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ATLANTIC WHITE MARLIN (*KAJIKIA ALBIDA*) STANDARDIZED CATCH RATES FROM THE INDUSTRIAL LONGLINE FISHERY OF MEXICO (1993-2023)

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SUMMARY

*Standardized index of relative abundance for Atlantic white marlin (*Kajikia albida*) was estimated using a Generalized Additive Mixed Model (GAMM) using the Delta method. The data comes from the scientific observer program of Mexico, that registers the activity of the Mexican industrial longline fleet operating in the Gulf of Mexico from the period 1993-2023. The variables considered were Year, Season, Month, Latitude - longitude, Vessel ID, Bait type, Bait condition, Sea Surface Temperature (SST), Dissolved Oxygen concentration (DO), Mixed Layer Depth (MLD), Chlorophyll a concentration (Chla) and Primary Productivity (PP). To assess overall model fitting we used, diagnostic plots were used, indicating no strong departure from expected for an acceptable model fitting. Predictors for the final sub-model of positive catch rates were year, month, latitude-longitude and sea surface temperature, while covariables for proportion of positive observations were the same but also including bait type. The standardized CPUE shows the highest values in 2004, 2012 and 2015, with an increasing trend from 2006 until 2012, followed by a sustained decline from 2012 onwards.*

RÉSUMÉ

Un indice standardisé de l'abondance relative du makaire blanc de l'Atlantique (Kajikia albida) *a été estimé en utilisant un modèle mixte additif généralisé (GAMM) en utilisant la méthode Delta. Les données proviennent du programme d'observateurs scientifiques du Mexique, qui enregistre l'activité de la flottille de palangriers industriels mexicains opérant dans le golfe du Mexique entre 1993 et 2023. Les variables prises en compte sont l'année, la saison, le mois, la latitude et la longitude, l'identification du navire, le type d'appât, l'état de l'appât, la température de surface de la mer (SST), la concentration d'oxygène dissous (DO), la profondeur de la couche mixte (MLD), la concentration de chlorophylle a (Chla) et la productivité primaire (PP). Pour évaluer l'ajustement global du modèle que nous avons utilisé, des diagrammes de diagnostic ont été utilisés, indiquant qu'il n'y avait pas d'écart important par rapport à ce qui était attendu pour un ajustement acceptable du modèle. Les variables prédictives du sous-modèle final des taux de captures positives étaient l'année, le mois, la latitude-longitude et la température de surface de la mer, tandis que les covariables pour la proportion d'observations positives étaient les mêmes, mais incluaient également le type d'appât. La CPUE standardisée présente les valeurs les plus élevées en 2004, 2012 et 2015, avec une tendance à la hausse de 2006 à 2012, suivie d'un déclin soutenu à partir de 2012.*

RESUMEN

*El índice estandarizado de abundancia relativa para la aguja blanca del Atlántico (*Kajikia albida*) se estimó mediante un modelo mixto aditivo generalizado (GAMM) utilizando el método delta. Los datos proceden del programa de observadores científicos de México, que registra la actividad de la flota palangrera industrial mexicana que opera en el golfo de México desde el periodo 1993-2023. Las variables consideradas fueron año, estación, mes, latitud - longitud, id del buque, tipo de cebo, condición del cebo, temperatura de la superficie del mar (SST),*

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concentración de oxígeno disuelto (DO), profundidad de la capa mixta (MLD), concentración de clorofila a (Chla) y productividad primaria (PP). Para evaluar el ajuste general del modelo que utilizamos, se utilizaron gráficos de diagnóstico, que indicaban que no había grandes desviaciones de lo esperado para un ajuste aceptable del modelo. Los predictores para el submodelo final de tasas de capturas positivas fueron el año, el mes, la latitud-longitud y la temperatura de la superficie del mar, mientras que las covariables para la proporción de observaciones positivas fueron las mismas, pero incluyendo también el tipo de cebo. La CPUE estandarizada muestra los valores más altos en 2004, 2012 y 2015, con una tendencia creciente desde 2006 hasta 2012, seguida de un descenso sostenido a partir de 2012.

KEYWORDS

Atlantic white marlin, CPUE standardization, longline fishery, Mexico

Introduction

Blue marlin (*Makaira nigricans*) and white marlin (*Kajikia albida*) are highly migratory pelagic marine fish species, with tropical and subtropical distribution. In Mexico, their capture is incidental by industrial longline Mexican fleet in the Gulf of Mexico by medium-sized vessels (DOF 2014), obtaining a small portion of the total catch in the Gulf of Mexico (Grande-Vidal *et al.* 1988, González *et al.* 2001, Solana-Sansores *et al.* 2004); in a target species it is carried out exclusively for recreational fishing, within a 50 nautical mile band from the coast along the entire coastline of the Gulf of Mexico and Caribbean Sea (DOF 1995).

Bycatch of blue marlin and white marlin and other related species is managed by the NOM-023-SAG/PESC-2014, which regulates the exploitation of tuna species with longline vessels in waters under federal jurisdiction of the Gulf of Mexico and Caribbean Sea (DOF 2019), and represents approximately 7.7% in number of fishes and 13.5% in weight of the total catch made by the tuna longline fleet in the Gulf of Mexico and Caribbean Sea (INAPESCA 2019).

