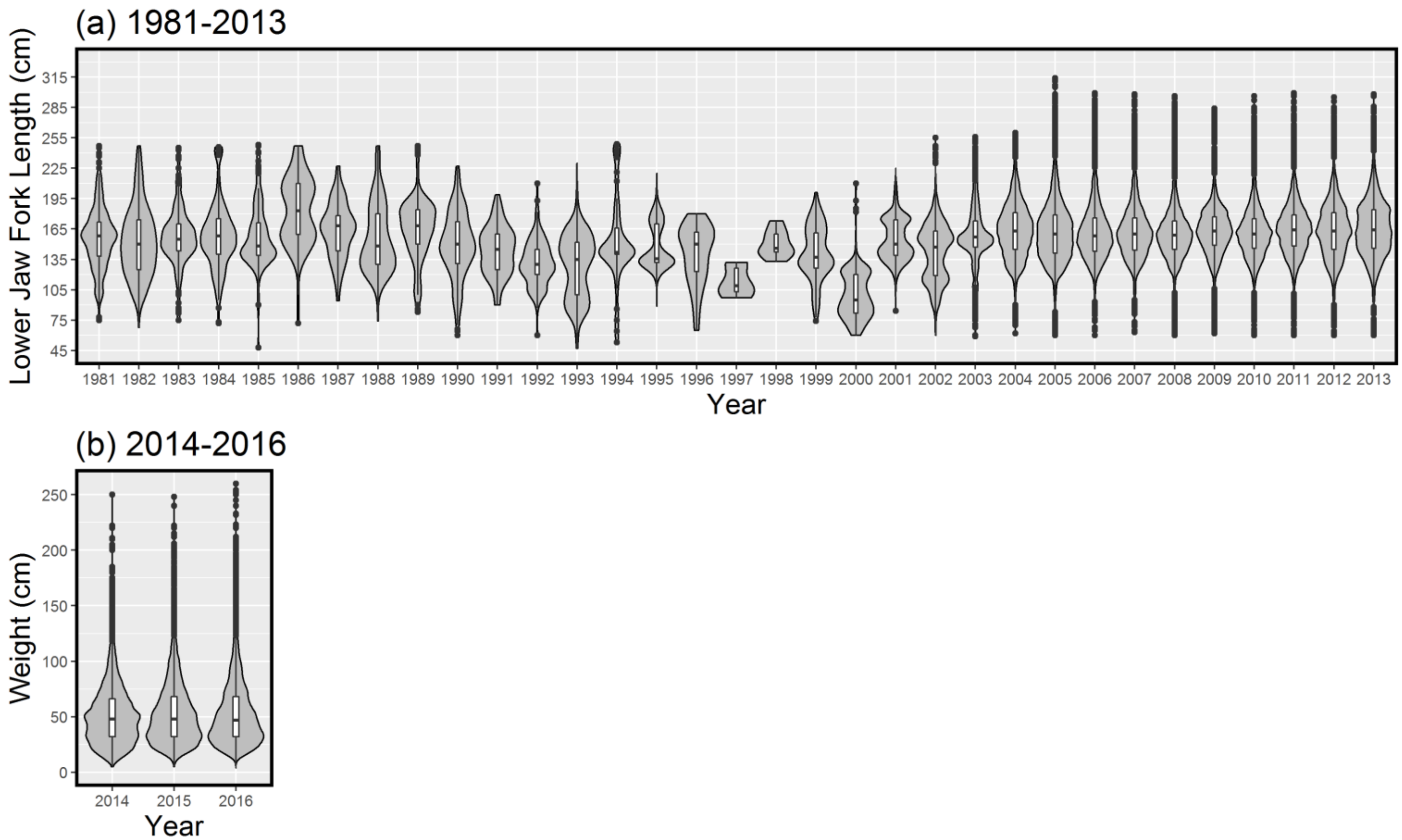


Figure 4. Box-violin plots of annual trend of swordfish length (lower jaw-to-fork length, cm) and weight (kg) from the Taiwanese distant-water longline fishery in the Pacific Ocean during 1981-2016.

