ISC/22/ALBWG-2/11

Candidate relative abundance indices of juvenile albacore tuna for the US surface fishery in the north Pacific Ocean[1]

Steven L. H. Teo[2]

[2] NOAA Fisheries
Southwest Fisheries Science Center
8901 La Jolla Shores Drive
La Jolla, CA 92037, USA

Email: steve.teo@noaa.gov

[1] This working paper was submitted to the ISC Albacore Working Group Intercessional Workshop, 06-12 December 2022, held at the National Research Institute of Fisheries Science, Yokohama, Japan.

ABSTRACT

The objective of this paper is to describe the data sources and methods used to develop relative abundance indices of juvenile albacore tuna for the US surface fishery in the north Pacific Ocean. The US surface fishery for albacore tuna consists of troll and pole-and-line vessels that primarily capture albacore tuna ranging from ages-2 to 4. In previous assessments, relative abundance indices for three periods (1966 – 1978, 1979 – 1998, and 1999 – current, excluding 2012), which corresponded to periods of major changes in fishing operations in this fishery, were developed. Here, we focus on the terminal 1999- 2021 period because the assessment model had a start year of 1994 in the 2020 assessment. The standardization approach for these abundance indices in previous assessments was to apply generalized linear models (GLMs) to catch per unit effort data (CPUE; fish per boat day). In this study, we update the post-1999 index by including data until 2021 using the same approach for previous assessments. In addition, this study also developed a series of Bayesian generalized linear mixed models (GLMM) to examine the effect of explicitly incorporating spatial and vessel effects into the standardization approach. The main source of data used in this study was a vessel logbook program. For the GLM-based approach, catch and effort data were aggregated into strata of 1 x 1° spatial blocks by month while for the GLMM-based approach, strata were vessel-specific catch and effort by fishing day. Only logbook data where locations were recorded at ≤1° resolution and the vessel was actively fishing were included. The GLM-based approach used a lognormal model to standardize abundance indices for the three periods using year, quarter, and area as main explanatory factors, and interactions between quarter and area. For the GLMM-based approach, six candidate Bayesian GLMMs were developed using the INLA package to explicitly incorporate spatial and vessel effects into the standardization approach. For these models, the response variables were the number of albacore caught instead of ln(CPUE + 1) for the GLM model. Therefore, discrete probability distributions like Poisson and negative binomial distributions were investigated for the GLMM-based approach. The explanatory variables considered for the GLMM-based approach were: year, month, bathymetry, distance to shore, vessel, and fishing location. A candidate abundance index was developed from the best fitting GLMM and confidence intervals were calculated from the estimated posterior marginal distributions. Residual and Q-Q plots for the GLM indicated that the models were not fitting the data well at low and high CPUE values. The standardization process did not appear to perform well and may not have adequately standardized the changes in catchability for the US surface fishery. For the GLMM-based approach, Model 3 (negative binomial with vessel effects) is the best fitting model with the lowest deviance information criteria (DIC). The abundance index from Model 3 shows similar overall trends to the GLM-based index. It is clear that the negative binomial distribution is a better distribution than the Poisson, and appears to be appropriate for the data. However, including a spatially explicit component, with spatial autocorrelation, did not appear to substantially improve model fit over a model with spatially implicit fixed effects of bathymetry and distance from shore. Given the limited spatial distribution of this fishery during 1999 – 2021, it is not likely that the CPUE of this fishery would be representative of the juvenile albacore stock abundance as a whole. Instead, the CPUE of this fishery would represent the abundance of juvenile albacore that migrated to the North American coast, and would be sensitive to variable movement rates. Given that the assessment model uses a fleets-as-areas approach and is not explicitly spatially structured, it is not recommended to fit to these indices in the base case model. Instead, it is recommended to consider using these indices in sensitivity model runs. If these indices are used in sensitivity model runs, it is recommended to use the

index derived from the GLMM Model 3 because the use of a negative binomial distribution is more appropriate than assuming a lognormal distribution.

INTRODUCTION

The objective of this paper is to describe the data sources and methods used to develop relative abundance indices of juvenile albacore tuna for the US surface fishery in the north Pacific Ocean. These abundance indices are candidates for representing the population trends of juvenile albacore tuna in the 2023 stock assessment of north Pacific albacore tuna, which is conducted by the albacore working group (ALBWG) of the International Scientific Committee on Tuna and Tuna-like Species in the North Pacific (ISC). The US surface fishery for albacore tuna consists of troll and pole-and-line vessels that primarily capture albacore tuna ranging from ages-2 to 4. Although the US albacore surface fishery can be nominally divided into troll and pole-and-line fisheries, it is difficult to consistently separate the fishing effort of these two fisheries based on available logbook data. In addition, the fishing operations of both fisheries are similar enough that the data from both fisheries were combined in previous studies developing abundance indices for these fisheries (Xu et al. 2013).

