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LARVAL HABITATS AND CATCHES OF SWORDFISH (*XIPHIAS GLADIUS*) IN THE BALEARIC ISLANDS (2001-2020): OCEANOGRAPHIC DRIVERS AND OPPORTUNITIES FOR RESEARCH

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SUMMARY

Since 2001, ichthyoplankton and hydrographic surveys directed to tuna species have been conducted in the Balearic Islands, a main tuna spawning ground in the Mediterranean. These campaigns provide today key information about the interannual changes on larval abundances for Bluefin tuna and albacore, also allowing the investigation of the early-life ecology of various species. The Balearic Islands have been identified as a prominent oceanographic retention area within the western Mediterranean as well as the main spawning area for tuna species. Hence, the regular ichthyoplankton surveys become an opportunity to increase the knowledge of those species whose pelagic early-life stages are encountered during the summer in this area. This is the case of swordfish (Xiphias gladius). Here we analyse the possibility of applying those surveys to investigate the early life ecology of the Mediterranean swordfish, exploring the interannual changes on larval abundances and the hydrographic preferences of larval habitats.

RÉSUMÉ

*Depuis 2001, des prospections ichtyoplanctoniques et hydrographiques axées sur les espèces de thonidés sont menées dans les îles Baléares, une des principales frayères de thon en Méditerranée. Ces campagnes fournissent aujourd'hui des informations essentielles sur les changements interannuels de l'abondance des larves de thon rouge et de germon, et permettent également d'étudier l'écologie des premières phases de vie de diverses espèces. Les îles Baléares ont été identifiées comme une zone de rétention océanographique importante en Méditerranée occidentale, ainsi que comme la principale zone de frai des espèces de thonidés. Par conséquent, les prospections ichtyoplanctoniques régulières sont l'occasion d'améliorer les connaissances sur les espèces dont les premiers stades de vie pélagique ont lieu en été dans cette zone. C'est le cas de l'espadon (*Xiphias gladius*). Nous analysons ici la possibilité d'appliquer ces prospections à l'étude de l'écologie des premiers stades de vie de l'espadon méditerranéen, en explorant les changements interannuels des abondances larvaires et les préférences hydrographiques des habitats larvaires.*

RESUMEN

*Desde 2001, en las islas Baleares, una importante zona de desove de túnidos en el Mediterráneo, se han realizado prospecciones hidrográficas y de ictioplancton dirigidas a los túnidos. Estas campañas proporcionan hoy en día información acerca de los cambios interanuales en la abundancia de larvas de atún rojo y atún blanco, permitiendo también la investigación de la ecología de las primeras etapas de vida de varias especies. Las islas Baleares han sido identificadas también como una prominente zona de retención oceanográfica en el Mediterráneo occidental, así como la principal zona de desove de los túnidos. Por ello, las prospecciones regulares de ictioplancton son una oportunidad de aumentar los conocimientos sobre estas especies, cuyas primeras etapas pelágicas tienen lugar durante el verano en esta zona. Este es el caso del pez espada (*Xiphias gladius*). En este documento se analiza la posibilidad de aplicar estas prospecciones para investigar la ecología de las primeras etapas de vida del pez espada del Mediterráneo, explorando los cambios interanuales en la abundancia de larvas y las preferencias hidrográficas de los hábitats larvarios.*

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KEYWORDS

Catchability, Fish larvae, Fishery sciences, Mathematical models, Mixed layer, Oceanography, Pelagic environment, Spawning grounds, Swordfish

1. Introduction

One of the main objectives of fisheries management is a sustainable exploitation of fish populations. The provision of fishery-independent indices is a cornerstone input in stock assessment models to allow more accurate and *a priori* less biased estimates of fish stocks. In the case of swordfish (*Xiphias gladius*), the Mediterranean population is considered an independent stock from the one from the Atlantic, unlike other large pelagic highly migrant fishes like tuna (Macías *et al.* 2005; Arocha 2007). However, catches of swordfish are declining since the last decade of the twentieth century in both areas which brought out the establishment of a 15-year recovery plan in 2016 including the adoption of a total allowable catch (TAC) that was implemented the following year (ICCAT 2016). The species spawning stock biomass in the Mediterranean, which is annually assessed using fisheries data, is less than 15% of biomass at maximum sustainable yield and a high proportion of the yearly catches (50-70%) consist of small-sized individuals (ICCAT 2019).

Swordfish spawning grounds have been identified in all Mediterranean basins, mainly in the northern shores (Rey 1988; Tserpes *et al.* 2001; Arocha 2007; Alemany *et al.* 2006; 2010) and rarely in the southern basins (Taning 1955; Koched *et al.* 2015). In the western Mediterranean, the species reproduction area has been identified to be found between the Strait of Gibraltar and the Balearic Islands (Arocha 2007). The Balearic Islands is an important spawning area for many species (Alemany 1997; Alemany *et al.* 2010; Torres *et al.* 2011) and, during the months of June and July, the most important concentration area in the western Mediterranean in terms of oceanographic and hydrodynamic circulation (Díaz-Barroso *et al.* 2018).