The industrial longline Mexican fleet in the Gulf of Mexico has been carried out by Japan (Compeán-Jiménez and Yañez 1980), the United States (Iwamoto 1965, Compeán-Jiménez 1989), and Mexico (Compeán-Jiménez 1987); the latter coexist and interact currently with the Mexican fishery in the Gulf of Mexico (González-Ania *et al*. 1998). On the part of Mexico, since 1955 there has been reference to the possibilities of tuna fishing in the Gulf of Mexico and the construction of drifting longlines (Carranza 1955). However, until 1982, longline fishing began its development in a more formal way (González-Ania and Zarate 1991) because during 1980 its technological research program was carried out through exploratory longline fishing cruises in the Gulf of Mexico, with a view to harvesting tuna (Grande-Vidal *et al.* 1988). Regarding the observer program, in 1993 they began with variable coverage on longline vessels in the Gulf of Mexico with the objective of obtaining information on materials, equipment, and biological data during fishing set, as well as maintaining a monitoring of fishing effort to complement the studies deployed to develop and consolidate the Mexican tuna fishery, minimizing its effects on associated species (Compeán-Jiménez 2000).

With the objective of contributing to the knowledge of white marlin in the Gulf of Mexico, the analysis of data from the observer's program of the Trust for Research and Development of the National Tuna Utilization and Dolphin Protection Program (FIDEMAR for its acronym in Spanish) in the care of Mexican Institute for Research in Fisheries and Aquaculture Sustainable (IMIPAS for its acronym in Spanish), is presented for the consideration of the Billfish Species Group.

Until now there are no available standardizations for the white marlin catch rates of this particular fishery, which is why the objective of this document is to provide for the first time this index for the period 1993-2023, considering also the possible effect of environmental variables by using a Generalized Additive Mixed Model (GAMM) using the Delta method, with collaboration between Venezuelan and Mexican scientists as a first step to know the species dynamic into the Gulf of Mexico and Caribbean Sea.

Materials and Methods

Data employed in this research comes from the FIDEMAR for the industrial longline Mexican fleet that operates in the Gulf of Mexico and includes the period 1991-2023. Percentage of coverage for this program was 72% from 1993 until 1996, and onwards the coverage corresponds to 100% of fishing operations. This fishery targets yellowfin tuna and swordfish, for which white marlin is a bycatch species, presented only in 18% of the total longline sets, which is why a Delta method was used for modelling in order to consider the high proportion of zeros in the data.

The variables considered as predictors (covariates) in the analysis were year, season (Q1: January-March, Q2: April-June, Q3: July-September, Q4: October-December), month, latitude and longitude, vessel identity code (ID), bait type (squid, fish, octopus), bait condition (live, dead) and environmental variables. These last ones include chlorophyll *a*, sea surface temperature, concentration of dissolved oxygen, mixed layer depth and primary productivity, all of them were obtained from the analysis of satellite imagery compiled from E.U. Copernicus Marine Service. Fishing sets with geographical coordinates (latitude - longitude) that were on land, were the only data point exclusions in the analysis. A total of 79642 fishing sets were used for CPUE standardization, of which 14249 were positive for Atlantic white marlin (CPUE > 0). This data includes landings and discards (alive and dead).

Generalized Additive Mixed Models (GAMM) were used for the standardization in combination with the Delta method (Wood, 2017). This methodology entails fitting two distinct models: one for non-zero catch records and another for the likelihood of a non-zero catch (Lo *et al*. 1992, Ortiz and Arocha 2004, Arocha and Ortiz 2012). For instances of positive catch rates, several types of probability distributions were tested, and the one that offered best results was the log-normal error distribution, which implied the logarithmic transformation of the CPUE. For the proportion of positives, the binomial error distribution was used.

To handle possible problems of collinearity, correlograms using Kendall rank correlations were done for environmental variables, and in those cases in which there were significant high correlations ($|\tau| > 0.7$ or $|\tau| < -0.7$), one of the two variables were excluded from posterior modelling (Dormann *et al*. 2013).

The environmental variables were all considered as smooth terms in the GAMM and vessel ID was set as a random covariate. The number of basis dimensions for each smooth term was iteratively selected using the test presented by Wood (2017). The smoothness selection criterion applied was restricted maximum likelihood (REML), as recommended by Wood (2011) and Pedersen *et al*. (2019).

Selection of explanatory factors and variables was guided by deviance analysis, considering both the relative percentage of deviance each factor added to the evaluation (selecting those contributing over 5%) and their χ^2 significance. The final model was chosen based on Akaike's Information Criterion (AIC), Bayesian Information Criterion (BIC), and a χ^2 test comparing the [–2 loglikelihood] statistic between successive model formulations (Littell *et al*. 1996).

All models and maps were developed using the R programming language (R Core Team, 2025) and combining functions of the R packages 'mgcv', 'gratia', 'corrplot', 'ggcorplot', 'marmap', 'sf', 'ggspatial', 'dplyr' and 'ggplot2'.

Results and discussion

Industrial longline Mexican fleet effort

Fishing effort in terms of number of hooks, is usually higher in the south western area of the Gulf of Mexico, with lower values and occasional activities in the Caribbean during the years 2003 and 2017. Geographical coordinates correspond to the pelagic longline gear retrieval (**Figure 1**). Lobato and Sánchez (2001), refer that white marlin distribution within the Exclusive Economic Zone of Mexico, ranged from 18°43 to 21°57' N and -92°21' and -97°11' W.

Atlantic white marlin nominal CPUE

Despite most of the effort concentrated in the south western of the Gulf, nominal CPUE of white marlin tends to be higher towards the central region which might be owing to the fact that it is not the target species of this fishery (**Figure 2**).

