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Environmental, spatial, temporal and operational effects on swordfish (*Xiphias gladius*) catch rates of eastern Mediterranean Sea longline fisheries

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Abstract

Generalized additive models (GAMs) were applied to examine the relative influence of environmental, spatial, temporal and operational factors on swordfish catch rates in the Greek swordfish longline fishery between 1998 and 2004. GAM analysis accounted for 47% of the variance in nominal catch per unit effort (CPUE) expressed in number of fish per 1000 hooks. Stepwise GAM building revealed the relative importance of eight variables ranked by decreasing magnitude: Fishing gear type, Month, Year, Sea surface temperature, Longitude, Latitude, Lunar index and Bottom depth. Longlines having deeper, thicker and more resilient branch lines with illuminated fish attractants yielded significantly higher swordfish catches. CPUE peaked during the last quarter of the fishing season, at sea surface temperatures 16–18 °C and over 26 °C, when the Lunar disc illumination was high and at greater depths. Elevated relative abundance was observed in southern and eastern longitudes, corresponding to the Levantine region. A moderate decline in swordfish abundance was detected from 1998 to 2003 followed by a sharp rise in 2004, while average individual swordfish weight decreased from 30 kg in 1998 to 23 kg in 2004.

Keywords: Swordfish; Generalized additive models; CPUE; Longline; SST; Bathymetry; Lunar index

1. Introduction

Broadbill swordfish, *Xiphias gladius*, a large pelagic oceanic marine species, occasionally found in coastal waters, has a worldwide distribution outside of polar areas. It is a highly migratory species, found in temperate or cold waters in summer and returning to warmer waters in fall. One of the larger predators of the oceans, it can attain a size of 455 cm fork length (650 kg weight). An opportunistic feeder, it forages over a wide depth range (0–800 m), feeding mainly on smaller fish and squid as well as on crustaceans (Froese and Pauly, 2005). It also exhibits diel horizontal and vertical migrations, found in coastal bottom waters during the day and moving to offshore surface waters prior to sunset (Carey and Robison, 1981). Swordfish species have proven to be very sensitive to specific environmental parameters and tend to congregate near converging oceanic fronts, strong thermoclines or underwater features, such as seamounts and shelving banks (Ward et al., 2000).

At least 27 nations participate in the swordfish catch and the annual global take is estimated to be about 80,000 metric tonnes (mt). Various fishing implements are used, such as harpoons, driftnets and longlines, but more than half of the world's swordfish catch is taken as an incidental catch of the longliners targeting tuna (Ward et al., 2000). Currently, the swordfish catch is conducted throughout the Mediterranean, with 16 nations reporting catches. Average annual catches were about 14,500 mt from 1984 to 2001, and the greatest yields in the recent years (1997–2001) were those of Italy (44%), Morocco (23%), Greece (10%) and Spain (9%) (ICCAT, 2004). Mediterranean catch levels are comparable to those of the North Atlantic (averaging ∼12,300 mt annually), despite the Mediterranean being a much smaller water body (Ward et al., 2000). Mediterranean swordfish are genetically distinct from the Atlantic type, and little genetic exchange occurs between the two populations (Magoulas et al., 1993; Kotoulas et al., 1995), the Mediterranean ones exhibiting higher growth rates and maturing at a younger age (De Metrio and Megalofonou, 1987; Megalofonou et al., 1990).

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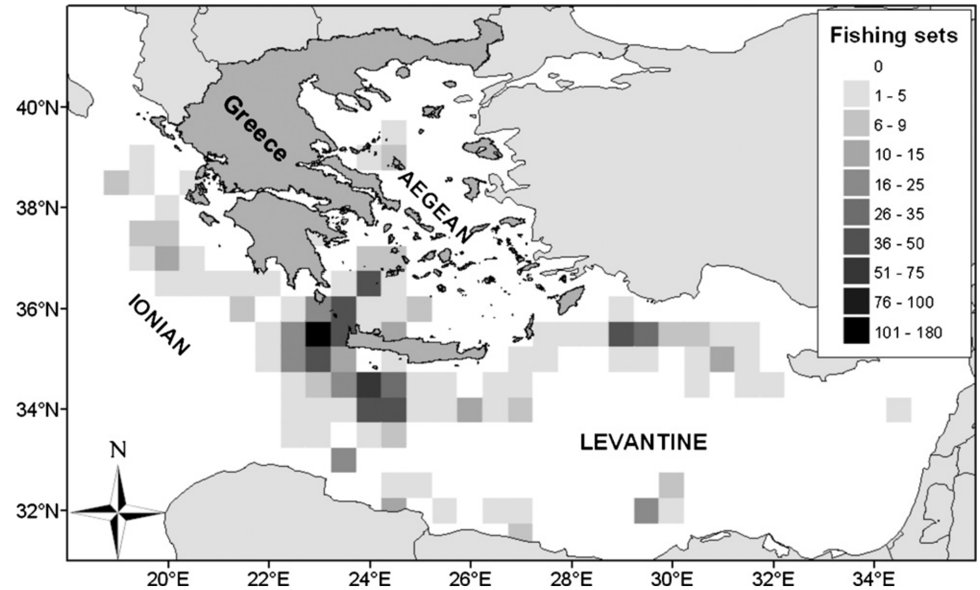