Reproduction of swordfish in the Mediterranean occurs only in the summer months (June-August) with a peak in early July (Palko *et al.* 1981; Macías *et al.* 2005) while it spans from April to September in tropical and subtropical Atlantic waters and throughout the year in equatorial regions (Palko *et al.* 1981; Nishikawa and Ueyanagi 1974). In the Balearic Islands, swordfish larvae are recurrently found in the ichthyoplanktonic surveys conducted in the summer months in the Balearic Islands (Alemany *et al.* 2006; 2010; Torres *et al.* 2011). The vertical distribution of swordfish larvae in the Mediterranean has not yet been described. In the Atlantic, however, larvae are mainly found at surface waters, between 0 and 75 m depth (Nakamura 1985) while recently hatched swordfish larvae are at about 30 m depth (Tanning 1955).

Ichthyoplanktonic surveys have been conducted regularly in the Balearic Islands between 2001 and 2020. However, along the time series the surveys have been undertaken in the framework of different projects. Hence the methodology for data collection has varied to accommodate the different main goals, e.g the fishing gear, the mesh size of the net, depth of the hauls. Since 2018, the surveys have been incorporated within the European Data Collection Framework to estimate a Bluefin tuna larval index. This raises an opportunity to maintain the collection of larvae of many species.

In the present work, we take advantage of already existing summer ichthyoplanktonic surveys conducted in the Balearic Islands between 2001 and 2020. We explore the presence and abundance of swordfish larvae in the ichthyoplanktonic surveys, exploring the potential relationships with oceanographic environmental variables that define planktonic habitats. Additionally, we produce an index of larval catches, following a similar approach to that already applied for the eastern stock of the Atlantic Bluefin tuna (*Thunnus thynnus*) and albacore (*Thunnus alalunga*) to produce a larval index in the framework of the ICCAT community (Alvarez-Berastegui *et al.* 2021; Alvarez-Berastegui *et al.* 2018). The index of swordfish larval catches is an abundance index standardised by the volume of water filtered and the towing depth, as well as for the environmental factors that influence the spawning habitat of the species, providing the number of larvae/m^2.

2. Material and methods

2.1 The study area

The study area is located in the western Mediterranean, encompassing the waters around the Balearic Islands between 37.5 and 41.0 ºC latitude and 0.5 and 5.0º E longitude (**Figure 1**). The area is characterised by high mesoscale variability of the surface circulation due to the presence of a front generated by the coexistence of two important water masses, i.e. the modified Atlantic waters that recently entered into the Mediterranean through the Strait of Gibraltar and Mediterranean waters, whose location varies annually (Balbín *et al.* 2014). Fronts are known areas that gather particulates and they have been related to spawning areas of small and large pelagic in many areas worldwide.

2.2 Ichthyoplanktonic surveys

In the Balearic Islands ichthyoplankton surveys have been conducted since 2001 and, since 2020, the surveys are standardised and target Bluefin tuna larvae during its hatching period. Surveys are performed in summer (June-July) using a regular sampling, consisting of a square mesh of 10 x10 nautical miles (**Figure 1**). Some variation in sampling intensity and spatial and temporal coverages over the years (**Table 1**). Ichthyoplanktonic hauls have been performed using two different hauling deployments at two periods: i) deep oblique (bongo-60, 333 µm mesh size and 70 m towing depth), in the first period (2001-2005) and ii) mixed layer oblique (bongo-90, 500 µm mesh size and around 25-30 m towing depth), in the second period (2012-2020). Besides tuna larvae of non-tuna species like swordfish (*Xiphias gladius*) are captured during the campaigns. A summary of TUNIBAL surveys sampling dates and sampling intensity is compiled in **Table 1**, together with the data regarding swordfish samples.

In-situ environmental data was also retrieved by means of a CTD probe. Collected variables are: the mean salinity down to the mixed layer depth (SML, psu), temperature down to the mixed layer depth (TML, in ºC), fluorescence down to the mixed layer depth (FML, in mg/m^3), oxygen down to the mixed layer depth (OML, ml/l) and depth of the mixed layer (MLD, m). Other variables such as latitude, longitude, day of the year (jd), year and month were also checked.

2.3 Data exploration and selection

In order to develop an index, it is important to select those data that are comparable among the different years. This will help avoid potential biases introduced by the variability of sampling and environmental variables in the mean abundance estimates. So, the sampling dates, filtered volumes and the environmental data that more commonly affect the timing and spatial distribution of pelagic species spawning are visually inspected through box whisker plots (**Annex 1. Figure S1**). Box whisker plots were performed by means of the 'ggplot2' packages (Wickman 2016).

For the whole time series available (2004-2016), the earliest recorded larval presence occurred on a 20th of June (**Figure S2**), at a sea water temperature of 22.4ºC (average temperature in the mixed layer depth), salinity of 37.7 psu, oxygen of 5.4 ml/l and a fluorescence of 0.37 mg/m^3. Samples performed in 2004 and 2005 were excluded due to the use of a different fishing gear for which intercalibrations coefficients of catchability for swordfish is not available. An amount of 662 stations were finally included in the analysis of the larval index, i.e. samples performed in the years already processed for non-tuna species (**Table 1**).

