Comparing four nominal CPUEs indices of swordfish (*Xiphias gladius*) with longline observer data in the Indian Ocean

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Abstract

The catch per unit effort (CPUE) is an essential statistical indicator of the status of stocks. In the longline fishery, because of the different statistical methods of catch and fishing effort, there are many forms for calculating nominal CPUE. Using the swordfish (Xiphias gladius) of Chinese tuna longline fishery in the Indian Ocean as an example, we evaluate the performance of four nominal CPUEs of two effort forms (1000 hooks and 10000 hours) and two catch forms (number and weight) combinations in CPUE standardization. This study uses 2,305 sets recorded by Chinese observers from 2012 to 2019 and the Tweedie GAM model for comparison. The results show that the explanatory variables of the best model for the four forms of nominal CPUE are the same, including year, month, hook type, bait type, longitude, latitude, hooks between floats (HBF), and sea surface temperature (SST). Those model's explanation rates are 50.1%-53.8%, and the four standardized annual CPUEs have a very similar trend. This study suggests that the logbook of the tuna longline fishery should prioritize ensuring accurate records of swordfish numbers and hook numbers each set because they are easier to obtain and have higher credibility, particularly in developing countries with limited conditions.

Keywords

nominal CPUE, longline fisheries, Indian Ocean, swordfish, CPUE standardization

1. Introduction

Regional Fisheries Management Organizations (RFMOs) will regularly conduct fishery resource assessments for species under their jurisdiction to better conserve and manage fishery stocks. Historical catch time series and standardized relative resource abundance will be used as the reference base in methods such as surplus production models and age-structured models for stock assessment. Catch Per Unit Effort (CPUE) is usually assumed to be the indicator of abundance (Harley et al., 2001; Kimura, 1981).

Ideally, CPUE represents the resource, but CPUE is often influenced by many factors, such as fishing capacity and environmental conditions (Maunder & Punt, 2004). Therefore, the collected fishing data need to be standardized to eliminate the influence of additional factors. In the study of CPUE standardization in longline fisheries, past research has focused on comparative studies of different models (Bigelow et al., 2002; Song & Wu, 2011), parameter construction (Campbell, 2015), target strategy effects (Shibano et al., 2021), and effects of spatial scales (Tian et al., 2009).

However, different statistical units are used to count catch and effort, which potentially gives rise to multiple nominal CPUE. The impact of these various forms of nominal CPUEs on the standardization of CPUE has been little studied (Song et al., 2012). For example, in tuna longline fisheries, the catch is usually expressed as the number(Lan et al., 2012; Wu et al., 2021; Zagaglia et al., 2004) or weight (Usman et al., 2017), and the effort is generally defined as the number of hooks(Lan et al., 2012; Zagaglia et al., 2004). Some studies suggest that effort can use hooks soak time represent as well (Carruthers et al., 2011; Song et al., 2012). That multiple measures constitute at least four forms of nominal CPUE.

Swordfish (*Xiphias gladius*), the most widely distributed billfish and occur worldwide from about 45N to 45S in all tropical, subtropical, and temperate seas, play an essential role in maintaining ecosystem stability (Palko et al., 1981). They are a common catch in commercial swordfish longline fisheries or bycatch in tuna longline fisheries, with a total global catch of about 110,000-130,000 t per year (FAO, 2021). In recent years, swordfish catches by longline have accounted for 46% of total swordfish catches in the Indian Ocean (IOTC, 2020). Multiple nominal CPUE also occurs in the swordfish fishery(Hsu et al., 2015).

In this study, we compared the standardization results of four nominal CPUE data for longline fishing based on different combinations of statistical units of catch and effort using scientific observer data for swordfish bycatch by the Chinese tuna longline fleet in the Indian Ocean.

Observer data are used because they are more credible and informative than commercial fishing logs, including fishing operations and individual biological records. It means more scientific information for research on the CPUE standardization process. The goals of this work are to determine the impact of nominal CPUE selection on standardization and to provide additional references for improving the use of logbook data in pelagic swordfish fisheries under limited conditions.

2 Material and methods

2.1 *Study area*

The study area of this paper is the fishing grounds of the Chinese tuna longline fleet in the western Indian Ocean (Zhu et al., 2020), with the main fishing locations including the high seas of the northwest Indian Ocean, the EEZs of Somalia and Zambia (10˚N-10˚S, 40˚E-70˚E) and the high seas of the southwest Indian Ocean, the EEZs of Madagascar and Mauritius (10˚S-35˚S, 48˚E-75˚E) (Fig.1).

2.2 *Data source*

2.2.1 Observer data

During 2012-2019, the China Overseas Fisheries Association (COFA) continuously dispatched scientific observers to Chinese longline fishing vessels in the Indian Ocean waters, which mainly caught bigeye tuna (*Thunnus obesus*), albacore tuna (*Thunnus alalunga*), and yellowfin tuna (*Thunnus albacores*), with an annual bycatch of swordfish is at the level of 1000-2000t. Annual observer coverage varies but has remained above 5% after 2016 with an increasing trend (Zhu et al., 2020). Observer data include operation date, center location (longitude and latitude), number of deployed hooks, start time and end time of deployment and retrieval, hook type, bait type, catches in number, and biological information (species, length, and sex et al.). We finally used the 2305 sets of data in our work (Table 1).