Catch rate standardization

The preliminary exploratory analysis that included pair correlations and collinearity tests between environmental predictor or covariates, showed that there were significative correlations between several pair of variables, and following recommendations of Dorman *et al.* (2013), dissolved oxygen concentration was excluded because it had a strong negative correlation with sea surface temperature (**Figure 3**). Although the correlation coefficient between chlorophyll *a* and primary productivity was 0.5, the second environmental variable was also excluded for having a very similar trend over the years. In this sense, the environmental variables selected for the posterior modelling process were sea surface temperature, mixed layer depth and concentration of chlorophyll *a*.

The positive catch rates are examined through various model diagnostics, including plots that assess the link function and variance function, as well as checks for the model's error distribution and the QQ-plot of the standardized deviance residuals (**Figure 4**). The model QQ-plot suggested that the fit of the model to the data was generally reasonable. There were some discrepancies between the theoretical and predicted quantiles, particularly at the lower end of the theoretical quantiles range for the lognormal component and at higher values for the binomial, where also fitted probabilities of 0 or 1 may occur (Hoyle *et al*. 2019). However, in general these diagnostic plots reveal that there are no significant deviations from the expected pattern for this type of model (**Figure 5**).

According to the deviance analysis, major covariates explaining the positive CPUEs and the proportion of positive CPUEs for Atlantic white marlin were: year, month, latitude and longitude, and sea surface temperature (**Table 1**). For the second one (proportion of positive catch rates), the bait type was also considered as relevant.

According to the Akaike's Information Criterion (AIC), Bayesian Information Criterion (BIC), and a χ^2 test comparing the [–2 loglikelihood] statistic between successive model formulations, the final sub-models selected were: "Year + s(Month) + s(Latitude, Longitude) + s(Sea surface temperature)" for positive catch rates and "Year + s(Month) + s(Latitude, Longitude) + Bait type + s(Sea surface temperature)" (**Table 2**). Both models explained 11.2% and 12.5% of the variability, respectively. The nominal and standardized CPUE series (ind/1000 hooks) for Atlantic white marlin from the industrial longline Mexican fleet (1993-2023) is shown in **Table 3**.

Marginal or partial effect plots show that positive CPUE of the species increases for the second part of the year, with highest concentration towards the center of the study area (the more oceanic region of the Gulf of Mexico) as observed in the latitude-longitude partial effect plot, and it increases until it reaches temperatures around 25 ºC after which it stabilizes (**Figure 6**). This same type of plots for the proportion of positive catch rates presents similar trends for the mentioned variables (month, latitude-longitude, temperature) that those observed for the positive CPUE, and for the bait type the probability of catching a white marlin individual seems to be higher when octopus and squid are used instead of fish or sardine (**Figure 7**).

A relation between CPUE of white and blue marlin with sea surface temperature has been reported before by Godyear (2003) with results that show spatio-temporal heterogeneity in catch rates that may be partly explained by seasonal changes in sea surface temperatures.

Nominal and standardized CPUE of Atlantic white marlin both show similar trends over the years, with the standardized catch rate presenting its highest values in 2004, 2012 and 2015; afterwards there is an increasing trend from 2006 until 2012, followed by a sustained decline from 2012 onwards (**Figure 8**). The type of bait with the highest probability for positive white marlin catch rate were octopus and squid. Regarding the second one, white marlin has been reported as a top predator that opportunistically feeds on schools of juvenile flying fish, small tuna, dolphinfish and squid (ICCAT 2006-2016).

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Table 1. Deviance analysis table for explanatory variables in the GAMM's for Atlantic white marlin catch rates. Percent of total deviance refers to the deviance explained by the full model, *p* value refers to the probability Chi-square test between two nested models, LRT: Likelihood Ratio Test, SST: Sea Surface Temperature, MLD: Mixed layer depth, Chla: Chlorophyll *a*. The bold lettering indicates the selected covariates for each component of the delta method.

	Resid. Df	***Resid. Dev***	***Df***	***Change in deviance***	***p***	***% of total deviance***
Model covariates for positive catch rates (CPUE >0)						
Intercept	14235.00	4439.41				
Year	**14205.00**	**4204.34**	**30**	**235.07**	**<0.001**	**46.00**
s(Month)	**14193.98**	**4101.78**	**11.02**	**102.56**	**<0.001**	**20.07**
Season	14193.70	4101.32	0.29	0.46	0.05	0.09
s(Lat, Lon)	**14155.70**	**3970.50**	**38.00**	**130.81**	**<0.001**	**25.60**
s(Vessel ID)	14154.11	3969.96	1.59	0.54	0.29	0.11
Bait type	14151.59	3967.24	2.52	2.73	0.01	0.53
Bait condition	14150.63	3967.14	0.96	0.09	0.55	0.02
s(SST)	**14142.83**	**3942.51**	**7.80**	**24.63**	**<0.001**	**5.82**
s(MLD)	14138.04	3937.11	4.78	5.40	<0.001	1.06
s(Chla)	14129.42	3928.35	8.63	8.76	<0.001	1.71
Model covariates for proportion of positive catch rates						
Intercept	8059.00	33487.06				
Year	**8029.00**	**32042.84**	**30**	**1444.23**	**<0.001**	**32.39**
s(Month)	**8020.01**	**30371.94**	**8.99**	**1670.90**	**<0.001**	**37.48**
Season	8018.00	30328.14	2.01	43.80	<0.001	0.98
s(Lat, Lon)	**7970.41**	**29519.49**	**47.59**	**808.64**	**<0.001**	**18.14**
s(Vessel ID)	7969.46	29512.93	0.95	6.57	0.01	0.15
Bait type	**7966.37**	**29356.03**	**3.09**	**156.90**	**<0.001**	**4.52**
Bait condition	7965.35	29351.95	1.02	4.07	0.04	0.09
s(SST)	**7917.35**	**29102.83**	**48.00**	**249.13**	**<0.001**	**5.59**
s(MLD)	7910.12	29060.67	7.23	42.15	<0.001	0.95
s(Chla)	7901.46	29028.44	8.66	32.23	<0.001	0.72

