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RESEARCH ARTICLE

Characterization and standardization of the Atlantic albacore French pelagic trawl fishery

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Abstract – We compiled and analysed logbook data from the French trawl albacore fishery covering the period 1991–2015. The dataset comprised catch and effort data for the French fleet operating in the Bay of Biscay and Celtic Sea, as well as spatiotemporal and gear characteristics. Generalized linear modelling was used to model spatial, seasonal, environmental, and gear covariates of fleet CPUE rates. A long-term index of relative abundance is provided that can be integrated into the stock assessment of North Atlantic albacore. The analysis revealed higher albacore CPUE associated with relatively low sea surface temperature and distinct seasonal effects. The derived abundance trend for the French trawl fishery agreed with the estimated time series of stock abundance from recent assessments.

Keywords: Albacore / catch / Atlantic / trawl / fisheries / stock

1 Introduction

Albacore (*Thunnus alalunga*) are highly migratory and distributed throughout most tropical and temperate oceans (Collette and Nauen, 1983). Global commercial catches top all other temperate tuna species, contributing around 6% by weight to global tuna catches over the last decade (FAO, 2012). Similar to most tunas, fishing pressure on albacore has increased over the last three decades (Dragon et al., 2015). The International Union for Conservation of Nature (IUCN) classify albacore as near threatened across much of its range (The IUCN Red List of Threatened Species. Version 2017-3. <www.iucnredlist.org>. Downloaded on 16 May 2018). Despite some raised concern over species status, the North Atlantic albacore stock was estimated to have been rebuilding in recent years (ICCAT, 2013a).

Fisheries management objectives for albacore range from conservation to socioeconomic benefits, including maximizing long-term sustainable yield (Maunder et al., 2006). The albacore stock assessments relied on fishery dependent data, particularly, catch and effort information from the commercial fisheries (Coelho et al., 2014). Catch rates, or catch-per-unit-effort (CPUE), data from commercial fisheries are often used as the primary source of information for estimating stock trend and current status. Standardization methods that account for spatiotemporal asynchrony of fishing effort, gear characteristics, and environmental conditions are important to correct for changes in fleet catchability that are unrelated to changes in stock abundance. Examples include shifts in the spatial distribution of the fleet (Walters, 2003), a change in the species targeted (Quirijns et al., 2008), changing oceanic conditions (Bigelow and Maunder, 2007; Prince et al., 2010), and gear (Damalas et al., 2007) including technological innovation. These factors influence fish availability, gear catchability, or both, and bias CPUE time series (i.e. the change in observed CPUE is unrelated to a change in stock abundance).

The goal of a CPUE standardization analysis is to estimate the time series of relative abundance (typically annual or seasonal) that is proportional to the stock abundance, from which the fishery dependent and other effects have been removed. In other words, the analysis aims to explain the variation in fishing catch rates in the context of site conditions, vessel properties, and gear characteristics of individual fishing trips, in order to account for the influence of these factors on the annual index of abundance (Maunder and Punt, 2004; Chang et al., 2017). Hence, the standardized index (standardized CPUE) is more appropriate for the estimation of stock status and trend compared to the observed mean.

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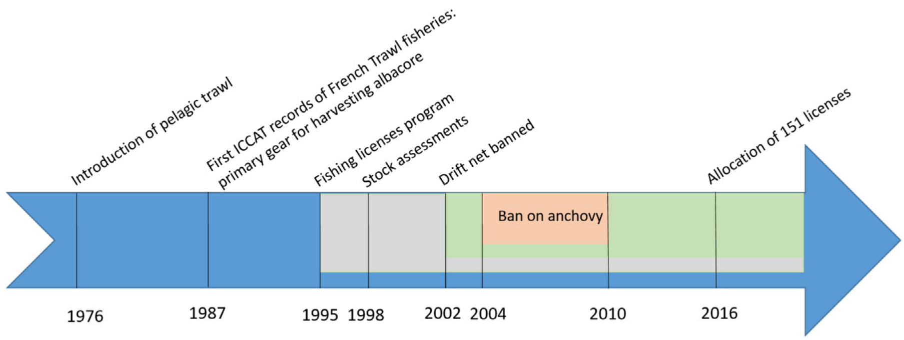


Fig. 1. Chronology of French albacore fishery and management regulations.

The North Atlantic albacore stock is governed internationally by the International Commission for the Conservation of Atlantic Tunas (ICCAT). Beginning in 1998, a limit for the number of vessels in the trawl targeted fishery was implemented by ICCAT; prior to this no international harvest regulations existed for the stock. However, France's National Committee for Marine Fisheries and Marine Fish Stocks (CNPMEM) implemented a fishing license program for albacore in 1995 that restricted access to the fishery to permitted individuals (NOR: AGRM1108873A). Since the implementation of that measure, the number of French licenses has decreased progressively to a current allocation of 151 licenses distributed among the different gears (Order of May 27, 2016–Art. 11). Additional regulation limit vessel size to less than 25 m for newly licensed vessels; or alternatively, if the quantity caught, kept on board, transshipped or landed exceeded 2 tons in the previous year (AGRM1108873A). In 2002, a prohibition of gillnets resulted in the development of the pelagic pair trawl fishery. Currently, pelagic trawling is the fishing technique most used by French fishermen for this species.

Albacore are caught by seven gears, including longlines, gillnets, purse-seines, trolls, mid-water trawls, and pole and line (Nikolic et al., 2016). Since the 1950s, there have been high catches of albacore in the northeast Atlantic by surface fisheries of Spain, France, Portugal, and more recently by Ireland. Further, longline fleets (e.g. Taiwanese fleet) targeting albacore or other tuna species operate year round in the central and western North Atlantic (Cosgrove et al., 2014a; ICCAT, 2014). Catches decreased in the North Atlantic from 52 869 tons in 1960 (Nikolic et al., 2016) to 25 443 tons in 2015 (ICCAT statistical database, accessed 19 May 2018). Stock assessments for the North Atlantic stock have been carried out since 1998, with the most recent management advice being based on the 2016 assessment (ICCAT, 2016). The results of that assessment indicated the stock was subjected to overfishing between the mid-1960s and mid-2000s which depleted the spawning biomass to the extent that it has been overfished since the 1980s (ICCAT, 2013b, c). Stock projections predict the stock to be rebuilt by 2019 with 53% probability under an annual total allowable catch (TAC) of 28 000 t (ICCAT, 2016). The conclusions of the last assessment indicated that quotas near the current TAC would allow for continued stock rebuilding or maintain the target biomass at or near that which produces the maximum sustainable yield (ICCAT, 2016). The targeting of the trawl fishery has been relatively constant over the time series, making the dataset more appropriate as a measure of albacore relative abundance compared to other fisheries (e.g. longlines and seines) which have undergone significant shifts in species targeted over time (ex. ICCAT statistical database).

The main goal of this study was to compile all available fisheries data from the French pelagic trawl fleet and generate a standardized fishery-dependent abundance index for the Bay of Biscay region. The French fleet accounted for the majority of the albacore catch in the trawl fishery (mean of 94% from 1991 to 2000 and 71% from 2001 to 2015), and a significant proportion of the total harvest of North Atlantic albacore. Therefore, accurate description of fleet dynamics, catches, and catch rates provide valuable information on the fishery operations, long-term harvest trend, and potentially, stock abundance trend. The pelagic trawl is the primary gear used for targeting and harvesting albacore, and the French fishing fleet is the second largest fleet (after Spain) harvesting albacore (Nikolic et al., 2016). The spatial coverage of the trawl fishery spans a considerably large area where albacore are abundant, particularly in the Bay of Biscay and Atlantic Ocean in the region south of Ireland. Pelagic trawling for albacore has increased steadily between the 1980s and recent decades, reaching ~20% of total albacore catches in the North Atlantic (Nikolic et al., 2016). In France, the pelagic trawl was introduced in 1976 (Fournet, 1978) and since 1987 has been the primary gear for harvesting albacore (Liorzou, 1989). A historical chronological synthesis of French albacore fisheries is provided in Figure 1.