Those vessels of 21 voyages used different gear. These gears have a mainline length of 115,000 to 132,480 m, a mainline length between floats of 828 to 891 m (number of branch lines 17 to 26, spacing between branch lines 33 to 46 m), a float line length of 25 to 35 m, and a branch line length of 21 to 45 m. In general, the gear deployment occurred from 04:00 to 11:00 local time, lasted for about 6 to 8 hours. The gear generally deploys 2000 to 4100 hooks and retrieve at 12:00 to 17:00, drifting to the end of deployment location or sailing to the start location depending on the current conditions—the difference in gear and operating time results in different calculated soak times.

2.2.2 Environmental data

Habitat suitability, such as dissolved oxygen concentration and water temperatures in the pelagic environment, can affect fish availability or catchability (e.g., altering fish behavior) (Bigelow et al., 1999; Forrestal et al., 2019). Pop-up satellite archival tags studies have been conducted to show the potential impact of temperature on swordfish habitat (Dewar et al., 2011). Meanwhile, in addition to anthropogenic factors, climate change (e.g., increased temperature) has led to changes in swordfish's spatial distribution and abundance (Hill et al., 2016; Lan et al., 2015). Swordfish respond dynamically to changes in bait organisms caused by currents and eddies, and elevated feeding conditions such as chlorophyll concentrations and zooplankton lead to localized aggregations (Bigelow et al., 1999; Chang et al., 2013; Seki et al., 2002).

Therefore, this paper applied two environmental variables, Sea Surface Temperature (SST) and Sea Surface Chlorophyll-a Concentration (SSC), for CPUE standardization. Environmental data were obtained from the website of the National Oceanic and Atmospheric Administration (NOAA, https://oceanwatch.pifsc.noaa.gov/erddap/index.html) with a temporal resolution of months and a spatial resolution of 0.05° for SST and a temporal resolution of months and a spatial resolution of 4.17 km for SSC.

2.2.3 Operation and gear

In this paper, the required information about the operation and fishing gear parameters is extracted from observer data. The average hook soak time was calculated by the start time and end time of deployment per set, i.e., approximating the soak time of the first hook and the last one (Song et al., 2012). Hook types were divided into three categories, namely circle hooks, J-hooks, and other hook shapes. The bait types were divided into 12 combinations of categories: chub mackerel (*Scomber japonicus*) with a fork length of 21 to 29 cm, sardine (*Sardinella*) with a fork length of 18 to 25 cm, japanese scad (*Decapterus maruadsi*) with a fork length of 18 to 25 cm, milkfish (*Chanos chanos*) with a fork length of 22 cm, jack mackerel (*Trachurus japonicus*) with a fork length of 23 cm, squid with a length of 18 to 23 cm, and artificial squid with a length of 18 cm.

2.3 *Calculation of four nominal CPUE*

The number of hooks calculates by floats number and hooks between floats. The following equation was the number of deployed hooks of the *k*-th operation:

$$N_k = M_k * HBF_k \qquad (1)$$

where M_k is the gear section of the *k*-th operation ($M_k + 1$ floats) and HBF_k is the hooks between floats of the *k*-th operation; N_k is the total number of deployed hooks of *k*-th operation.

There are two general scenarios for hook immersion time: (1) retrieval was started from the starting position of deploying; (2) retrieval was started from the end position of deploying (Song et al., 2012). Since the order of gear retrieval was not recorded in the observer data, the hook soak time was calculated uniformly from the start of gear retrieval in this study, but this did not affect the calculation of the total soak time because the whole soak time is equal for the two scenarios. The following equation was used to calculate the total soak time of the k-th operation:

$$T_k = \frac{(t_k^{rs} - t_k^{ds}) + (t_k^{re} - t_k^{de})}{2} \qquad (2)$$

$$ST_k = T_k N_k \quad (3)$$

where t_k^{ds} and t_k^{de} are the start time and end time of longline gear deployment of k-th operation and t_k^{rs} and t_k^{re} are the start time and end time of retrieval; T_k is the average soak time per-hook of the k-th operation; ST_k is the sum of soak time of all hooks of the k-th operation.

According to the four Catch-Effort recording methods of the longline fishery, the four forms of nominal CPUE of the k-th operation is calculated as:

$$CPUE_{nh} = \frac{Catch_k^n}{N_k} \times 1000 \qquad (4.1)$$

$$CPUE_{wh} = \frac{Catch_k^w}{N_k} \times 1000 \qquad (4.2)$$

$$CPUE_{nt} = \frac{Catch_k^n}{ST_k} \times 10000 \qquad (4.3)$$

$$CPUE_{wt} = \frac{Catch_k^w}{ST_k} \times 10000 \qquad (4.4)$$

where $Catch_k^n$ denotes the number of caught in the k-th operation; $Catch_k^w$ denotes the weight of catch in the k-th operation. In subscript of $CPUE$, the letter n represents the catch in number, w represents the catch in weight, h represents the number of hooks, and t represents the soak time. The above four forms of nominal CPUE are matched with environmental data in spatial location and temporal consistency to derive pre-analysis data for CPUE standardization.

2.4 *CPUE standardization*

2.4.1 Tweedie GAM model

GAM is a nonparametric multiple linear regression model. The GAM model provides more information in analyzing the spatial relationship between resource abundance and environment compared to traditional linear regression models and can better describe the nonlinear relationship between CPUE and other variables (Braun et al., 2019; Campbell, 2004), which is a kind of statistical model for CPUE standardization and is a commonly used statistical model for CPUE standardization (Hua et al., 2019; Setyadji & Fahmi, 2020; Tian et al., 2009). Unlike nominal CPUE calculations for tuna longline fisheries, the details of CPUE standardization for swordfish differ significantly compared to tuna, mainly because swordfish is primarily used as bycatch in tuna longline fisheries, with more zero catches (Ortiz & Arocha, 2004), and the swordfish CPUE in this study also had more zero values. Some studies have concluded that the Tweedie distribution has better performance in fitting catch-zero values in fisheries (Shono, 2008). The Tweedie distribution is a composite distribution of the Poisson and gamma distributions. Where the parameter p controls the degree of the composite distribution, when p = 1, Tweedie is Poisson distribution, when p = 2, Tweedie is gamma distribution, Tweedie random variable is the sum of X gamma random variables, Tweedie distribution is characterized by a certain probability of generating samples with a value of 0. Therefore, the Tweedie distribution is used to fit this study.