Fig. 1. Map of the studied area and spatial distribution of fishing effort, during 1998–2004 in the eastern Mediterranean Sea (spatial resolution of fishing effort is 1/2 of a degree).

Several fisheries and biological studies indicate that there is limited movement from the Mediterranean to areas immediately adjacent in the North Atlantic (Magoulas et al., 1993; Alvarado Bremer et al., 1999). Additionally, life history differences between Atlantic and Mediterranean swordfish have been described and support the hypothesis (ICCAT, 2004).

Oceanographic effects as well as changes in ocean productivity on the inter-annual variability of swordfish abundance are an important focus for current research, which uses data derived from satellite remote sensors and commercial fishing catch reports (Podesta et al., 1993; Bigelow et al., 1999; Sedberry and Loefer, 2001; Seki et al., 2002). Information on possible interactions might facilitate the interpretation of catch rates and the management of several swordfish fisheries (Ward et al., 2000). Then again, seeking to exploit marine resources with lower effective costs has created a strong need in fishermen for saving both fuel and time in fishing activities. Satellite-generated fishery-aid charts may reduce search times for some US commercial fisheries by 25–50% (Santos and Miguel, 2000).

In this study, we examine the relative influence of various operational, spatial, temporal and environmental factors on swordfish catch rates of the Greek swordfish longline fishing fleet operating in the eastern Mediterranean. We sought to act in accordance with the International Commission for the Conservation of Atlantic Tunas (ICCAT) recommendations on Mediterranean swordfish, which advises the better identification of environmental effects on swordfish on as fine a scale as possible (spatial, temporal) and to apply CPUE analysis in developing additional methods explicitly incorporating environmental variability into the model (ICCAT, 2004). In addition, the General Fisheries Commission for the Mediterranean required that advice derived from stock and environmental assessments be translated into fisheries management (FAO GFCM, 2003), and the Scientific, Technical and Economic Committee for Fisheries (STEFC) of the European Union encouraged its' member states to undertake studies on the influence of environmental factors on priority fisheries.[1] Our objective was to expand the limited knowledge regarding the effect of the environment on the eastern Mediterranean swordfish population distribution.

Hence, we applied an analysis on a fishery dependent swordfish dataset in an exploratory way, modeling catch rates as a function of the aforementioned parameters, in order to identify which of them influence swordfish catches and to quantify their effects.

2. Materials and methods

2.1. Study area

The Mediterranean is a semi-enclosed sea with pronounced oligotrophy in surface waters due to low discharge input from land, which is reflected in low catch levels (1.4 t/km^2) over the continental shelf. It is composed of two nearly equal size basins (eastern and western), which meet at the narrow and shallow Straits of Sicily. Five regions comprise the eastern basin (Straits of Sicily, Adriatic Sea, Ionian Sea, Aegean Sea, Levantine basin). In general, the eastern part of the Mediterranean is characterized by higher temperatures, increased salinity and lower trophic potential compared to the western basin (Stergiou et al., 1997).

A network of sampling stations throughout the eastern Mediterranean was developed to cover a wide range of fishing grounds, fleets and gear that targeted swordfish. The sampling areas were located in Ionian Sea, Aegean Sea and Levantine basin (Fig. 1).

[1] stecf.jrc.cec.eu.int/meetings/sgrnDataColRev2/sgrn-final-v2.doc.