The aims of this paper were to: (1) analyze the fishery effort distribution of the French pelagic trawl fishery in the North Atlantic; (2) estimate the power of environmental variables for explaining spatiotemporal variations in catches; and (3) obtain a standardized relative abundance time series as potential data input to future stock assessments.

2 Material and methods

2.1 Data collation

Compared to conventional stock assessments, this work required an investment of several months to recover, improve and correct the fisheries and environmental data. Catch, effort, and gear characteristics were collated for the French mid-water trawlers operating in the Bay of Biscay and adjacent waters since 1987. This surface fishery fishes at depths between 10 and 80 m (mainly 50 m) using a trawl with a gear opening (headrope) between 100 and 150 m (mainly around 130 m). The data were derived from the French Fisheries Information

Table 1. Summary of the French mid-water trawl historical albacore data time series (from 1991 to 2015). Fishing operation (FO). Nominal Catch Per Unit Effort (CPUE) (catches of albacore (kg)/per vessel fishing time (hours)).

			Mean							Percentage of representativeness of these data according to the total french trawl catches recorded in ICCAT
Year	Number of data	Number of boats	Number of FO	Fishing time per FO (hours)	Fishing time per Trip	Number of fishing days per trip	Total catch (Kg) per trip	Total catch (Kg) per FO	CPUE	
1991	118	29	4.991525	6.240424	28.601695	7.115385	3536.9322	1072.8664	195.0317	86.64
1992	219	49	4.831050	6.175616	28.255708	7.566667	6207.1566	1391.1264	238.6444	54.24
1993	153	41	5.647059	5.233333	27.816993	8.558824	5556.6804	1124.1319	243.2333	49.83
1994	135	30	6.103704	5.658444	30.955556	9.548387	6356.2600	1446.1210	293.7556	43.62
1995	187	25	4.176471	5.424706	21.641711	8.000000	5027.2615	1200.8133	246.6192	31.69
1996	120	26	7.041667	5.268250	34.775000	8.368421	8799.5825	1217.0564	253.2111	40.37
1997	91	27	6.461538	4.952857	31.736264	5.818182	13496.7363	2665.3586	616.9231	41.16
1998	80	19	6.412500	4.994375	32.875000	11.875000	5178.0813	1012.4531	217.8708	35.17
1999	95	46	3.915789	5.244211	22.400000	2.900000	3355.4032	981.3528	240.0326	6.61
2000	551	69	5.613430	5.684628	30.728131	3.206780	3855.3100	785.9789	163.4323	59.15
2001	2409	126	1.777501	6.170100	11.182731	4.276695	1929.7611	1066.8600	222.7978	93.29
2002	3281	96	1.545261	5.737434	9.089424	3.832757	969.4101	651.0354	132.2540	72.98
2003	2207	91	1.499773	6.679547	9.375895	4.151643	1017.8424	751.4524	140.7049	69.07
2004	140	28	1.264286	7.128571	8.552857	3.983607	858.2007	687.8971	109.6750	5.48
2005	4095	121	1.643712	6.438386	9.803810	3.698891	1541.9074	1057.5378	189.8252	92.13
2006	3566	92	1.511778	5.985499	8.569125	3.357501	1648.2544	1215.5966	235.1722	99.99
2007	2855	75	1.634676	5.648459	8.744133	3.092086	994.3924	662.9531	128.0397	99.88
2008	916	41	1.575328	7.144574	10.356659	4.587054	994.6103	637.0739	102.8738	32.47
2009	440	48	1.322727	5.755886	6.936364	4.209945	1822.3705	1387.8308	320.1861	102.43
2010	400	36	1.300000	5.522250	6.676000	4.336735	1830.2650	1444.3325	341.5779	59.32
2011	822	40	1.392944	4.770012	5.995620	4.296000	3411.1588	2665.1944	682.0077	85.07
2012	1228	58	1.259772	10.685399	12.073860	3.472756	2652.3352	2148.3997	275.6677	103.84
2013	1172	40	1.411263	5.242577	7.273464	4.976449	3731.3910	2703.6276	534.2505	100.88
2014	901	36	1.597114	5.254018	8.289012	4.268692	5699.3700	3676.9622	734.7769	76.65
2015	821	40	1.438490	5.983557	8.588307	6.138264	2950.1504	2191.5469	366.2473	71.42

System (SIH), official logbooks and catch reports, fish markets, and an onboard observer program (OBSMER) compiled in an IFREMER database (http://sih.ifremer.fr/Description-des-donnees). Data from 1991 to 2015 were considered the most comprehensive and reliable. Earlier years were excluded because of missing, incomplete or inconsistent records and low fleet coverage as data collection started in 1989 with approximately 8% fleet coverage and increased to 16% coverage in 1990. Fleet coverage further increased to more than 60% beginning in 1991 with near 95% coverage since 2008. The dataset comprised trip level information on total albacore catches in weight, the date, the number and duration (time) of fishing operations (FOs), gear mesh size, vessel length and power, and geographical location (ICES statistical rectangles). Latitude and longitude were assigned to a daily FO based on ICES statistical rectangles (Patucca, 2015). Size composition information was missing for 74% of data records, with no size sampling from 2006 to 2014. Therefore, size was not considered for modeling but the available information was assessed to determine the size range targeted by the fishery.

2.2 Data selection

Data from French vessels targeting albacore with pelagic trawls in the Bay of Biscay were selected for analysis (48 666 FOs in total). Weekly mean sea surface temperature (SST), ocean depth and sea floor slope (local maximum gradient of bottom topography) were assigned based on date, latitude, and longitude from the U.S. National Oceanic and Atmospheric Administration satellite observation and general bathymetric chart databases.

The total number of vessels in the database was 289, with a minimum of 19 vessels and a maximum of 126 operating per year (mean of 53 vessels per year) (Tab. 1). Based on the number of licenses (151 for all gears), the database covered a minimum of 13% and a maximum of 83% of vessels. Trawl mesh size was predominantly 100 mm (range 45–300 mm). Mean vessel length was 21.7 m (CI 95%, 20.8–23.4 m) and mean vessel power was 403 KW (CI 95%, 324–450 KW). Hence, most vessels were <25 m, as recommended by the French ministerial bylaw, with only 23 vessels (representing 1939 trips) measuring more than 25 m. Both fishing vessel size