Table 2. Analyses of GAMM formulations for Atlantic white marlin catch rates. The difference in log-likelihoods was compared with a Chi-squared distribution. The bold lettering indicates the selected model for each component of the delta method.

	AIC	***BIC***	***Log likelihood***	***LRT***	
				Chi²	***p***
Models for positive catch rates					
Year	23100.98	23343.01	-11518.49		
Year + s(Month)	22769.39	23087.00	-11342.71	351.56	<0.001
Year + s(Month) + s(Lat, Lon)	22362.03	22883.79	-11112.03	461.35	<0.001
Year + s(Month) + s(Lat, Lon) + s(SST)	**22284.34**	**22844.87**	**-11068.06**	**87.94**	**<0.001**
Models for proportion of positive catch rates					
Year	40948.75	41165.58	-20443.37		
Year + s(Month)	39295.42	39573.72	-19607.93	1670.90	<0.001
Year + s(Month) + s(Lat, Lon)	38561.02	39136.46	-19198.24	819.36	<0.001
Year + s(Month) + s(Lat, Lon) + Bait type	38409.48	39007.58	-19119.23	158.02	<0.002
Year + s(Month) + s(Lat, Lon) + Bait type + s(SST)	**38324.69**	**38960.99**	**-19071.37**	**95.72**	**<0.003**

Table 3. Nominal and standardized (GAMM) CPUE series (ind/1000 hooks) for Atlantic white marlin catch rates from the industrial longline Mexican fleet (1993-2023).

Year	*n*	*Nominal CPUE*	*Standardized CPUE*	*Standard Error*	*%CV*
1993	237	0.4205	0.3607	0.0061	25.92
1994	890	0.5199	0.4239	0.0057	12.66
1995	1505	0.4012	0.3115	0.0031	12.05
1996	828	0.1928	0.1665	0.0026	14.00
1997	282	0.3714	0.3155	0.0058	9.78
1998	692	0.3134	0.2442	0.0028	9.63
1999	2282	0.2094	0.1762	0.0016	14.09
2000	2402	0.4132	0.3597	0.0030	12.83
2001	2480	0.4870	0.4157	0.0032	12.12
2002	2554	0.5705	0.4839	0.0035	11.59
2003	3021	0.4436	0.3888	0.0029	12.77
2004	3341	0.7556	0.6406	0.0035	9.91
2005	3363	0.7147	0.6139	0.0039	11.51
2006	3579	0.4214	0.3860	0.0026	12.67
2007	3243	0.4260	0.3883	0.0027	12.44
2008	3147	0.4721	0.4396	0.0030	12.10
2009	3050	0.6638	0.5990	0.0046	13.32
2010	2945	0.7138	0.6189	0.0052	14.29
2011	2880	0.9819	0.8325	0.0065	13.23
2012	3387	1.1158	0.9739	0.0063	11.88
2013	3131	0.9747	0.8442	0.0056	11.67
2014	3232	0.6176	0.5269	0.0035	12.00
2015	3208	0.7601	0.6372	0.0047	13.34
2016	3408	0.5886	0.5265	0.0035	12.29
2017	3611	0.3242	0.3079	0.0025	15.49
2018	3519	0.4171	0.3661	0.0024	12.25
2019	3017	0.3022	0.2827	0.0023	13.99
2020	2682	0.3708	0.3433	0.0029	13.99
2021	2745	0.4700	0.4194	0.0028	11.26
2022	2449	0.3679	0.3462	0.0031	14.04
2023	2395	0.3132	0.2953	0.0029	15.01