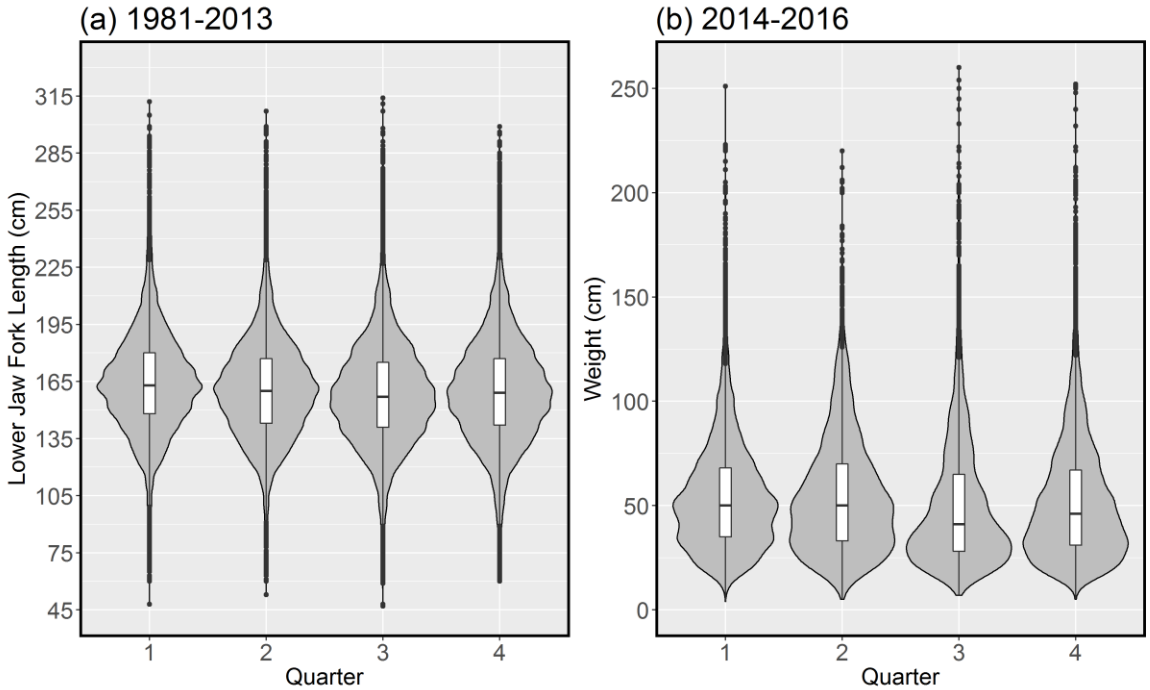


Figure 5. Box-violin plots of quarterly swordfish length (lower jaw-to-fork length, cm) and weight (kg) from the Taiwanese distant-water longline fishery in the Pacific Ocean during 1981-2016 (Quarter 1: Dec -Feb; Quarter 2: Mar - May; Quarter 3: June - Aug; Quarter 4: Sep - Nov).

Figure 6. Box-violin plots of swordfish length (lower jaw-to-fork length, cm) and weight (kg) by different stock area from the Taiwanese distant-water longline fishery in the Pacific Ocean during 1981-2016.

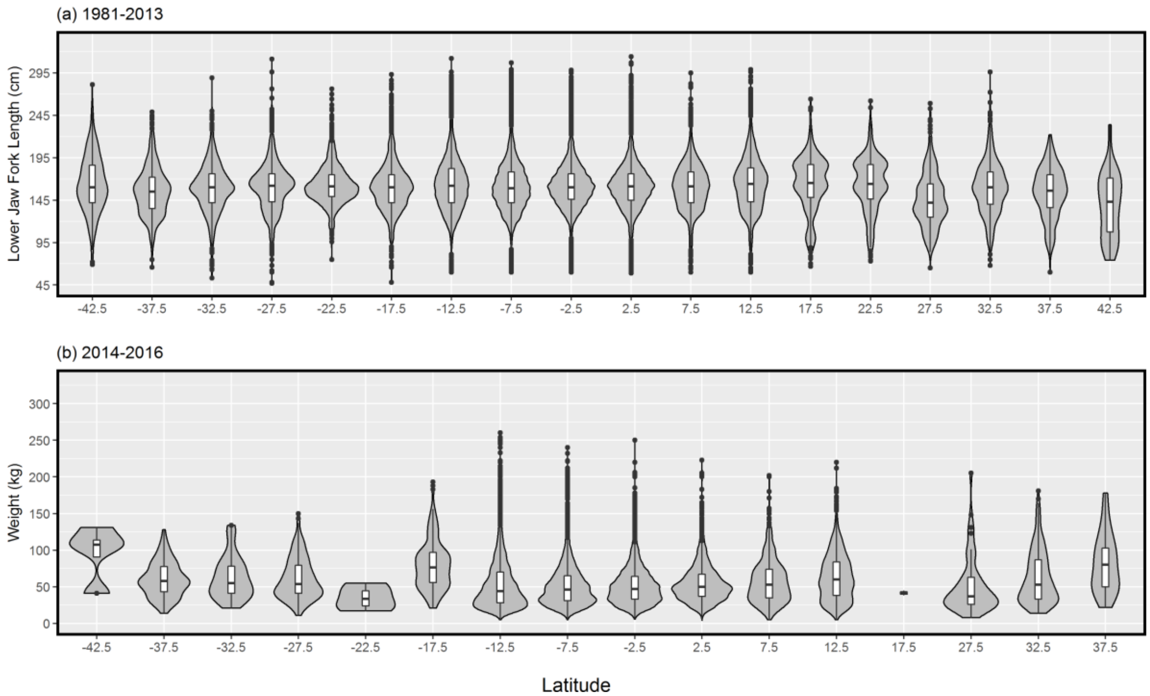


Figure 7. Box-violin plots of swordfish length (lower jaw-to-fork length, cm) and weight (kg) by 5 degree latitude level from the Taiwanese distant-water longline fishery in the Pacific Ocean during 1981-2016.