In the previous assessments, relative abundance indices were developed for three periods (1966 – 1978, 1979 – 1998, and 1999 – current), which were defined based on changes in the fishery operations of these fisheries (Xu et al. 2013). The first (1966 – 1978) period was characterized by fishing effort concentrated along the Pacific coast of North America coast. The fishing effort expanded substantially into the open ocean of the Pacific Ocean during the second period (1979 – 1998). In the most recent period (post-1999), most of the fishing effort has concentrated on the Pacific coast of North America coast (>40 °N). It should be noted that although data was available for 2012, the ALBWG previously recommended not to use the 2012 data because the operations of both US and Canadian vessels may have changed during 2012, when there was no agreement between the US and Canada on the number of Canadian vessels allowed to fish for albacore in the US EEZ and vice versa. After 2012 (2013 – 2016), a fishing regime was agreed upon by both countries and albacore fishing in each other's EEZs was allowed albeit at different numbers of vessels. For previous assessments, the ALBWG recommended that these abundance indices be used as alternative abundance indices in sensitivity analyses. Only the 1999 – current index was used in the 2020 assessment because the start year of the assessment was 1994.

The standardization approach for these abundance indices in previous assessments was to apply lognormal generalized linear models (GLMs) to catch per unit effort data (CPUE; fish per boat day) with strata of 1 x 1° spatial blocks by month (Teo 2017). The nominal CPUE (fish per boat day) of each stratum was first calculated and log-transformed by ln(CPUE + 1) in order to accommodate strata with zero catch. In this study, we update the post-1999 index by including data until 2021 using the same approach for previous assessments (Teo 2017).

In addition, this study also developed a series of Bayesian generalized linear mixed models (GLMM) to examine the effect of explicitly incorporating spatial and vessel effects into the standardization approach. As detailed in Teo (2017), the previous standardization approach accounted for spatial (Fig. 1) and temporal effects on relatively large scales (3-month seasons), and did not account for vessel effects. In this study, the models accounted for spatial and temporal effects on finer scales as well as individual vessel effects and spatially-explicit models.

MATERIALS AND METHODS

Data sources

The main source of data used in this study was a vessel logbook program, which was used to obtain time and location specific catch and effort information of the US surface fishery. An annual logbook monitoring program for this fishery has been managed by NOAA's Southwest Fisheries Science Center (SWFSC) since 1961 (Childers and Betcher 2008). Although logbook data has been collected since 1961, only 1966 – 2021 data were used in order to match previous assessment periods. The logbook data format has changed over the years but time and location-specific catch-effort information have been consistently recorded throughout the program's existence. Prior to 2005, logbooks were voluntarily submitted to the SWFSC and the logbook coverage varied from 7 – 33% (McDaniel et al. 2006). However, logbook submission became mandatory in 2005 for this fishery and logbook coverage has since increased to approximately 75% of total number of boat trips. Importantly, the logbooks included daily (sometimes partial-day) information on the location (latitude and longitude) of the vessel, the number of albacore kept and discarded, and if the vessel was actively fishing.

In previous assessments, catch and effort data were aggregated into strata of 1 x 1° spatial blocks by month. Only logbook data where the location was recorded at ≤1 ° resolution and the vessel was actively fishing were included in this analysis. For each time-area strata, effort was calculated as the number of boat days and catch was calculated as the total number of fish caught (sum of retained and discarded albacore). Strata with <3 boat days of effort were removed from analysis to reduce the influence of peripheral fishing areas with minimal effort. Three data subsets representing the three abovementioned periods were assembled: 1) 1966 – 1978; 2) 1979 – 1998; and 3) 1999 – 2021 (excluding 2012) but the focus for this study was on the 1999 – 2021 period.

For this study, vessel-specific catch and effort data was also assembled without aggregation so that vessel effects could be examined. Each line of data represented the number of albacore caught from 1 day of fishing effort by a specific fishing vessel. The bathymetry (m) and distance (km) from shore of each day's recorded fishing location was also extracted from the 2-minute Gridded Global Relief Data (ETOPO2; National Geophysical Data Center 2006) and calculated from the Global, Self-consistent, Hierarchical, High-resolution Geography (GSHHG; Wessel and Smith 1996) database, respectively. The fishing locations in degrees latitude and longitude were converted to Universal Transverse Mercator coordinates for Zone 9N (km). Most (84.5%) of the fishing effort during 1999 – 2021 occurred within the U.S. EEZ. Therefore, the scope of this part was limited to the U.S. EEZ.

Generalized Linear Model

For previous assessments, a GLM approach was used to standardize abundance indices from the data strata of 1 x 1° spatial blocks by month. The abundance index for the 1999 – 2021 period was updated in a consistent manner with those developed for previous assessments (McDaniel et al. 2006; Teo et al. 2010; Xu et al. 2013; Teo 2017).

The nominal CPUE (fish per boat day) of each stratum was first calculated and log-transformed by ln(CPUE + 1) in order to accommodate strata with zero catch. Less than 1% of the strata had zero catch. Previous studies have found that results of the GLM to be robust to the choice of constant (McDaniel et al. 2006; Teo et al. 2010) and resultant indices using 0.1, 1, or 8.1 (10% of mean CPUE) as the constant were all highly and significantly correlated ($R > 0.99$, $p << 0.0001$) (Teo et al. 2010). Similar to Yi et al. (2013), each strata was assigned to one of eight areas (Figure 1) based on distance from the coast, latitude, and/or longitude bounds: 1) inshore-central (region 1, ≤200 nm from coast, 40 – 48 °N); 2) inshore-north (region 2, ≤200 nm from coast, >48 °N); 3) inshore-south (region 3, ≤200 nm from coast, <40 °N); 4) inshore-offshore transition (region 4, >200 nm, east of 140 °W); 5) offshore-northeast (region 5, ≥40 °N, 140 – 160 °W); 6) offshore-southeast (region 6, <40 °N, 140 – 160 °W); 7) offshore-northwest (region 7, ≥40 °N, 160 °E – 160 °W); and 8) offshore-southwest (region 7, <40 °N, 160 °E – 160 °W). Xu et al. (2015) identified these eight areas as potentially having heterogeneity in catchability of albacore because of different environmental conditions in these areas. The year and quarter (quarter 2: Apr – Jun; quarter 3: Jul – Sep; quarter 4: Oct - Dec) of each stratum were also used as factors in the GLM. Data from January to March were excluded from this analysis due to very low catches during those months.