3. Standardised index of larval catches

The abundance of swordfish larvae (N larvae) was standardised by i) the volume filtered (V_{filt}) in cubic meters (m^3) and ii) by the maximum depth of the haul at each collector (D_{tow}) in meters (m), providing a catch-per-unit-effort of swordfish (CPUA) in number of larvae by squared meter (N larvae/m^2):

$$CPUA = \frac{N\ larvae}{V_{filt}}\ D_{tow} \quad \text{(Eq. 1)}$$

In a subsequent step, the species CPUA is standardised in relation to environmental variables that influence the species spawning using a modelling approach and compensating the mean and error estimation through marginal means, following Alvarez-Berastegui *et al.* (2021). The modelling approach is suited to zero-inflated distributions and consists of a two-stage general additive model (GAM), computed using the 'mgcv' package (Wood 2017). First, a binomial model with a logit link function is used to model the presence-absence of swordfish larvae and second, a Gaussian model with a logarithmic link function is used to model the CPUA of swordfish in the collectors in which presence of larvae was confirmed. Models were fitted by means of restricted maximum likelihood (REML, Wood 2011), which is considered a more efficient method than other available, e.g. general cross-validation (Marra and Wood 2011).

For each of the two sub-models, the mean prediction and variance estimation of the mean were estimated by means of marginal means using the ‘emmeans’ package (Lenth 2020). Marginal means uses the mean of the continuous variables included in a model to predict mean and error estimates of the independent variable and compensates for unbalanced factors (Searle *et al.* 1980). Then, the index value for each year (I'_y) was calculated using the following formula:

$$I'_y = c'_y \, p'_y \text{ (Eq. 2)}$$

where c'_y is the back-transformed mean CPUA from the lognormal submodel in the year ‘y’ and p'_y probability of presence of albacore larvae estimated from the binomial submodel, both compensated accounting for changes in factors among years by means using estimated marginal means with the ‘emmeans’ package (Searle *et al.* 1980; Lenth 2020). The variance of the index, var (I'_y), was estimated from the variances of the two sub-models and assuming dependency between the two so that:

$$var\ (I'_y) = var\ \left(p'_y\right) {c'_y}^2 + var\ \left(c'_y\right) {p'_y}^2 - var\ \left(p'_y\right) var\ \left(c'_y\right) \text{ (Eq. 3)}$$

Where var(c’y) and var(p’y) are the back-transformed variance of the mean abundance and the variance of the mean probability of swordfish larvae presence, respectively obtained using ‘emmeans’.
The 95% confidence limits were computed using an approximation for log-normal data, following Ingram *et al.*, 2010:

$$UCI = I'_y \times C \text{ (Eq. 4)}$$

$$LCI = \frac{I'_y}{C} \text{ (Eq. 5)}$$

where $C = e^{2 x \sqrt{log\,(1 - CV'^2)}}$, *CV’* is the coefficient of variation of the index I'_y, computed as the standard error of the index (*se’*) divided by the value of the index (I'_y). All the analysis was performed within the R free programming software (R Core Team 2020).

4. Results and conclusions

The probability of capturing swordfish larvae in a particular year is low, ranging the percentage of positive stations for swordfish between 2.1 and 8.9% (**Table 1**). The abundance of swordfish larva in each positive haul is as well very low, with maximum abundance in a haul of 4 larvae and generally only one larvae being caught. The spatial distribution of swordfish larvae showed no spatial aggregation at the scale of the analysis but rather dispersed hauls were positive (**Figure 1**).

For the presence-absence of swordfish, the final selected binomial model included the year as a factor and SML, FML and OMLA as smoothed functions (**Table 2**). The model explained 19.9% of the deviance (AIC: 161.6) and showed an AUC of 0.84 (**Figure 3A**). In the Balearic Islands and for the period 2012-2016, swordfish larvae were present at intermediate salinity values (37.4 - 38.0 psu), suggesting a spatial distribution related to the areas with mixture of water masses, i.e. the oceanic front (**Figure 3B**). The higher concentrations of oxygen (above 5.0 ml/l) and fluorescence (above 0.5 mg/m^3) in the mixed layer within the available ranges seem to have negative effects on the presence of swordfish larvae (**Figure 3B**).

The final model selected for the CPUA of swordfish in the positive stations, included the year as a factor, and the smoothed effects of the depth of the mixed layer (**Table 3**). The model explained 40.2% of the deviance (AIC 12.43) and showed good performance of model residuals (**Figure 4A**). Swordfish larvae were more abundant when the depth of the mixed layer was below 14 m (**Figure 4B**).

The estimated larval index of swordfish in the period 2012-2016 shows an initial increase between 2012 and 2014, followed by a decrease of abundance between 2014 and 2016 (**Figure 5**).

The present work confirms the recurrent presence of swordfish larvae in the Balearic Islands in the years 2004, 2005 and between 2012 and 2016. Previous studies had already shown their presence in the Balearic Islands in 1996 (Alemany *et al.* 2006), in the years 2006 and 2008 (Torres *et al.* 2011) and between 2001 and 2005 although the particular year in which they were present was not stated (Alemany *et al.* 2010). On the other hand, other summer ichthyoplanktonic surveys in the northwestern Mediterranean found no swordfish larvae (e.g. Sabatés 1990; Sabatés and Olivar 1996; Olivar *et al.* 2010; Álvarez *et al.* 2012). The presence of swordfish larvae, specific fisheries and the particular hydrodynamic scenarios suggest that the Balearic Sea is relevant spawning area of the species in the W Mediterranean as it is also an important spawning area for other tuna species (Alemany *et al.* 2010; Torres *et al.* 2011).