In this study, the CPUE was normalized using a GAM model based on a Tweedie distribution with a power function as the link function (Ebango Ngando et al., 2020; Shono, 2008) with the following equation:

$$g(\mu_i) = \alpha + \sum_{i=1} f_i(X_i) + \varepsilon_i \qquad (5)$$

where f_i is the smooth function of covariates, X_i are the independent variables, and ε is error. The complete GAM formula for the CPUE standardization in this study can be written as:

$$\mathrm{CPUE} = year + month + type + bait + s(lat) + s(lon) + s(HBF) + s(SST) + s(SSC) + \varepsilon \quad (6)$$

where s is spline smoother, HBF is hooks between floats; $type$ is hook type, $bait$ is bait type, lat is latitude, lon is longitude. Year, month, hook type, and bait type were categorical variables, while longitude, latitude, HBF, SST, and SSC were continuous variables (Table 2). The selection of variables in this study was based on the significance of each variable ($p<0.05$), and the selection of the optimal model was based on the minimized Akaike information criterion (AIC) (Zhang & Holmes, 2010). In this paper, due to the small sample size of the observer data and the fact that Corrected AIC (AICc) is more applicable to small samples than AIC, AICc is used as the actual selection criterion for the model in this paper (Burnham, 2004). R (ver. 4.0.4) and package *mgcv* (ver. 1.8-33) were used to implement GAM analysis.

2.4.2 Calculation of standardization CPUE

The four forms of standardized CPUE are calculated from the annual means of the fitted CPUE derived from the corresponding optimal model. Annal standardized CPUE can be calculated as:

$$SCPUE_i = \frac{1}{n_i}\sum_{k=1}^{n_i} FIT_{ik} \qquad (7)$$

where $SCPUE_i$ is the standardized CPUE in the i-th year, n_i is the amount of operation in the i-th year, and FIT_{ik} is the CPUE of the model fit of the k-th operation.

2.5 *Comparison of standardized CPUE*

For relative abundance indices, the most important thing is the trend of temporal variability. Because different forms of CPUE are measured on different scales, this study calculated the coefficient of variance (CV) of the annual standardized CPUE of the GAM to analyze how the choice of catch and fishing effort affects the estimation of CPUE and to compare the differences in CV between the different forms of CPUE.

The four forms of standardized CPUE with different magnitudes were normalized for comparison purposes. The normalization method used in this paper is min-max normalization, where the maximum and minimum values of the four standardized CPUE are normalized to the [0,1] interval, and the standardized CPUE are scaled equally. The formula is as follows:

$$NCPUE_i = \frac{SCPUE_i - \min(SCPUE)}{\max(SCPUE) - \min(SCPUE)} \qquad (7)$$

where $NCPUE_i$ is standardized CPUE in the i-th year after nominalization, and $SCPUE_i$ is standardized CPUE in the i-th year before nominalization.

3 Result

3.1 *Model details*

A stepwise regression of the model using AICc begins to get progressively smaller as more explanatory variables are added, with the final AICc being the smallest. The final model indicated that the four forms of the best model were identical, and the variables included together were year, month, hook type, bait type, longitude, latitude, number of hooks between floats, and sea surface temperature

(Table 3). The final model is also the best model selected for this study. All variables except SSC were significant ($p<0.05$). The ΔAICc of model based on the four forms of constructing stepwise regression showed that the bait type was the most important variable, followed by month.

In addition, the four models' performance very closely, with adjusted R^2 range from 0.429 to 0.463, and the deviance explained by the models range from 50.1% to 54%, with the GAM_{nt} model having the highest deviance explained and the second-highest R^2 (Table 4).

Figure 2 shows the residual plots for the four best models. The average residuals of the four best models range from -0.14 to -1.03, with an overall convergence to zero values. The residuals of the four optimal models have the same distribution regardless of the regression value and satisfy the model assumptions.

3.2 *Nominal CPUE and standardized CPUE*

The annual trends of the four nominal CPUEs and the standardized CPUEs are shown in Figure 3. The results show three main patterns: (1) the time trends of the four nominal CPUEs and standardized CPUEs are similar, but the degree of variation is slightly different; (2) the variation of the nominal CPUE is larger than the standardized CPUE; (3) the end phase (2019) of the four nominal CPUEs time series showed significant overestimation relative to the normalization, and three nominal CPUEs ($CPUE_{nh}$, $CPUE_{nt}$ 和 $CPUE_{wh}$) in the beginning phase (2012) showed underestimation.

The standardized CPUE of Indian Ocean swordfish showed a decreasing trend during 2012-2015 and an increasing trend during 2015-2019 (Figure 3). All four results show that the maximum value of annual standardized CPUE occurred in 2012, and the minimum value occurred in 2015. The minimum values of nominal CPUE and standardized CPUE are different in the four results, with nominal CPUE shown for 2014 and standardized CPUE shown for 2015.

