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# Update standardized CPUE for North Pacific albacore caught by the Japanese longline data from 1976 to 2018

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## Summary

In this document, adult abundance indices (i.e. standardized CPUEs) of albacore were calculated from operational data reported by Japanese longline fisheries for definition of area 2 as an input data for stock assessment in 2020. Data of quarter 1 in the period between 1996 to 2018 were used, since the operational patterns (hooks per basket) were stable in the season and it was the main fishing season of longline targeted this species. Considering necessity of the calculation of coefficient of variation of standardized CPUE, we carried out generalize liner mixed model analysis with Bayesian inference for the CPUE standardization. The standardized CPUE calculated in this document used the same procedures and assumptions of previous study (Ochi et al., 2017), which showed similar trends with the previous CPUE values, indicating that it can be a candidate for the next stock analysis.

## Introduction

Abundance index (i.e. standardized CPUE) as an input data for the stock assessment model is usually calculated from operational data with statistical modeling methods such as a generalized liner model (GLM, Maunder and Punt 2004). In the case of albacore, the abundance indices of juveniles are obtained from the data of pole-and-line (Kinoshita et al. 2016), while that of adults are based on longline fisheries data (Ijima et al. 2014). When applying the GLM to the CPUE standardization, however, it is difficult to consider factors that affect variance of CPUE estimation such as operation areas or vessel IDs. Besides, it is also difficult to calculate accurate coefficient of variation (CVs) for each standardized CPUE by GLM with maximum likelihood estimation which is required in the in the stock assessment model (Stock Synthesis). To cope with these difficulties, arbitrary CV values have been input in the past stock assessment models for the north Pacific albacore stocks. To improve the model settings and reduce uncertainty, Ochi et al. (2017) had implemented to calculate data-oriented CV with the Bayesian inference methods.

The Bayesian inference is considered preferable to the maximum likelihood method for the CPUE standardization because accuracy of the prediction such as coefficient of variation can be easily calculated from its posterior distribution. Ochi et al. (2017) showed the standardized CPUE and CV by using the generalized liner mixed with Bayesian inference methods from Japanese longline fisheries data, and the results were determined reasonable to use in the stock assessment model as an input data as adult abundance indices (ISC 2017).

In this document, the Japanese longline fishery data was updated for the period 1976-2018 and the standardized CPUE with CV was calculated as using the same methods of Ochi et al. (2017), then the trends of the standardized CPUE compared to the previous results in 2017 was discussed. In addition, we calculated the juvenile abundance indices which is the standardized CPUE and CV based on the data of Japanese longline fisheries operated relatively in high latitudinal areas (Fig. 1a). Although the juvenile abundance indices have been estimated based on the pole-and-line fishery data as shown in the stock assessment in 2017 (Kinoshita et al. 2016), the CPUE trends based on the longline would provide a comprehensive perspective for this species.

## Data and Methods

### Fisheries Data

*Updated data and the data period*

Longline operational datasets include the number of albacore caught, year, quarter, location type of fleet (Distant, Offshore, Coastal), hooks per basket, total hooks and vessel ID for each operation. We updated the data during 1976-2018 and compared the updated data to the previous study (Ochi et al., 2017) in the number of records and the number of albacore caught for each year, which is shown in Table 1. As the summary of the data, decadal spatial distributions of albacore catch, effort (number of hooks) and nominal CPUE (catch/effort*1000) are illustrated in Figure 2.

Because the number of hooks per basket and vessel IDs were not available in the data recorded during 1971-1975, the operational data from 1976 were used for the analysis. Additionally, the data format and target range of the data collection was changed in 1994. The longline operation patterns targeted albacore had changed significantly in 1990s (Ochi et al., 2017), and the hooks per basket stabilized around 15 to 20 after 1994. Ijima et al. (2017) also described that catch at length of the longline fishery in area 2 had an obvious shift in the middle of the 1990s. These previous studies have been implying the need for reduction of uncertainty in the estimation of standardized CPUE due to variations in the operational patterns. Therefore, the previously calculated standardized CPUE along with the stock assessment in 2017 employed the data from 1996 (Ochi et al., 2017; ISC 2017). The calculation of the standardized CPUE in this document also adhere the previous studies and the stock assessment, thus employed the data from 1996 to 2018.

*Definition of area and quarter for adult and juvenile abundance indices*

Considering the migration patterns of this species recognized so far (Fig. 1a), Longline operational data recorded in Japanese logbook was used for the calculation of the adult abundance index in area 2 and juvenile abundance index in area 1 & 3 (Fig. 1b). In this documents, the area was defined from the catch at length frequency recorded in the longline fishery operating areas (Ijima et al., 2017) and by following the previous studies (Ochi et al., 2017; ISC 2017). The data period selected for the analysis was based on the quarter 1 with higher albacore catches compared to other the quarters (Table 2) for both juvenile and adult abundance indices. Area 2 had larger fish (adults) regardless of quarters in the catch at length data compared to area 1 & 3 that observed smaller juveniles especially in 1-2 quarters (Ijima et al., 2017). These trends are shown in Figure 3a and 3b, with decadal spatial distributions of albacore catch, effort (number of hooks) and nominal CPUE (catch/effort*1000) in area 2 and area 1 & 3. Appendix A and B also show the same data in area 4 and 5.

**CPUE standardization**

Generalized liner mixed model (GLMM) was applied for the estimation of the standardized CPUE. It is expected to better explain CPUE variation among vessels and operation areas without over-estimation by assuming these variables as random factors than GLM which was used in the past analysis (Ijima et al., 2014). Because the dataset includes reasonable number of zero catch operations (Ochi et al., 2017), zero-inflated negative binomial (ZINB) error distribution had been adopted. The ZINB distribution is characterized by mixture of Bernulli distribution with parameter $p$ (rate of zero-occurrence) and negative binomial distribution with parameters $\mu$ (mean) and $\theta$ (scale). Probability mass functions of Bernulli and negative binomial distribution were calculated as below.

$$Bernoulli(y|\theta) = \begin{cases} \theta & if\ y = 1 \\ 1-\theta & if\ y = 0 \end{cases}$$

$$NegBinomial(y|\alpha,\beta) = \binom{y+\alpha-1}{\alpha-1}\left(\frac{\beta}{\beta+1}\right)^{\alpha}\left(\frac{1}{\beta+1}\right)^{y}$$

Catch number of albacore in the $i$th operation ($ALBcatch_i$) is described as below.

$$ALBcatch_i \sim \begin{cases} Bernulli(0|p) + Bernulli(1|p) \times NegBinomial(ALBcatch_i = 0|\mu,\theta) & if\ ALBcatch_i = 0 \\ Bernulli(1|p) \times NegBinomial(ALBcatch_i = 0|\mu,\theta)) & if\ ALBcatch_i > 0 \end{cases}$$

and $p$, $\mu$ and $\theta$ were extended by following equations.

$$\mu = exp\left(log(\widehat{cpue}_i) + log\,(\frac{hooks_i}{1000})\right)$$

$$logit(p) = \alpha_z + \beta_{z1}yr_i + \beta_{z2}qtr_i + \beta_{z3}hpb_i + \beta_{z4}fleet_i + r_{zlatlon_i} + r_{zid_i}$$

$$log(\widehat{cpue}_i) = \alpha + \beta_1 yr_i + \beta_2 qtr_i + \beta_3 hpb_i + \beta_4 fleet_i + r_{latlon_i} + r_{id_i}$$

$$r_{latlon_i} \sim Normal(0,\, {\sigma_1}^2);\; r_{id_i} \sim Normal(0,\, {\sigma_2}^2)$$

$$\theta \sim HalfCauchy(25);\; {\sigma_1}^2 \sim HalfCauchy(25);\; {\sigma_2}^2 \sim HalfCauchy(25)$$

$$r_{zlatlon_i} \sim Normal(0,\, {\sigma_{z1}}^2);\; r_{zid_i} \sim Normal(0,\, {\sigma_{z2}}^2)$$

$${\sigma_{z1}}^2 \sim HalfCauchy(25);\; {\sigma_{z2}}^2 \sim HalfCauchy(25)$$

where *i* indicates operation id, $\widehat{cpue}$ indicates expected CPUE, *ALBcatch* and *hooks* indicates albacore catch in number and number of hooks in each operation, $\theta$ indicates scale parameter, *yr*, *qtr*, *hpb* and *fleet* indicate operation year (categorical), quarter (categorical), hooks per basket (categorical) and fleet type (categorical; 3 categories; distant, offshore and coastal), respectively. $\beta_1$ - $\beta_4$ and $\beta_{z1}$ - $\beta_{z4}$ indicate vectors of coefficients of *yr*, *qtr*, *hpb* and *fleet*, $r_{latlon}$, $r_{id}$, $r_{zlatlon}$ *and* $r_{zid}$, indicate random effects of operation area (5°×5°grid; categorical)) and vessel identity (categorical), $\sigma_1^2$, $\sigma_2^2$, $\sigma_{z1}^2$ and $\sigma_{z2}^2$ indicate variance of random variables.

Posteriors and predicted standardized CPUE were calculated with the variational Bayesian method (Automatic differentiation variational inference, ADVI).

The standardized CPUE in specific year *yr* ($stdCPUE_{yr}$) was calculated based on the framework of *lsmeans* as described below.

$$predictedCPUE_{ij} = exp\left(\widehat{\alpha}_i + \hat{\beta}_{1,ij} + \hat{\beta}_{2,ij}qtr_j + \hat{\beta}_{3,ij}hpb_j + \hat{\beta}_{4,ij}fleet_j\right)$$

$$lsmean_i = \frac{1}{N_j}\sum_{j=1}^{N_j}\left(predictedCPUE_{ij}\right)$$

$$stdCPUE_{yr} = \left\{\frac{1}{N_i}\sum_{i=1}^{N_i} lsmean_i\right\}$$

$$N_j = K \times L \times M\,;\; N_i = 500$$

where $N_i$ indicates total number of iterations in ADVI algorism. In Bayesian inference, each set of estimated parameters (i.e., posteriors) in the model was repeatedly calculated along with the likelihood function of the model. $N_j$ indicates total cases of prediction dataset which includes all possible combination of explanatory variables without variables of random effect in year *yr*. *K, L* and *M* indicates number of categories in quarter, hooks per basket and fleet type. $\widehat{\alpha}_i$ and $\hat{\beta}_1 - \widehat{\beta}_4$ indicates estimated posteriors of each coefficient and intercept, respectively. Therefore, 95% Bayesian credible interval and CV of standardized CPUE could be calculated from *lsmean* based on the posteriors. Calculated standardized CPUEs and CVs were shown in Table 3.

We used R 3.6.1 for data processing and summarizing the estimation output, and Stan 2.18.2 (http://mc-stan.org/) for parameter estimation by automatic differential variational inference (ADVI). The ADVI algorism maximizes its lower bound of marginal likelihood (ELBO) by automatic differentiation. Thus, only converged model was adopted for the latter results of the analysis.