For each of the three time periods, the log-transformed CPUE was related to three main factors – year (Y), quarter (Q), and area (A) by,

$$\ln(CPUE_{ijk} + 1) = X + Y_i + Q_j + A_k + Q_j * A_k + \varepsilon_{ijk}$$

where $CPUE_{ijk}$ is the CPUE (fish per boat day) in year i, quarter j, and area k, and X is the intercept representing the reference block. The standardized CPUE indices, I_t, were obtained by back-transforming the above GLM for the reference block and given year using,

$$I_t = \exp\left(\hat{\alpha}_t + \frac{\hat{\sigma}_t^2}{2}\right)$$

where $\hat{\alpha}_t$ was the estimated year factor and $\hat{\sigma}_t^2$ was the variance of $\hat{\alpha}_t$, to minimize the log-transformation bias. Confidence intervals of the abundance indices were subsequently estimated from 10000 bootstrap runs.

Generalized Linear Mixed Models

Six candidate Bayesian GLMMs were developed using R version 4.2.1 (R Core Team 2022) and the INLA package (Rue et al. 2009) to explicitly incorporate spatial and vessel effects into the standardization approach. For these models, the response variables were the number of albacore (N) caught instead of ln(CPUE + 1) for the GLM model. Therefore, the appropriate distributions for the models were discrete probability distributions like Poisson and negative binomial (NB) distributions. The explanatory variables considered were: 1) year (Y_i), 2) month (M_i), 3) bathymetry (Z_i), 4) distance to shore (D_i), 5) vessel (V_i), and 6) fishing location (U_i) of fishing day i.

The six models were:

<u>Model 1: Poisson model</u>

$N_i \sim Poi(\mu)$, $E(N_i) = \mu$, $var(N_i) = \mu_i$

$\ln(\mu_i) = \text{Intercept} + Y_i + M_i + Y_i \times M_i + Z_i + D_i$

<u>Model 2: Negative binomial model</u>

$N_i \sim NB(\mu)$, $E(N_i) = \mu$, $var(N_i) = \mu_i + \mu_i^2 / k$

$\ln(\mu_i)$ = Intercept + $Y_i + M_i + Y_i{\times}M_i + Z_i + D_i$

Model 3: Negative binomial model with vessel effects

$N_i \sim NB(\mu)$, $E(N_i) = \mu$, $\text{var}(N_i) = \mu_i + \mu_i^2 / k$

$\ln(\mu_i)$ = Intercept + $Y_i + M_i + Y_i{\times}M_i + Z_i + D_i + V_i$

$V_i = N(0, \sigma_v^2)$

Model 4: Negative binomial model with explicit spatial effects

$N_i \sim NB(\mu)$, $E(N_i) = \mu$, $\text{var}(N_i) = \mu_i + \mu_i^2 / k$

$\ln(\mu_i)$ = Intercept + $Y_i + M_i + Y_i{\times}M_i + Z_i + D_i + U_i$

$U_i = \text{GMRF}(0, \Sigma)$

Model 5: Negative binomial model with explicit spatial effects but without implicit spatial fixed effects

$N_i \sim NB(\mu)$, $E(N_i) = \mu$, $\text{var}(N_i) = \mu_i + \mu_i^2 / k$

$\ln(\mu_i)$ = Intercept + $Y_i + M_i + Y_i{\times}M_i + U_i$

$U_i = \text{GMRF}(0, \Sigma)$

Model 6: Negative binomial model with spatial and vessel effects

$N_i \sim NB(\mu)$, $E(N_i) = \mu$, $\text{var}(N_i) = \mu_i + \mu_i^2 / k$

$\ln(\mu_i)$ = Intercept + $Y_i + M_i + Y_i{\times}M_i + Z_i + D_i + V_i + U_i$

$V_i = N(0, \sigma_v^2)$, $U_i = \text{GMRF}(0, \Sigma)$

where $N(0, \sigma_v^2)$ were the estimated random effects of individual vessels with mean 0 and variance σ_v^2, and GMRF(0, Σ) were the estimated random effects of the fishing locations at the nodes of the spatial mesh (Fig. 2; number of nodes in mesh = 926) and were assumed to be a spatially correlated Gaussian Markov random field (GMRF) with mean 0 and covariance matrix Σ. The sparse covariance matrix Σ consisted of the solutions of the Matern correlation function between neighboring nodes that were solved as continuous domain stochastic partial differential equations (SPDE) (Lindgren et al. 2011). A candidate abundance index was developed from the best fitting model and confidence intervals were calculated from the estimated posterior marginal distributions.