In this study, coefficients of variation were calculated for four forms of annual nominal CPUE and standardized CPUE (Figure 4). The CV of annual nominal CPUE (Fig. 4a), 0.605 to 0.672, was generally less different. The CV of annual nominal

CPUE for the catch in number ($CPUE_{nt}$ and $CPUE_{nh}$) was slightly greater than that of catch in weight ($CPUE_{wt}$ and $CPUE_{wh}$); there was no significant difference in the CV of annual nominal CPUE between the number of the hooks and soak time ($CPUE_{nh}$ and $CPUE_{nt}$, $CPUE_{wh}$ and $CPUE_{wt}$).

The CV of annual standardized CPUE (Figure 4b), 0.475 to 0.781, varied widely among the four results. The CV of annual standardized CPUE for the catch in weight ($SCPUE_{wh}$ and $SCPUE_{wt}$) was smaller than the catch in number ($SCPUE_{nh}$ and $SCPUE_{nt}$). The CVs of annual standardized CPUE for hook net soak time ($SCPUE_{nt}$ and $SCPUE_{wt}$) were smaller than those for the number of hooks ($SCPUE_{nh}$ and $SCPUE_{wh}$), but the differences were minimal.

Figure 5 illustrates the trends of the four nominal CPUE normalized standardized CPUEs. The normalized CPUE trends are very similar between the four forms after normalization, with the best year of resource abundance (2012) and the worst year (2015) being the same. Annual trends in normalized CPUE from 2012-2018 were the same in all four results, while trends in normalized CPUE in 2019 were slightly different in all four forms. In 2019, the catch in number ($NCPUE_{nh}$ and $NCPUE_{nt}$) showed a flat trend, while the catch in weight ($NCPUE_{wh}$ and $NCPUE_{wt}$) showed a slightly decreasing trend.

Overall, the normalized CPUE for the catch in weight and catch in number (NCPUEnh and NCPUEwh, NCPUEnt and NCPUEwt) were extremely similar with slight local differences; the normalized CPUE for hook number and soak time (NCPUEnh and NCPUEnt, NCPUEwh and NCPUEwt) were almost identical and showed minimal differences.

4. Discussion

4.1 *CPUE standardization*

The aim of this study was to examine the differences in the four nominal CPUEs of swordfish in the longline fishery and to explore the implications of these CPUEs for expressing population trends. The results of the study emphasize the similarity between the catch in number and catch in weight expressing catch, soak time and number of hooks expressing effort in longline bycatch. The general sources of swordfish fishing data are commercial fishing logbook data recorded by fishing vessels, observer data recorded by scientific observers, and independent survey data recorded by scientific researchers (Hilborn & Walters, 1992). Observer data usually have higher credibility and are more informative than commercial fishing logbook data. Therefore, observer data from the Chinese tuna fleet were selected for this study to calculate different forms of nominal CPUE. Since 2010, the Chinese tuna longline fleet has been recording bycatch of swordfish in the Indian Ocean, with catches ranging from about 1000 to 2000 t per year. After 2016, Chinese observer coverage has remained at more than 5% with an increasing trend (Zhu et al., 2020).

For the sake of data privacy and monitoring costs, commercial fishing data are usually integrated based on fixed spatial and temporal scales when processed, as differentiated spatial scales better reflect spatial variation in CPUE (Tian et al., 2009). However, fishery driven fluctuations in aggregate CPUE would exaggerate fluctuations in aggregate abundance (Kleiber & Maunder, 2008). Considering that the use of integrated CPUE leads to reduced variability and significance for variables other than Spatio-temporal factors, especially categorical variables, this study used unaggregated observer data.

Besides Spatio-temporal and gear factors, numerous studies have shown that CPUE standardization requires consideration of environmental factors (Bigelow et al., 1999; Dewar et al., 2011; Forrestal et al., 2019), but environmental variables are rarely considered in the current CPUE standardization Research of the Indian Ocean longline fleet (Taki et al., 2020; Wang, 2020). Reports that have considered environmental factors have also discarded environmental variables due to data availability (Parker & Kerwath, 2020). The results showed that only SST among the environmental factors passed the significance test, but its contribution to the model was not as significant as the Spatio-temporal and gear factors. Hook type significantly enhanced the performance of the model in the stepwise analysis, which may be hook type cause differences in swordfish catches (Reinhardt et al., 2018; Serafy et al., 2009). Ultimately, all four CPUE-standardized models in this study included gear and operational variables (hook type, bait type, HBF), Spatio-temporal variables (year, month, LON, LAT), and environmental variables (SST).

Zero catches were recorded in 45.3% of the data in this study. To address the problem of zero catch due to bycatch, common approaches include: 1) modifying the spatial and temporal scales of the statistics (Tian et al., 2009); 2) adding a constant term to the CPUE (Porch & Scott, 1994); 3) using the product of two models fitted separately to zero and non-zero data (Thorson & Ward, 2013); and 4) directly selecting probability density distribution function that allows CPUE to be zero (Punt et al., 2000; Shono, 2008) . 1) and 2) result in information loss and estimation bias; there is a possible correlation between the two model variables in 3). Therefore, this study uses the Tweedie distribution function in 4), which is applicable to the zero value of CPUE, as an estimate of the standard error of the prediction model.

The standardization model applied to the Tweedie GAM, and the Indian Ocean Chinese fleet fishing swordfish data eventually achieved R^2 of 0.429 to 0.463 and explained 50.1%-54% of the bias. This indicates that the model fits the data with excellent performance and can be applied for CPUE comparisons.

4.2 *Comparison of CPUE*

The trends of the four nominal CPUEs in this study were approximately the same after normalization (Figures 3 and 5) but showed differences in the trends for specific years. This suggests that the study results capture the similarity in CPUE trends despite the same modeling structure of the four models.