2.2. Gear description

Two types of fishing gears were studied: traditional swordfish longline (SWO-LL_T) and "American type" swordfish longline (SWO-LL_A). Traditional swordfish longline consists of a nylon monofilament main line from 2 to 3 mm diameter in cross-section hung in a sagging curve between surface floats. The main line is suspended by the floats at a depth of 1 m. Between two consecutive floats, five branch lines with lengths of 5–18 m descend from the main line, each terminating with a single baited hook. Branch lines separated by distances of approximately 30 m. The number of hooks ranges from 800 to 1200 and hook size varies from type no. 0 to 3. "American type" swordfish longline is a name used by the Greek fishermen and was introduced in the fishery in the mid 1980s. It is a variation of the aforementioned gear with less hooks (350–700), of size no. 2, having much longer branch lines (15–50 m) which are separated by 100 m (three between two consecutive floats) and a fish attractant light-stick (Duralumes® Lindgren-Pitman Inc.) attached to each branch line 1 m above the bait (Megalofonou et al., 2005a,b). The main line is suspended by floats at a depth of more than 2 m. The gear is set in the evening and the setting operation ends before midnight. The catch starts at the beginning of each day, from the last hook placed, and can last from 6 to 9 h, depending on the length of the gear, on the conditions of the sea and on the quantity of fish caught.

2.3. Data collection

Sampling was conducted from 1998 to 2004 and data were recorded by observers stationed at pilot fishing ports and on board commercial fishing vessels. These data included fishing and operational data, fish identification and measurements as well as spatial and temporal variables. Fishing and operational data series incorporated the name of the boat, gear used, duration of trip, daily fishing effort (number of hooks), number and weight of fish caught per day. Spatial and temporal variable data included the date and exact geographical coordinates of each fishing set. Catch rates were expressed using the nominal catch per unit effort (CPUE) which is a fishery performance index representing the success of fishing from commercial fishery statistics. CPUE values were calculated as the number of fish/1000 hooks.

Daily sea surface temperatures (SST) were obtained indirectly from daily satellite-derived estimates. SST fields were calculated from multi-channel SST data of NOAA's[2] advanced very high-resolution radiometer (AVHRR) fine scale measurements (1.1 km pixel). All were downloaded from the German on-line database GISIS-DLR[3] and a translation of grayscale to colorscale to increase color contrast using MATLAB (Mathworks Inc.) was applied before finalizing the SST data maps.

The daily lunar index was calculated based on the illuminated portion of the face of the moon, ranging from 0 (new moon) to 1 (full moon). Calculations were made using "Focus on Today" software (RAJE Software, 2001).

Bathymetry at each fishing location was estimated using a digitized bathymetric map of the region, created after processing ASCII data downloaded from the "Interactive Global Map of Sea Floor Topography" (NOAA Laboratory for Satellite Altimetry) in MATLAB software package.

Distance from the coast, was estimated for each fishing location, applying a MATLAB script which located the nearest land pixel (bottom depth >0) on a grid map and calculated the distance between the two points in nautical miles (after correcting for the spheroid shape of the Earth).

2.4. Statistical analyses—modeling

Fishery performance (CPUE) was modeled as a function of categorical and continuous effects in two steps. Initially, we applied a simple general linear model (GLM) to gain insight of how the independent variables relate to swordfish catches in our dataset and afterwards we shifted to non-parametric generalized additive models (GAMs) and tested whether they are an improvement over the linear approach (GLM). GAMs are extensions of generalized linear models (GLMs) in which a link function describing the total explained variance is modeled as a sum of the covariates (Hastie and Tibshirani, 1990). The terms of the model can in this case be local smoothers or simple transformations with fixed degrees of freedom (Maunder and Punt, 2004; Venables and Dichmont, 2004). The main reason for selecting GAMs, was to assess the factors affecting swordfish abundance. The functional relationships between fishing performance and environmental conditions are very likely to be non-linear (Bigelow et al., 1999). GAMs are tools for identifying non-linearities by incorporating terms non-parametrically into the model (Chambers and Hastie, 1997).

Nine independent variables were considered for inclusion in the model: Latitude, Longitude, SST, Bathymetry, Distance from coast, Lunar index, Month, Year and Fishing gear type. The first six are continuous and the last three are categorical.