**Results and Discussion**

As the adult abundance indices, the standardized CPUE calculated in this document shows similar fluctuation trends with that of Ochi et al. (2017) (Fig. 5), although those values were slightly lower among years compared to previous study in the period 1996-2015. Updated standardized CPUE for each year of 2016-2018 were 25.9, 27.3, 31.0, respectively. With the data summary, calculated standardized CPUEs, fitted value of the GLMM and Pearson residuals of adults were illustrated in Figure 4a. Also, these values of juveniles are shown in Figure 4b. Yearly trends of standardized CPUE remained approximately at the same level since 2000 to the present with several peaks (Figure 4b). When we examined the timing of these prominent peaks between juvenile and adult indices (Fig. 6), it was detected five peaks showing that an adult peaks appearance after 3 years from a juvenile peak. This means that their migration patterns were properly reflected in the catch at length data of the longline fishery, and the area definition and seasons defined for the standardization were set appropriately. In the future, further quantitative analysis will be required. Calculated values of standardized CPUEs and CVs for both adult and juvenile abundance indices were given in Table 3.

**Reference**

Ijima, H. and Satoh, K. (2014) Abundance indices of albacore tuna for the Stock Synthesis III by Japanese longline fishery in the north west Pacific Ocean. ISC/14/ALBWG-01.

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Kinoshita, J., Ochi, D. and Kiyofuji, H. (2016) Update standardized CPUE for North Pacific albacore caught by the Japanese pole and line data from 1972 to 2015. ISC/16/ALBWG-02/04.

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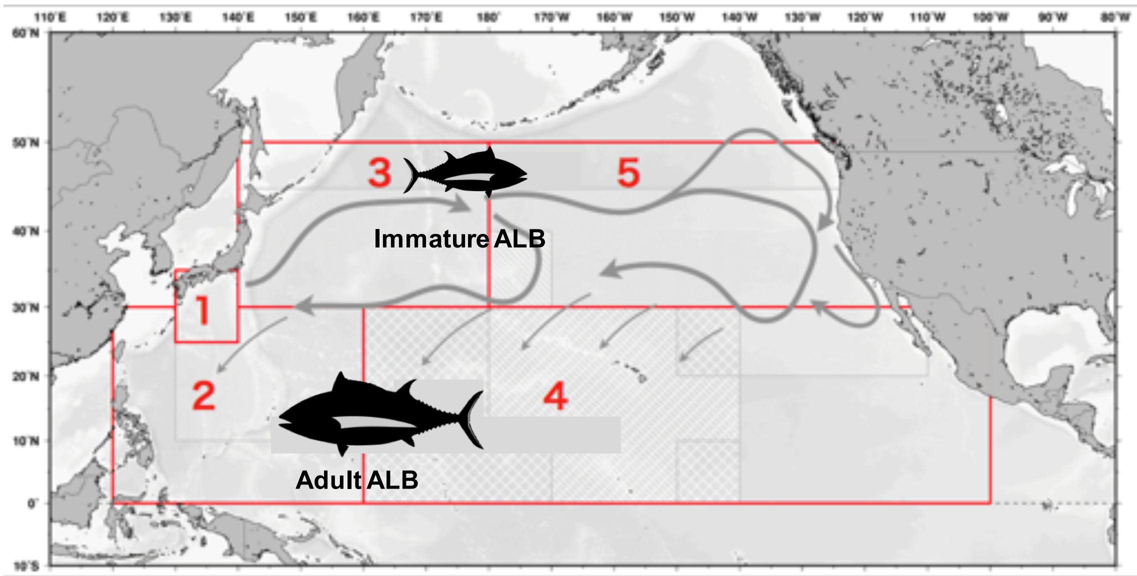
Kiyofuji, H. (2014) Update standardized CPUE for North Pacific albacore caught by the Japanese pole and line data. ISC/14/ALBWG-01/06.

Maunder, M. N., and Punt, A. E. (2004). Standardizing catch and effort data: a review of recent approaches. Fisheries Research, 70(2), 141-159.

Ochi, D., Ijima, H., Kinoshita, J. and Kiyofuji, H. (2016) New fisheries definition from Japanese longline North Pacific albacore size data. ISC/16/ALBWG-02/03

Ochi, D., Ijima, H. and Kiyofuji, H. (2017) Abundance indices of albacore caught by Japanese longline vessels in the North Pacific during 1976-2015. ISC/17/ALBWG/01

(a)

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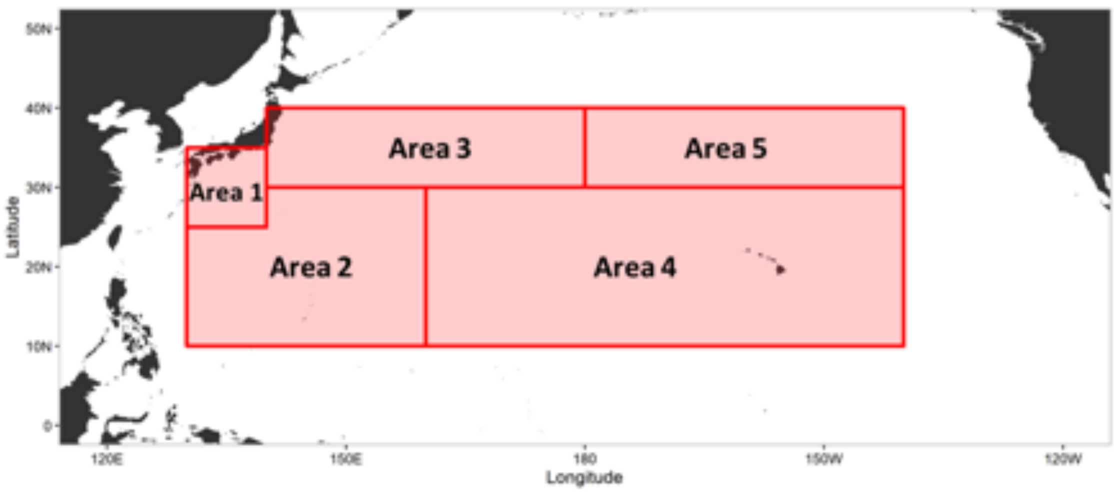



**Figure 1.** (a) A schematic model of migration pathways of immature and adult albacore (*Thunnus alalunga*), and the five areas used in the stock assessment models in 2017. (b) The area definition of Japanese longline fisheries and target areas of this study which are considered as core areas of albacore distribution.

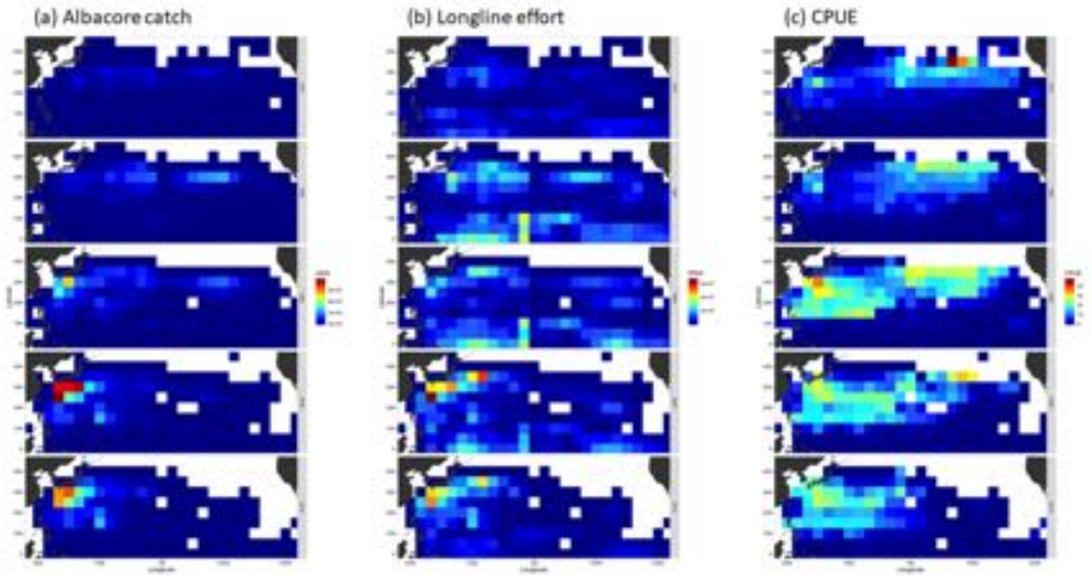
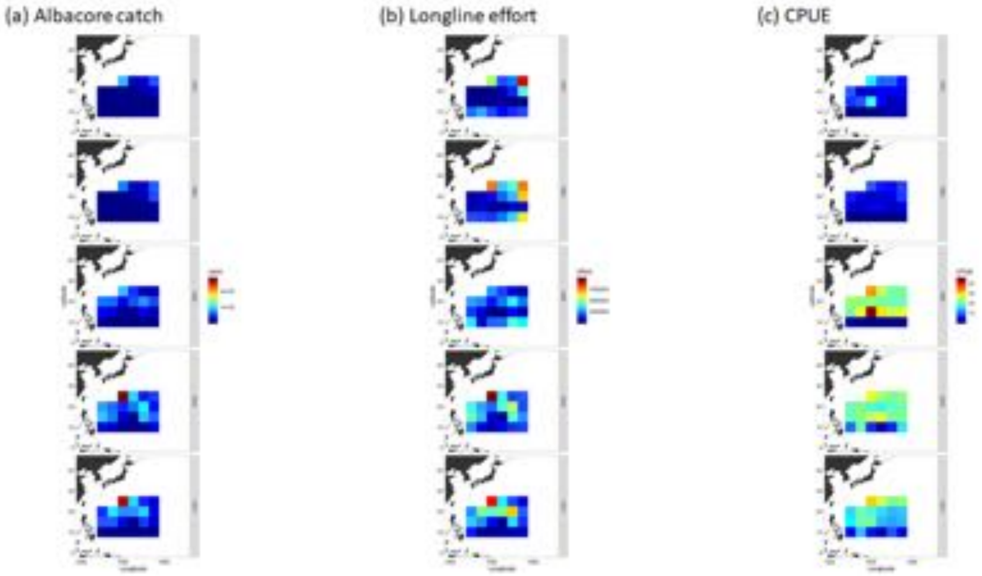



**Figure 2.** Decadal spatial distributions of (a) albacore catch, (b) effort (number of hooks), and (c) CPUE (catch/effort*1000) that were aggregated by 5 × 5 degrees in the all area during 1976-2018.