For the selection of effort, the standardized CPUE of the four results showed minimal differences between the number of hooks and soak time. This is consistent with the results of Song et al., which showed little variation in the soak time of the branch line (Song et al., 2012). The hook number is easier to record statistically with little systematic error than hook soak time in fisheries productivity. Therefore, the hook number is currently the most reasonable choice, which is also the practice of most longline CPUE standardization studies.

For the selection of catch, the standardized CPUE for the catch in number and catch in weight was different but not significant, and the difference was even smaller than the difference between two CPUEs that include catch in weight (Figure 5). This difference may be due to individual differences in swordfish bycatch by commercial longline vessels. Biological information from the southwest Indian Ocean indicates that swordfish's lower jaw fork length (LJFL) ranges from 75 to 289 cm with a significant individual difference (Poisson & Fauvel, 2009). Catch in weight is more scientifically relevant for counting population biomass and expressing individual differences than for counting the number of individuals to express population size. The catch in weight showed a more significant long-tail effect, affecting more fluctuations in the catch in weight to express CPUE than the catch in number. The CV results (Figure 4) clarify that differences in the degree of standardized CPUE dispersion were also associated with the weight of swordfish caught. In addition, there are more errors and difficulties in counting weight than quantity when recording fishery production. Therefore, the number of catches is more advantageous when the fishery is small and monitoring and management costs are limited.

4.3 *Research recommendations*

Through the comparative analysis of this study, we recommend that fishing logbooks in developing countries with limited monitoring and management costs should prioritize ensuring accurate information on the number and the number of hooks of swordfish caught. This is because catch in number and hook number are more readily available and credible than the catch in weight and soak time, and the four forms of CPUE are very similar.

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Table 1. Overview of observer data for the Chinese Indian Ocean tuna longline fleet during 2012-2019

Year	Fleet	Sets	Effort		Catch	
			Number of hooks	Soak time(h)	Number(ind.)	Weight(kg)
2012	1	53	167230	1931026	156	4647
2013	1	95	258154	2971442	127	4571
2014	2	111	336046	4265016	57	2412
2015	1	15	35056	408105	7	289
2016	4	267	783353	9196129	225	9658
2017	4	796	2464217	30601101	1164	45517.5
2018	5	552	1751997	21052000	714	28680
2019	3	416	1368463	16187561	1396	52634
总计	21	2305	7164516	1931026	3846	148408.5

Table 2. Variables used to standardize CPUE for swordfish in the Chinese Indian Ocean tuna longline fleet observer data during 2012-2019

Variables	Category	Range
Year	Categorical	2012-2019
Month	Categorical	1-12
Latitude	Continuous	34.6˚S-10.2˚N
Longitude	Continuous	40.0˚E-89.9˚E
Hooks between floats	Continuous	16-33
Hook type	Categorical	1-3(3 class hook type)
Bait type	Categorical	1-12(12 class combination of bait type)
Sea surface temperature	Continuous	16.05-30.57
Sea Surface Chlorophyll-a Concentration	Continuous	0.03-1.33

Note: Hook types were divided into three categories, namely circle hooks, J-hooks, and other hook shapes. The bait types were divided into 12 combinations of categories: chub mackerel (*Scomber japonicus*) with a fork length of 21 to 29 cm, sardine (*Sardinella*) with a fork length of 18 to 25 cm, japanese scad (*Decapterus maruadsi*) with a fork length of 18 to 25 cm, milkfish (*Chanos chanos*) with a fork length of 22 cm, jack mackerel (*Trachurus japonicus*) with a fork length of 23 cm, squid with a length of 18 to 23 cm, and artificial squid with a length of 18 cm.

Table 3. The results of the ΔAICc-based stepwise regression GAM model constructed by the four forms of CPUE

Model	NH	WH	NT	WT
year	-	-	-	-
year+month	-7541	-9969	-7598	-9874
year+month+type	-2954	-2217	-3066	-2293
year+month+type+bait	-23325	-23655	-23752	-24389
year+month+type+bait+s(lon)	-1217	-1363	-1263	-1395
year+month+type+bait+s(lon)+s(lat)	-2644	-4308	-2887	-4470
year+month+type+bait+s(lon)+s(lat) +s(HBF)	-916	-1847	-877	-1739
year+month+type+bait+s(lon)+s(lat) +s(HBF)+s(SST)	-347	-704	-377	-697

Note: NH is the CPUE in the form of the combination of the catch in number and the number of hooks; NT is the CPUE in the form of the combination of the number of catches and the soak time of hooks; WH is the CPUE in the form of the combination of the catch in weight and the number of hooks; WT is the CPUE in the form of the combination of the weight of catches and the soak time of hooks. HBF is hooks between floats; type is hook type, bait is bait type, lat is latitude, lon is longitude.