GLM was calculated using the least squares method and assuming a normal error distribution (Glantz and Slinker, 2001):

$$\begin{aligned}\log(\mathrm{CPUE}+1) = {} & b_0 + b_1\mathrm{Latitude} + b_2\mathrm{Longitude} + b_3\mathrm{SST} \\ & + b_4\mathrm{Bathymetry} + b_5\mathrm{Distance\ from\ coast} \\ & + b_6\mathrm{Lunar\ index} + b_7\mathrm{Month} + b_8\mathrm{Year} \\ & + b_9\mathrm{Fishing\ gear\ type} + b_k\mathrm{INTER}_k,\end{aligned}$$

where CPUE stands for number of swordfish caught per 1000 hooks, b_i's the regression coefficients and, INTER_k any combination of two-way interactions between Fishing gear type and variables expressing time (Month, Year) or area (Latitude, Longitude). CPUE was log-transformed in order to assess the departure of original data from normality. A constant of 1 was added so as to eliminate zero data points which pose a problem to the log function. Marginal sums of squares (Type III) were

[2] National Oceanic and Atmospheric Administration.

[3] Graphical Interface to the Intelligence Satellite data Information System—Deutsches Zentrum fuer Luft und Raumfahrt e.V.

used to test the significance of each regression coefficient and residual analysis was conducted to check whether the results were consistent with the model assumptions.

The GAM model was fitted in the following way:

$$\begin{aligned} g(\text{CPUE}) = {} & c + f_1(\text{Latitude}) + f_2(\text{Longitude}) + f_3(\text{SST}) \\ & + f_4(\text{Bathymetry}) + f_5(\text{Distance from coast}) \\ & + f_6(\text{Lunar index}) + \text{Month} + \text{Year} \\ & + \text{Fishing gear type} + f_k(\text{INTER}_k) + \varepsilon \end{aligned}$$

where g is the link function, f_i smoothers or simple transformations of the explanatory variables, c a constant, ε a random error term and, $f_k(\text{INTER})_k$ as described previously.

The explanatory factors influencing catch rates that should be incorporated into the model were identified applying a stepwise GAM (Chambers and Hastie, 1997). Models were built by adding in new terms and seeing how much they improved the fit, and by dropping terms that did not degrade the fit significantly. An initial model was the 'minimal model' consisting only of the overall mean. Adding or removing a new term was based on the reduction of AIC selection criterion. The procedure stopped when no further steps could decrease the criterion. Additionally, p-values based on an ANOVA F-ratio test and a Chi-squared test statistic were used to evaluate: (1) the significance of each additional factor and (2) the non-linear contribution of a non-parametric term.

Identification of the underlying probability distribution for the errors in the dependent variable (catches of swordfish) was performed following the methodology described in Burnham and Anderson (2002), using the Akaike information criterion (AIC) to discriminate among error distributions. AIC is defined as:

$$\text{AIC} = -2 \log L(\hat{\theta}) + 2K$$

where $L(\hat{\theta})$ is the likelihood function maximized over the vector of estimated parameters, $\hat{\theta}$, and K is the number of estimated parameters. The model with the smallest AIC is best supported by the data. Several available error distributions (limited by available software packages), with their corresponding link functions, were investigated: Gaussian, lognormal, Gamma and Poisson. In order to compare models assuming different error distributions, we used the same number of parameters for each model, explanatory variables being the same for consistency and comparison purposes (all nine variables plus interactions). After calculating AIC scores for each candidate model, the standard procedure to discriminate among several distributions was based on the computation of the corresponding 'Akaike weights':

$$w_i = \frac{\exp(-(1/2)\Delta_i)}{\sum_{r=1}^{R} \exp(-(1/2)\Delta_i)}$$

that represents the relative weight of evidence for the ith model in the context of R candidate models. Δ_i is the difference between the value of AIC for the ith model and the smallest AIC value for all candidate models. Usually, the model with the highest Akaike weight is selected as the 'best' model. An application of this method on fishery data can be found in Dick (2004). In our case, such a comparison will confound structural and stochastic model components. The correct comparison is done using an evidence ratio (ER) by structural model pairs defined as:

$$\text{ER} = \frac{\exp(-(1/2)\Delta_k)}{\exp(-(1/2)\Delta_j)}$$

where Δ_i is as described previously and the subscripts k, j correspond to the kth and jth model, respectively. The larger the ER values, the larger the evidence against the jth model in favor of the kth one (Burnham and Anderson, 2002, Section 6.7.3, Comparing Across Several Distributions, p. 320).