Quarter 1




Quarter 2

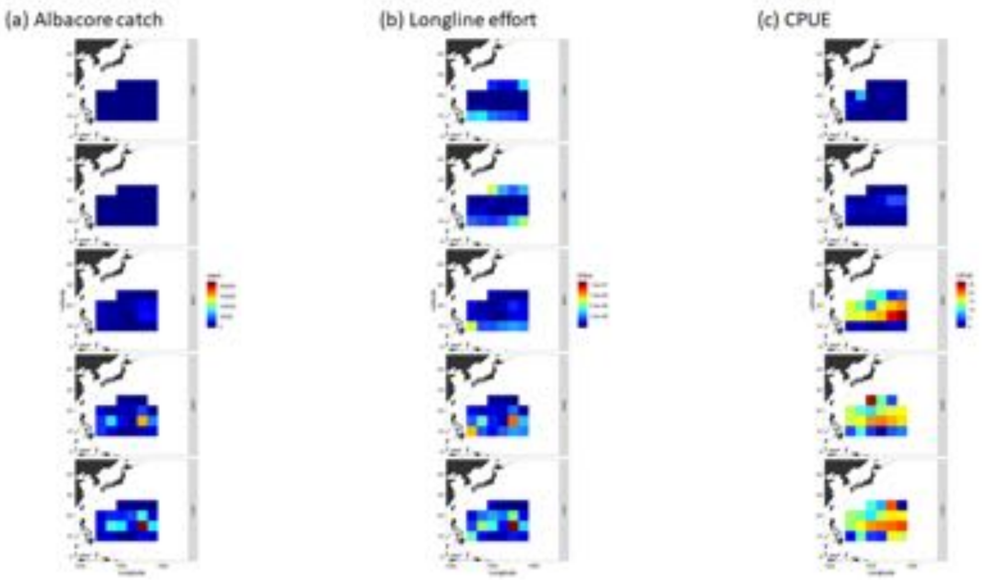
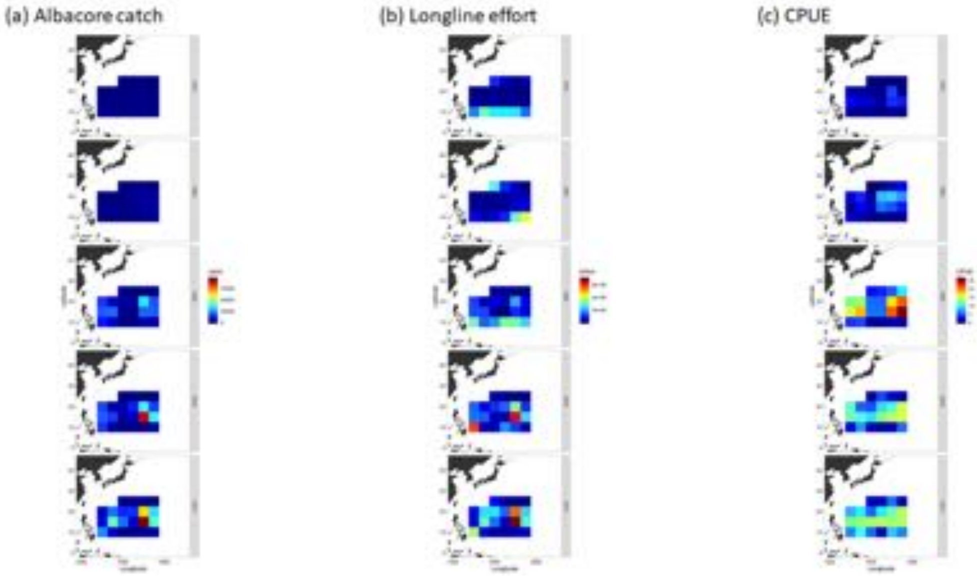



**Figure 3a.** Decadal spatial distributions of (a) albacore catch, (b) effort (number of hooks), and (c) CPUE (catch/effort*1000) in area 2 that were aggregated by 5 × 5 degrees during 1976-2018.

Quarter 3




Quarter 4

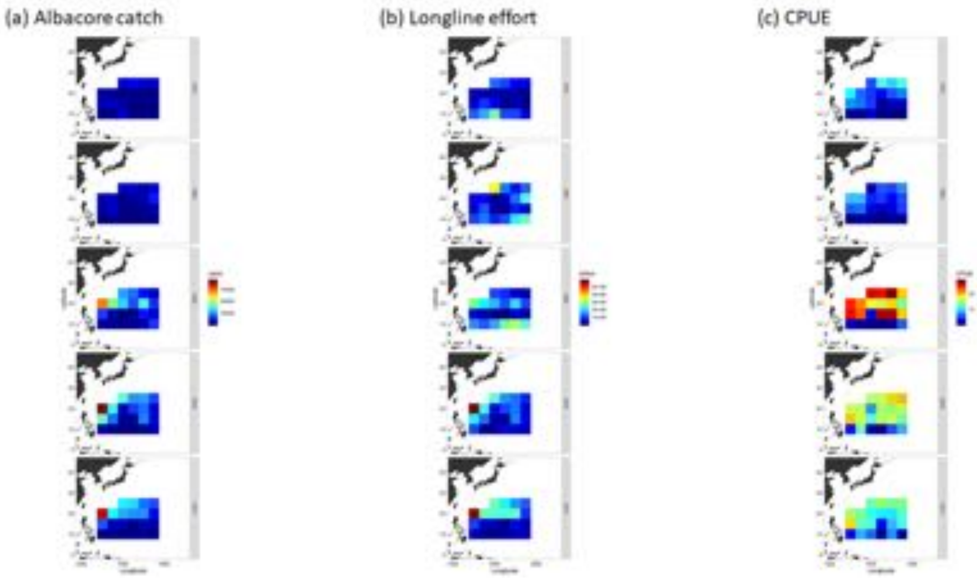
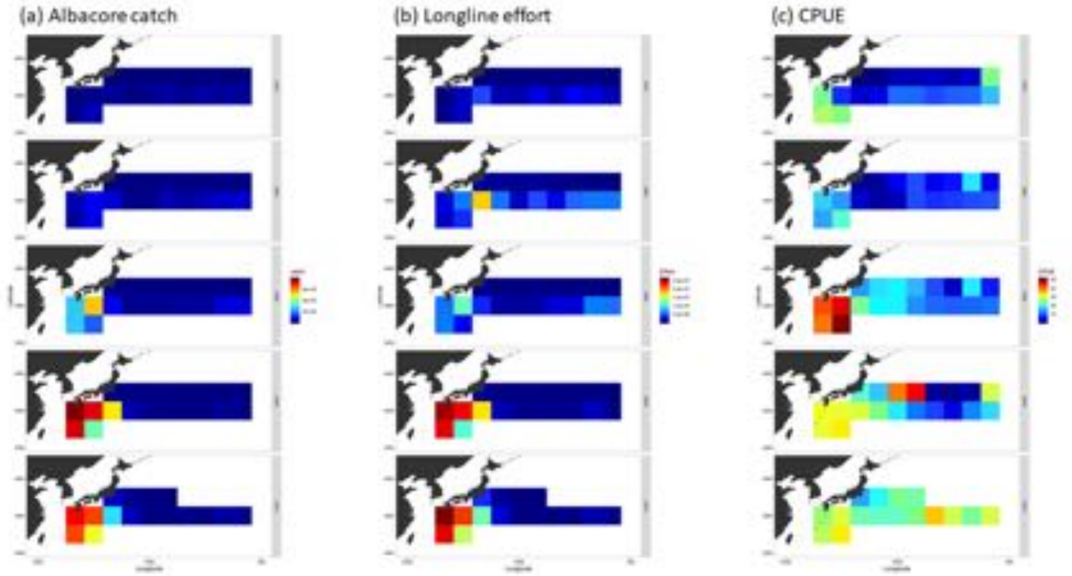



**Figure 3a.** *Continue*

Quarter 1




Quarter 2

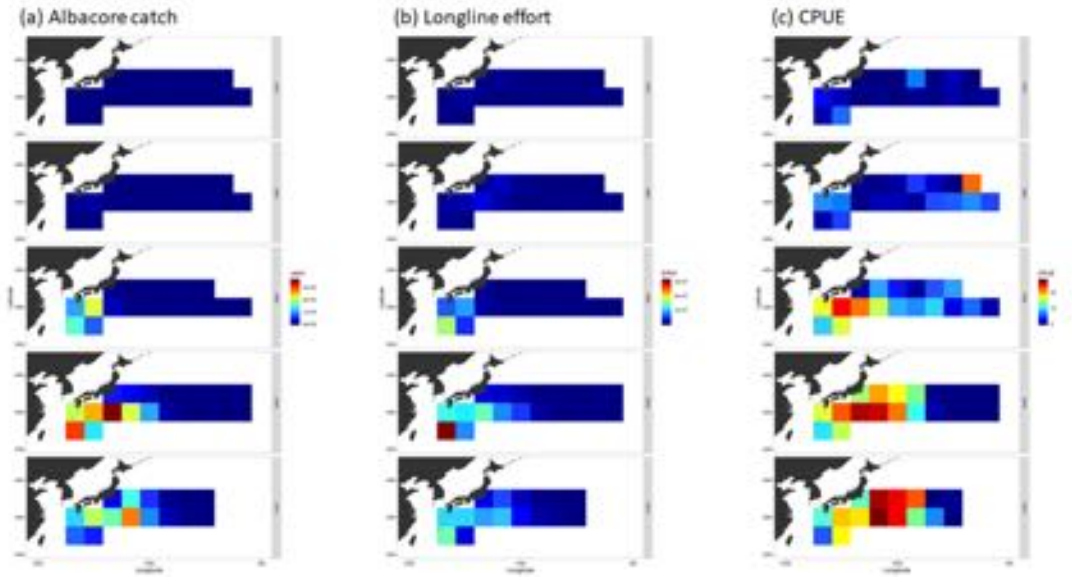
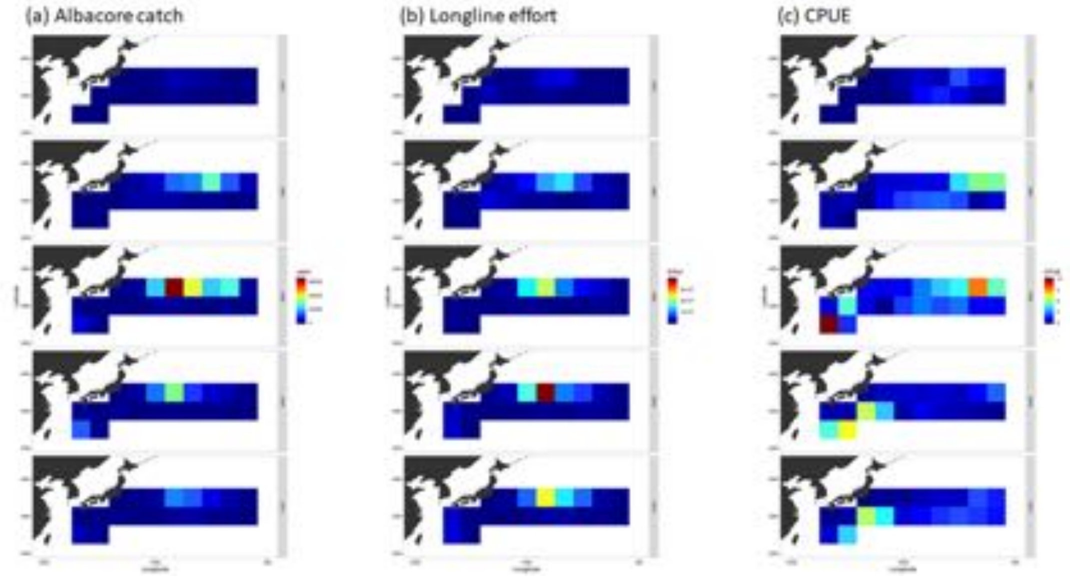



**Figure 3b.** Decadal spatial distributions of (a) albacore catch, (b) effort (number of hooks), and (c) CPUE (catch/effort*1000) in area 1 & 3 that were aggregated by 5 × 5 degrees during 1976-2018.