RESULTS AND DISCUSSION

Generalized Linear Model

Table 1 show the summarized results of the GLM for abundance indices from the 1999 – 2021 (excluding 2012). Standard diagnostics (residual and Q-Q plots) indicate that the model is not fitting the data well at low and high CPUE values (Fig. 3). These results suggest that other models (e.g., negative binomial, random effects) should be considered for standardizing the CPUE of this fishery. The standardized abundance indices and corresponding coefficients of variation (CVs) are shown in Figure 4, and Table 2.

The standardization process using GLMs did not perform well and may not have adequately standardized the changes in catchability for the US surface fishery. Given the poor diagnostics of the standardization models and the uncertainty in the representativeness of these indices with respect to abundance trends of the entire north Pacific stock, it is recommended that the ALBWG do not use these abundance indices as the primary abundance indices for juvenile albacore tuna in the 2023 stock assessment.

Generalized Linear Mixed Model

Based on the model fit statistics of the six GLMMs (Table 3), Model 3 (negative binomial with vessel effects) is the best fitting model with the lowest deviance information criteria (DIC). The abundance index from Model 3 is shown in Figure 4 and largely shows the same overall trend as the GLM-based index. It is clear that the negative binomial distribution is a better distribution than the Poisson, and appears to be appropriate for the data, with all five negative binomial models having limited overdispersion (Table 3). However, including a spatially explicit component (i.e., GMRF) did not appear to substantially improve model fit over a model with spatially implicit fixed effects of bathymetry and distance from shore (e.g., compare Models 3 and 6). One possible reason for the lack of improvement from spatially explicit models is the relatively restricted area for most of the fishing effort (Fig. 2). Given that these spatial models have not been adequately explored, it is currently difficult to definitively exclude spatially explicit models from further consideration. In addition, it should be noted that model diagnostics have not yet been adequately performed on these models.

Overall

Given the limited spatial distribution of this fishery during 1999 – 2021, it is not likely that the CPUE of this fishery would be representative of the juvenile albacore stock abundance as a whole. Instead, the CPUE of this fishery would represent the abundance of juvenile albacore that migrated to the North American coast, and would be sensitive to variable movement rates. Given that the assessment model uses a fleets-as-areas approach and is not explicitly spatially structured, it is not recommended to fit to these indices in the base case model. Instead, it is recommended to consider using these indices in sensitivity model runs. If these indices are used in sensitivity model runs, it is recommended to use the index derived from the GLMM Model 3 because the use of a negative binomial distribution is more appropriate than assuming a lognormal distribution. However, more work will be needed on the GLMM-based approach in the future.

REFERENCES

Childers, J., and A. Betcher. 2008. Summary of the 2006 US North and South Pacific albacore troll fisheries. ISC/08/ALBWG/03. Working document submitted to the ISC Albacore Working Group Meeting, February 28-March 6, NOAA\NMFS, Southwest Fisheries Science Center, 8604 La Jolla Shores drive, La Jolla, CA 92037, USA.

Lindgren, F., H. Rue, and J. Lindström. 2011. An explicit link between Gaussian fields and Gaussian Markov random fields: the stochastic partial differential equation approach. Journal of the Royal Statistical Society: Series B (Statistical Methodology) 73(4):423–498.

McDaniel, J. D., P. R. Crone, and E. Dorval. 2006. Critical evaluation of important time series associated with albacore fisheries (United States, Canada, and Mexico) of the Eastern North Pacific Ocean. Page Report of the ISC Albacore Working Group Workshop, 28 November - 5 December, 2006. ISC/06/ALBWG/09, Shimizu, Shizuoka, Japan.

National Geophysical Data Center. 2006. ETOPO2v2 2-minute Global Relief Model. National Geophysical Data Center, NOAA.

R Core Team. 2022. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Rue, H., S. Martino, and N. Chopin. 2009. Approximate Bayesian inference for latent Gaussian models by using integrated nested Laplace approximations. Journal of the Royal Statistical Society: Series B (Statistical Methodology) 71(2):319–392.

Teo, S. L. H. 2017. Relative abundance indices of juvenile albacore tuina for the US surface fishery in the north Pacific Ocean. ISC/17/ALBWG/09. Working document submitted to the ISC Albacore Working Group Meeting, 11-19 April 2017, Southwest Fisheries Science Center, La Jolla, California, USA.

Teo, S. L. H., J. Holmes, and S. Kohin. 2010. Joint standardized abundance index of US and Canada albacore troll fisheries in the North Pacific. ISC/10-3/ALBWG/01. Working document submitted to the ISC Albacore Working Group Meeting, 12-19 October 2010, Southwest Fisheries Science Center, NOAA, La Jolla, California, USA.

Wessel, P., and W. H. F. Smith. 1996. A global, self-consistent, hierarchical, high-resolution shoreline database. Journal of Geophysical Research: Solid Earth 101(B4):8741–8743.

Xu, Y., K. Nieto, S. L. H. Teo, S. McClatchie, and J. Holmes. 2015. Influence of fronts on the spatial distribution of albacore tuna (Thunnus alalunga) in the Northeast Pacific over the past 30 years (1982-2011). Progress in Oceanography.

Xu, Y., S. L. H. Teo, and J. Holmes. 2013. An update of standardized abundance index of US and Canada albacore troll fisheries in the North Pacific (1966-2012). ISC/13/ALBWG-03/06. Working paper submitted to the ISC Albacore Working Group Workshop, 5-12 November, 2013.