Conclusions

1. Balearic Islands confirmed as a recurrent area of swordfish reproduction by the presence of larvae.
2. Future research:
   - Processing already collected B90 samples not processed for non-tuna ichthyoplanktonic species (recent years and historic time series)
   - Attempt gear standardisation of B60 haul data
3. Environmental indicators at the spawning sites and during the species spawning season, in the line of that already presented for Bluefin tuna (Alvarez-Berastegui 2020) would help fine tuning the index.
4. The index might benefit from improving the biological knowledge regarding the species reproduction and early-life stages survival.
5. The main difference between swordfish index and that of Bluefin tuna and albacore is that the swordfish index still needs to incorporate a retrocalculation for lengths and differences in the different hauling deployments on the species catchability.

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Table 1. Sampling characteristics of standard sampling of the TUNIBAL surveys, number of positive stations for swordfish larvae, total amount of swordfish larvae captured and percentage of positive stations. In bold: samples used in the calculation of the larval index. Data from 2001 to 2003 and from 2017 to 2020 is not already available.

Year	Gear	Tow depth (m)	Nº stations	Survey dates	N positive stations	N swordfish larvae	% positive stations
2001	B60	70	162	16/06 – 07/07	NA	NA	NA
2002	B60	70	171	07/06 – 28/06	NA	NA	NA
2003	B60	70	198	03/07 – 29/07	NA	NA	NA
2004	B60	70	166	18/06 – 08/07	2	2	1.2
2005	B60	70	186	27/06 – 23/07	8	8	4.3
2012	**B90**	**30**	**153**	**21/06 – 08/07**	**10**	**11**	**6.5**
2013	**B90**	**30**	**124**	**20/06 – 10/07**	**11**	**15**	**8.9**
2014	**B90**	**30**	**92**	**13/06 – 30/06**	**4**	**5**	**4.3**
2015	**B90**	**30**	**94**	**23/06 – 09/07**	**2**	**2**	**2.1**
2016	**B90**	**30**	**95**	**21/06 – 07/07**	**3**	**3**	**3.2**
2017	B90	30	92	26/06 – 12/07	NA	NA	NA
2019	B90	30	108	19/06 – 05/07	NA	NA	NA
2020	B90	30	44	24/06 – 06/07	NA	NA	NA

Table 2. Results of the binomial part of the delta-lognormal model, showing effects on the presence-absence of swordfish larvae (pa). Independent environmental variables included were salinity, fluorescence and oxygen of the mixed layer (SML, FML and OML, respectively). Significant codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Model formula	pa ~ as.factor (year) + s(SML) + s(FML) + s(OML)				
		Estimate	Std. Error	z value	Pr(>|z|)
Parametric coefficients	(Intercept)	-5.26	1.237	-4.253	2.11E-05***
	as.factor(year)2013	2.55	1.21	2.108	0.0351*
	as.factor(year)2014	3.818	1.991	1.917	0.0552.
	as.factor(year)2015	-1.217	1.064	-1.144	0.2527
	as.factor(year)2016	1.748	1.31	1.335	0.1819
Approximate significance of smoothed terms		edf	Ref.df	Chi.sq	p-value
	s(SML)	0.8553	2	5.129	0.01418 *
	s(FML)	0.7864	9	3.453	0.03604 *
	s(OML)	0.9106	9	9.027	0.00159 **

Table 3. Results for the lognormal part of the delta-lognormal model, showing the effects on standardized catches of swordfish larvae (N larvae/m^2). Independent environmental variables included were the depth of the mixed layer (MLD).

Model formula	N larvae/m^2 ~ as.factor (year) + s(MLD)				
		Estimate	Std. Error	z value	Pr(>|z|)
Parametric coefficients	(Intercept)	-0.308823	0.183587	-1.682	0.111
	as.factor(year)2013	0.225976	0.206025	1.097	0.288
	as.factor(year)2014	-0.029196	0.256158	-0.114	0.911
	as.factor(year)2015	-0.195018	0.339439	-0.575	0.573
	as.factor(year)2016	-0.001251	0.278682	-0.004	0.996
Approximate significance of smoothed terms		edf	Ref.df	Chi.sq	p-value
	s(MLD)	0.8918	9	0.85	0.00913***