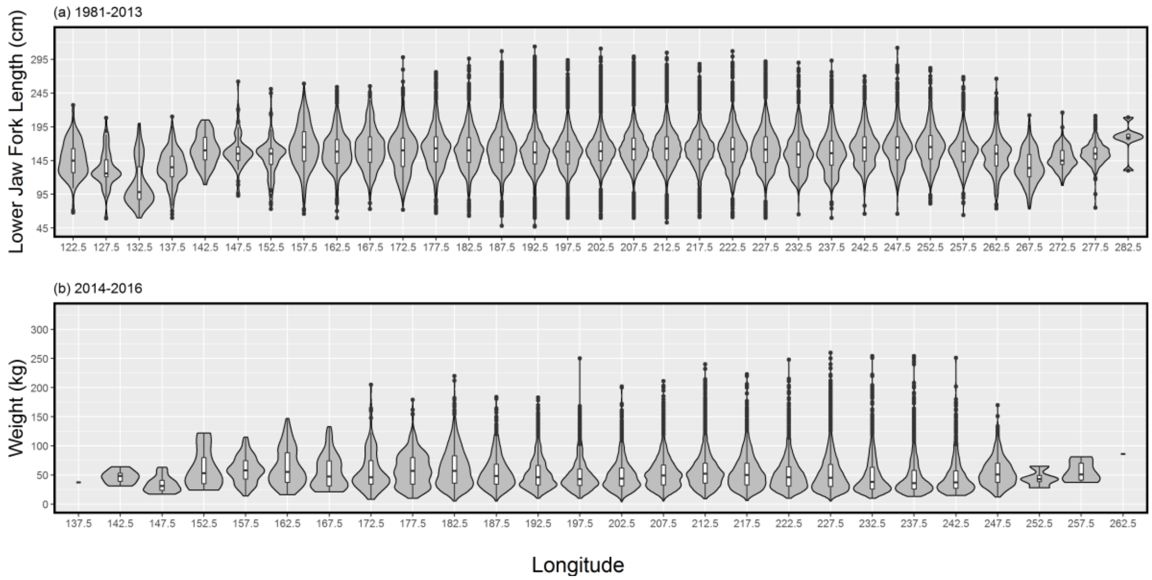


Figure 8. Box-violin plots of swordfish length (lower jaw-to-fork length, cm) and weight (kg) by 5 degree longitude level from the Taiwanese distant-water longline fishery in the Pacific Ocean during 1981-2016.