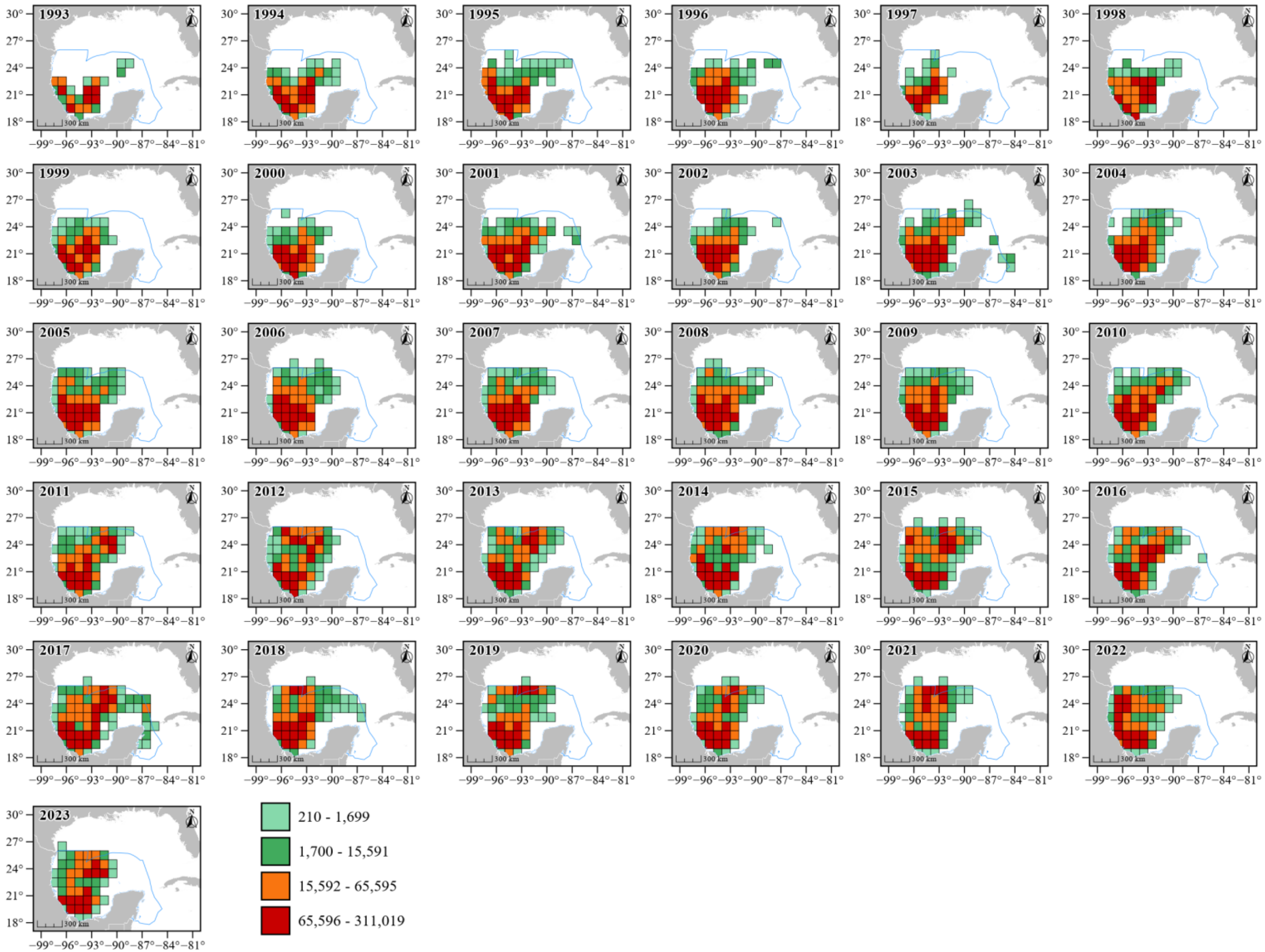

Figure 1. Spatial distribution (1º x 1º) of fishing effort (number of hooks) by the Mexican longline fleet during 1993-2023.