Table 1. Summarized results of GLM for 1999 – 2021 (excluding 2012).

Parameter	Estimate	Standard error	t value	P(>|t|)
Intercept	3.820	0.078	48.94	<2.00E-16
2000	-0.136	0.095	-1.43	1.53E-01
2001	0.494	0.096	5.16	2.61E-07
2002	0.389	0.111	3.52	4.38E-04
2003	0.404	0.119	3.39	7.03E-04
2004	0.501	0.120	4.17	3.17E-05
2005	0.404	0.118	3.41	6.53E-04
2006	0.998	0.133	7.49	8.26E-14
2007	0.476	0.134	3.56	3.72E-04
2008	0.500	0.133	3.77	1.68E-04
2009	0.683	0.122	5.58	2.55E-08
2010	0.425	0.112	3.81	1.43E-04
2011	0.299	0.116	2.59	9.57E-03
2013	0.535	0.122	4.36	1.30E-05
2014	0.394	0.149	2.64	8.24E-03
2015	0.580	0.145	4.00	6.34E-05
2016	0.473	0.149	3.18	1.48E-03
2017	-0.027	0.121	-0.22	8.23E-01
2018	0.246	0.142	1.73	8.29E-02
2019	0.657	0.138	4.75	2.07E-06
2020	0.619	0.134	4.61	4.11E-06
2021	0.570	0.135	4.22	2.48E-05
Quarter 2	-0.552	0.100	-5.53	3.39E-08
Quarter 4	-0.411	0.081	-5.09	3.69E-07
Area 2	-0.159	0.089	-1.79	7.38E-02
Area 3	-0.587	0.092	-6.38	1.96E-10
Area 4	-0.604	0.078	-7.71	1.53E-14
Area 5	-0.332	0.088	-3.78	1.59E-04
Area 6	-0.523	0.301	-1.74	8.28E-02
Area 7	-0.545	0.098	-5.57	2.77E-08
Area 8	-1.263	0.210	-6.03	1.77E-09
Quarter 2:Area 2	0.522	1.413	0.37	7.12E-01
Quarter 4:Area 2	-0.510	0.422	-1.21	2.28E-01
Quarter 2:Area 3	0.419	0.268	1.56	1.18E-01
Quarter 4:Area 3	-0.267	0.178	-1.50	1.33E-01
Quarter 2:Area 4	-0.009	0.207	-0.04	9.66E-01
Quarter 4:Area 4	0.748	0.351	2.13	3.30E-02
Quarter 2:Area 5	0.456	0.425	1.07	2.83E-01
Quarter 4:Area 5	0.612	0.228	2.69	7.21E-03
Quarter 2:Area 6	0.598	0.334	1.79	7.37E-02
Quarter 4:Area 6	2.336	0.768	3.04	2.37E-03
Quarter 2:Area 7	-1.442	0.642	-2.25	2.46E-02
Quarter 4:Area 7	1.009	0.275	3.67	2.43E-04
Quarter 2:Area 8	0.752	0.240	3.14	1.72E-03
Quarter 4:Area 8	2.720	0.435	6.25	4.58E-10

Table 2. GLM-standardized abundance index of juvenile north Pacific albacore tuna for the US troll and pole-and-line fisheries for 1999 – 2021 (excluding 2012). Coefficient of variations (CVs) were estimated from 10000 bootstrap runs.

Year	Value	CV
1999	53.55	0.096
2000	46.74	0.100
2001	87.71	0.098
2002	79.03	0.129
2003	80.16	0.134
2004	88.33	0.155
2005	80.20	0.110
2006	145.25	0.115
2007	86.19	0.128
2008	88.32	0.148
2009	105.96	0.110
2010	81.93	0.105
2011	72.24	0.103
2013	91.39	0.106
2014	79.41	0.129
2015	95.66	0.121
2016	85.93	0.129
2017	52.12	0.120
2018	68.45	0.134
2019	103.29	0.108
2020	99.45	0.108
2021	94.72	0.097

Table 3. Likelihood, deviance information criteria (DIC), and overdispersion of the six GLMMs. Bold indicates best fitting model.

Model name	Log-Likelihood	DIC	Overdisp.
Model 1: Poisson	-11831845.6	21274029.9	155.68
Model 2: NB	-1204907.9	2408253.7	1.02
Model 3: NB with vessel effects	**-1176582.5**	**2348382.0**	**1.32**
Model 4: NB with explicit spatial effects	-1204941.1	2408253.4	1.02
Model 5: NB with explicit spatial effects but without implicit spatial fixed effects	-1210222.4	2418892.4	0.98
Model 6: NB with vessel and explicit spatial effects	-1176618.4	2348382.8	1.32

Table 4. Standardized abundance index for 1999 – 2021 from Model 3: NB with vessel effects. Coefficient of variations (CVs) were estimated from posterior marginal distributions.