Finally, we used the K-fold cross-validation method (Hastie et al., 2001) to test if the non-linear model analysis (GAM) was superior to the linear model analysis (GLM). The procedure involved using part of the available data to fit the model ('training dataset') and a different part to test it ('test dataset'). We split the data into K roughly equal-sized parts, and for the kth part we fitted the model to the other $K-1$ parts of the data. We then calculated the prediction error of the fitted model when predicting the kth part of the data. We did this for $k = 1, 2, \ldots, K$ and combined the K estimates of prediction error. The cross-validation estimate of prediction error was calculated as:

$$\text{CV} = \frac{1}{N}\sum_{i=1}^{N} L(y_i, \hat{f}^{-k(i)}(x_i))$$

where N was the sample size, $\hat{f}^{-k(i)}(x_i)$ the fitted function computed with the kth part of the data removed, k: $\{1, \ldots, N\} \rightarrow \{1, \ldots, K\}$ an indexing function that indicated the partition to which observation i was allocated by the randomization, and $L(y_i, \hat{f}(x_i)) = |y_i - \hat{f}(x_i)|$ the absolute error.

Evaluation of the model with the best predictive power was based on the lower estimate of prediction error CV.

3. Results

Between April 1998 and September 2004 the observers monitored 35 fishing boats operating from 19 ports and reported a total of 5523 swordfish as part of the swordfish longline catch in 1001 fishing days of sampling (Figs. 1 and 2). Swordfish reached an overall 79.5% of the total catch, in number of fish, with an average of 8.96 swordfish/1000 hooks deployed (Table 1). In total, there were only 13 American type swordfish longline sets out of 777 and 4 out of 224 traditional swordfish longline sets where no swordfish were caught.

3.1. GLM analysis

Type III analysis revealed that seven out of nine main effects and Longitude × Month interaction were significant. However, variance inflation factors, used to measure the extent to which the predictor variables were correlated amongst themselves, indicated the presence of serious multicollinearity between Longitude and Month, greatly increasing the estimation error of the model coefficients as compared with an orthogonal sample. This can make the model fitting process numerically unstable

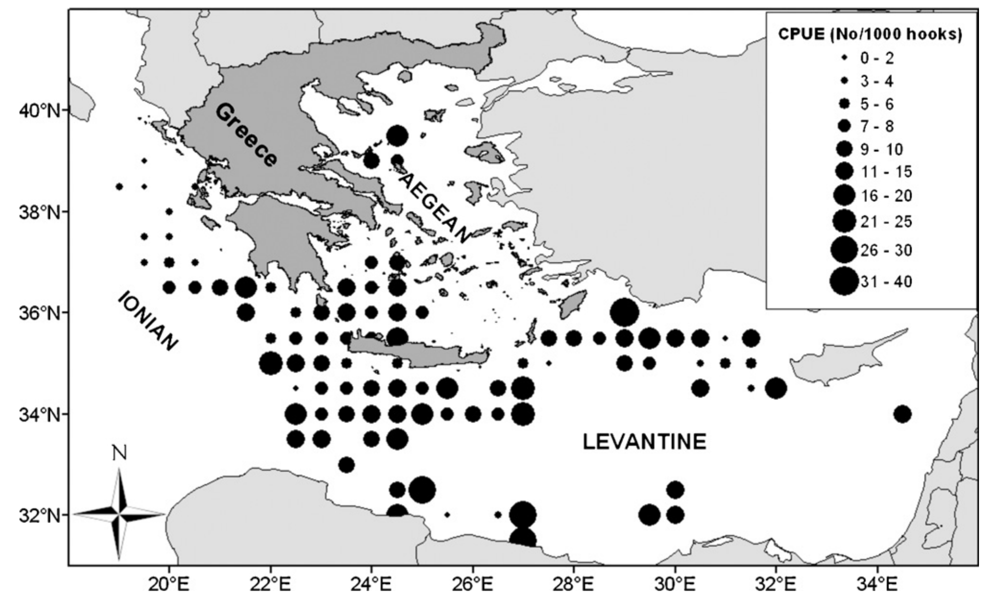

Fig. 2. Geographical distribution of swordfish CPUE (no. of swordfish/1000 hooks), during 1998–2004 in the eastern Mediterranean Sea (spatial resolution of fishing effort is 1/2 of a degree).