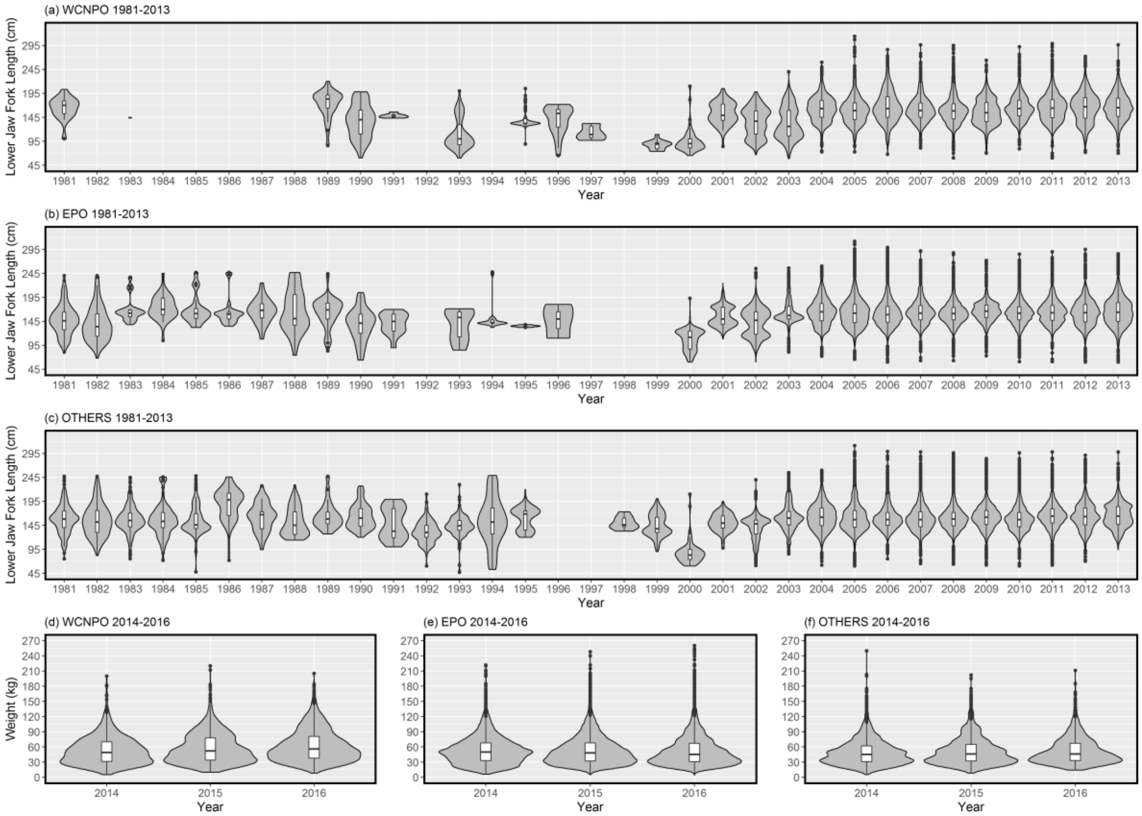


Figure 9. Box-violin plots of annual trend of length (lower jaw-to-fork length, cm) and weight (kg) by stock area from the Taiwanese distant-water longline fishery in the Pacific Ocean during 1981-2016.

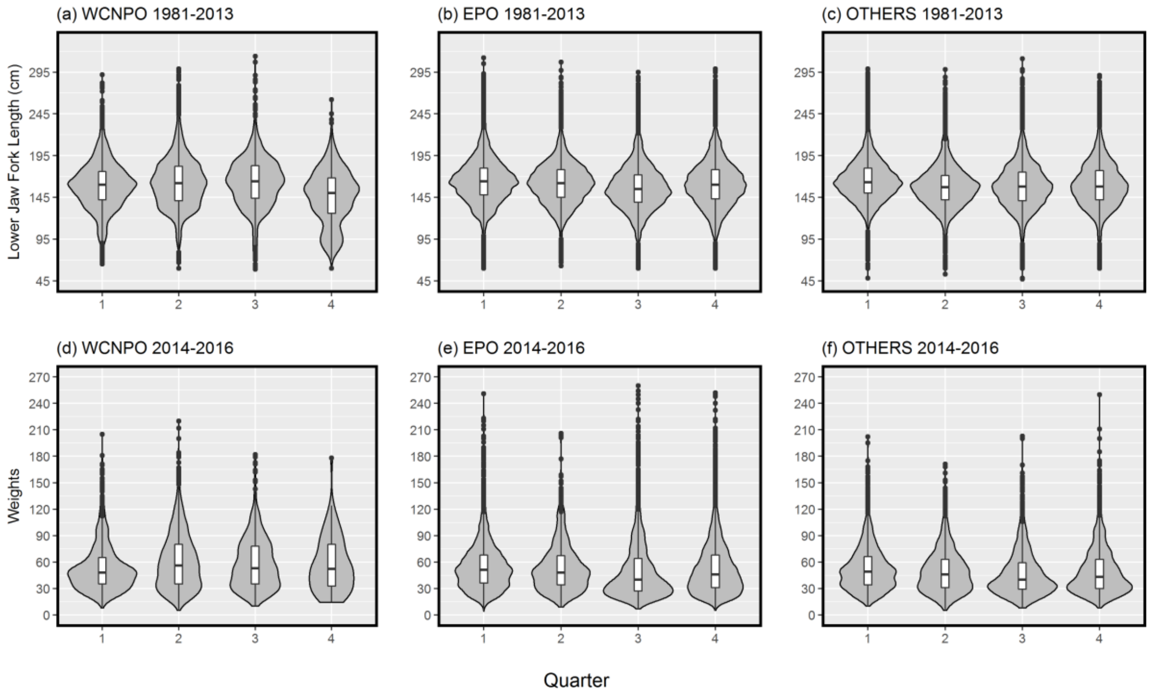


Figure 10. Box-violin plots of quarterly trend of length (lower jaw-to-fork length, cm) and weight (kg) by stock area from the Taiwanese distant-water longline fishery in the Pacific Ocean during 1981-2016. (Quarter 1: Dec -Feb; Quarter 2: Mar - May; Quarter 3: June - Aug; Quarter 4: Sep - Nov)