Table 4. Significance of variables and model results for the four forms of CPUE constructed models

Model		GAMnh	GAMwh	GAMnt	GAMwt
R^2		0.463	0.431	0.459	0.429
DE		53.80%	50.10%	54.00%	50.50%
Intercept		<0.001	<0.001	<0.001	<0.001
Lon		<0.001	<0.001	<0.001	<0.001
Lat		<0.001	<0.001	<0.001	<0.001
HBF		<0.001	<0.001	<0.001	<0.001
SST		<0.001	0.022	0.003	0.025
SSC		-	-	-	-
year	2013	-	-	-	-
	2014	-	-	-	-
	2015	0.001	0.033	<0.001	0.031
	2016	0.047	-	0.043	-
	2017	-	-	-	-
	2018	-	-	-	-
	2019	-	-	-	-
month	2	-	-	-	-
	3	0.003	0.041	0.002	0.03
	4	<0.001	<0.001	<0.001	<0.001
	5	0.031	0.005	0.024	0.005
	6	<0.001	<0.001	<0.001	<0.001
	7	0.003	0.003	0.001	0.001
	8	0.002	0.005	<0.001	0.004
	9	0.005	-	0.002	0.074
	10	<0.001	0.008	<0.001	0.003
	11	<0.001	0.007	<0.001	0.004
	12	0.005	0.05	0.003	0.032
Hook type	J-hook	<0.001	0.019	0.001	0.021
	Other	-	-	-	-
Bait Type	B02	<0.001	<0.001	<0.001	<0.001
	B03	<0.001	0.004	<0.001	0.002
	B04	-	-	-	-
	B05	0.011	-	0.005	-
	B06	0.003	-	0.001	-
	B07	0.012	-	0.003	-
	B08	-	-	0.043	-
	B09	-	0.043	-	0.082
	B10	<0.001	-	<0.001	-
	B11	<0.001	0.012	<0.001	0.013
	B12	<0.001	0.023	<0.001	0.013

Note: GAMnh is the GAM model constructed by combining the CPUE in the form of catch in number and number of hooks as the dependent variable; GAMnt is the GAM model constructed by combining the CPUE in the form of catch in number and soak time of hooks as the dependent variable; GAMwh is the GAM model constructed by combining the CPUE in the form of catch in weight and number of hooks as the dependent variable; GAMwt is the GAM model constructed by combining the CPUE in the form of catch in weight and soak time of hooks as the dependent variable; DE is the model deviation explanation rate.

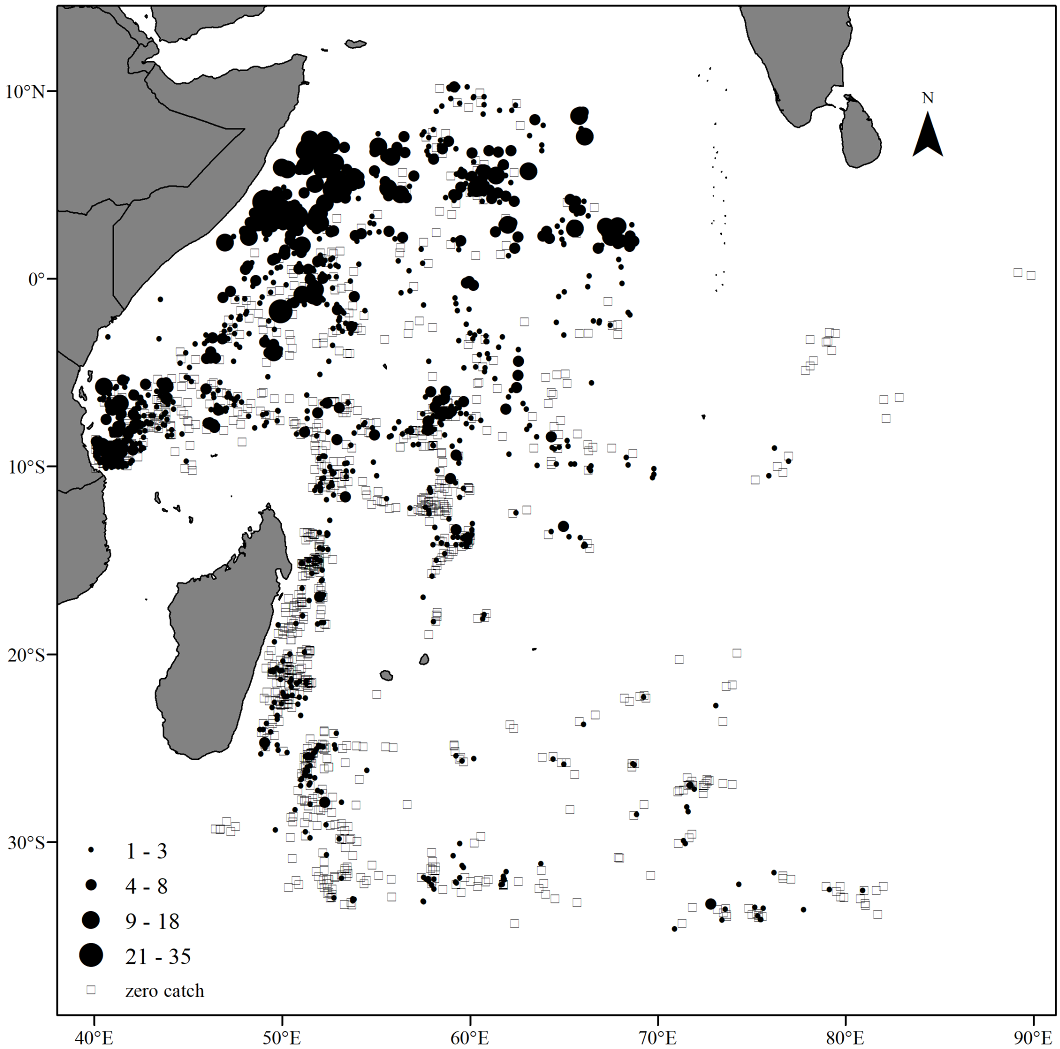

Figure 1. Distribution of hook catches by Chinese fleet observers from 2012 to 2019; hollow rectangles indicate zero catch hook catches, and the size of black solid circles indicate hook catches of different numbers.