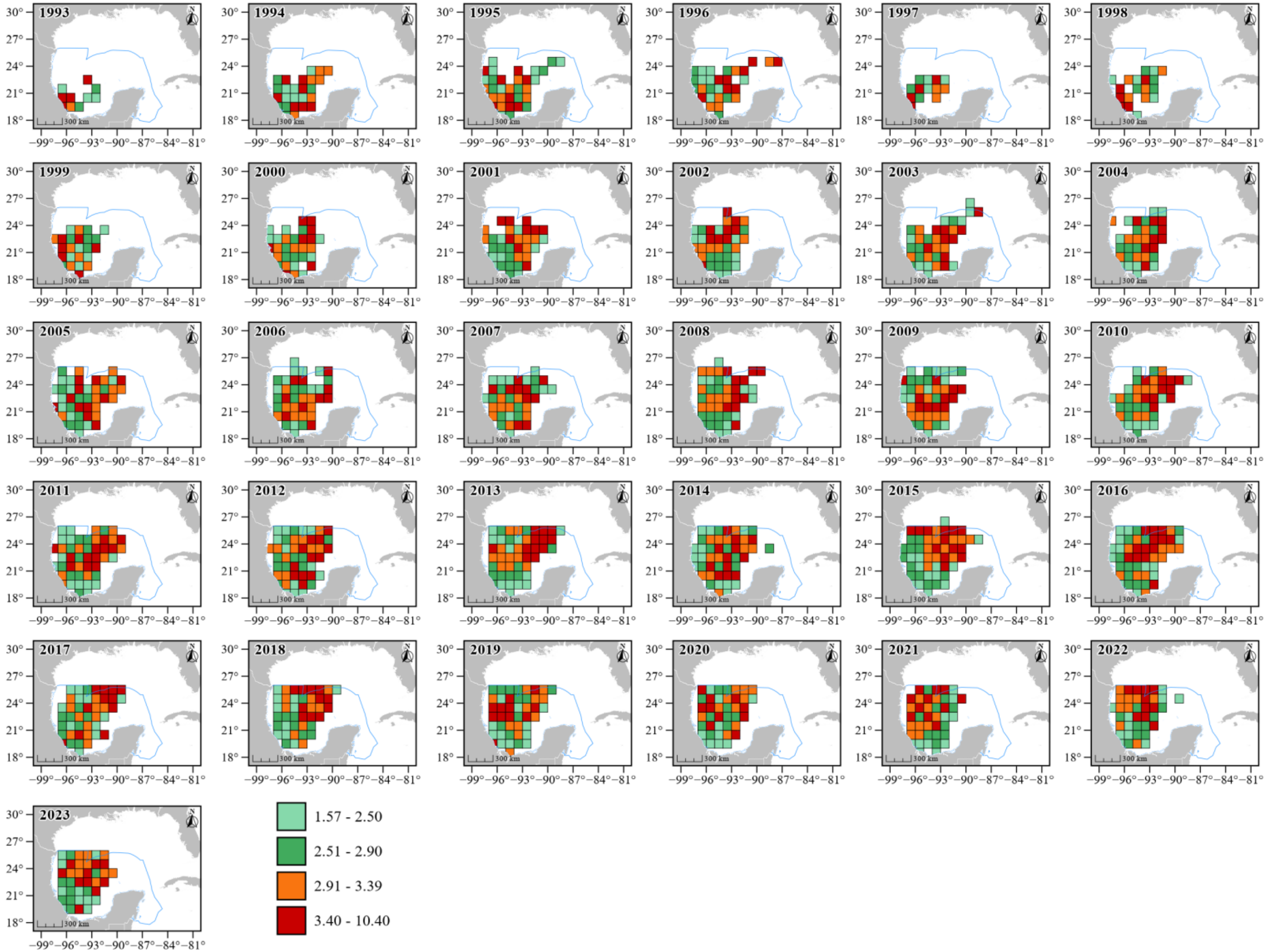

Figure 2. Spatial distribution (1º x 1º) of white marlin CPUE (ind/1000 hooks) caught by the Mexican longline fleet during 1993-2023.

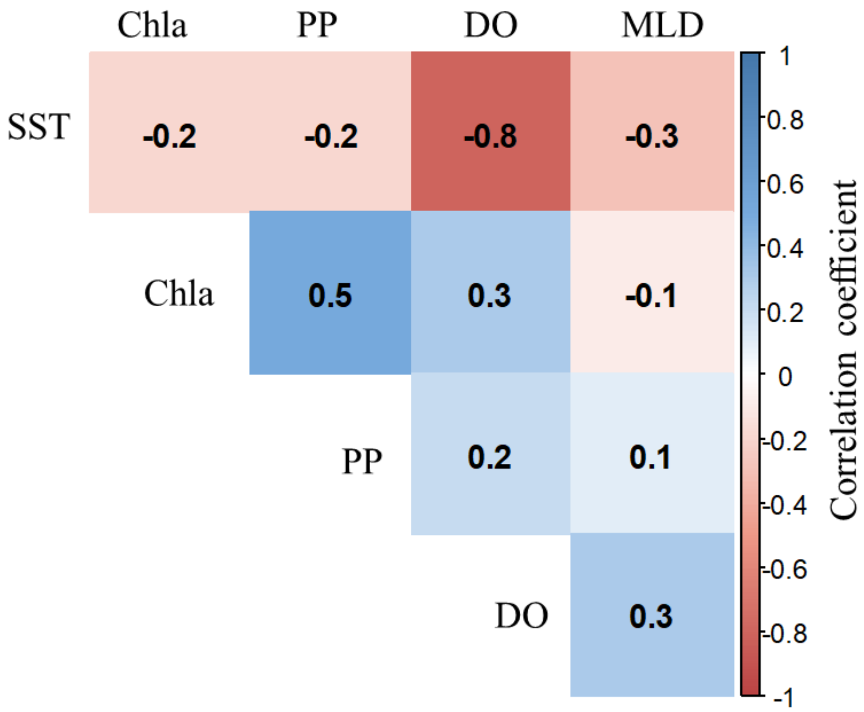

Figure 3. Correlogram that shows only significative correlations ($p<0.05$) between pairs of environmental variables (SST: Sea Surface Temperature, Chla: Chlorophyll *a* concentration, PP: primary productivity, DO: concentration of dissolved oxygen, MLD: Mixed layer depth).