Quarter 3




Quarter 4

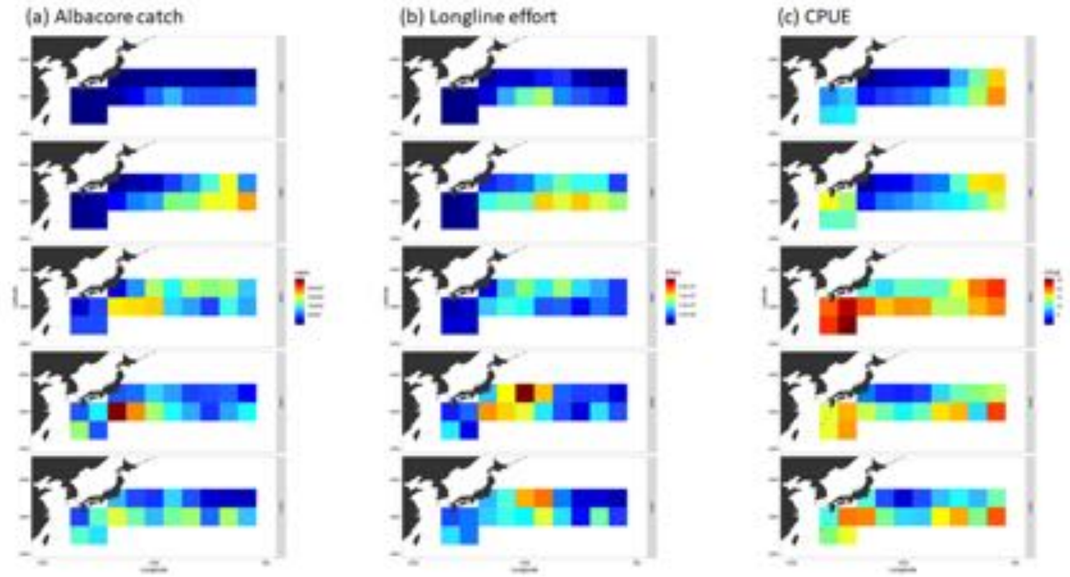



**Figure 3b.** *Continue*

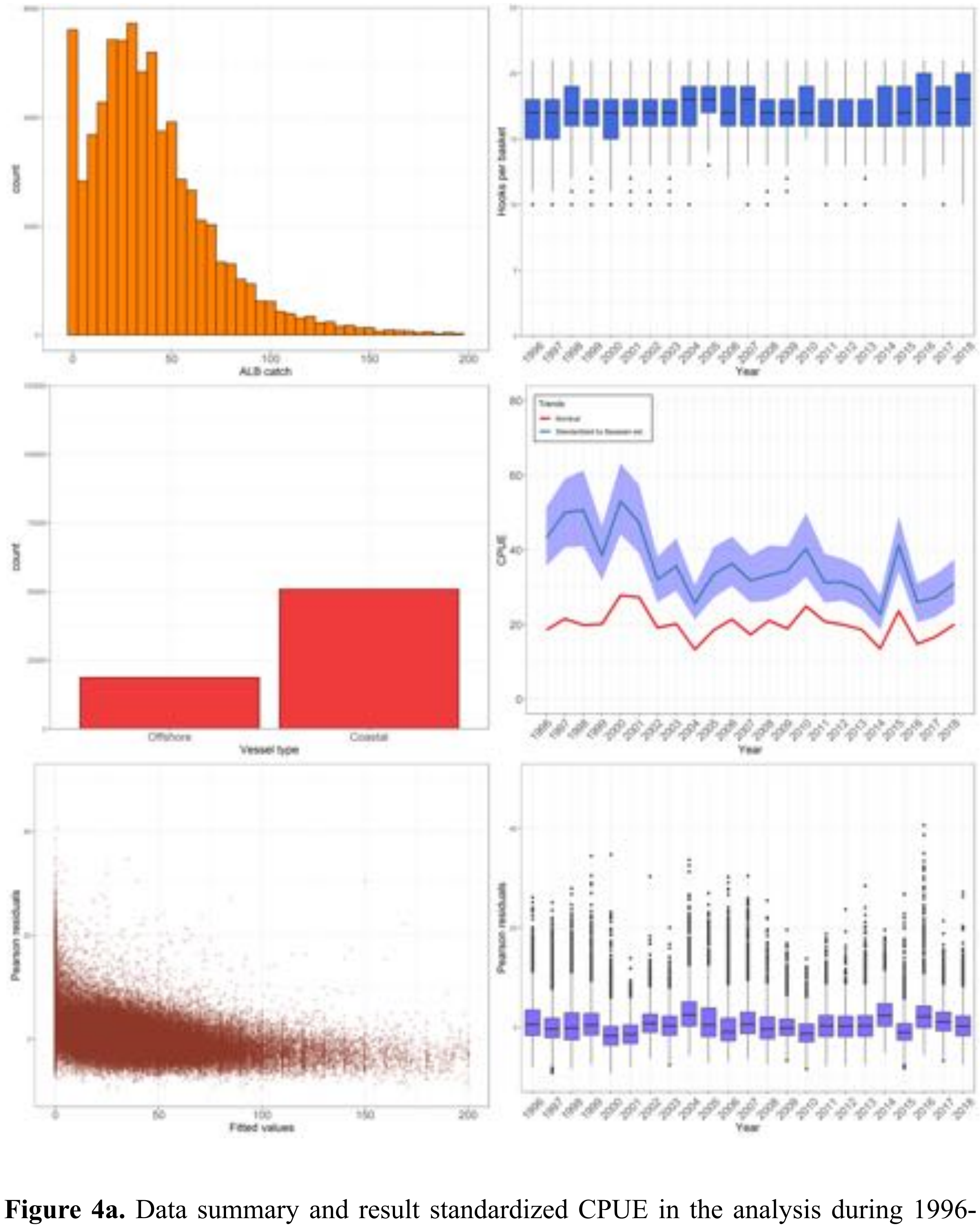



**Figure 4a.** Data summary and result standardized CPUE in the analysis during 1996-2018 in area 2 of quarter 1. Distribution of albacore catch (left top), annual change of hooks per basket (right top), frequency of fleet type (left middle), nominal and standardized CPUE and 95% Bayesian credible interval (blue shaded area; right middle), scatter plot between fitted value of the GLMM and Pearson residuals (left bottom), and distribution of Pearson residuals in each year (right bottom).

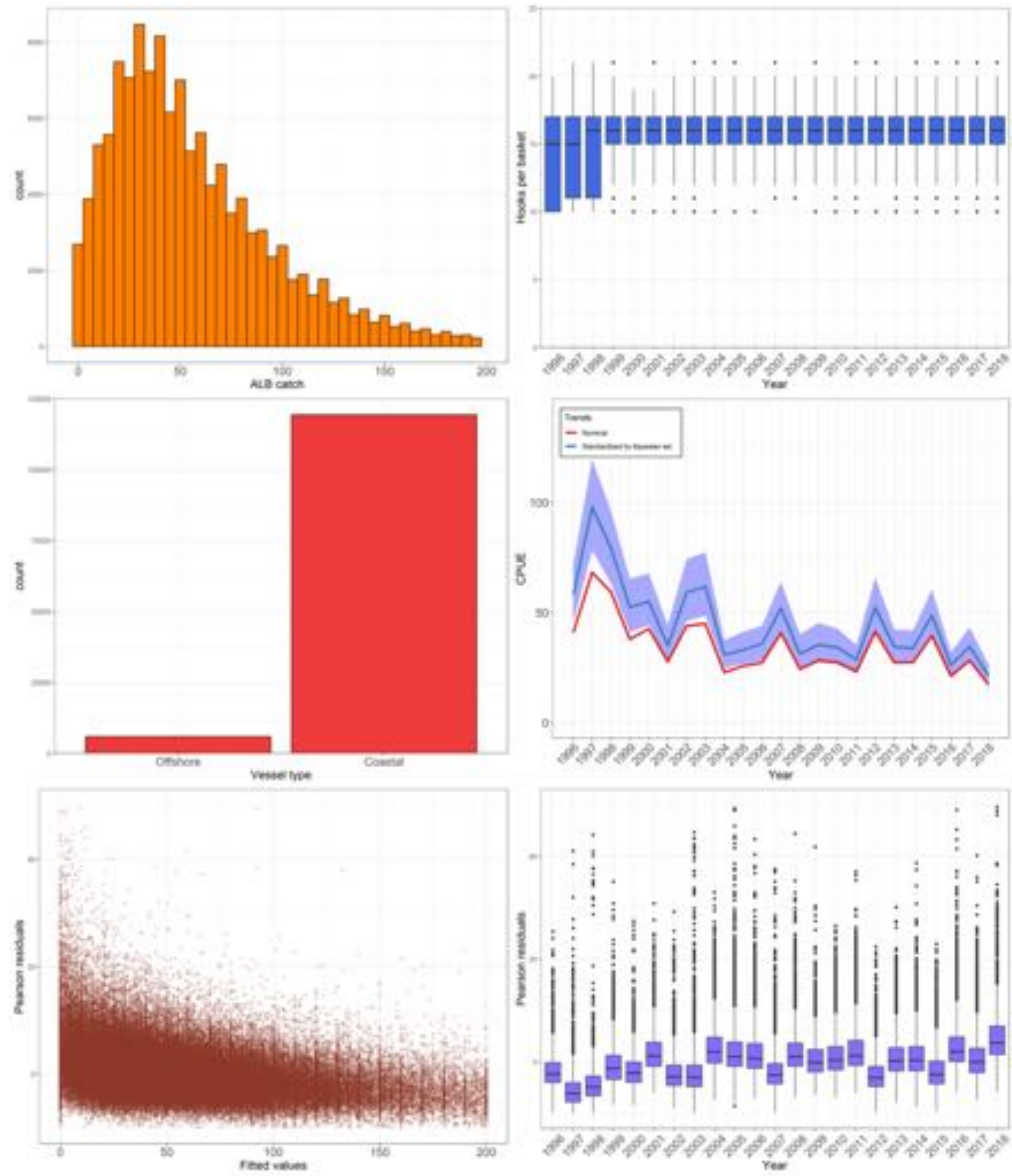



**Figure 4b.** Data summary and result standardized CPUE in the analysis during 1996-2018 in area 1 & 3 of quarter 1. Distribution of albacore catch (left top), annual change of hooks per basket (right top), frequency of fleet type (left middle), nominal and standardized CPUE and 95% Bayesian credible interval (blue shaded area; right middle), scatter plot between fitted value of the GLMM and Pearson residuals (left bottom), and distribution of Pearson residuals in each year (right bottom).