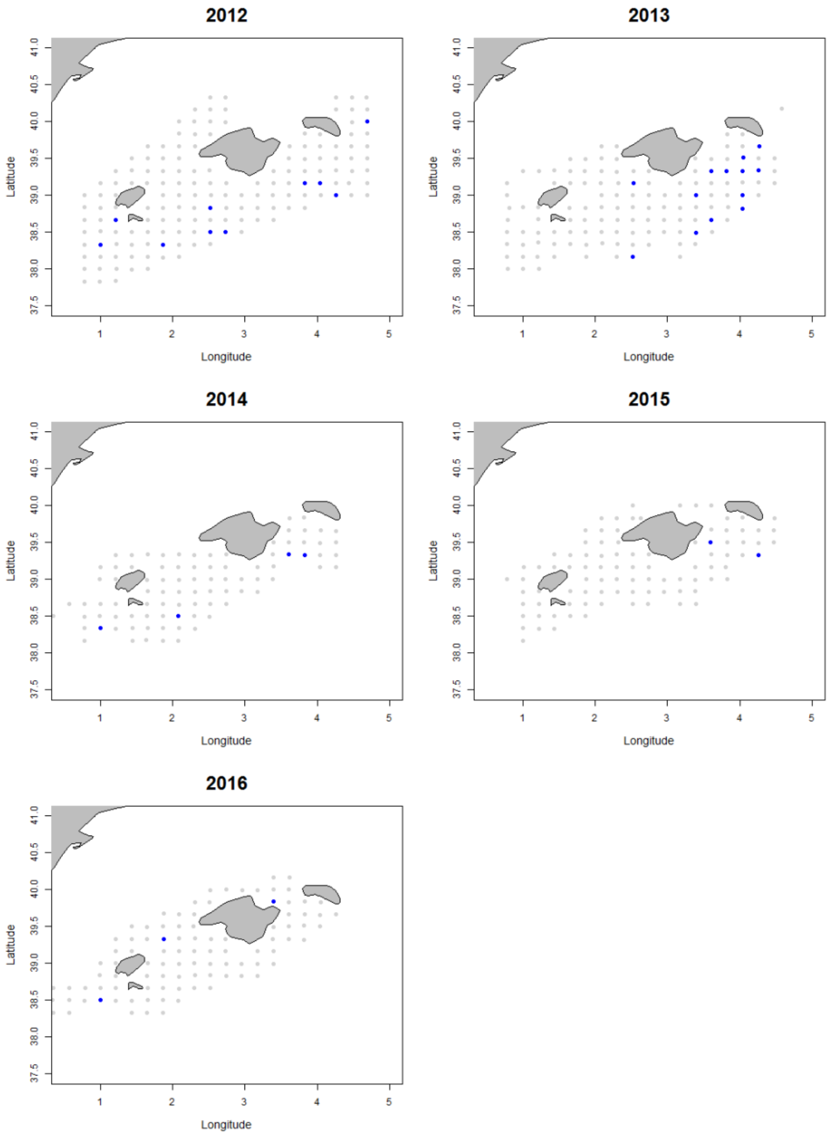


Figure 1. Sampling design (grey) and positive stations for swordfish larvae (blue).

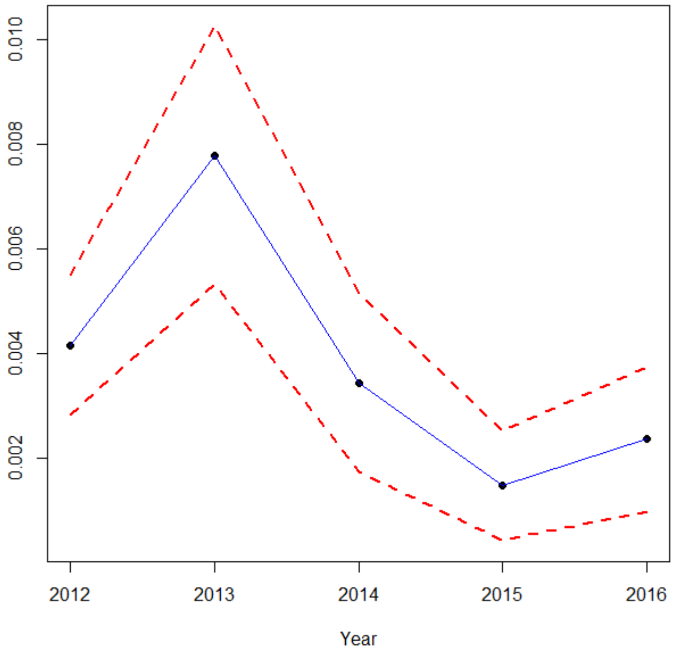
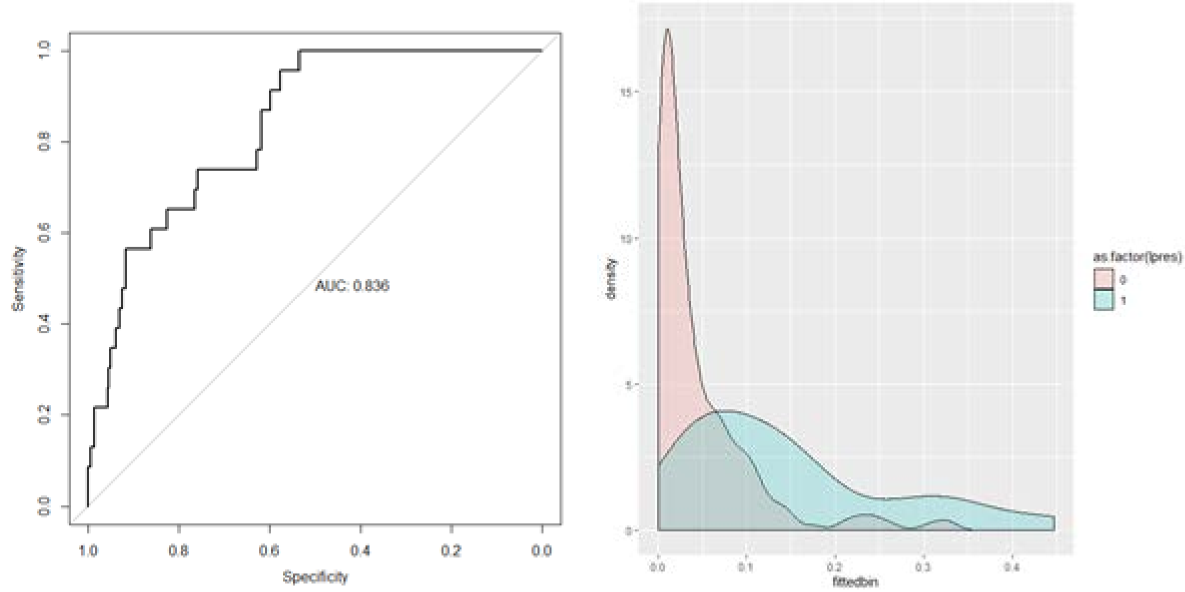


Figure 2. Mean CPUA of swordfish larvae (blue line) and standard error (red dashed line) between 2012-2016.