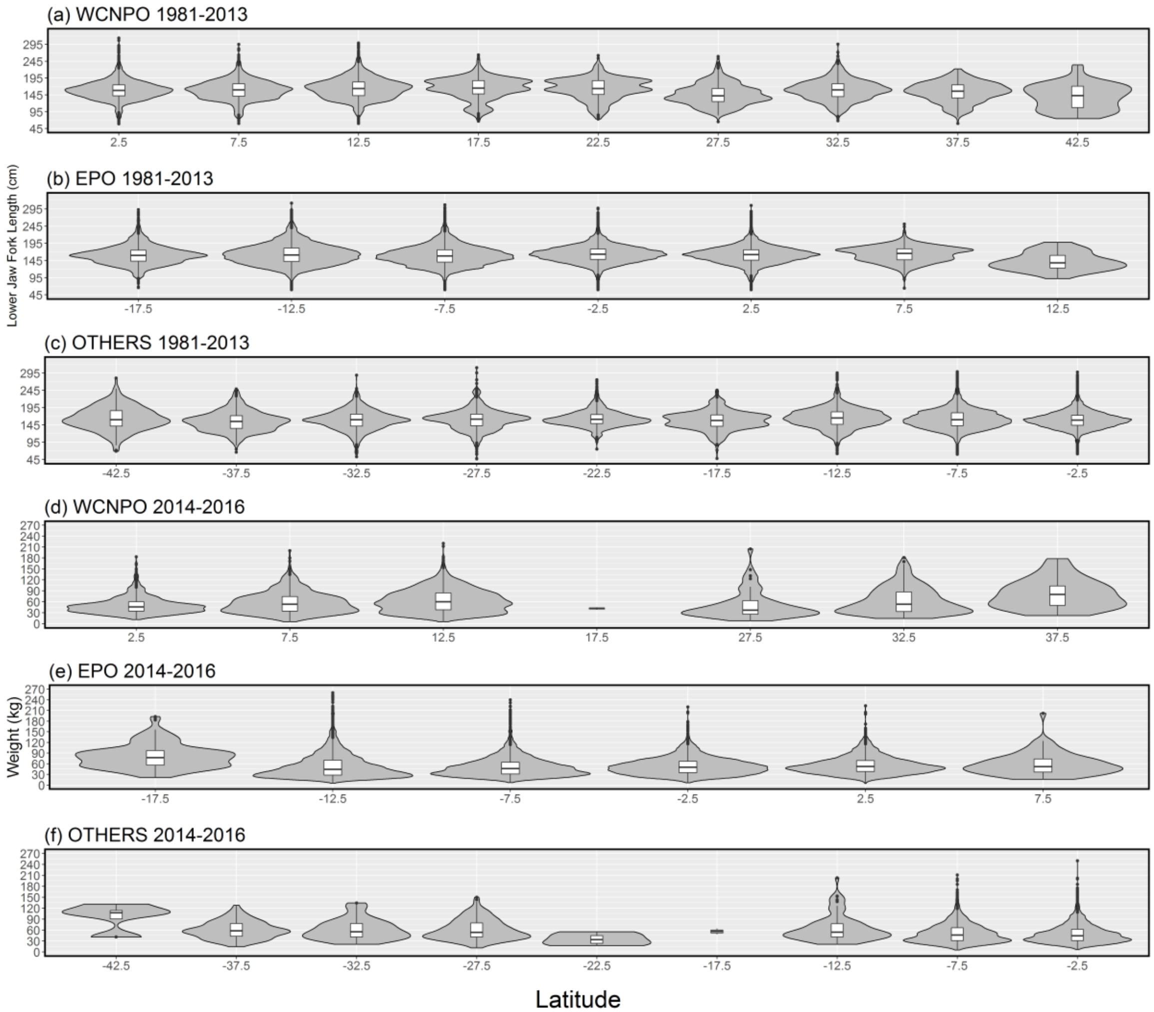


Figure 11. Box-violin plots of length (lower jaw-to-fork length, cm) and weight (kg) by 5 degree latitude and stock area from the Taiwanese distant-water longline fishery in the Pacific Ocean during 1981-2016.