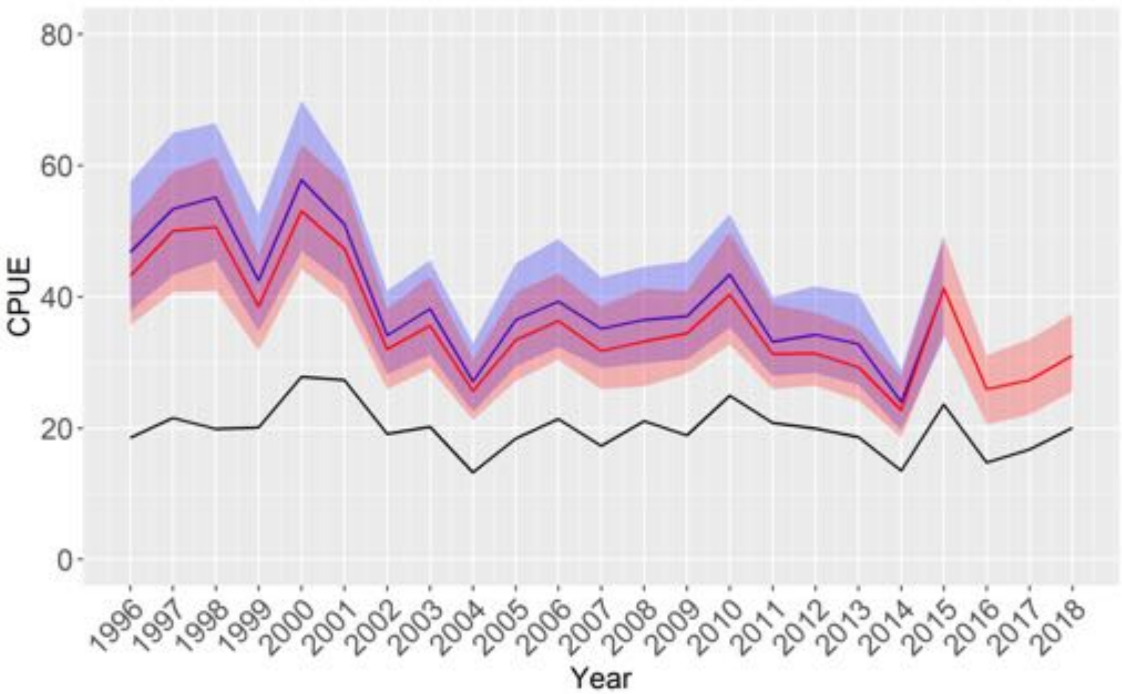



**Figure 5.** Comparison of two standardized CPUEs with 95% Bayesian credible interval (blue; Ochi et al. 2017, red; the present study) and nominal CPUE (black) in area 2.

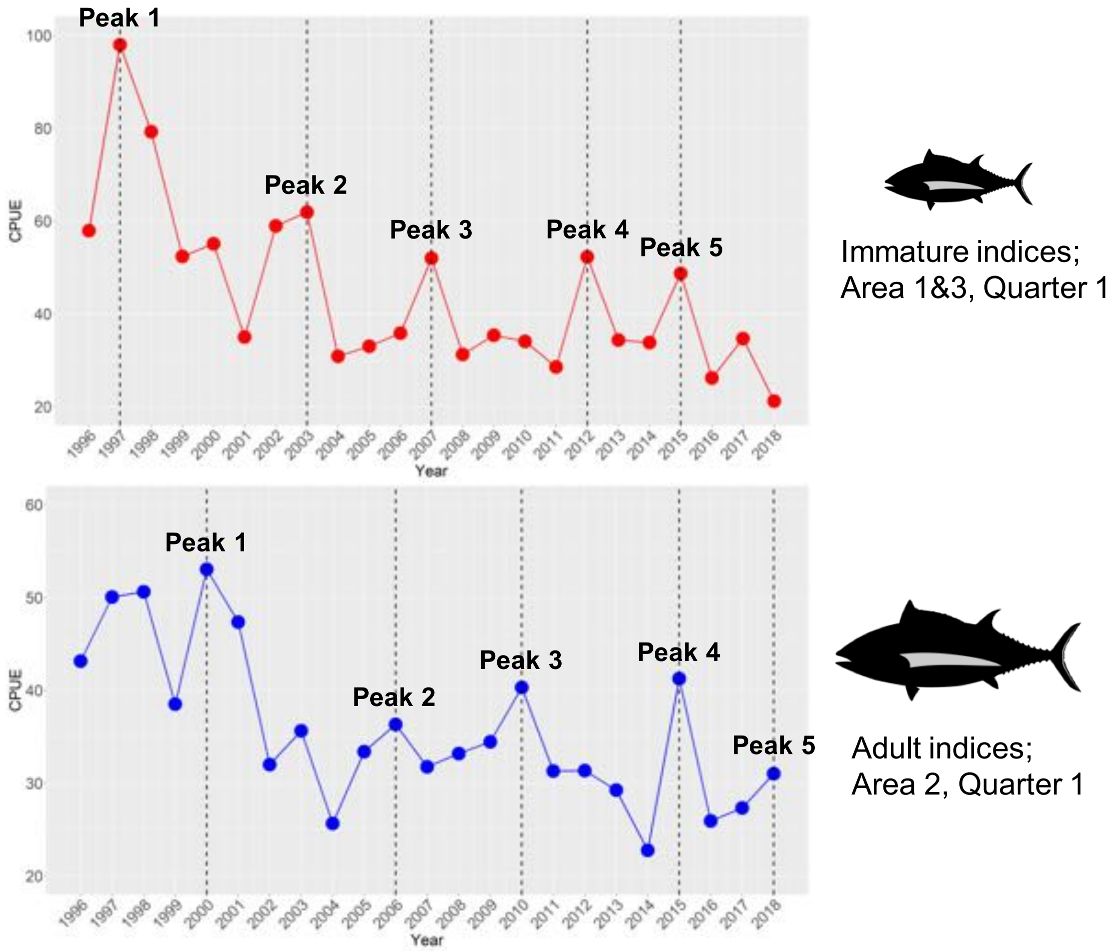



**Figure 6.** Comparison of immature abundance index (top) and adult abundance index (bottom) (i.e., standardized CPUEs) in the period 1996-2018. The peaks that correspond to each index with time-lags are numbered.

**Table 1** Summary of updated longline operational data between 1976 and 2018 compared with previous data used in the stock assessment 2017 (Ochi et al. 2017).

| | Number of total records | | | Number of ALB catches | | | |
|---|---|---|---|---|---|---|---|
| Year | Ochi et al. 2017 | Present | Differences | Ochi et al. 2017 | Present | Differences | Updated catch rate |
| 1976 | 184,952 | 184,952 | 0 | 881,781 | 881,781 | 0 | 0 |
| 1977 | 183,284 | 183,284 | 0 | 836,220 | 836,220 | 0 | 0 |
| 1978 | 184,291 | 184,291 | 0 | 723,254 | 723,254 | 0 | 0 |
| 1979 | 220,229 | 220,229 | 0 | 952,351 | 952,351 | 0 | 0 |
| 1980 | 236,820 | 236,820 | 0 | 990,846 | 990,846 | 0 | 0 |
| 1981 | 246,888 | 246,888 | 0 | 1,422,739 | 1,422,739 | 0 | 0 |
| 1982 | 223,291 | 223,291 | 0 | 1,289,776 | 1,289,776 | 0 | 0 |
| 1983 | 200,810 | 200,810 | 0 | 1,217,265 | 1,217,265 | 0 | 0 |
| 1984 | 211,832 | 211,832 | 0 | 1,180,879 | 1,180,879 | 0 | 0 |
| 1985 | 204,778 | 204,778 | 0 | 1,145,105 | 1,145,105 | 0 | 0 |
| 1986 | 202,123 | 202,123 | 0 | 1,064,261 | 1,064,261 | 0 | 0 |
| 1987 | 195,750 | 195,750 | 0 | 1,013,851 | 1,013,851 | 0 | 0 |
| 1988 | 195,092 | 195,092 | 0 | 1,124,801 | 1,124,801 | 0 | 0 |
| 1989 | 193,051 | 193,051 | 0 | 994,689 | 994,689 | 0 | 0 |
| 1990 | 187,018 | 187,018 | 0 | 1,139,052 | 1,139,052 | 0 | 0 |
| 1991 | 190,861 | 190,861 | 0 | 1,080,452 | 1,080,452 | 0 | 0 |
| 1992 | 177,520 | 177,520 | 0 | 1,158,391 | 1,158,391 | 0 | 0 |
| 1993 | 173,546 | 173,546 | 0 | 1,489,594 | 1,489,594 | 0 | 0 |
| 1994 | 213,174 | 213,174 | 0 | 2,315,490 | 2,315,490 | 0 | 0 |
| 1995 | 215,780 | 215,780 | 0 | 2,315,871 | 2,315,871 | 0 | 0 |
| 1996 | 209,736 | 209,736 | 0 | 2,373,051 | 2,373,051 | 0 | 0 |
| 1997 | 201,354 | 201,354 | 0 | 2,681,323 | 2,681,323 | 0 | 0 |
| 1998 | 198,817 | 198,817 | 0 | 2,732,157 | 2,732,157 | 0 | 0 |
| 1999 | 179,480 | 179,480 | 0 | 2,225,648 | 2,225,648 | 0 | 0 |
| 2000 | 178,368 | 178,368 | 0 | 2,029,797 | 2,029,797 | 0 | 0 |
| 2001 | 180,748 | 180,748 | 0 | 2,122,987 | 2,122,987 | 0 | 0 |
| 2002 | 171,149 | 171,149 | 0 | 1,987,395 | 1,987,395 | 0 | 0 |
| 2003 | 171,374 | 171,374 | 0 | 1,770,829 | 1,770,829 | 0 | 0 |
| 2004 | 165,426 | 165,426 | 0 | 1,798,401 | 1,798,401 | 0 | 0 |
| 2005 | 155,365 | 155,365 | 0 | 2,147,369 | 2,147,369 | 0 | 0 |
| 2006 | 147,553 | 147,553 | 0 | 2,131,829 | 2,131,829 | 0 | 0 |
| 2007 | 138,882 | 138,882 | 0 | 2,071,064 | 2,071,064 | 0 | 0 |
| 2008 | 132,954 | 132,954 | 0 | 1,831,252 | 1,831,252 | 0 | 0 |
| 2009 | 123,737 | 123,737 | 0 | 1,951,172 | 1,951,172 | 0 | 0 |
| 2010 | 123,719 | 123,719 | 0 | 1,973,829 | 1,973,829 | 0 | 0 |
| 2011 | 115,687 | 115,712 | 25 | 1,955,538 | 1,956,577 | 1,039 | 0.1 |
| 2012 | 111,711 | 112,077 | 366 | 2,380,636 | 2,390,665 | 10,029 | 0.4 |
| 2013 | 102,234 | 102,692 | 458 | 2,075,021 | 2,084,455 | 9,434 | 0.5 |
| 2014 | 94,506 | 95,431 | 925 | 1,841,719 | 1,862,206 | 20,487 | 1.1 |
| 2015 | 81,721 | 88,576 | 6,855 | 1,752,529 | 1,863,047 | 110,518 | 6.3 |
| 2016 | | 86,905 | | | 1,485,119 | | |
| 2017 | | 81,968 | | | 1,437,119 | | |
| 2018 | | 78,382 | | | 1,215,975 | | |