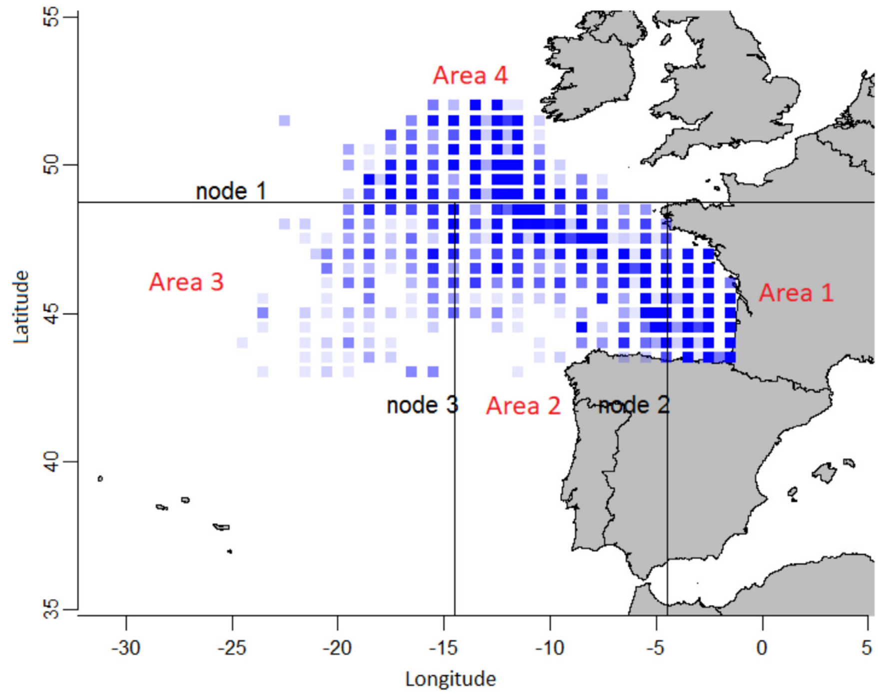


Fig. 2. Spatial partitioning based on regression tree analysis of albacore CPUE (catches of albacore (kg) per fishing time (hours)) represented on 1°x1° grid. The boxes indicate the four main sub-regions where the fleet is operating.

and power, and gear mesh size were included in our analysis. Records with missing information on mesh size, vessels size, vessel power, latitude, or longitude were excluded. The final dataset comprised 47 831 FOs (26 599 trips).

2.3 Data analysis

CPUE was calculated as albacore yield in kg per fishing hour per vessel. The nominal CPUE was then calculated as the annual arithmetic mean CPUE for the period 1991–2015.

Statistical and graphical analyses were performed using the R statistical software, version 3.3.0, and several add-in packages to explore the data (FactoMineR, geosphere, gplots, ggplot2, maps, maptools, mapdata, marmap, prettymapr, RColorBrewer, sp, stats, AICcmodavg, ResourceSelection, corrplot) and to standardize the CPUE (boot, glmmADMB, gmodels, lsmeans). For more details on the packages used, see the supplementary text (S1).

2.3.1 Exploratory analysis

Annual albacore CPUE were analyzed for the period 1991–2015. Multiple Factor Analysis (MFA) was performed to identify primary covariates of CPUE. A correlation matrix was built to assess and correct for multicollinearity using the method of Friendly (2002). Collinearity of explanatory variables was evaluated using the statistical software R with the function *vif* of the package car (Fox and Weisberg, 2011).

To define spatial areas for modelling, a regression tree analysis (Hothorn and Zeileis, 2015) was conducted on the raw CPUE trip level data to determine the most appropriate statistical breaks by latitude and longitude. For the spatial partitioning analysis, a small constant (0.000001) was added to CPUE observations, and a generalized linear model (GLM) with Gamma distribution and log-link function was fitted with latitude and longitude as explanatory variables. The addition of the constant allowed for samples with zero catches to be included in the spatial partitioning analysis. The tree analysis resulted in three nodes, or area splits, resulting in four spatial areas. The defined areas included the region north of 48° (Celtic Sea), and an open ocean area to the west of 14° west (Fig. 2). One of the four areas was assigned to each trip record and included as explanatory factor in the standardization model.

Using the notation of the Table 2 and a simplified representation (Bentley et al., 2012), the tested model to explore the effects of these explanatory variables is:

$$\mathrm{CPUE}_i = e^{a^Y_{y^i} + a^A_{a^i} + a^S_{s^i} + a^L_{l^i} + a^D_{d^i} + a^M_{m^i}}. \quad (1)$$

where $\mathrm{CPUE_i}$ is the catch per unit effort for the ith record, $a^Y_{y^i}$ the coefficient associated with the year y_i, and similarly for the coefficients associated with the sub-regions (A), SST (S), characteristic of vessels (P or L), sea depth (D), and month (M).

2.3.2 Standardization

Extensive research on CPUE standardization has been conducted, including within the ICCAT Working Group on Stock Assessment Methods and within ICCAT species working groups. Among the existing methods, GLMs and generalized additive models are most commonly used to standardize CPUE (Hinton and Maunder, 2004; Maunder and Punt, 2004; Venables and Dichmont, 2004). We applied a two-stage GLM (delta-gamma regression) to determine covariates of frequency of occurrence (logistic regression GLM for presence-absence of albacore per trip) and catch rates of trips

Table 2. Explanatory variables included in the Gamma-GLM model tested in deviance reduction for selection.

Standardizing variable	Model parameter	Category levels	Category definitions	Model deviance reduction (greater than 1%)
Statistical effects				
Year	Y	15	1991–2015	Yes
Month	M	7	June–December	No
Sub-regions	A	4	Refer to Figure 1	Yes
Fishing effects				
Vessel power	P	Continuous	From 40 to 818 KW	Yes
		11	Truncated each 50 KW	Yes (higher than continuous)
Vessel length	L	Continuous	From 5 to 35 m	No
		9	=<15 m; 16–29 m; >= 30 m	Yes (higher than Power)
Mesh size	MS	Continuous	from 45 to 300 mm	No
		5	Truncated each 20 mm : =<60 mm; 80 mm; 100 mm; 120 mm; >=140 mm	No
Oceanographic and environmental effects				
Ocean depth	D	Continuous	from 0 to 5000 m	No
		10	from 0 to 5000 m at each 500 m.	Yes
Sea surface temperature	SST	Continuous	from 11 to 25°C	Yes
		12	=<12; 13 to 22; >=23°C	Yes (higher than continuous)
Sea floor gradient	SFG	Continuous	from 0 to 362	No
		8	Truncated each 40 m	No

with albacore presence (Gamma GLM with a log-link). The standardized CPUE for year i (annual abundance index) was calculated as the product of the estimated annual probability of albacore occurrence (annual least-squares mean of the probability of occurrence) and the estimated catch rate of positive trips (annual least squares mean of positive CPUE). The explanatory variables considered and tested for both the probability of occurrence and positive CPUE GLMs are presented in Table 2. The index was rescaled to the mean of the time series for comparison with nominal CPUE values derived for other fisheries operating in the North Atlantic.

A Kolmogorov-Smirnov test (KS-test) was used to test the goodness-of-fit of the Gamma distribution. Deviance reduction by factor was estimated to select important explanatory variables (>1% deviance explained (DE)) (Tab. 2). Classical in ICCAT model we have the year, month and area, even if it is lower than 1%. Here only the month was equal to 0.9%. For the selected variables the method of Bentley et al., (2012) (R influ package) was used to estimate covariate influence (effect) on CPUE, and validate factor selection. The influence index plots quantified how much a predictor variable contributed to the difference in CPUE patterns between standardized and unstandardized values. An influence index >1 means that inclusion of the variable increased the estimated CPUE in that year.

The final model selection was based on the Akaike's information criterion (AIC), Bayesian information criterion (BIC), and residual deviance reduction by factor inclusion compared across different candidate models (factor combinations). The percentage of total DE by each final model was calculated as null model residual deviance minus final model residual deviance divided by the null model deviance times 100 (Mèndez-Fernandez et al., 2013). The adjusted DE was estimated using the modEvA package (Barbosa et al., 2013). When the AIC was not significantly different between models, the simpler model was selected. Model validation was carried out with a residual analysis (normality and homogeneity). Residual patterns were inspected to determine model goodness-of-fit. Finally, we applied a Hosmer-Lemeshow goodness-of-fit analysis to test the degree of difference between the fitted GLMs and the observed data.