or lead to problems similar to those of over-fitting (Maunder and Punt, 2004). Therefore, the interaction factor was excluded from the final model (Table 2). After the log-transformation of catches, residuals analysis showed no deviation from the constant variance assumption. In a total of 1001 data points, there were only 3 Studentized residuals greater than 3.0 and 3 leverage values greater than three times the average leverage. No data points had unusually large values of Cook's distance (no Cook's distance greater than 0.0006). The model identified the three categorical factors (Fishing gear type, Month and Year) as the most influential and in total explained 36% of the variance in swordfish CPUE. GLM effects of the predictor variables on log-transformed swordfish CPUE are illustrated in Fig. 3. However, scatterplots of transformed catches against the independent variables showed indications of non-linearity (Fig. 4) for some of them (SST, Latitude, Longitude).

Table 1
Number of ports, vessels, fishing sets, hooks deployed, average hooks per set, swordfish caught, percentage of total catch and nominal CPUE by fishing gear in the eastern Mediterranean Sea, during the period 1998–2004 (ports and vessels may overlap between fishing gears)

Fishing gear	No. of ports	No. of vessels	Fishing sets	Effort (×1000 hooks)	Average hooks per set	Swordfish caught (no.)	% of total catch	Nominal CPUE (no. of fish/1000 hooks)
SWO-LL_T	10	11	224	232.3	1037	1066	86.7	4.59
SWO-LL_A	15	30	777	384.4	495	4457	78.1	11.59
Total	19	35	1001	616.7	616	5523	79.5	8.96

SWO-LL_T: traditional swordfish longline; SWO-LL_A: "American" type swordfish longline.

Table 2
Summary of fitting a general linear statistical model, relating swordfish catches to the seven significant predictive factors in the swordfish fishery of the eastern Mediterranean Sea (1998–2004)

Source	Sum of squares	d.f.	Mean square	*F*-ratio	*p*-Value
GLM—dependent variable: log(CPUE + 1)					
Fishing gear type	48.107	1	48.107800	169.66	0.0000
Month	17.726	6	2.954417	10.42	0.0000
Year	9.467	5	1.893424	6.68	0.0000
Latitude	4.742	1	4.742580	16.73	0.0000
SST	2.508	1	2.508580	8.85	0.0029
Longitude	1.540	1	1.540990	5.43	0.0197
Bathymetry	1.093	1	1.093320	3.86	0.0496
Residual	279.017	984	0.283554		
Total (corrected)	443.789	1000			

R^2 = 37.1%; R^2 (adjusted for d.f.) = 36.1%; standard error of est. = 0.532; All *F*-ratios are based on the residual mean square error.