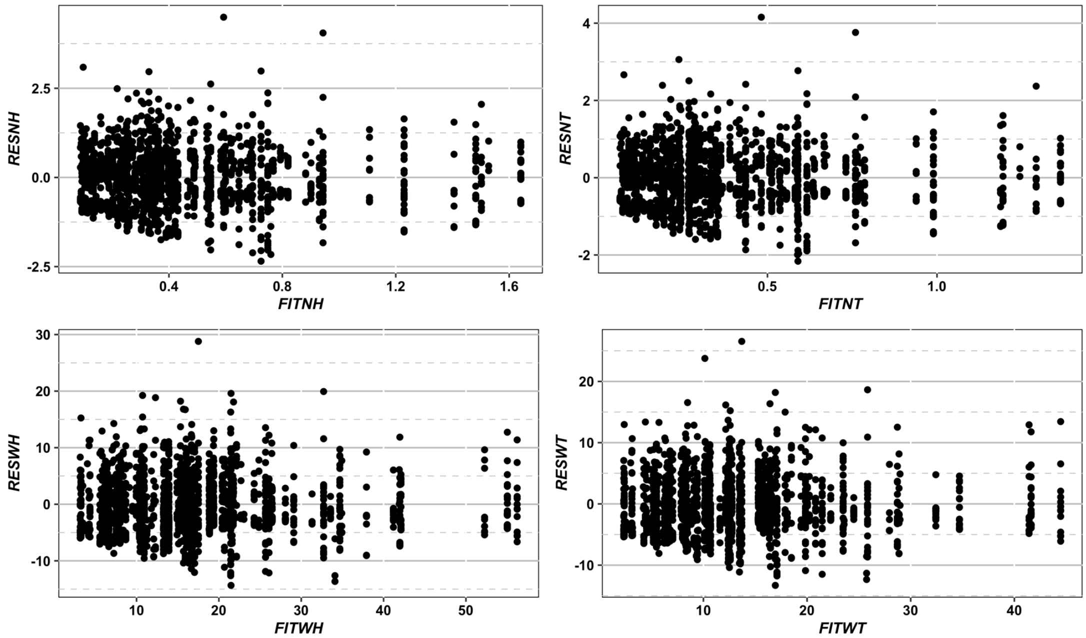

Figure 2. Residual plots for the four best models. FIT is the regression value; res is the residual. NH is the CPUE in the form of the combination of the catch in number and the number of hooks; NT is the CPUE in the form of the combination of the number of catches and the soak time of hooks; WH is the CPUE in the form of the combination of the catch in weight and the number of hooks; WT is the CPUE in the form of the combination of the weight of catches and the soak time of hooks.

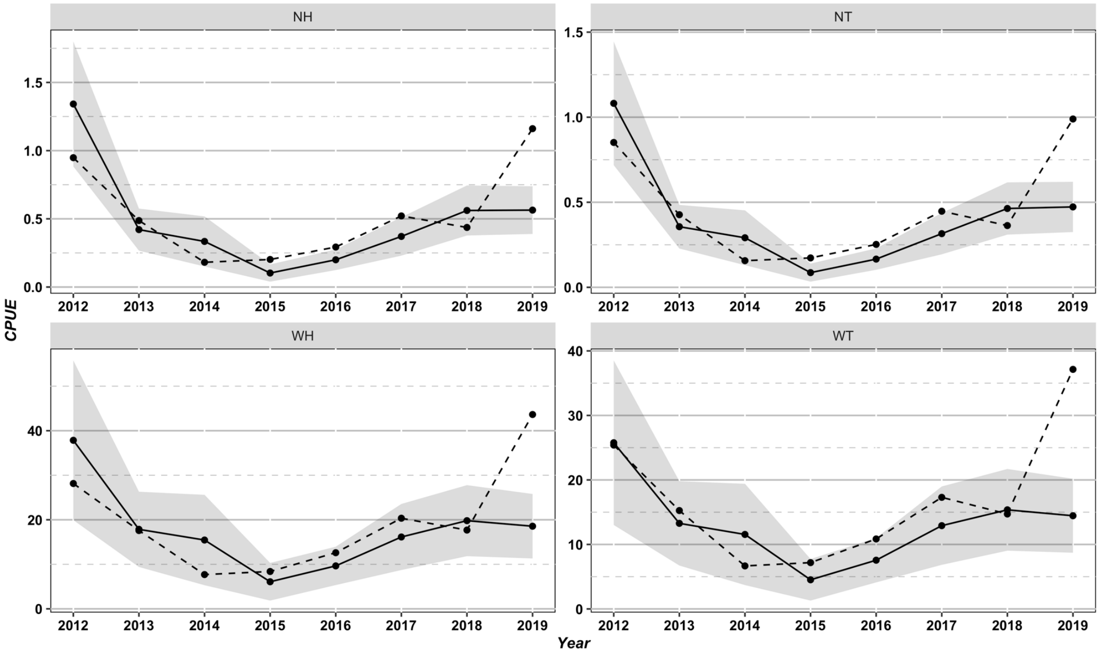

Figure 3 Annual comparison of the four CPUEs from 2012 to 2019. Nominal CPUE, standardized CPUE, and 95% confidence intervals are included. The dashed line is the nominal CPUE, the solid black line is the standardized CPUE, and the shaded area is the 95% confidence interval. NH is the CPUE in the form of the combination of the catch in number and the number of hooks; NT is the CPUE in the form of the combination of the number of catches and the soak time of hooks; WH is the CPUE in the form of the combination of the catch in weight and the number of hooks; WT is the CPUE in the form of the combination of the weight of catches and the soak time of hooks.