3 Results

3.1 Data characteristics

3.1.1 French pelagic trawl characteristic

French pelagic trawling occurred primarily at night with one to three hauls (range 1–7 hauls) per trip with an average duration of 5 h per haul. French vessels frequently deployed an alternative gear during the day, line trolling, to locate areas with albacore higher abundances. The total number of fishing vessels identified in our database was 290 over the assessed period. The number of fishing vessels declined between 1991 and 1998 (an average of 31 boats made up the fleet during the period), then increased between 1999 and 2008 to an average of 78 vessels. After 2009, the fleet was comprised of 36–58 vessels operating per year (Tab. 1). In 2015, the pelagic French trawl fishery was operated by 40 vessels.

No significant inter-annual variability was observed in the percentage of FOs with no albacore catches (range 0–13.6%; proportion test: chi-square = 350, df (degrees of freedom) = 336, p-value = 0.29).

3.1.2 Temporal variability

The primary fishing season for the French trawl fishery is summer to autumn (June–December). Over the period

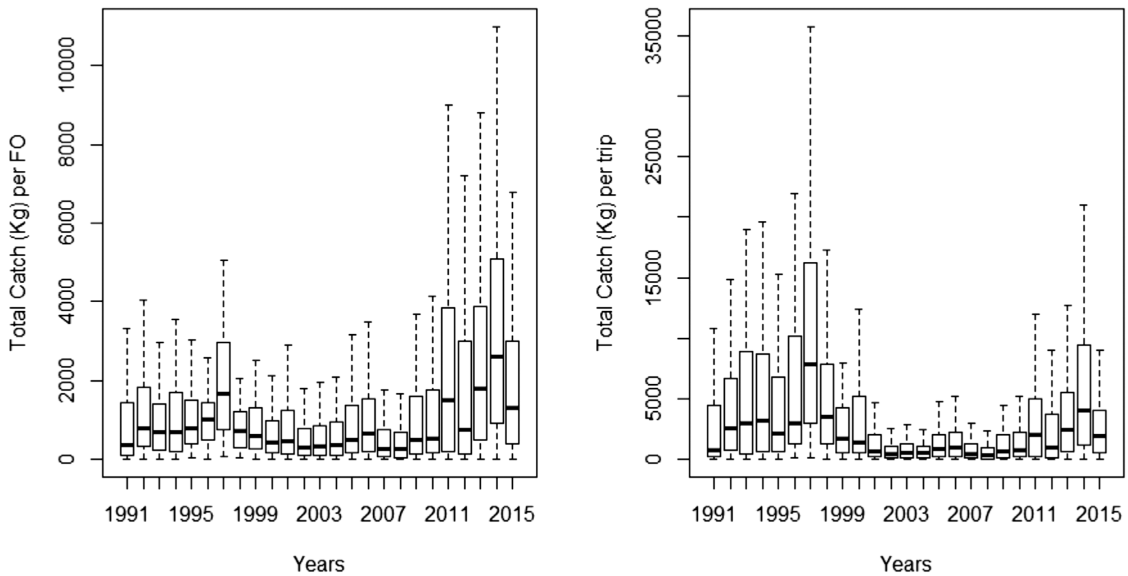


Fig. 3. Boxplots of albacore catches (kg) per Fishing Operation (FO) (left) and fishing trip (right) for French pelagic trawlers from 1991 to 2015.

1991–2014, albacore catches varied considerably (Fig. 3). Catches peaked in 1997, and the period 2001–2008 had the lowest catches of the time series. Since 2009, catches have been relatively high compared to earlier years.

FO time fluctuated around a mean of 5 h (Tab. 1) while the number of FOs by trip decreased. Between 2002 and 2008 (except 2005 and 2006), a decrease in catches and nominal CPUE was observed (Figs. 3 and 4) concurrent with an increase in fishing activity (Tab. 1) as more fishing vessels operated over shorter time intervals. The increase in trawl fishing effort can be explained by the prohibition of gillnets in 2002 while the decrease in catches during the early years was caused by a decline in stock abundance. Since the early 1980s a steady decline in catches has been observed, except in 2005 and 2006 (Hoang, 2008).

We observed significant variations in the total number of fishing days by quarter, with the lowest effort occurring between 1991 and 2000, during the period when the number of fishing days per trip was highest. During the period 2001–2008, the fleet increased fishing activity (with a maximum of 4095 fishing vessel days recorded in 2006). The year 2004 was an exception when fishing activity was limited to 140 vessel days. This period corresponds to a decrease of albacore nominal CPUE. The nominal albacore CPUE for the French pelagic trawl fishery is presented in Table 3 for the entire fishing area and by sub-region. It indicated a peak in 1997 and an increase since 2009 with significantly lower values in 2012 and 2015 compared to other recent years.

The gamma distribution was found to be an appropriate error distribution for the data as it showed good fit to the positive total catches and CPUE values for most years (KS-test p-value$>$0.05).

3.1.3 Spatial variability

The spatial distribution of albacore catches by the French trawl fleet is shown in Figure 2. The fleet focused their effort mainly along the continental slope and extended west to the southwest coast of Ireland. No spatial expansion of French pelagic trawling activity was observed across time. The highest catches in the northern regions were found in the Porcupine trough around the Gollum channel system (Fig. A). The highest catches in the southern regions were from the area of the Canyon of Capbreton and Cap Ferret, followed by the Platier Landais. Relatively higher caches were associated with ridges containing multiple channel features (Fig. A).

3.2 Model diagnostics

MFA allowed identifying important explanatory variables, on their own and in combination. MFA indicated a significant year effect and strong correlation between vessel length and power (Fig. 4). SST with area and month were significantly negatively correlated. The eigenvalues for the first axes were highest for area, SST, month, vessel length, and power; for other main axes the most important variables were year and depth range. There was no collinearity between explanatory variables.

The tested models for explaining CPUE incorporated all four variables (year, area, SST, power) which were found to be correlated with CPUE in the MFA, as well as interactions. Only variables leading to at least 1% of deviance reduction were retained for the final model (Tab. 2). The results indicated that year and area were major explanatory factors (Fig. 5a). Although vessel length or power had an explanatory power $>$1% (percent of r^2), their addition to the model had little influence on the annual CPUE indices. Similar results were found for month and depth.

Analysis of deviance for GLM fits, using a Rao coefficient score test indicated similar explanatory variables. Model selection using AIC, BIC, percentage of DE and the best plotted residuals favored the inclusion of year, area, SST, vessel length, and month. The final selected model, a log-linked gamma GLM was well supported across the multiple

Table 3. Nominal CPUE (catches of albacore (kg) / per vessel fishing time (hours)) and standardized CPUE (Index: on the scale of the predicted values) for the albacore French mid-water trawl fishery in the Atlantic Ocean between 1991 and 2015. Coefficient of variation (CV) and the 95% confidence intervals (CI) and standard errors (SE) of index values. Values are presented scaled by the mean and not scaled.