**Table 2** Annual albacore catches by quarter in each area, and the colors indicate catch levels (red; high, white; middle, blue; low).

| | Area 1 | | | | Area 3 | | | | Area 1&3 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 |
| 1976 | 21,531 | 1,540 | 0 | 421 | 1,930 | 274 | 2,014 | 7,907 | 23,461 | 1,814 | 2,014 | 8,328 |
| 1977 | 41,746 | 234 | 4 | 1,076 | 2,033 | 159 | 1,903 | 6,160 | 43,779 | 393 | 1,907 | 7,236 |
| 1978 | 4,131 | 187 | 3 | 1,450 | 1,428 | 303 | 1,096 | 7,321 | 5,559 | 490 | 1,099 | 8,771 |
| 1979 | 6,605 | 694 | 0 | 1,318 | 3,169 | 375 | 1,362 | 6,824 | 9,774 | 1,069 | 1,362 | 8,142 |
| 1980 | 21,411 | 4,155 | 0 | 370 | 1,162 | 119 | 1,599 | 8,282 | 22,573 | 4,274 | 1,599 | 8,652 |
| 1981 | 18,394 | 361 | 0 | 5,282 | 3,191 | 659 | 2,625 | 8,771 | 21,585 | 1,020 | 2,625 | 14,053 |
| 1982 | 42,443 | 1,299 | 0 | 557 | 2,998 | 376 | 4,268 | 8,061 | 45,441 | 1,675 | 4,268 | 8,618 |
| 1983 | 33,998 | 2,986 | 92 | 955 | 3,562 | 594 | 2,165 | 7,293 | 37,560 | 3,580 | 2,257 | 8,248 |
| 1984 | 17,778 | 918 | 52 | 1,594 | 2,563 | 578 | 3,491 | 9,222 | 20,341 | 1,496 | 3,543 | 10,816 |
| 1985 | 31,059 | 966 | 0 | 3,433 | 2,661 | 466 | 2,691 | 6,847 | 33,720 | 1,432 | 2,691 | 10,280 |
| 1986 | 30,148 | 1,186 | 0 | 1,696 | 2,017 | 329 | 2,390 | 6,140 | 32,165 | 1,515 | 2,390 | 7,836 |
| 1987 | 21,201 | 707 | 0 | 5,819 | 867 | 237 | 1,518 | 5,503 | 22,068 | 944 | 1,518 | 11,322 |
| 1988 | 24,308 | 3,659 | 50 | 951 | 1,881 | 244 | 2,251 | 5,079 | 26,189 | 3,903 | 2,301 | 6,030 |
| 1989 | 13,364 | 4,393 | 0 | 232 | 2,071 | 107 | 973 | 4,057 | 15,435 | 4,500 | 973 | 4,289 |
| 1990 | 25,135 | 3,617 | 0 | 1,017 | 1,281 | 87 | 905 | 4,222 | 26,416 | 3,704 | 905 | 5,239 |
| 1991 | 15,493 | 4,150 | 173 | 1,318 | 1,621 | 23 | 1,439 | 5,012 | 17,114 | 4,173 | 1,612 | 6,330 |
| 1992 | 20,375 | 7,769 | 0 | 797 | 1,280 | 25 | 708 | 3,242 | 21,655 | 7,794 | 708 | 4,039 |
| 1993 | 56,774 | 17,612 | 0 | 2,285 | 659 | 96 | 1,256 | 3,645 | 57,433 | 17,708 | 1,256 | 5,930 |
| 1994 | 191,135 | 85,000 | 25 | 8,757 | 1,643 | 88 | 3,742 | 6,633 | 192,778 | 85,088 | 3,767 | 15,390 |
| 1995 | 156,280 | 58,517 | 460 | 17,122 | 941 | 107 | 3,715 | 5,356 | 157,221 | 58,624 | 4,175 | 22,478 |
| 1996 | 182,749 | 88,878 | 457 | 12,168 | 617 | 72 | 3,132 | 4,271 | 183,366 | 88,950 | 3,589 | 16,439 |
| 1997 | 242,941 | 99,901 | 1,279 | 19,809 | 445 | 148 | 3,491 | 5,263 | 243,386 | 100,049 | 4,770 | 25,072 |
| 1998 | 279,510 | 84,781 | 1,176 | 38,114 | 326 | 204 | 4,910 | 5,812 | 279,836 | 84,985 | 6,086 | 43,926 |
| 1999 | 232,156 | 98,698 | 2,743 | 50,441 | 971 | 448 | 5,129 | 6,624 | 233,127 | 99,146 | 7,872 | 57,065 |
| 2000 | 296,880 | 119,491 | 3,065 | 19,971 | 390 | 191 | 4,662 | 6,996 | 297,270 | 119,682 | 7,727 | 26,967 |
| 2001 | 191,515 | 110,404 | 1,206 | 26,830 | 316 | 154 | 3,449 | 6,739 | 191,831 | 110,558 | 4,655 | 33,569 |
| 2002 | 376,510 | 90,908 | 1,757 | 22,820 | 642 | 1,019 | 4,330 | 5,931 | 377,152 | 91,927 | 6,087 | 28,751 |
| 2003 | 333,307 | 95,316 | 695 | 29,972 | 657 | 2,737 | 4,189 | 6,920 | 333,964 | 98,053 | 4,884 | 36,892 |
| 2004 | 257,253 | 53,366 | 1,122 | 22,990 | 570 | 1,140 | 3,968 | 7,484 | 257,823 | 54,506 | 5,090 | 30,474 |
| 2005 | 228,335 | 61,204 | 2,306 | 22,897 | 1,085 | 2,459 | 3,596 | 6,707 | 229,420 | 63,663 | 5,902 | 29,604 |
| 2006 | 258,287 | 104,327 | 745 | 23,078 | 1,045 | 2,490 | 3,874 | 7,705 | 259,332 | 106,817 | 4,619 | 30,783 |
| 2007 | 314,918 | 82,927 | 742 | 43,011 | 2,356 | 2,424 | 4,722 | 8,964 | 317,274 | 85,351 | 5,464 | 51,975 |
| 2008 | 203,607 | 69,592 | 1,998 | 23,519 | 2,168 | 2,429 | 3,791 | 8,380 | 205,775 | 72,021 | 5,789 | 31,899 |
| 2009 | 253,650 | 118,876 | 1,144 | 79,310 | 1,531 | 2,287 | 3,816 | 7,556 | 255,181 | 121,163 | 4,960 | 86,866 |
| 2010 | 278,427 | 44,467 | 861 | 27,802 | 897 | 1,760 | 4,055 | 7,265 | 279,324 | 46,227 | 4,916 | 35,067 |
| 2011 | 261,153 | 55,937 | 703 | 50,426 | 780 | 1,467 | 4,185 | 8,369 | 261,933 | 57,404 | 4,888 | 58,795 |
| 2012 | 488,473 | 83,171 | 165 | 16,234 | 701 | 1,535 | 4,330 | 7,137 | 489,174 | 84,706 | 4,495 | 23,371 |
| 2013 | 329,031 | 76,117 | 442 | 33,633 | 460 | 1,142 | 2,861 | 7,504 | 329,491 | 77,259 | 3,303 | 41,137 |
| 2014 | 326,134 | 83,241 | 82 | 55,114 | 809 | 2,021 | 2,893 | 6,407 | 326,943 | 85,262 | 2,975 | 61,521 |
| 2015 | 383,295 | 24,441 | 174 | 59,497 | 866 | 3,003 | 2,780 | 6,409 | 384,161 | 27,444 | 2,954 | 65,906 |
| 2016 | 167,163 | 34,683 | 1,257 | 43,979 | 2,028 | 2,481 | 3,155 | 6,406 | 169,191 | 37,164 | 4,412 | 50,385 |
| 2017 | 230,363 | 38,897 | 427 | 34,128 | 1,363 | 2,373 | 3,022 | 4,625 | 231,726 | 41,270 | 3,449 | 38,753 |
| 2018 | 124,267 | 9,824 | 237 | 19,685 | 1,826 | 1,516 | 2,073 | 4,563 | 126,093 | 11,340 | 2,310 | 24,248 |