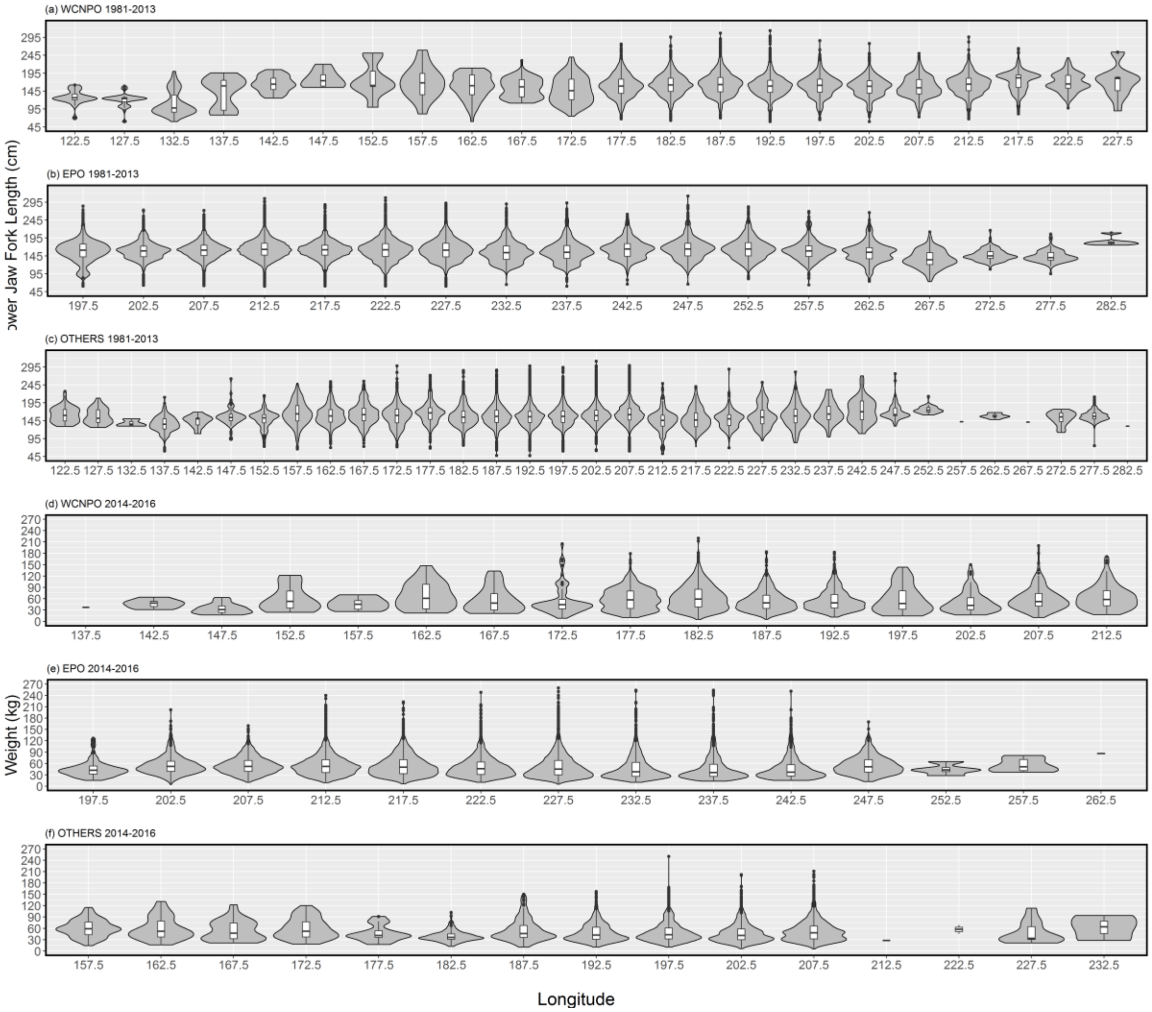


Figure 12. Box-violin plots of length (lower jaw-to-fork length, cm) and weight (kg) by 5 degree longitude and stock area from the Taiwanese distant-water longline fishery in the Pacific Ocean during 1981-2016.