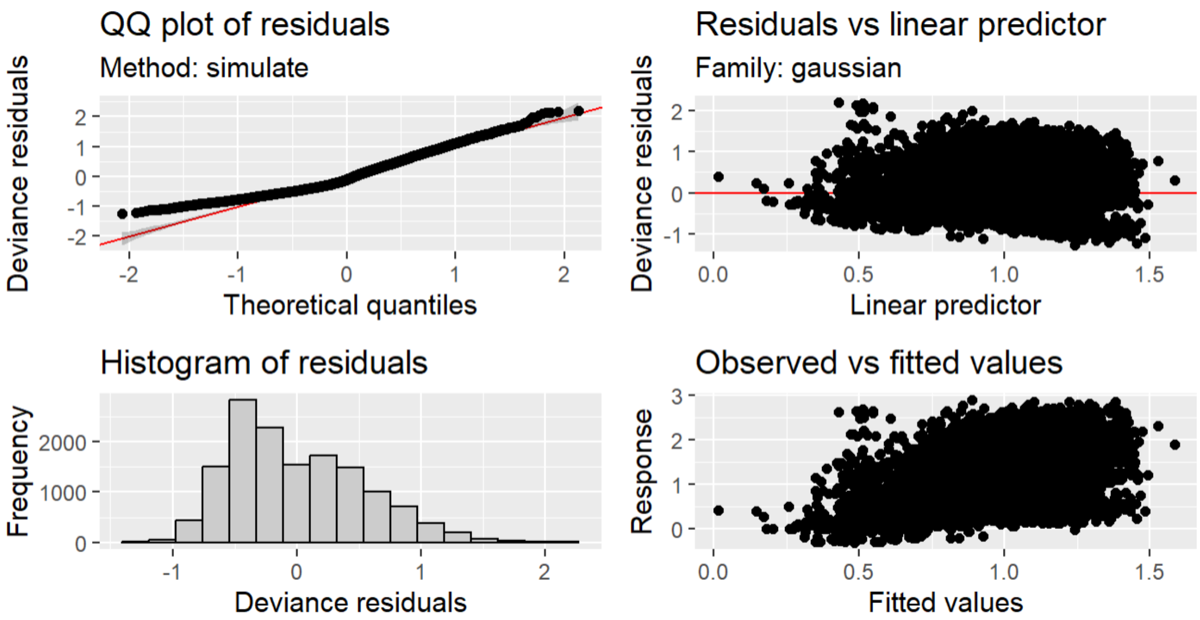

Figure 4. Diagnostic plots for the sub-model of positive catch rates of white marlin.

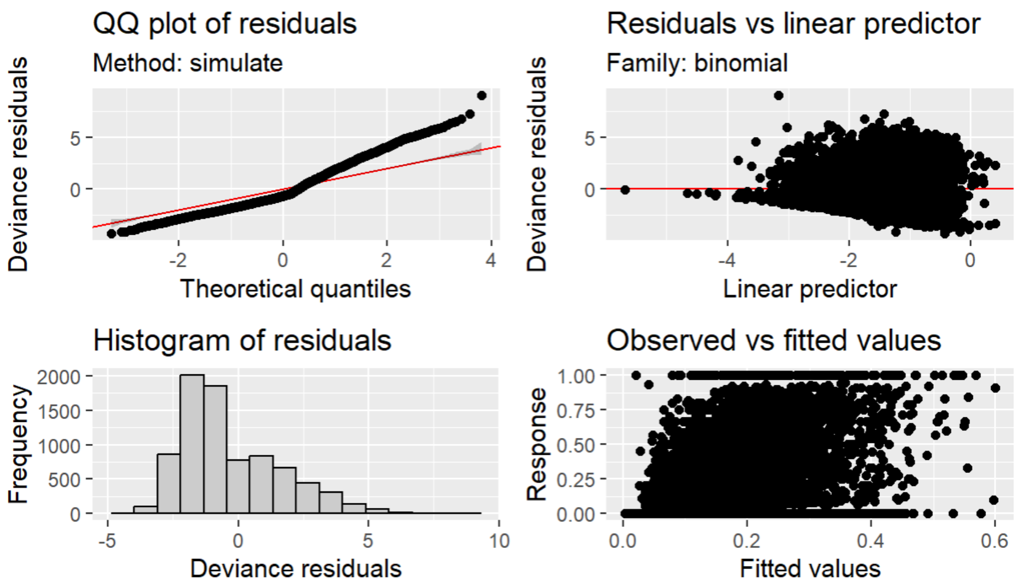

Figure 5. Diagnostic plots for the sub-model of proportion of positive catch rates of white marlin.

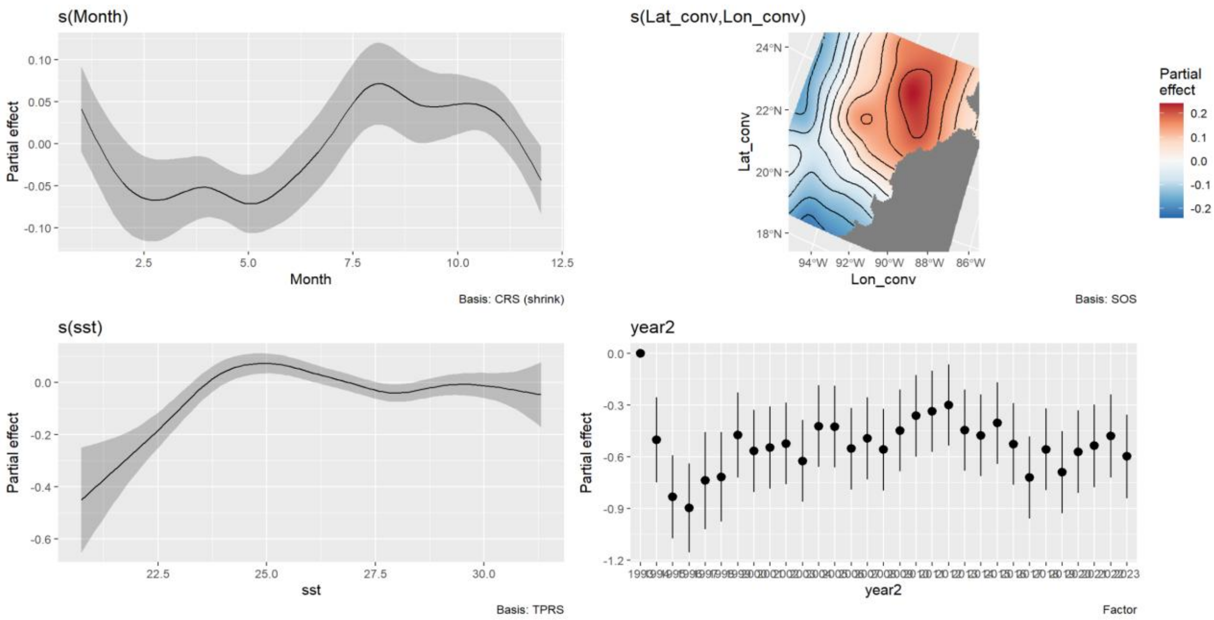

Figure 6. Partial effect plots for covariables of the final sub-model for positive observations (WHM CPUE > 0).