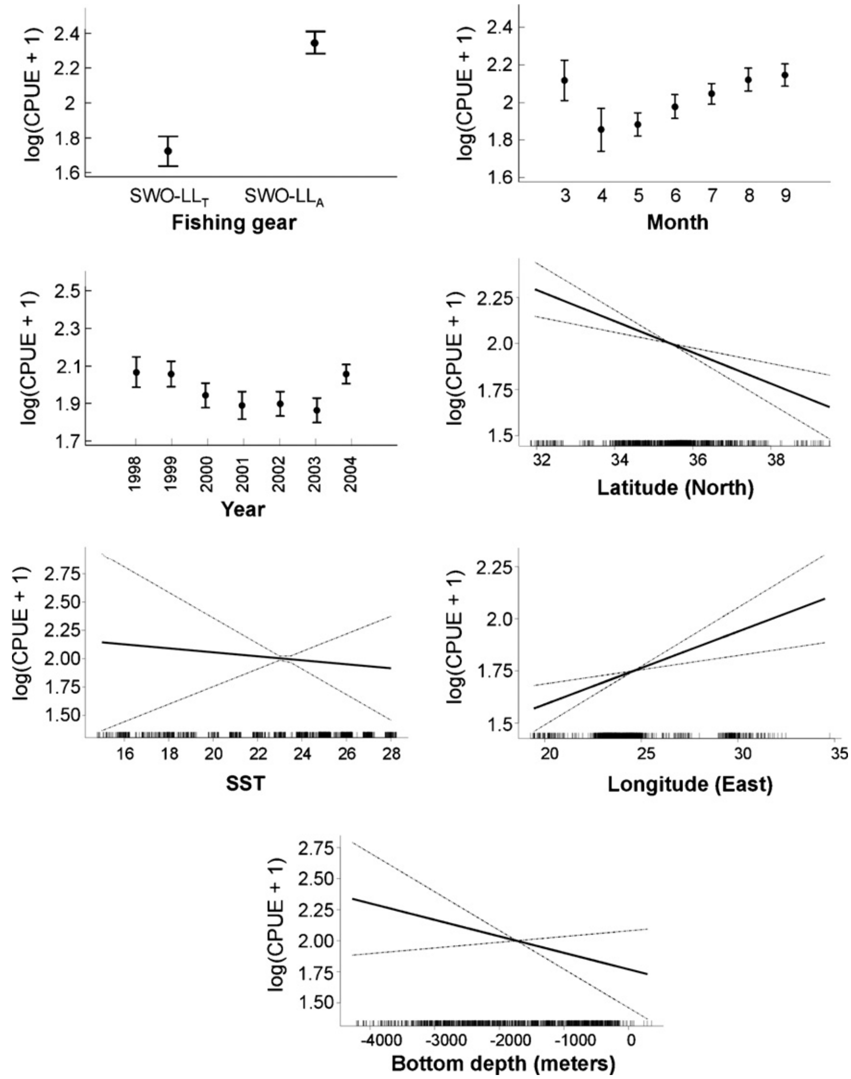

Fig. 3. GLM effects of the seven predictor variables on log-transformed swordfish CPUE, during 1998–2004 in the eastern Mediterranean Sea. Dashed lines (or upper and lower brackets) indicate centered 95% confidence intervals.

3.2. GAM analysis—selection of error-model and explanatory variables

Comparison among Akaike weights (w_i) and evidence ratios (ER) gave overwhelming evidence in favor of the Gamma distribution, relative to all the other candidate models, suggesting it as the best approximating distribution for our model (Table 3).

Table 3
AIC results, Akaike weights (w_i) and evidence ratios (ER), for several error distributions in a GAM for factors affecting swordfish catches, in the eastern Mediterranean Sea (1998–2004)

Model	AIC	Δ_i	wi Akaike weights	ER
Gaussian	31559	31348	~0	Infinity
Log-normal	286	75	5.17E−17	1.93E+16
Gamma	211	0	~1	1.0
Poisson	2031	1820	~0	Infinity

Explanatory variables for each error distribution were the same for consistency and comparison purposes. ER's were calculated for each distribution relative to the Gamma distribution.

Therefore, stepwise GAM model building was applied to our data, assuming a Gamma error distribution with log as the natural link function. Forward and backward stepwise model building using the AIC concluded that eight out of the nine investigated variables and no interaction terms were significant ($p<0.05$) in the GAM design and did significantly reduce the residual deviance. The final model took the following form:

$$\begin{aligned}&\log(\text{CPUE}+1) \sim \text{Fishing gear type} + \text{Month} + \text{Year}\\&\quad + \text{lo}(\text{SST}, \text{span} = 0.3) + \text{lo}(\text{Longitude}, \text{span} = 0.3)\\&\quad + \text{lo}(\text{Latitude}, \text{span} = 0.3) + \text{lo}(\text{Lunar index}, \text{span} = 0.3)\\&\quad + \text{Bathymetry}\end{aligned}$$

where lo stands for locally weighted polynomial scatterplot smoother (loess) and span for the number of observations in the neighborhood of the loess regression that should be taken in account (e.g., span 0.3 = 30% of surrounding data). Since the log–link function cannot handle zeros we added a constant of 1 (~10% of mean CPUE) to all CPUE values.

Table 4
Stepwise generalized additive model building for factors affecting swordfish catches in the eastern Mediterranean Sea (1998–2004)

Model structure-terms added	Residual d.f.	Residual deviance	Deviance decrement	Cumulative % of deviance explained	AIC statistic	Pr (F)	Pr (Chi)
NULL		396.81			396.61		
+Fishing gear type	999	295.07	101.74	25.6	296.17	0.000	
+Month	993	268.79	26.28	32.3	272.74	0.000	
+Year	988	248.42	20.37	37.4	254.17	0.000	
+lo(SST, 0.3)	977	231.85	16.57	41.6	241.38	0.000	0.000
+lo(Longitude, 0.3)	696	220.67	11.18	44.4	232.71	0.000	0.000
+lo(Latitude, 0.3)	961	216.58	4.09	45.4	231.83	0.006	0.030
+lo(Lunar index, 0.3)	953	213.01	3.56	46.3	230.89	0.013	0.004
+Bathymetry	952	211.47	1.54	46.7	229.93	0.039	

Assuming a Gamma-log error distribution. Pr(F) refers to the p-value from an ANOVA F-ratio test between the model for that row and the model for the previous row. Pr(Chi) represents a type of score test to evaluate the non-linear contribution of non-parametric effects.