Year	Value	CV
1999	35.05	0.05
2000	40.31	0.04
2001	51.51	0.04
2002	48.82	0.04
2003	62.64	0.04
2004	84.85	0.03
2005	46.12	0.03
2006	69.25	0.04
2007	76.03	0.03
2008	54.45	0.05
2009	61.54	0.04
2010	53.32	0.03
2011	50.53	0.04
2012	63.42	0.04
2013	55.94	0.04
2014	62.63	0.04
2015	71.89	0.04
2016	60.14	0.03
2017	35.51	0.03
2018	47.01	0.05
2019	60.54	0.05
2020	42.27	0.06
2021	42.45	0.05

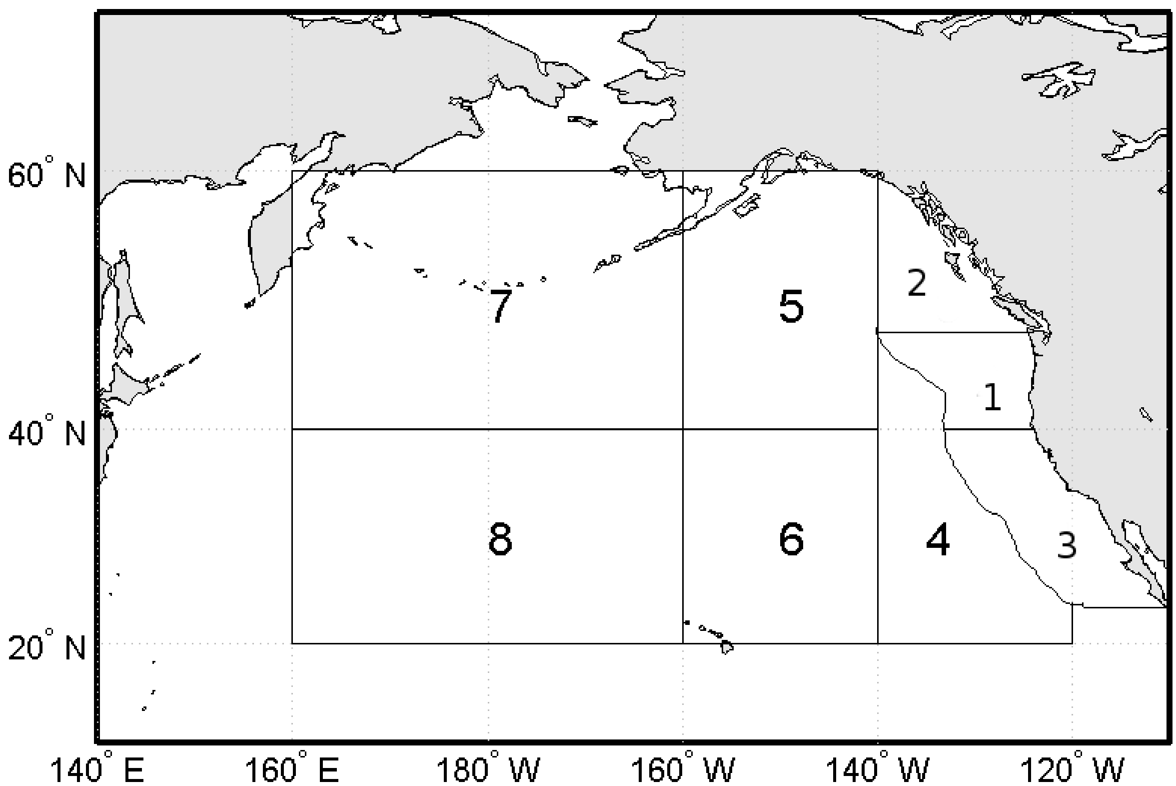

Figure 1. Map of the 8 areas in the generalized linear model used to standardize the catch-per-unit-effort (CPUE) of US surface fishery for previous assessments. See text for spatial definitions of areas.