Years	CPUE	Index	Index CV	Lower 95% CI	Upper 95% CI	SE	Scaled CPUE	Index	Index CV	Lower 95% CI	Upper 95% CI	SE
1991	195.7	99.87	0.21	58.55	141.19	21.08	0.68	0.5	0.21	0.29	0.7	0.1
1992	240.25	224.31	0.25	114.93	333.7	55.81	0.84	1.12	0.25	0.57	1.66	0.28
1993	243.23	213.38	0.26	106.56	320.2	54.5	0.85	1.06	0.26	0.53	1.59	0.27
1994	293.76	231.75	0.26	114.7	348.8	59.72	1.02	1.15	0.26	0.57	1.74	0.3
1995	242.1	220.97	0.25	112.09	329.85	55.55	0.84	1.1	0.25	0.56	1.64	0.28
1996	254.23	213.63	0.26	105.47	321.8	55.19	0.88	1.06	0.26	0.53	1.6	0.27
1997	570.73	384.91	0.26	185.02	584.81	101.99	1.99	1.92	0.26	0.92	2.91	0.51
1998	217.87	167.07	0.27	79.45	254.68	44.7	0.76	0.83	0.27	0.4	1.27	0.22
1999	240.43	275.02	0.27	130.75	419.3	73.61	0.84	1.37	0.27	0.65	2.09	0.37
2000	159.61	138.09	0.24	72.6	203.57	33.41	0.56	0.69	0.24	0.36	1.01	0.17
2001	225.16	107.21	0.24	57.23	157.18	25.5	0.78	0.53	0.24	0.28	0.78	0.13
2002	134.63	90.89	0.25	46.86	134.92	22.46	0.47	0.45	0.25	0.23	0.67	0.11
2003	140.76	73.64	0.25	38.21	109.08	18.08	0.49	0.37	0.25	0.19	0.54	0.09
2004	109.67	64.69	0.26	31.67	97.72	16.85	0.38	0.32	0.26	0.16	0.49	0.08
2005	192.58	120.57	0.25	62.23	178.91	29.76	0.67	0.6	0.25	0.31	0.89	0.15
2006	235.83	192.63	0.25	99.37	285.89	47.58	0.82	0.96	0.25	0.49	1.42	0.24
2007	128.04	79.85	0.25	40.83	118.87	19.91	0.45	0.4	0.25	0.2	0.59	0.1
2008	102.87	55.94	0.26	27.98	83.91	14.27	0.36	0.28	0.26	0.14	0.42	0.07
2009	323.67	134.26	0.24	70.39	198.13	32.59	1.13	0.67	0.24	0.35	0.99	0.16
2010	338.89	148.23	0.24	77.47	219	36.11	1.18	0.74	0.24	0.39	1.09	0.18
2011	682.54	325.3	0.25	164.57	486.02	82	2.38	1.62	0.25	0.82	2.42	0.41
2012	276.76	145.78	0.25	75.62	215.95	35.8	0.96	0.73	0.25	0.38	1.08	0.18
2013	534.44	292.24	0.24	152.92	431.56	71.08	1.86	1.45	0.24	0.76	2.15	0.35
2014	734.78	392.42	0.24	204.56	580.28	95.85	2.56	1.95	0.24	1.02	2.89	0.48
2015	365.74	200.64	0.24	106.1	295.17	48.23	1.27	1	0.24	0.53	1.47	0.24

diagnostic approaches (ex. Fig. 5b and c) with an overall percentage of DE of only 24%.

The highest influence on annual CPUE had the explanatories variables sub-region and SST (Fig. 5). A distinct change in the influence of the explanatory variables was detected around 2001. By looking at the variables, it was found that the influence of SST decreased significantly after 2001 (Fig. 6). SST coefficients were positive for temperatures up to 16–18 °C and negative above 18 °C (Fig. 6).

The scaled standardized CPUE index along with 95% confidence intervals is presented in Figure 7 (more information in Tab. 3). The standardized CPUE index diverged from the nominal CPUE due to changes in the spatiotemporal distribution, as well as in vessel characteristic and SST effects, especially in recent years. Standardized CPUE were globally above nominal CPUEs values until 2001 and below thereafter. The SST over which the fishery operated ranged between 12 and 24 °C, with the majority of albacore catches occurring between 15 °C and 23 °C (Figs. 6 and 8). The distribution of albacore CPUE across SST values revealed a somewhat bimodal distribution with modes around 16−19 °C and 20−24 °C (Fig. 8). The GLM revealed a significant and negative correlation with SSTs between 20 and 24 °C, particularly between 22 and 24 °C during the period November–December. High albacore catches were observed during periods with low SST (up to 19 °C), with highest catches at 16–17 °C (Fig. 8). September corresponded to high albacore catches compared to other months (Fig. 8). Sub-regions 2 and 4 produced the highest nominal CPUE. Further, mean CPUE increased with vessel length up to 25 m (not shown).

The scaled standardized CPUE index is likely to represent an important contribution to the stock assessment of the species in the North Atlantic Ocean, as it is the only continuous index of the trawl fleet, which represents a significant proportion of the total harvest of albacore in the region. This index has the advantages of using the entire time series available for the period when fleet data coverage was relatively high (1991–2015). Temporal trends in the CPUE revealed yearly fluctuation with significantly lower relative density in 2002, 2003, 2004, 2007 and 2008, significantly higher catch rates in the past (particularly in 1997 and 1999), and a general increase in recent years (since 2009).

4 Discussion

4.1 French albacore fisheries

Europe is the main albacore producer in the North Atlantic and France has played a major role in the exploitation with different gears, including pair pelagic trawls, trolls, bait boats, drift nets (banned since 2002; Fig. 1) and longlines. While the albacore fishery in France is now a secondary activity, the importance of historical catches (more than half a million tons

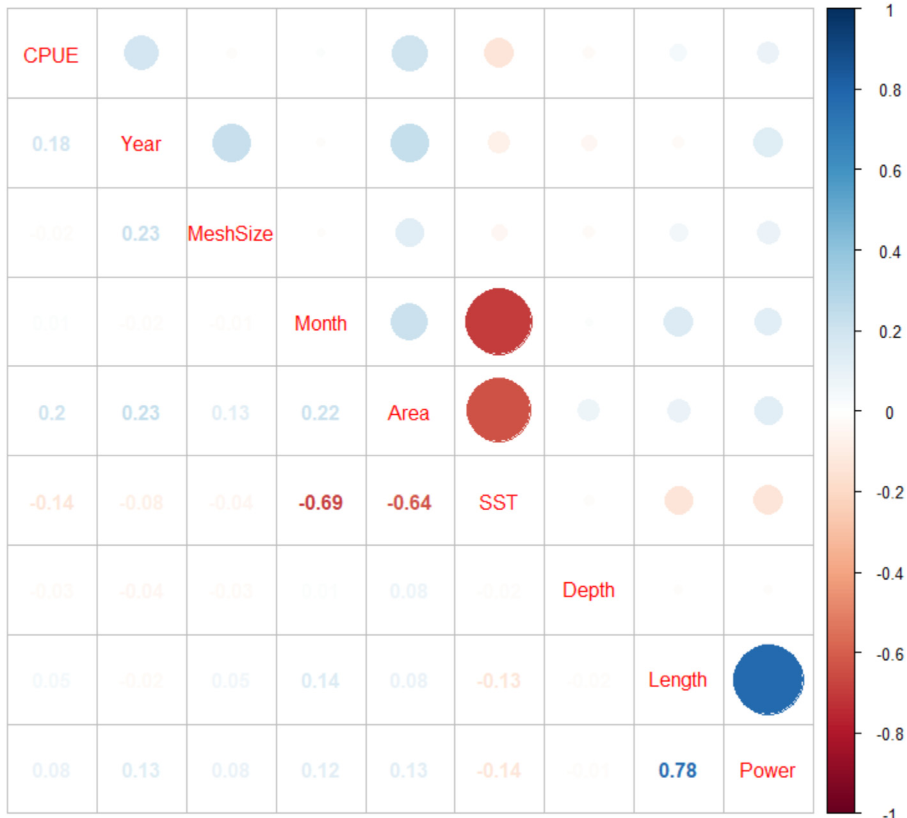


Fig. 4. Pairwise correlation coefficients among French pelagic trawl albacore CPUE and explanatory variables for the period 1991 to 2015. Positive correlations are displayed in blue and negative correlations in red color. Color intensity and the size of the circle are proportional to the correlation coefficients.

of albacore have been caught by the fleet since 1950) means its catch and effort data play an essential role for analyzing historical trends and current state of this stock. This study presents, for the first time, the catch statistics and characteristics of the French albacore trawl fishery. The presented index has the advantages of using the entire time series available for the period when fleet data collection coverage was relatively high (1991–2015). A comparison of the derived index with other surface fisheries operating in the North Atlantic is provided in Figure 9. While there is temporal overlap with the trawl fleets in the region (Cosgrove et al., 2014b), the spatial and temporal coverage of the French fleet is greater.