**Table 2** *Continue*

| Year | Area 2 Q1 | Q2 | Q3 | Q4 | Area 4 Q1 | Q2 | Q3 | Q4 | Area 5 Q1 | Q2 | Q3 | Q4 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1976 | 55,195 | 1,881 | 3,359 | 30,227 | 62,719 | 3,175 | 2,019 | 14,736 | 36,240 | 0 | 4 | 97,301 |
| 1977 | 105,097 | 1,496 | 1,396 | 15,216 | 65,983 | 2,151 | 3,390 | 27,942 | 24,419 | 0 | 642 | 88,838 |
| 1978 | 40,558 | 1,471 | 2,444 | 10,606 | 141,709 | 5,799 | 6,659 | 14,137 | 8,353 | 0 | 2,781 | 48,266 |
| 1979 | 42,485 | 1,416 | 508 | 10,007 | 101,422 | 10,063 | 3,453 | 21,858 | 55,046 | 111 | 1,755 | 63,491 |
| 1980 | 57,895 | 1,907 | 440 | 12,767 | 87,044 | 6,954 | 1,284 | 19,986 | 27,886 | 144 | 308 | 173,830 |
| 1981 | 54,601 | 2,002 | 2,105 | 21,375 | 160,643 | 13,413 | 1,884 | 25,336 | 58,905 | 1,320 | 5,119 | 153,713 |
| 1982 | 48,263 | 2,103 | 1,879 | 5,252 | 161,754 | 9,848 | 618 | 10,583 | 86,780 | 76 | 571 | 65,358 |
| 1983 | 18,589 | 1,825 | 4,061 | 9,661 | 95,066 | 9,518 | 3,869 | 19,747 | 39,965 | 60 | 2,833 | 140,450 |
| 1984 | 30,071 | 2,949 | 3,827 | 9,028 | 83,650 | 9,327 | 1,076 | 7,715 | 120,964 | 28 | 320 | 157,562 |
| 1985 | 11,648 | 1,622 | 854 | 6,396 | 35,671 | 10,701 | 3,325 | 20,333 | 94,634 | 0 | 384 | 138,886 |
| 1986 | 23,383 | 1,083 | 4,321 | 7,019 | 89,244 | 10,178 | 2,327 | 9,914 | 39,919 | 73 | 350 | 48,471 |
| 1987 | 17,886 | 1,645 | 1,642 | 5,234 | 28,114 | 5,380 | 1,530 | 9,732 | 42,717 | 2,458 | 465 | 110,757 |
| 1988 | 8,798 | 798 | 2,056 | 4,480 | 29,807 | 5,485 | 1,783 | 7,918 | 43,570 | 0 | 405 | 105,781 |
| 1989 | 13,647 | 741 | 1,920 | 1,994 | 29,000 | 5,494 | 1,975 | 9,991 | 76,953 | 120 | 148 | 60,436 |
| 1990 | 11,719 | 134 | 1,108 | 1,027 | 36,936 | 3,294 | 384 | 4,504 | 93,184 | 67 | 0 | 86,645 |
| 1991 | 15,210 | 940 | 2,243 | 2,541 | 38,011 | 6,780 | 985 | 7,225 | 121,525 | 1 | 41 | 103,980 |
| 1992 | 6,206 | 333 | 600 | 5,483 | 46,345 | 2,079 | 2,474 | 8,933 | 42,330 | 0 | 0 | 144,388 |
| 1993 | 16,410 | 3,328 | 1,574 | 13,080 | 76,992 | 3,649 | 842 | 9,394 | 62,142 | 0 | 11 | 175,003 |
| 1994 | 46,953 | 4,981 | 17,713 | 44,521 | 72,384 | 2,874 | 2,458 | 13,832 | 67,564 | 0 | 1 | 61,611 |
| 1995 | 97,511 | 12,826 | 21,342 | 30,369 | 68,111 | 6,832 | 6,530 | 30,063 | 51,367 | 0 | 0 | 45,514 |
| 1996 | 97,700 | 32,279 | 34,419 | 63,053 | 90,434 | 6,502 | 6,537 | 32,617 | 50,463 | 0 | 34 | 59,030 |
| 1997 | 94,456 | 44,742 | 34,477 | 46,018 | 117,748 | 17,904 | 3,192 | 34,862 | 44,107 | 402 | 0 | 64,343 |
| 1998 | 134,522 | 48,048 | 42,511 | 59,700 | 76,945 | 12,856 | 6,647 | 31,117 | 11,462 | 0 | 177 | 56,645 |
| 1999 | 121,861 | 37,514 | 36,563 | 87,831 | 63,829 | 25,791 | 9,773 | 27,024 | 33,488 | 0 | 1,847 | 38,640 |
| 2000 | 205,726 | 94,755 | 63,485 | 80,533 | 75,413 | 6,440 | 12,883 | 50,455 | 5,492 | 0 | 27 | 12,606 |
| 2001 | 221,677 | 97,497 | 31,506 | 51,382 | 93,516 | 19,336 | 27,234 | 39,835 | 15,890 | 0 | 0 | 47,034 |
| 2002 | 122,870 | 44,856 | 11,347 | 35,363 | 117,508 | 9,428 | 4,035 | 14,138 | 6,262 | 0 | 0 | 13,148 |
| 2003 | 157,287 | 32,456 | 28,645 | 35,885 | 30,197 | 2,099 | 1,264 | 3,750 | 1,175 | 0 | 48 | 12,503 |
| 2004 | 64,280 | 34,663 | 19,897 | 30,550 | 29,452 | 711 | 509 | 15,597 | 2,548 | 0 | 0 | 774 |
| 2005 | 92,072 | 42,353 | 27,996 | 47,059 | 32,732 | 2,696 | 4,905 | 6,317 | 160 | 0 | 10 | 9,009 |
| 2006 | 120,978 | 53,160 | 10,817 | 35,301 | 25,377 | 6,049 | 9,736 | 3,774 | 1,176 | 0 | 0 | 591 |
| 2007 | 97,002 | 42,100 | 22,224 | 20,206 | 15,934 | 1,659 | 1,293 | 963 | 1,753 | 0 | 28 | 374 |
| 2008 | 99,362 | 53,439 | 38,565 | 22,068 | 34,498 | 2,175 | 6,571 | 9,851 | 24,886 | 0 | 39 | 2,274 |
| 2009 | 118,355 | 52,991 | 34,681 | 43,937 | 11,372 | 547 | 7,802 | 2,440 | 1,037 | 0 | 206 | 11 |
| 2010 | 176,961 | 112,287 | 60,229 | 32,191 | 3,419 | 2,144 | 907 | 9,775 | 0 | 0 | 11 | 9 |
| 2011 | 142,618 | 85,542 | 19,428 | 35,945 | 26,941 | 2,724 | 12,431 | 9,178 | 0 | 0 | 25 | 3 |
| 2012 | 128,913 | 82,268 | 37,110 | 28,672 | 21,023 | 1,642 | 7,105 | 15,355 | 0 | 0 | 24 | 0 |
| 2013 | 105,109 | 91,626 | 61,215 | 24,177 | 27,648 | 2,006 | 4,912 | 7,729 | 0 | 0 | 38 | 9,152 |
| 2014 | 78,532 | 97,084 | 59,928 | 45,917 | 20,495 | 1,288 | 2,164 | 3,366 | 1,433 | 0 | 82 | 0 |
| 2015 | 165,655 | 90,455 | 52,249 | 36,075 | 7,843 | 587 | 5,330 | 2,011 | 0 | 0 | 0 | 0 |
| 2016 | 77,485 | 94,049 | 41,206 | 32,550 | 10,198 | 1,184 | 8,575 | 336 | 0 | 0 | 0 | 0 |
| 2017 | 104,908 | 59,672 | 42,835 | 76,277 | 4,006 | 2,413 | 13,864 | 1,442 | 0 | 0 | 0 | 382 |
| 2018 | 113,588 | 94,650 | 44,193 | 51,659 | 4,085 | 460 | 799 | 2,600 | 0 | 0 | 0 | 9 |

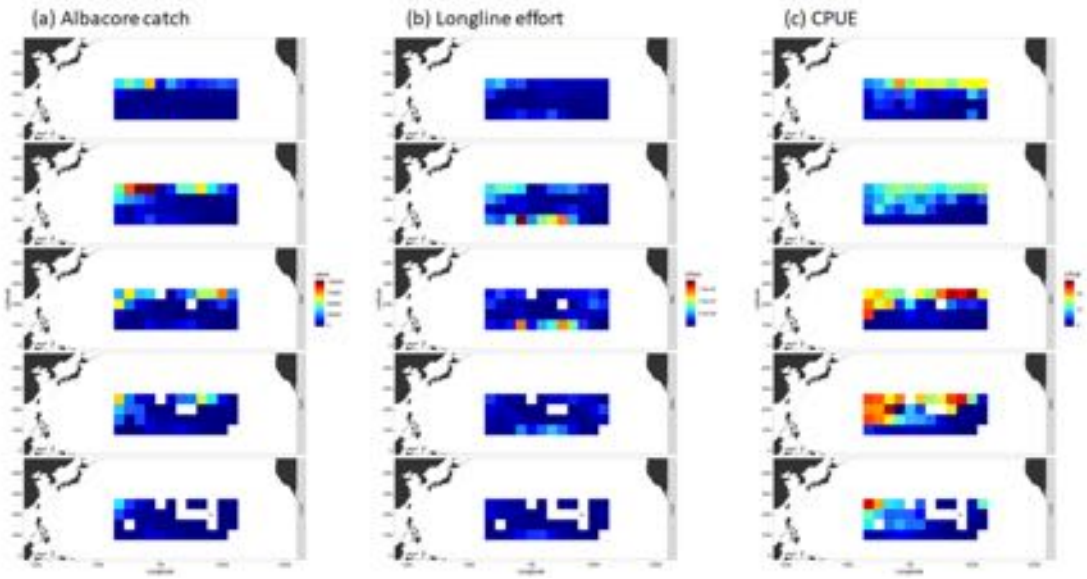
**Table 3** Abundance indices for albacore caught by the Japanese longline fisheries in area 2 and area 1 & 3 between 1996 and 2018.

| Year | Ochi et al. 2017 | | Present study | | | |
|---|---|---|---|---|---|---|
| | Area 2, Quarter 1 | | Area 2, Quarter 1 | | Area 1&3, Quarter 1 | |
| | StdCPUE | CV | StdCPUE | CV | StdCPUE | CV |
| 1996 | 46.81 | 0.11 | 43.15 | 0.09 | 57.90 | 0.12 |
| 1997 | 53.34 | 0.11 | 50.04 | 0.10 | 97.98 | 0.11 |
| 1998 | 55.12 | 0.10 | 50.61 | 0.10 | 79.24 | 0.11 |
| 1999 | 42.45 | 0.11 | 38.51 | 0.10 | 52.34 | 0.12 |
| 2000 | 57.79 | 0.10 | 53.04 | 0.10 | 55.07 | 0.12 |
| 2001 | 51.05 | 0.09 | 47.35 | 0.10 | 35.00 | 0.12 |
| 2002 | 34.12 | 0.10 | 31.99 | 0.10 | 58.93 | 0.12 |
| 2003 | 38.14 | 0.10 | 35.64 | 0.10 | 61.89 | 0.12 |
| 2004 | 27.11 | 0.10 | 25.64 | 0.09 | 30.86 | 0.11 |
| 2005 | 36.48 | 0.11 | 33.39 | 0.10 | 33.00 | 0.11 |
| 2006 | 39.27 | 0.11 | 36.33 | 0.09 | 35.82 | 0.11 |
| 2007 | 35.14 | 0.10 | 31.75 | 0.11 | 51.97 | 0.11 |
| 2008 | 36.46 | 0.10 | 33.18 | 0.11 | 31.22 | 0.13 |
| 2009 | 37.04 | 0.10 | 34.45 | 0.09 | 35.39 | 0.13 |
| 2010 | 43.38 | 0.11 | 40.30 | 0.11 | 34.08 | 0.12 |
| 2011 | 33.12 | 0.10 | 31.30 | 0.11 | 28.54 | 0.11 |
| 2012 | 34.21 | 0.10 | 31.34 | 0.09 | 52.27 | 0.12 |
| 2013 | 32.83 | 0.11 | 29.24 | 0.10 | 34.36 | 0.11 |
| 2014 | 23.97 | 0.10 | 22.75 | 0.11 | 33.82 | 0.11 |
| 2015 | 41.13 | 0.10 | 41.26 | 0.09 | 48.70 | 0.11 |
| 2016 | | | 25.92 | 0.10 | 26.16 | 0.11 |
| 2017 | | | 27.33 | 0.11 | 34.66 | 0.11 |
| 2018 | | | 31.02 | 0.10 | 21.19 | 0.12 |

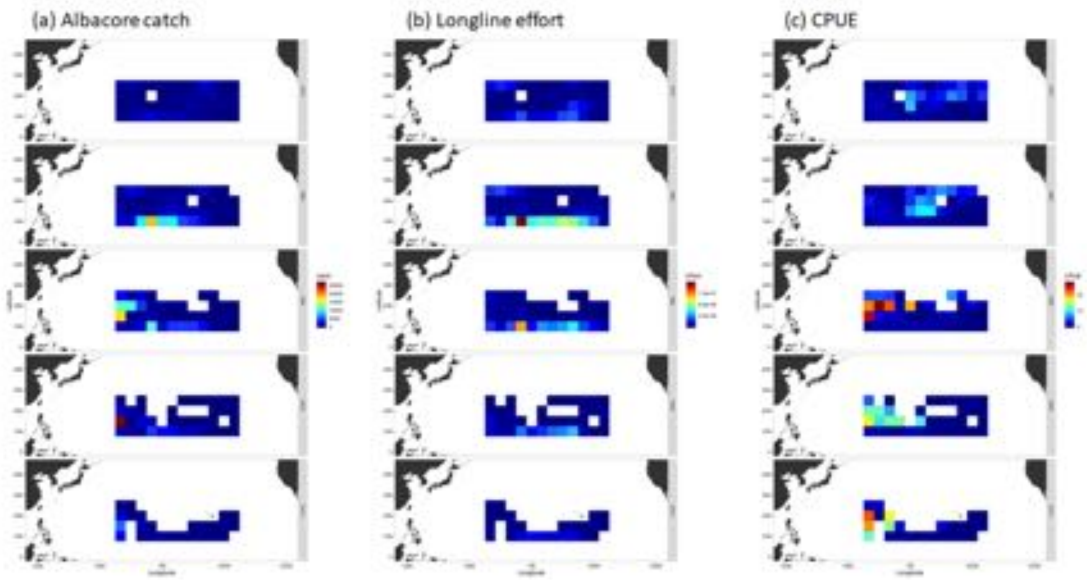
## Appendix

**A.** Decadal spatial distributions of (a) albacore catch, (b) effort (number of hooks), and (c) CPUE (catch/effort*1000) in area 4 that were aggregated by 5 × 5 degrees during 1976-2018. From the top figures, quarter 1, quarter 2, quarter 3, quarter 4 are shown.