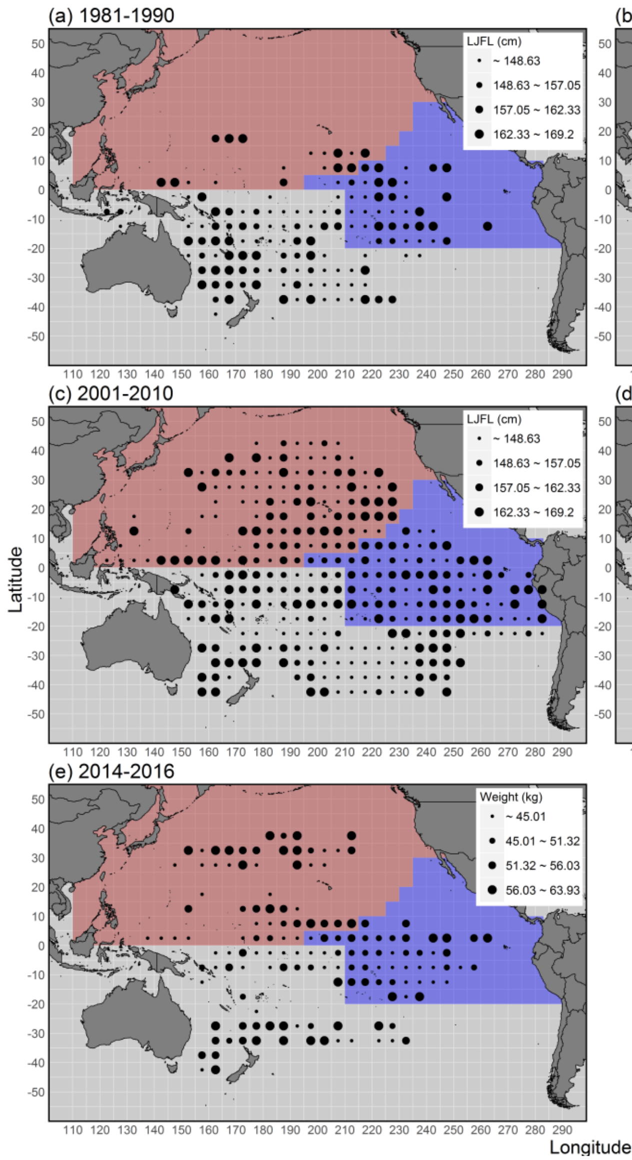
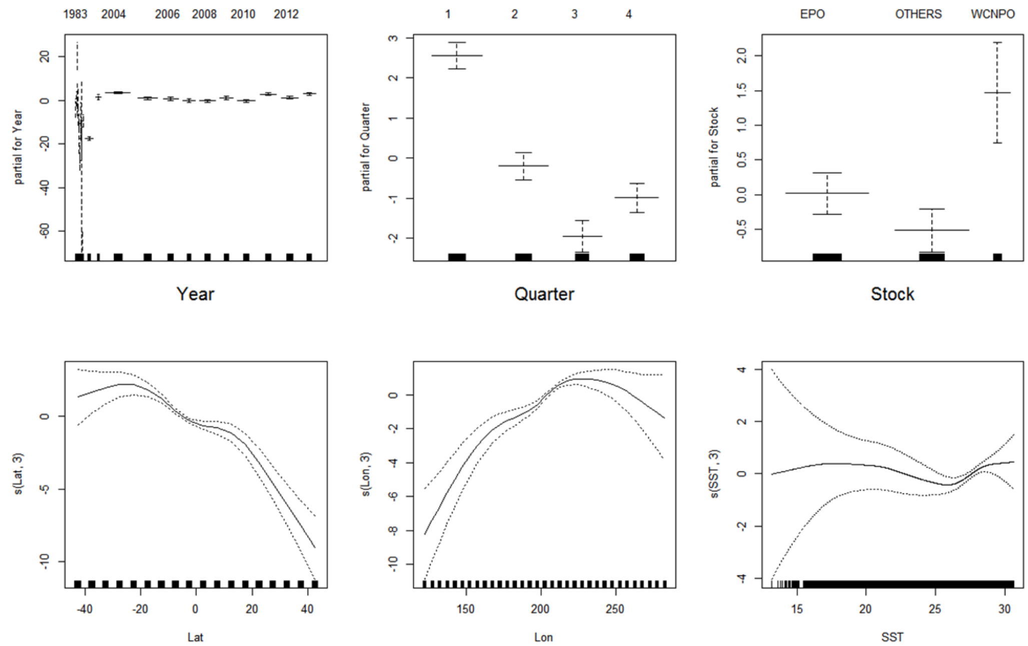


Figure 13. Spatial distributions of swordfish length (lower jaw-to-fork length, cm) and weight (kg) caught by the Taiwanese distant-water longline fishery in the Pacific Ocean during 1981-2016. The shaded polygons denote the stock areas of WCNPO and EPO (defined in figure 2).

(a)



(b)