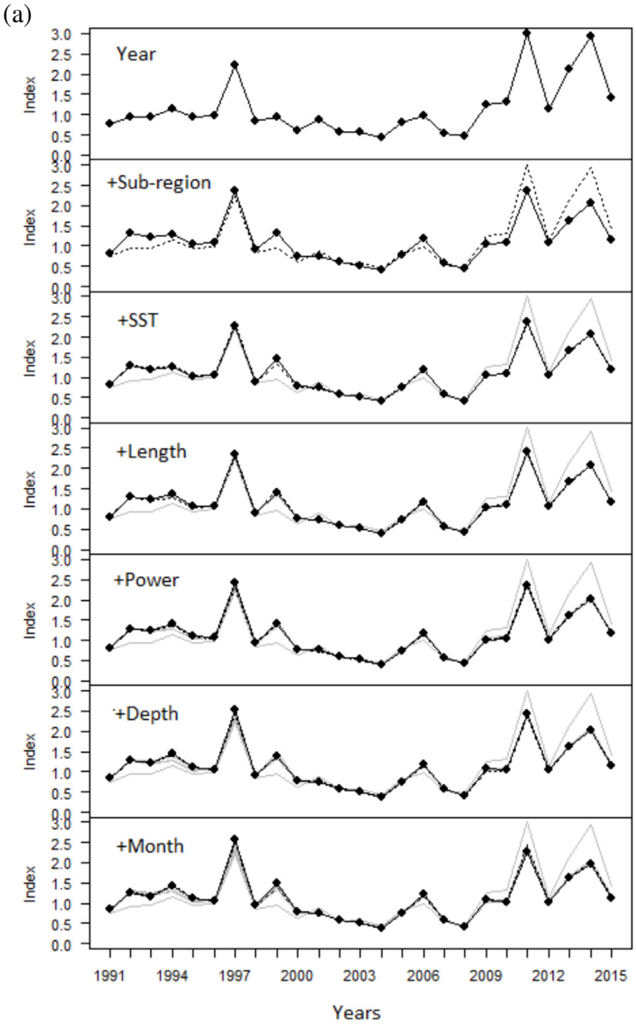
Data from French fisheries constitute an important input to ICCAT assessments in the Northeast Atlantic, and it is essential to provide accurate data for recent and past years, as recommended by the standing committee on research and statistics. The importance of improving the French trawl data series and creating a standardized CPUE was highlighted during the last North Atlantic albacore stock assessment in 2016. It therefore was essential that French scientists collated a complete data set. There is increasing demand to integrate French albacore fishery data due to its long time series of exploitation in the Northeast Atlantic and in response to heterogeneous fisheries distributions of albacore tuna and perceived local stock depletion in certain areas.

Standardization of fishery-dependent catch and effort data is fundamental to account for various factors affecting CPUE values, including changes in the spatial distribution of the fleet, seasonality, and the environment. Here we used recommended methods outlined by the ICCAT working group considering the catch information and multiple explanatory variables (environmental covariates, fleet characteristic, time and geolocation) to standardize CPUE and construct an annual index of abundance.

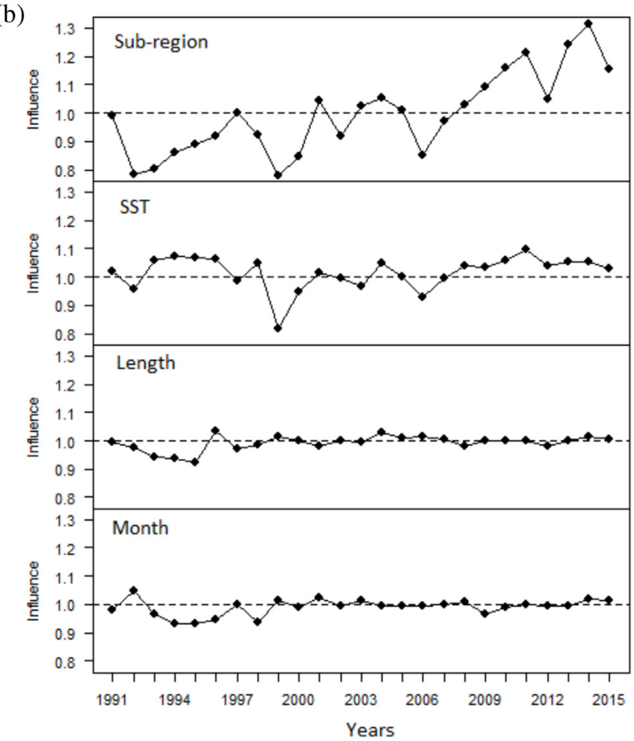
Management actions, spatial distribution of the stock (e.g. relatively higher catches at ridge features containing many channels), and seasonality (e.g. significant months and SST for higher catches) influenced the dynamics and efficiency of the French trawl fleet (i.e. surface fisheries were most effective during summer and autumn in the Northeast Atlantic). The ban on anchovy fishing implemented in 2004 (until 2010) (Fig. 1) is one factor that contributed to a change in targeting of the French fishery toward albacore (Taquet et al., 2008).

Environmental conditions (here SST) were found to be an important factor influencing albacore CPUE. Albacore CPUE were highest in September at lower SST values (16–17 °C). SST has been reported to be an important predictor of CPUE for immature albacore in surface waters (Chen et al., 2005; Philips et al., 2014; Sagarminaga and Arrizabalaga, 2010). Our results indicated that a SST range of 15–19 °C produced the highest catch rates of albacore, concordant with previous

(a)



(b)



(c)

Terms	Degree of freedom	Eplanatory power AIC	Overall influence (%)
Year	24	319161.6	-
Sub-region	3	318052.2	12.1
SST	11	317995.8	5.0
Length	8	317760.3	1.90
Month	6	317728.4	2.22

Fig. 5. (a) Standardized CPUE index at each step in the stepwise selection of variables for the tested models (only main effects). Each panel shows the standardized CPUE index as each explanatory variable is added to the model. The index obtained in the previous step (if any) is shown by a dotted line and for steps before that by grey lines. (b) Annual influence values for each explanatory variable in the final GLM model. (c) Statistics for explanatory power and influence of explanatory variables in the final GLM model.

biological studies that reported an optimum habitat range of 14–21 °C (Clemens, 1961; Johnsson, 1961; Talbot and Penrith, 1962; Flittner, 1963; Laurs and Lynn, 1977; Santiago, 2004; Boyce et al., 2008; Childers et al., 2011; IATTC, 2013).

The French trawl fleet focused their fishing effort mainly along the continental slope and westwards and to the southwest coast of Ireland. The highest caches occurred along geographical ridges with multiple channel features (ex. Porcupine Bay around the Gollum channel; Canyon of Capbreton; Cap Ferret; Platier Landais).