(A)



(B)

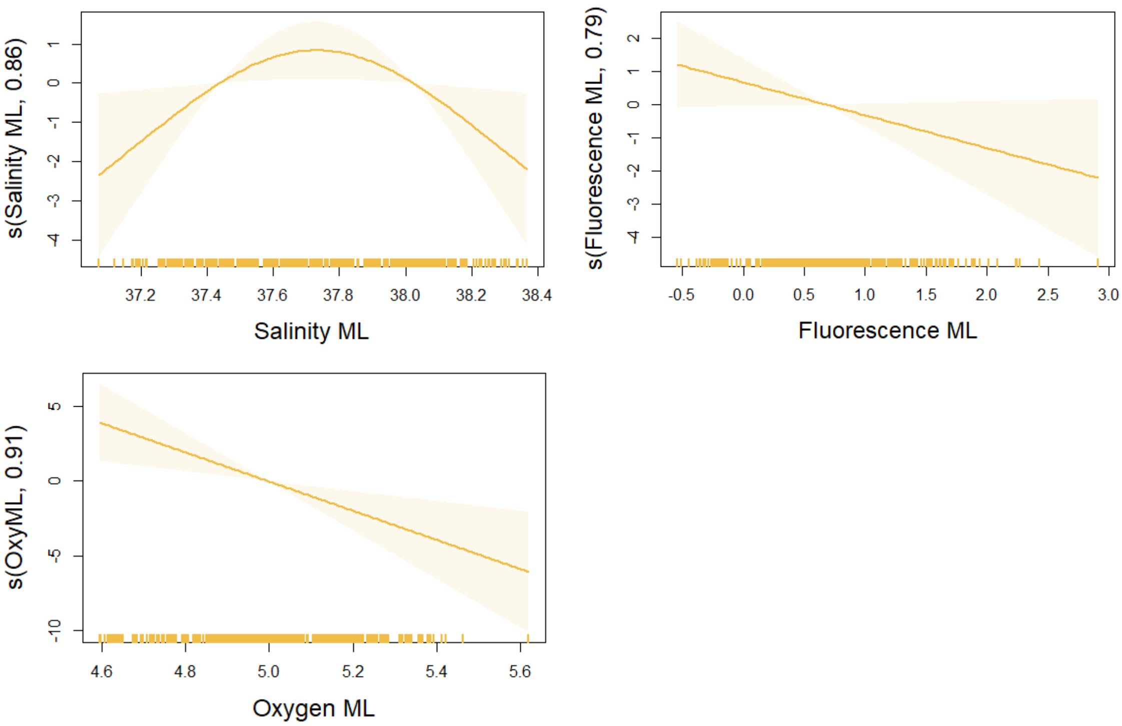
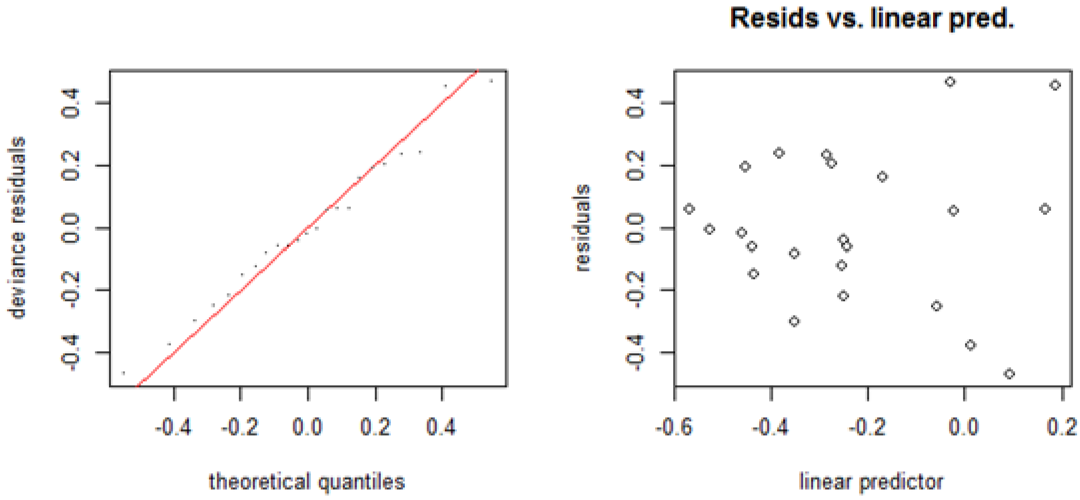


Figure 3. Selected binomial model for swordfish larvae: (A) performance showing Area Under the Curve (AUC) and density of predicted presences and absences and (B) partial effects of the smoothed parameters.