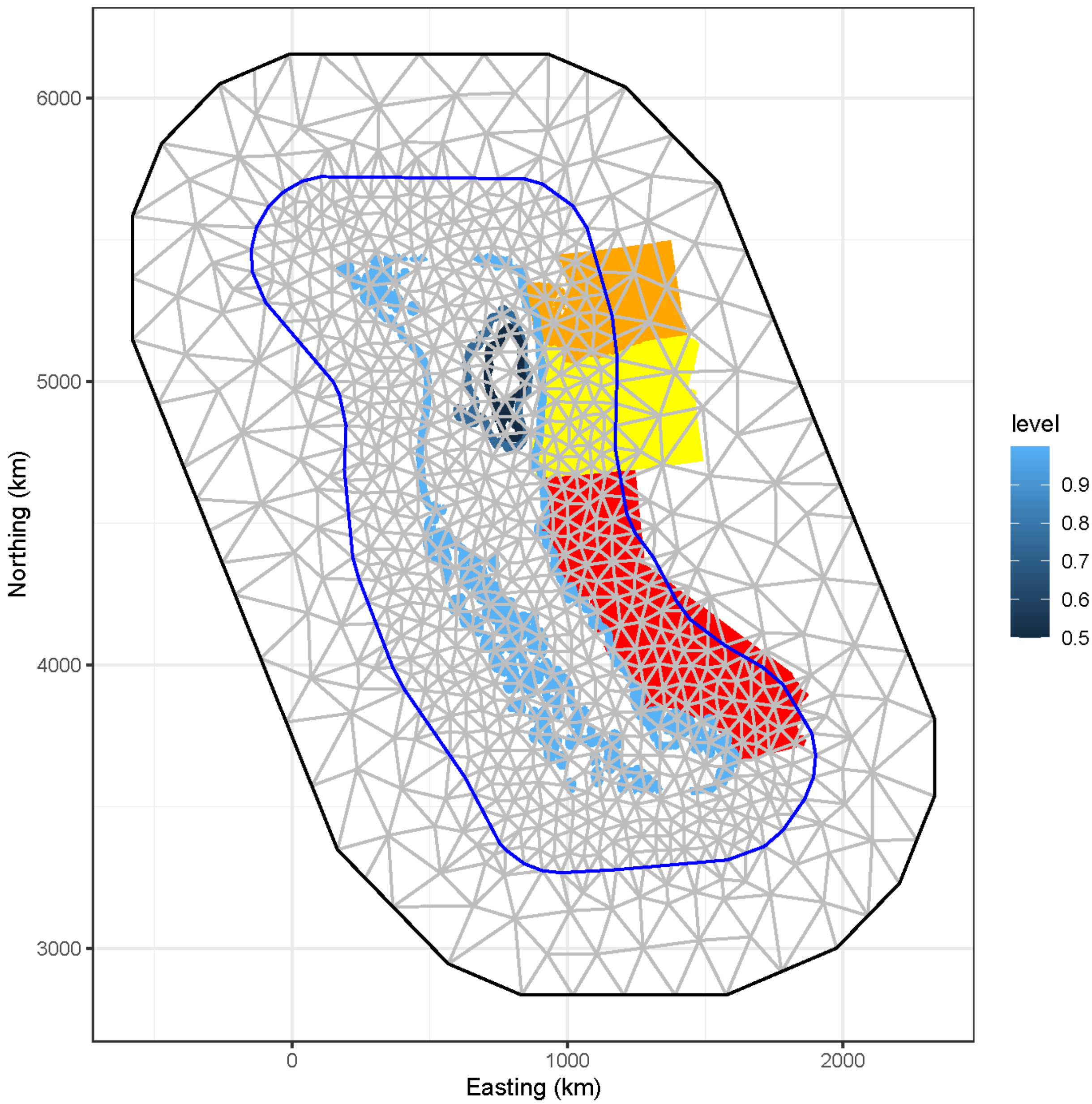

Figure 2. Distribution of fishing effort in relation to the spatial mesh used in generalized linear mixed models with explicit spatial effects (Models 4, 5, and 6). Fishing effort is shown as 99.9 (light blue), 75 (blue), and 50 (dark blue) percentile contours of fishing effort density. California, Washington, and Oregon are shown as red, yellow, and orange areas respectively.