Albacore sizes in the French pelagic trawl fishery ranged between 43 and 120 cm (Fig. B) with a mean of 68 cm. The predominant size class (CI 95%) captured was between 51 and 90 cm. Albacore estimates of length at 50% maturity are around 90 cm fork length (FL) in all oceans apart from the Mediterranean Sea where maturity is assumed to occur at a smaller size (Juan-jordá et al., 2016). Hence our results indicated the fishery caught mainly immature individuals, particularly since 1999. This agrees with the results of Havard-Duclos (1973) who indicated that juvenile and immature albacore seem to be mainly distributed in the Northeast Atlantic during summer and in the Central and the Southwest Atlantic during winter. Moreover analyses relating albacore catches to fishing gear and SST indicated that surface gear such as pole-and-line, troll and trawl fisheries catch albacore in colder surface temperatures (peak catch rates at 15–17 °C), and rarely in waters higher than 24 °C (Nikolic et al., 2016).

Index standardization is a commonly applied analysis to remove the effect of various factors affecting CPUE derived from fishery dependent information (Maunder and Punt, 2004). Our results are consistent with the estimated stock trend from recent stock assessments (ICCAT, 2016). The French trawl index is also in general agreement with indices derived from other fleets fishing North Atlantic albacore (Fig. 9).

Regarding the North Atlantic stock, the catch and effort data collated for the French mid- water trawl fleet is one of the main fisheries targeting the stock, with 15% of the total catch during recent years. Even using several covariates (SST, depth, month, year, vessel length and power, mesh size of gear, geographic location, and fishing effort), the GLM explained

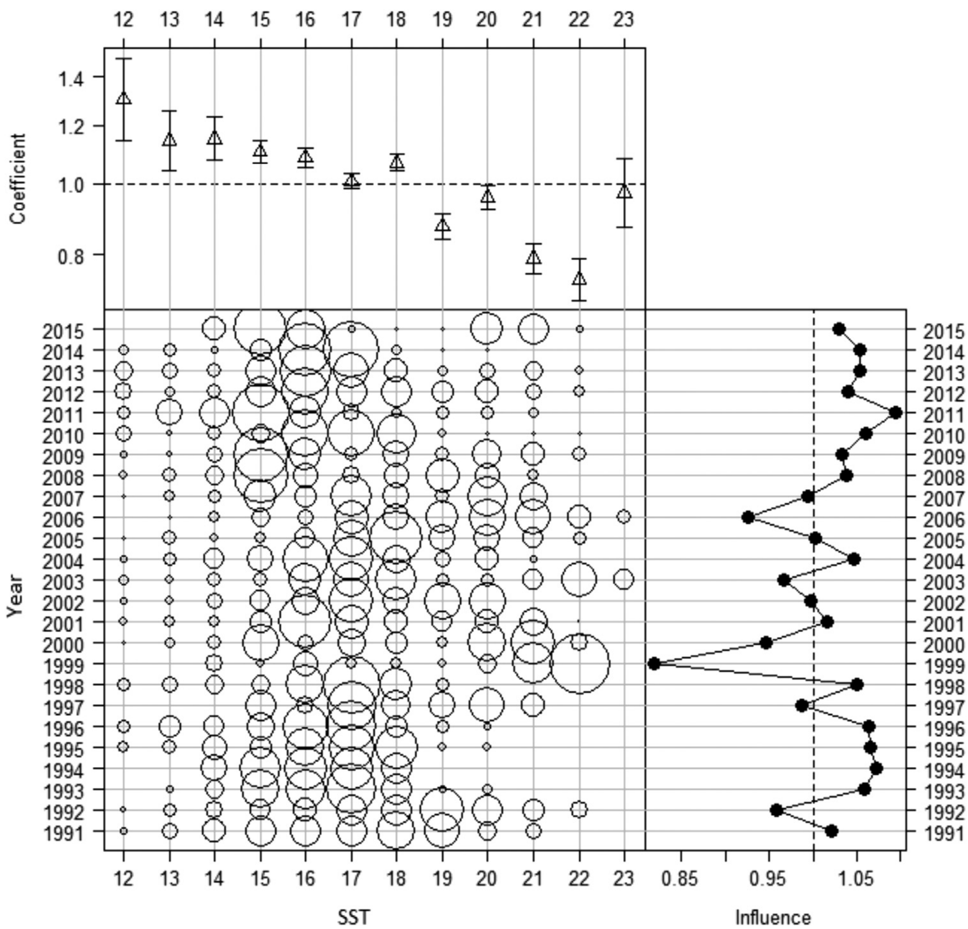


Fig. 6. SST coefficient-distribution-influence (CDI) plots using the method by Bentley *et al.* (2012).

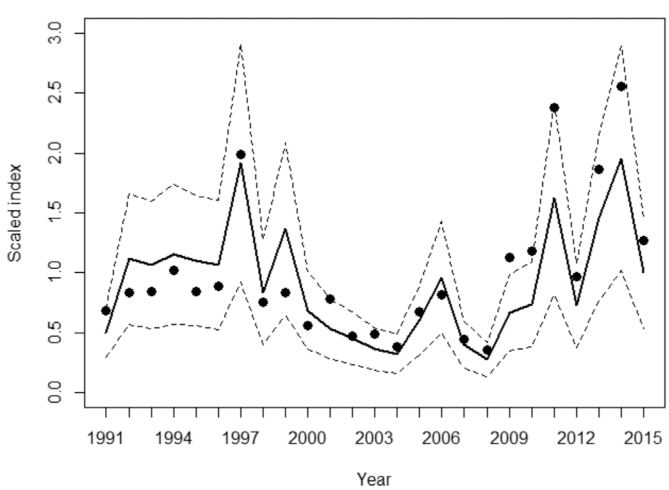


Fig. 7. Scaled standardized albacore CPUE (catches of albacore (kg) / per vessel fishing time (hours)) index based on the predicted values of the final two-stage model using data for the period 1991-2015 fom the French mid-water trawl fishery. The black points represent the nominal CPUE, the solid lines the scaled standardized CPUE (indexes of abundance) and the dashed lines the pointwise 95% confidence band.

only a low percentage of the variation in catch rates. The influence analysis (Bentley et al., 2012) suggested that year and areas had a major influence on standardized CPUE, i.e. changes in fishing distribution and timing had a large influence on catch rates of albacore. For many tuna stock species, it is not feasible to collect fishery-independent data over a large spatial scale (e.g. with a scientific trawl surveys), so fishery reported CPUE data are the main source of information on stock distribution and relative abundances (Maunder et al., 2006). For this reason, we encourage continued monitoring of the French fleet at high sample coverage together with increased biological sampling to best track fishery and stock trends.