(A)



(B)

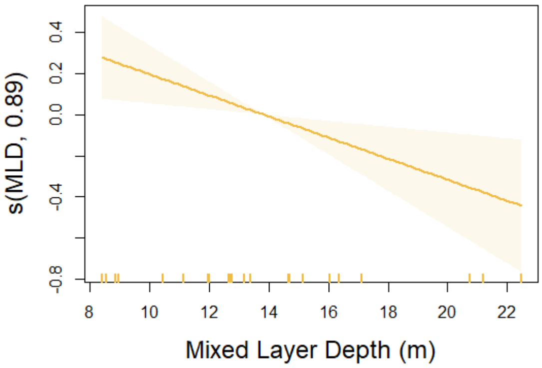


Figure 4. Selected Gaussian model for swordfish larvae: (A) qqplot of model residuals and residuals versus linear predictor and (B) partial effects of the smoothed parameters.

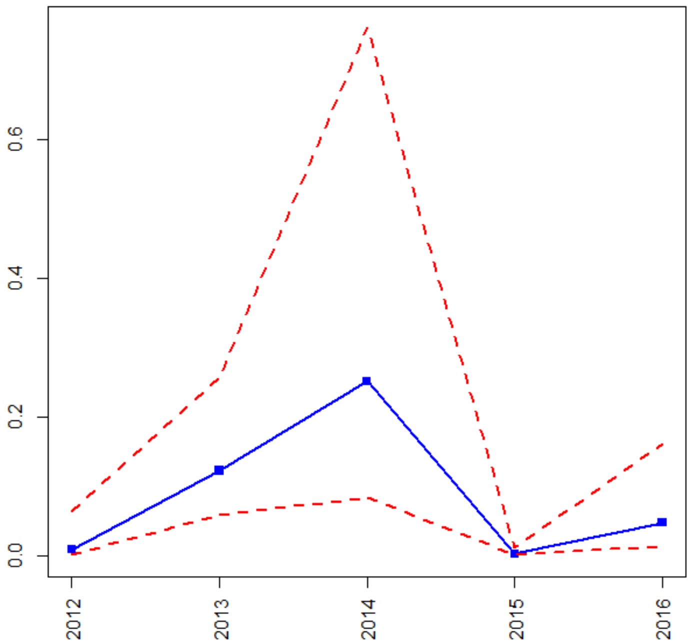
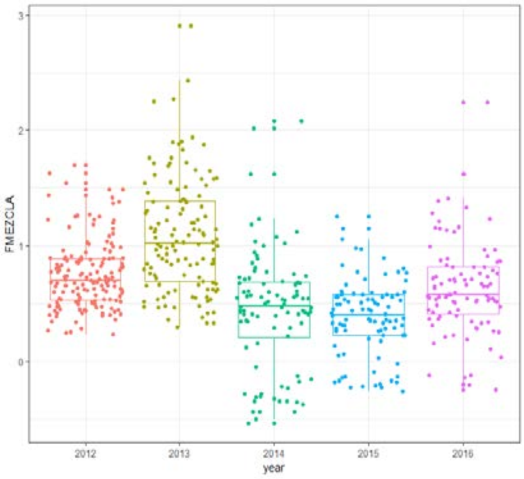


Figure 5. Index of swordfish larval catches (blue line) and confidence intervals (red dashed line) in the period 2012-2016.

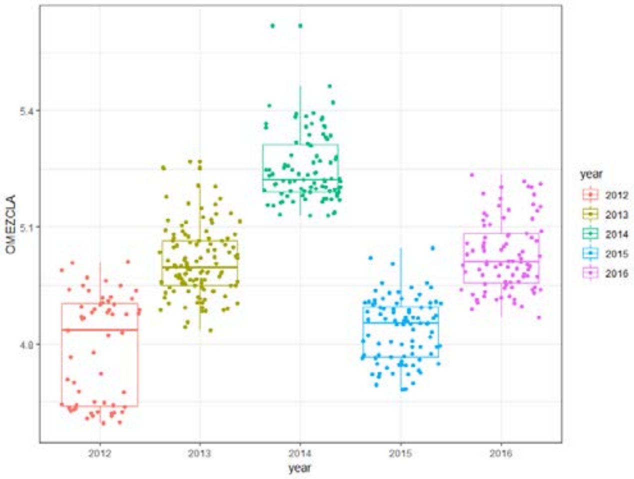
Annex 1

Whisker plots of oceanographic-environmental and sampling related variables

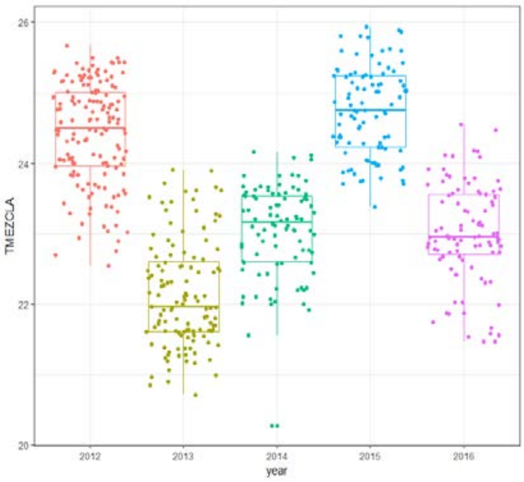
(A)



(B)



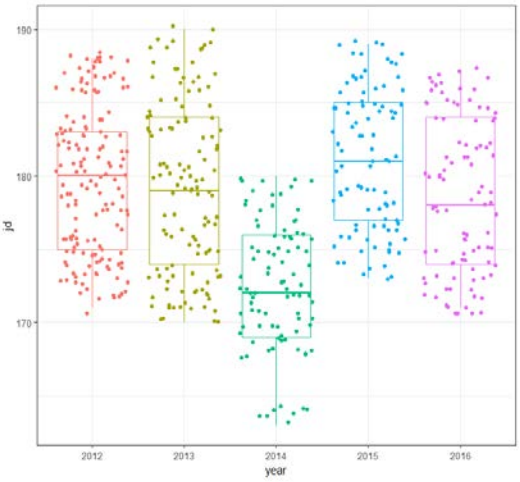
(C)