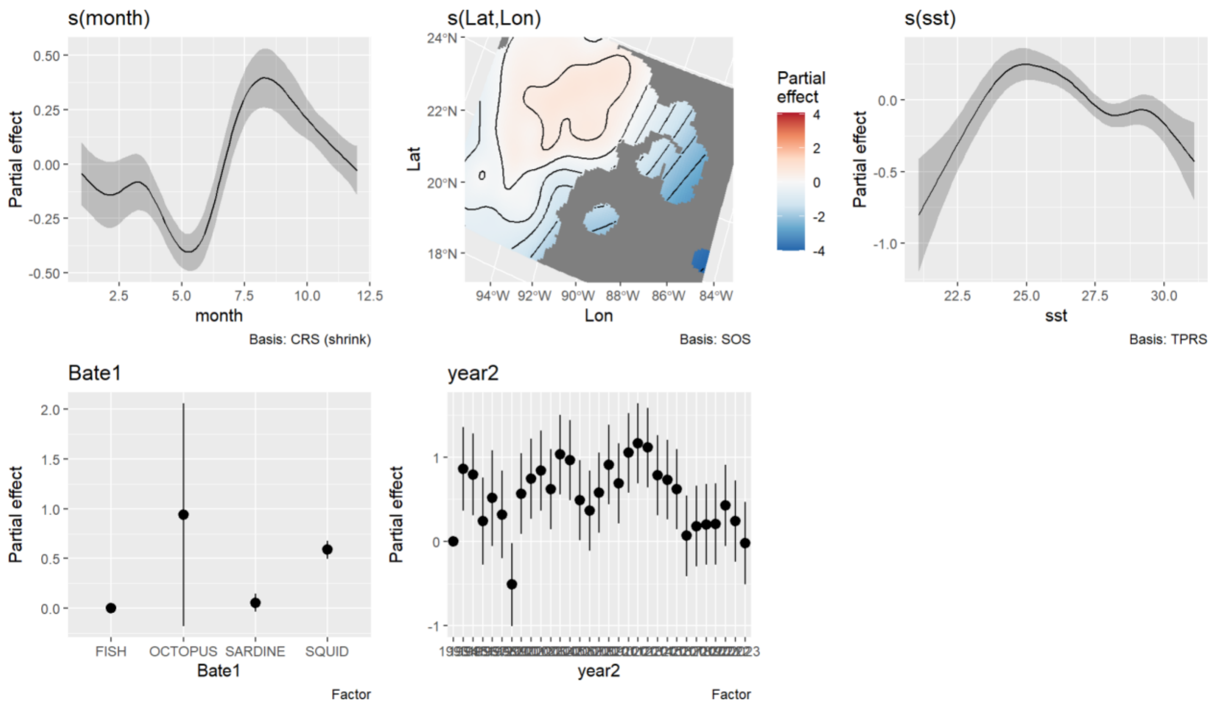

Figure 7. Partial effect plots for covariables of the final sub-model for proportion of positive observations.

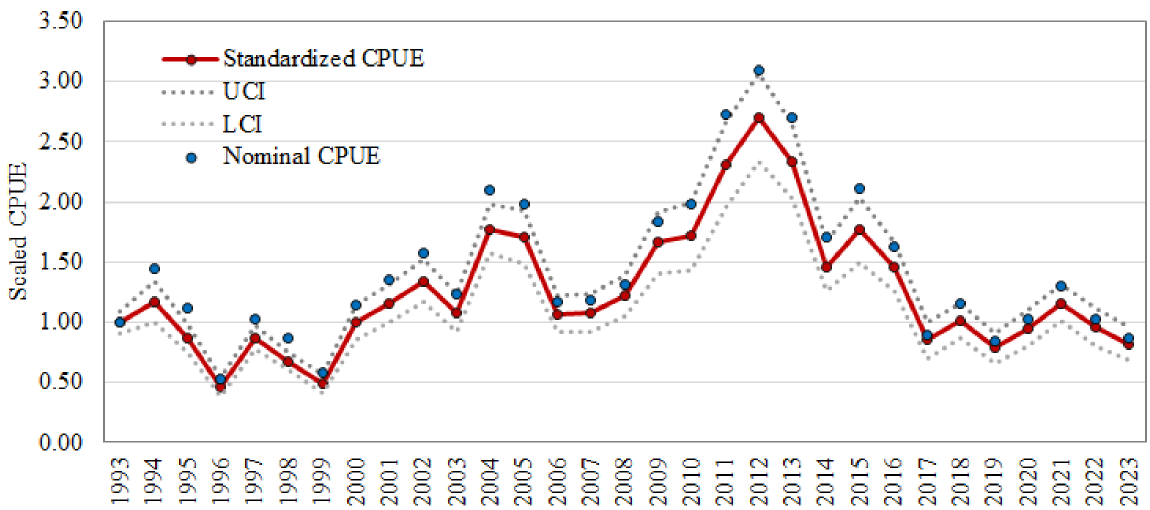

Figure 8. Scaled nominal (blue dots) and standardized (red circles) CPUE (ind/1000 hooks) of Atlantic white marlin. Dotted lines represent 95% confidence intervals for standardized CPUE.