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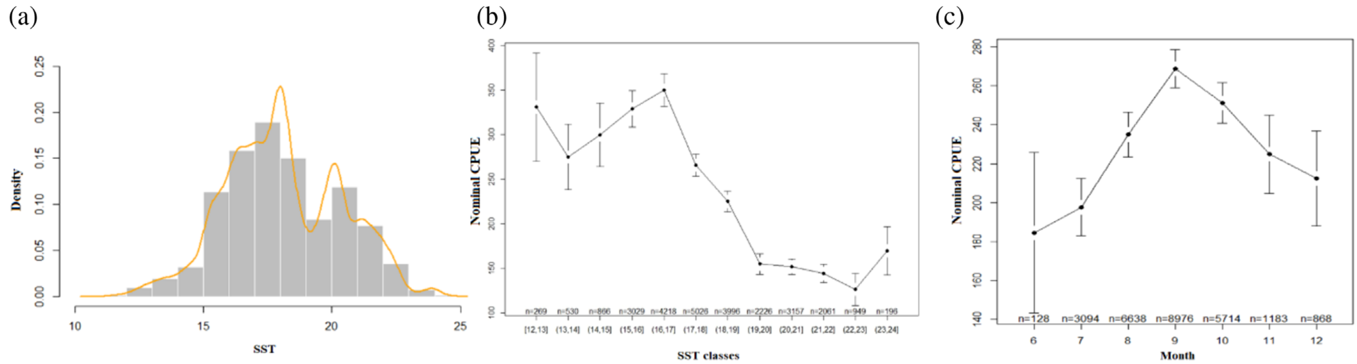

Fig. 8. Frequency of albacore total CPUE as a function of sea surface temperature (SST) classes (A). Observed mean CPUE (catches of albacore (kg) / per vessel fishing time (hours)) per SST class (B) and month (C) with 95% confidence intervals and sample size.

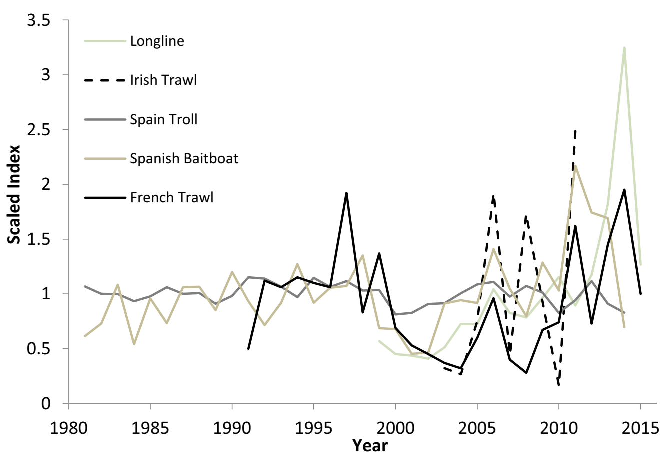

Fig. 9. Annual abundance index of albacore in the North Atlantic from different gears.

much data was missing to use them. We acknowledge all persons improving the historic French data (ex. Marc Taquet and Elodie Hoang). The authors thank Alain Biseau (IFREMER) and Gérard Biais for their help. Finally, we thank the editor and anonymous reviewers for their careful reading and their constructive comments, which helped us to improve the manuscript.

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Appendix

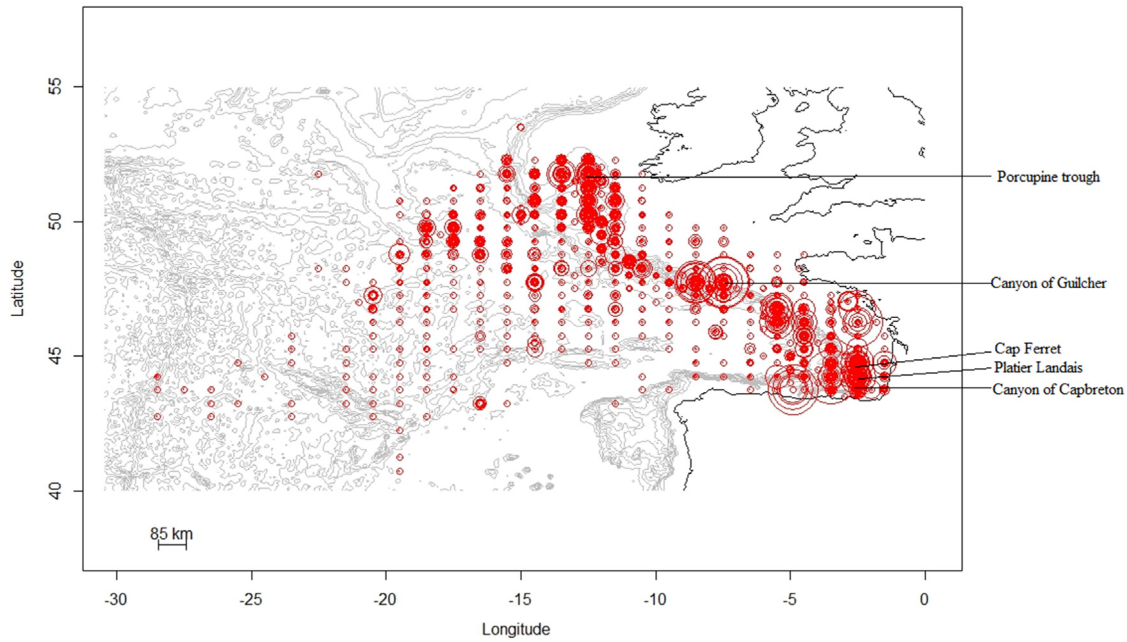

Fig. A. Map of albacore total catches (kg) per trip from 1991 to 2015 (red circle).

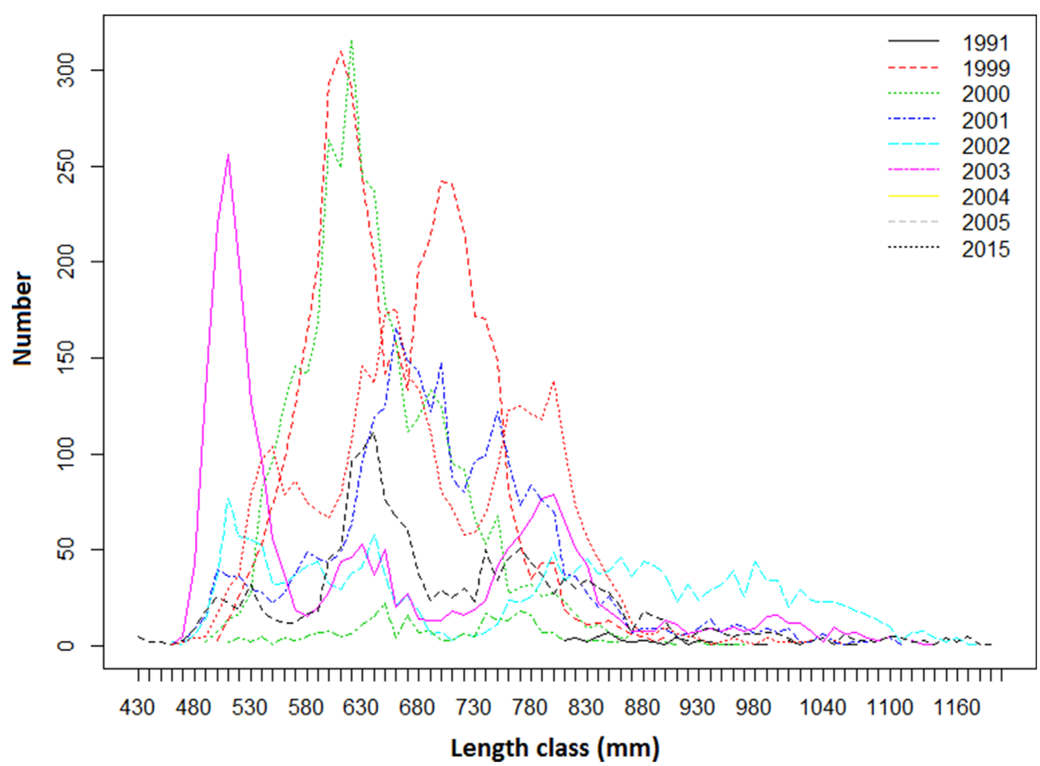

Fig. B. Number of albacore per fishing operation and length class (mm) from French pelagic trawl fisheries.