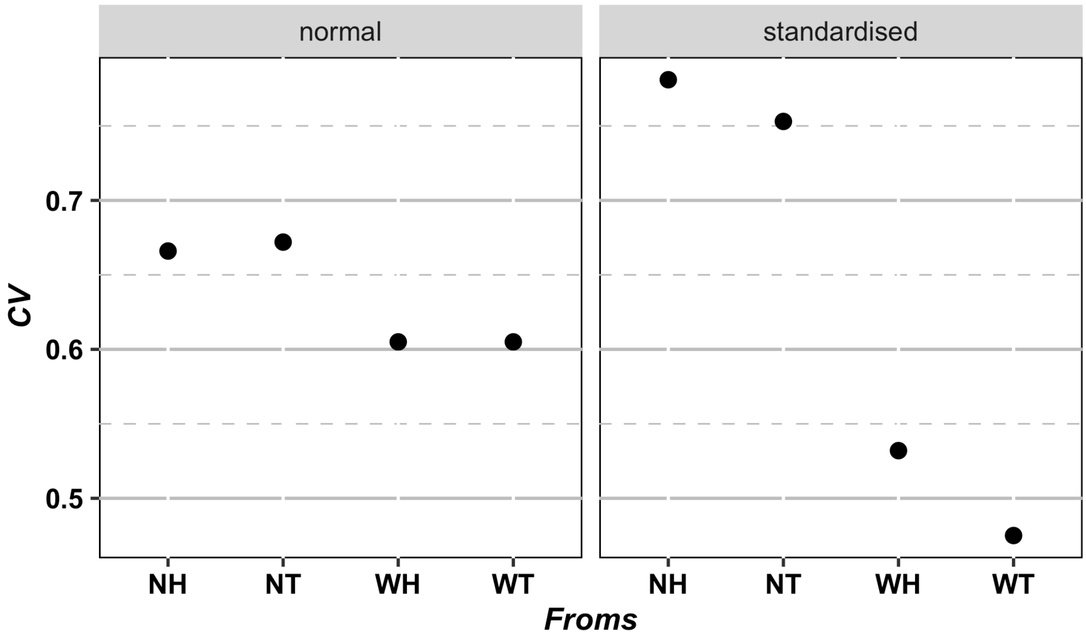

Figure 4. Coefficients of variation of annual nominal CPUE and standardized CPUE for the four outcomes. NH is the CPUE in the form of the combination of the catch in number and the number of hooks; NT is the CPUE in the form of the combination of the number of catches and the soak time of hooks; WH is the CPUE in the form of the combination of the catch in weight and the number of hooks; WT is the CPUE in the form of the combination of the weight of catches and the soak time of hooks.

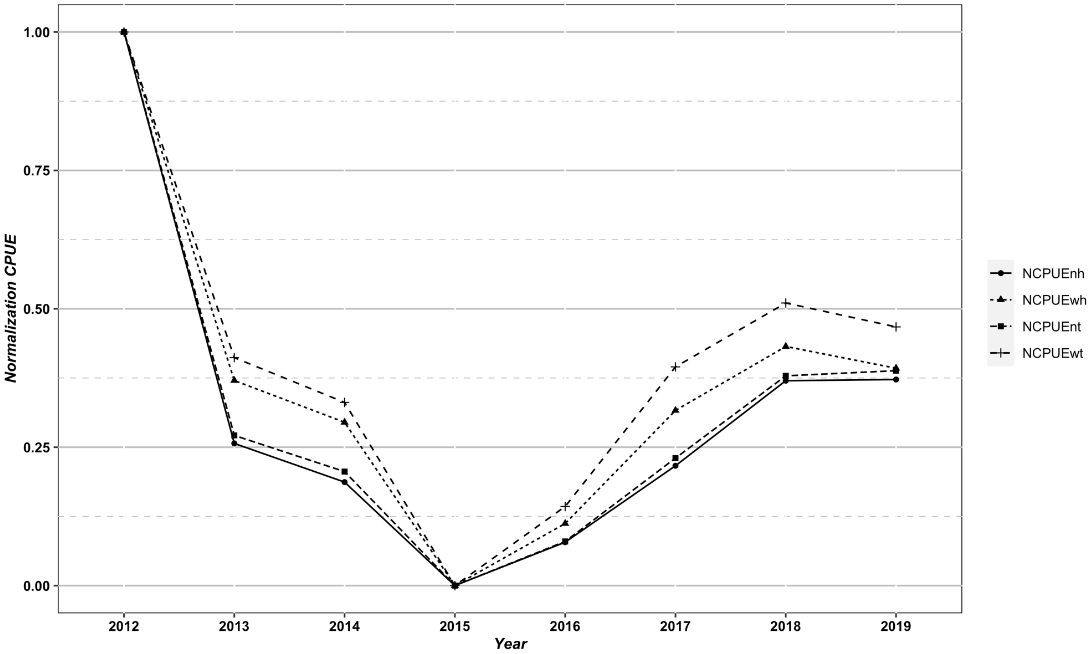

Figure 5 Comparison of the four forms of annual normalized CPUE after standardization from 2012 to 2019. NCPUEnh is the normalized CPUE in the form of the combination of the catch in number and the number of hooks; NCPUEnt is the normalized CPUE in the form of the combination of the of catch in number and the soak time of hooks; NCPUEwh is the normalized CPUE in the form of the combination of the catch in weight and the number of hooks; NCPUEwt is the normalized CPUE in the form of the combination of the catch in weight and the soak time of hooks.