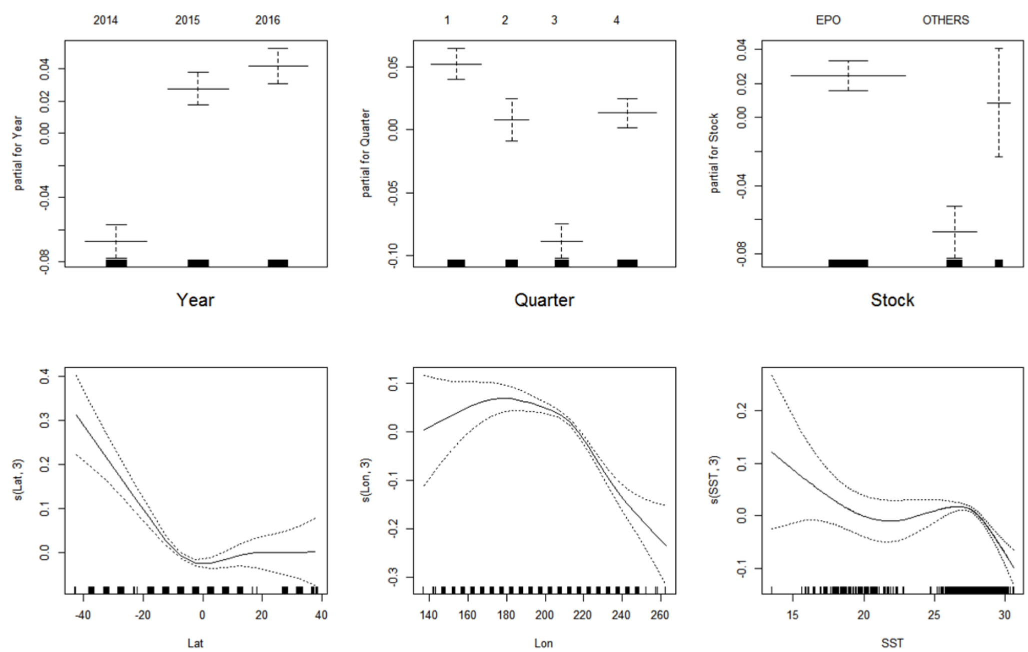


Figure 14. Impact of the GAM main effects on the swordfish mean length (a) and weight (b) (in log-space) by Taiwanese distant-water longline fishery in the Pacific Ocean. The curves denote the GAM smoothers; vertical and horizontal bars denote GLM factors.

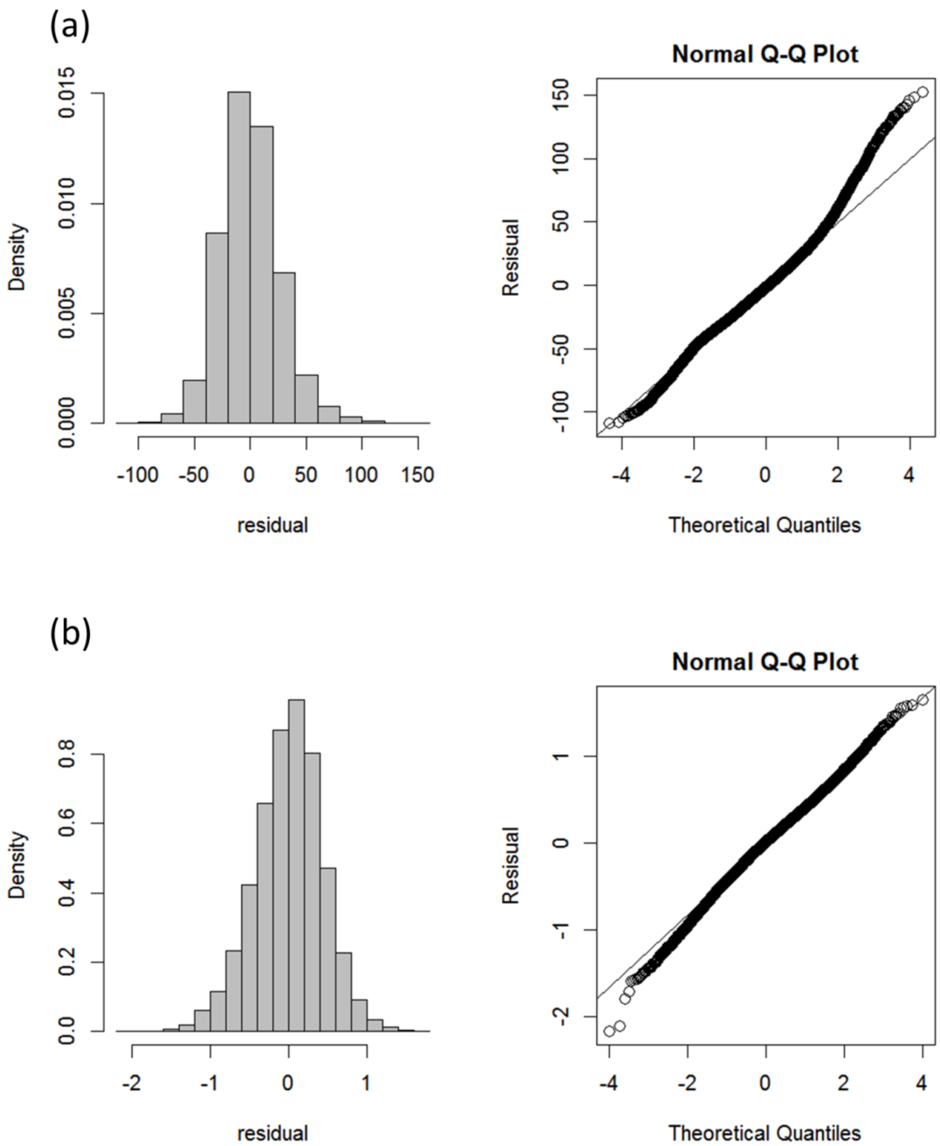


Figure 15. Histograms of standardized residuals and quantile–quantile plots for GAM models applied to mean length (a) and weight (b) for swordfish caught by the Taiwanese distant-water longline fishery in the Pacific Ocean.