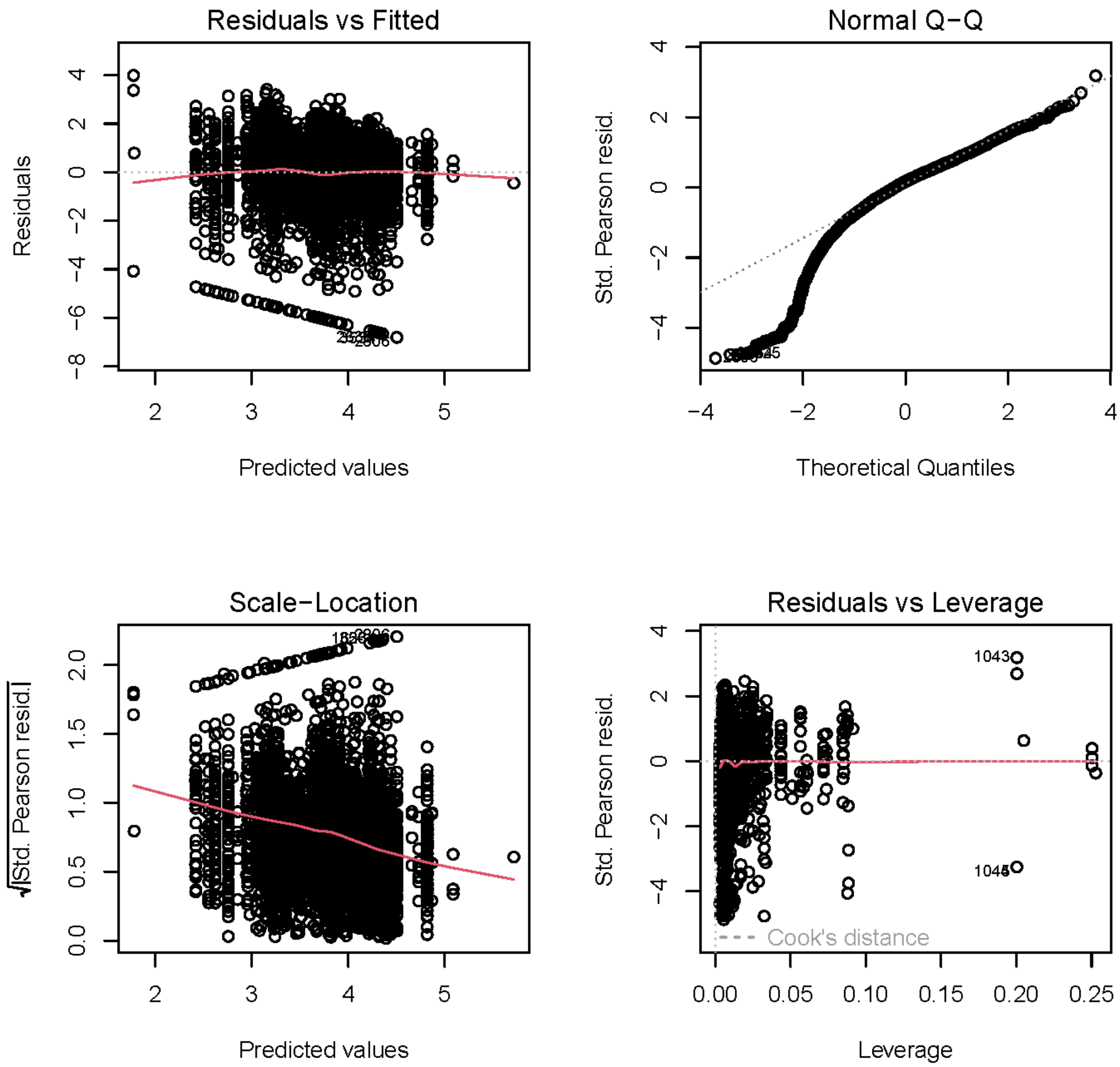

Figure 3. Residuals and Q-Q plots of the GLM for 1999 – 2021 (excluding 2012).

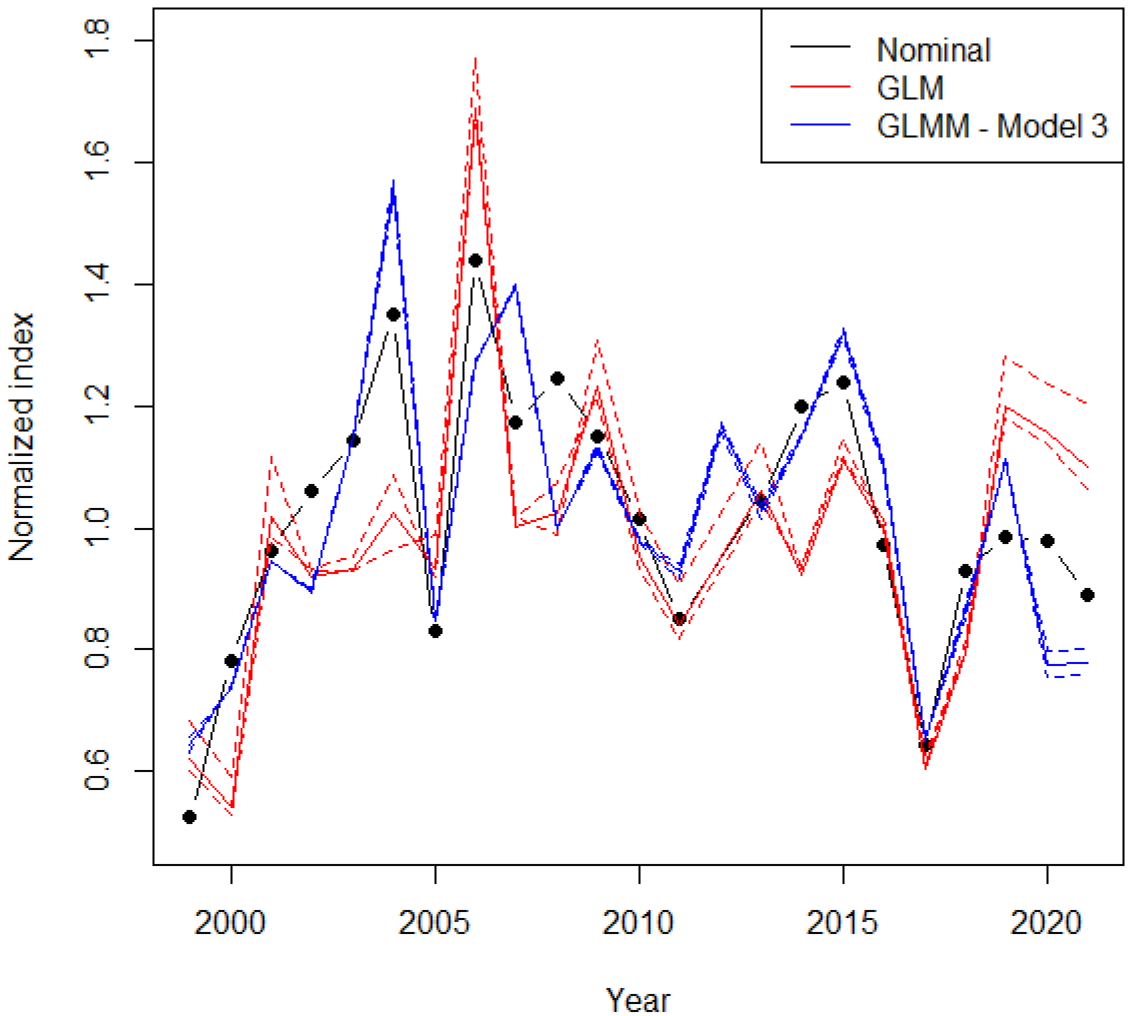

Figure 4. Standardized abundance indices of juvenile north Pacific albacore tuna for the US surface fishery for 1999 – 2021 using the GLM (red) and GLMM Model 3 (blue). Black lines indicate nominal CPUE. Dashed lines indicate 95% confidence intervals. Indices are normalized y dividing by the median of each index.