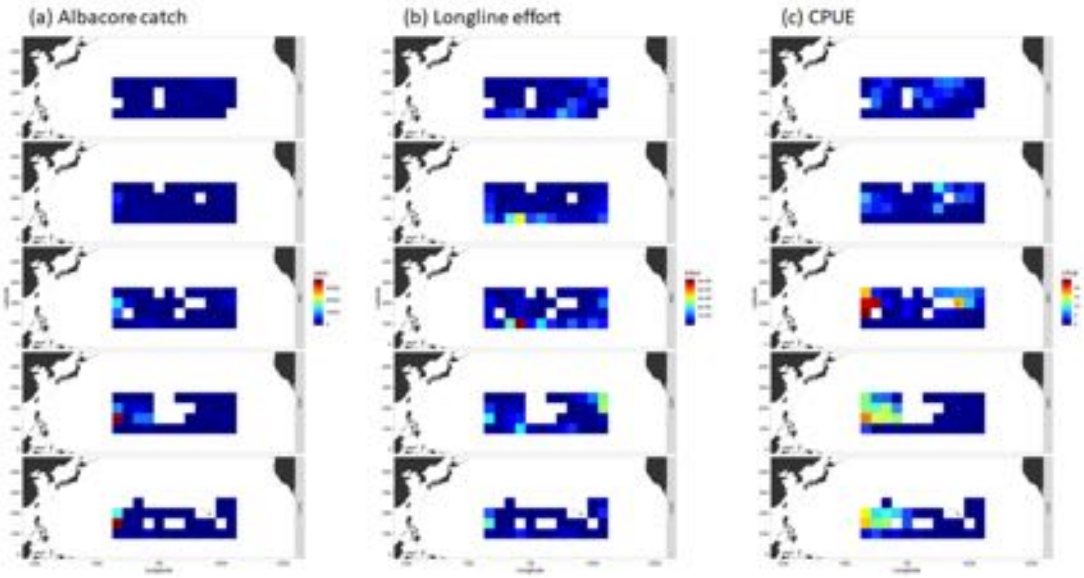
Quarter 1



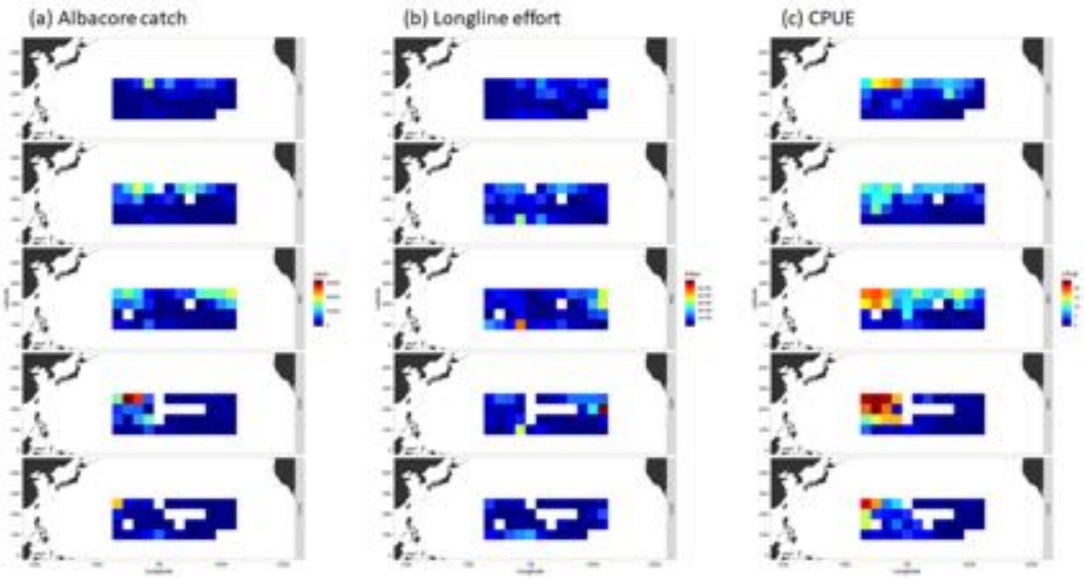

Quarter 2



Quarter 3

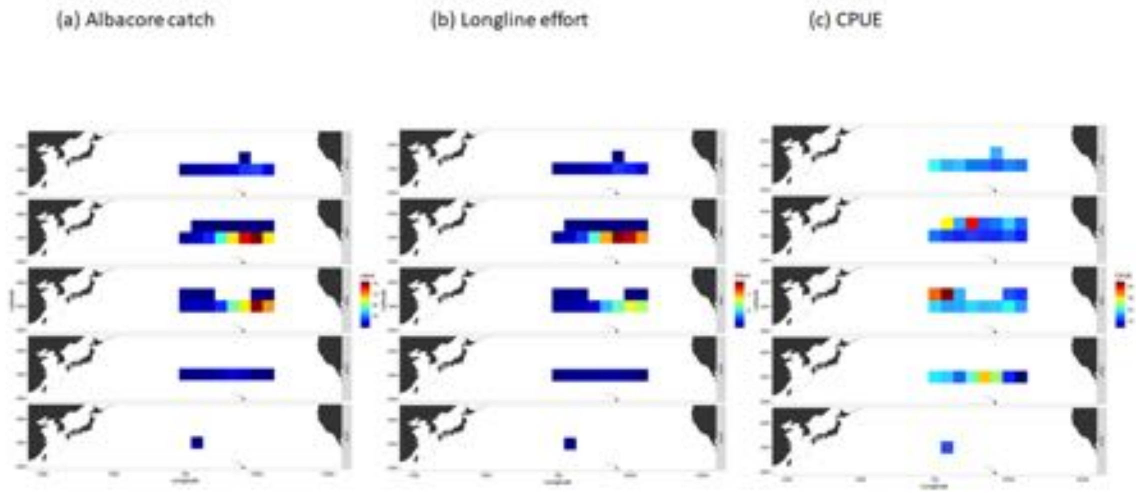



Quarter 4

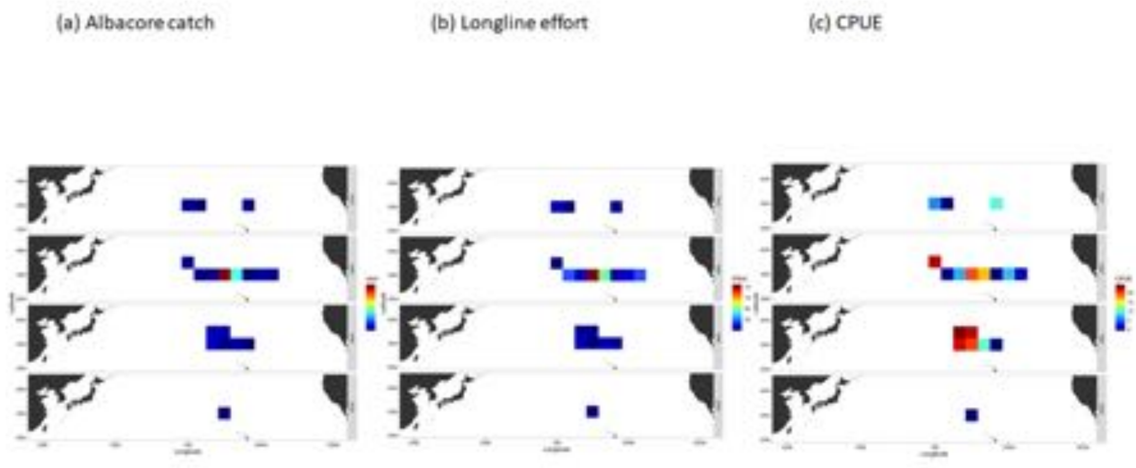


**B.** Decadal spatial distributions of (a) albacore catch, (b) effort (number of hooks), and (c) CPUE (catch/effort*1000) in area 5 that were aggregated by 5 × 5 degrees during 1976-2018. From the top figures, quarter 1, quarter 2, quarter 3, quarter 4 are shown.

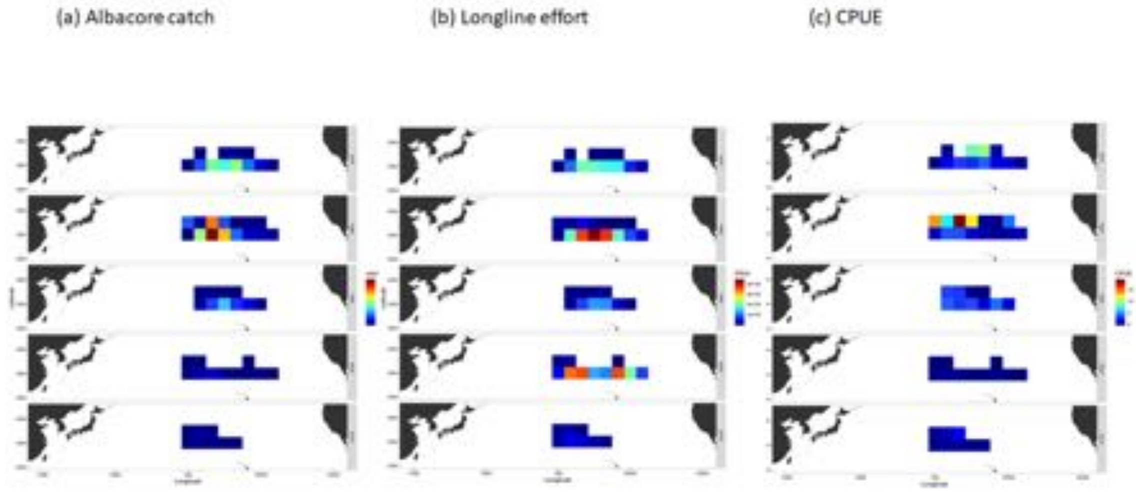
Quarter 1




Quarter 2



Quarter 3




Quarter 4