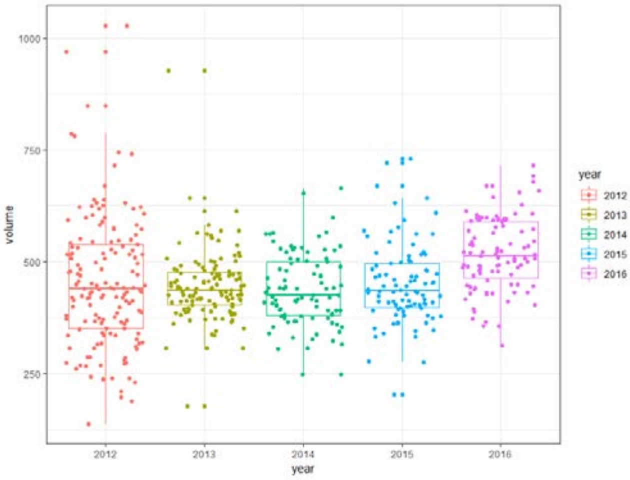
(D)

Figure S1. Whisker plots of environmental and sampling related variables. (A) Fluorescence; (B) Oxygen; (C) Temperature; (D) Salinity; (E) day of the year (jd); (F) filtered volume (volume) and (G) towing depth.

(E)



(F)



(G)

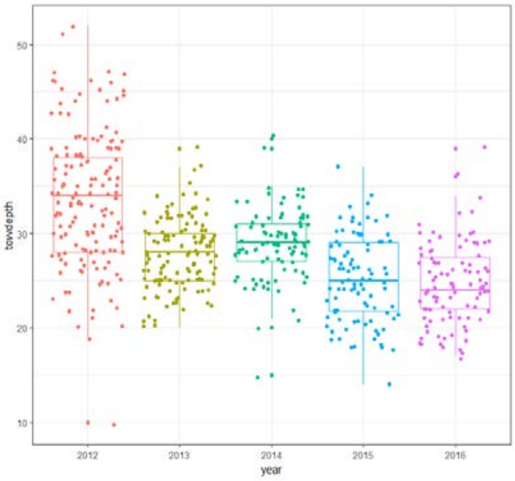


Figure S1. (Continued) Whisker plots of environmental and sampling related variables. (A) Fluorescence; (B) Oxygen; (C) Temperature; (D) Salinity; (E) day of the year (jd); (F) filtered volume (volume) and (G) towing depth.

Presence of swordfish larvae in the available time series (2004-2016)

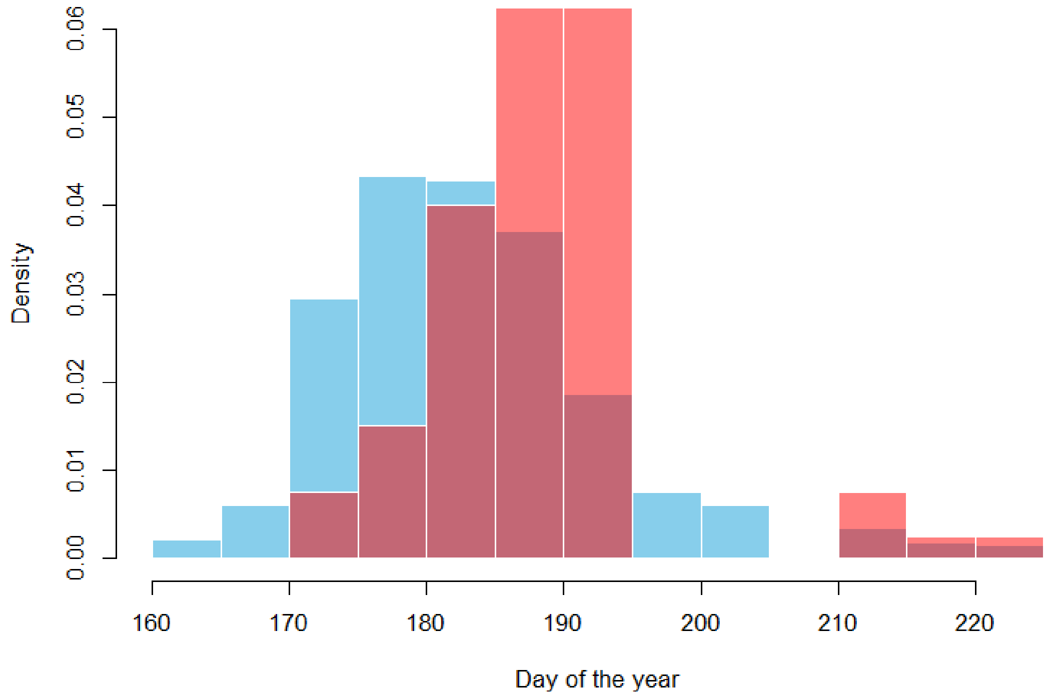


Figure S2. Presence of swordfish larvae in the available time series (2004-2016). Blue: absence; Red: presence.