The detailed deviance table for the applied model is shown in Table 4. Each row of this table displays information regarding the fitting process and the variability explained by the most significant explanatory variables under study, in eight columns: the factors added successively in the model, the residuals degrees of freedom, the residual deviance, the change in deviance due to the additional factor, the cumulative deviance explained in CPUE, the computed AIC statistic, the p-value from an ANOVA F-ratio test between the model for that row and the model for the previous row and the p-value from a Chi-squared test which represents a type of score test to evaluate the non-linear contribution of non-parametric effects (present only where non-parametric terms are added in the model). The computed AIC statistic differs from that in Table 3, since the latter was computed for the full model (nine variables plus interactions). The F-ratio test to compare among models is suggested as the most suitable for Gamma models (Chambers and Hastie, 1997). Results of the Chi-squared test justified the use of non-parametric smoothers (locally weighted polynomials in our case) to fit factors such as SST, Longitude, Latitude and Lunar index. In contrast, fitting Bathymetry by using a smoothing function indicated that this non-linear component is not significant. Thus, the variable was entered as a linear predictor. Model checking and fit diagnostics also supported the good fit of the model (Fig. 5). Graphs in Fig. 5 suggest that: (a) there is no systematic departure from the assumption of the error distribution and that model misspecification is not occurring (Fig. 5, top), (b) variance does not change dramatically through the range of predicted values (Fig. 5, middle) and, (c) the explanatory variables reduce satisfactorily the variance in the data (Fig. 5, bottom).

Distance from coast was excluded from the final model as insignificant, as well as all interaction terms. Even so, Time × Area interactions were investigated plotting a series of local estimators (loess) plots of Latitude and Longitude against log-transformed swordfish catches by Month and by Year. It was clear from all plots that the reason why the effects of all Time × Area interactions were insignificant in the model convergence, was the consistent trend in catches regardless of Latitude, Longitude, Month or Year. As one can observe in Fig. 6, catches were always higher to the south and to the east of the studied area during all months. Trends were similar throughout all years, although not presented here.

To confirm the superiority of the GAM approach, 10-fold cross-validation method (Hastie et al., 2001) was implemented using the "predict.gam" (GAM analysis) and "predict" (GLM analysis) functions in S-PLUS. Data ($N = 1001$) were partitioned in 10 almost equal-sized subsets, the "training" set comprised of the 9 subsets while the remaining subset was used as the "test" set. After models were fitted, the combined estimates of prediction error were used to compute the CV estimate. Results gave evidence in favor of the non-linear approach (GAM CV = 4.05; GLM CV = 7.47).

3.3. *Effects of explanatory variables*

In total, the final model explained almost 47% of the variance in swordfish CPUE (Table 4). GAM analysis indicated that Fishing gear type had the foremost effect explaining almost 26.0% of the deviance in swordfish CPUE. Month (6.6%), Year (5.1%), Sea surface temperature (4.2%), Longitude (2.8%) and Latitude (1.1%) were the next most influential parameters, while Lunar index (0.9%) and Bathymetry (0.4%) provided only minor explanatory ability.

Fishing gear type was the predominant factor, yielding a significant reduction in deviance (54.9% of total; Fig. 7a). The American type swordfish longline turned out to be the most 'successful' gear in catching swordfish (nominal CPUE = 11.59 swordfish/1000 hooks) than the traditional swordfish longline (4.59 swordfish/1000 hooks), although average hooks per fishing set was more than twice as much for the latter (Table 1).

The temporal factor (Month) had a significant influence in the model explaining 14.2% of total deviance. Monthly allocation of catch rates revealed peaks during the start and end of the fishing period. From April and onwards, catches increase monotonically (Fig. 7b), with fall being the most 'favorable' period, with increased abundance occurring during September. Greek legislation (since 1987) prohibits sword-fishing during the winter months, so our dataset suffered a limitation on available data only during the period from March to September.

The plot for Year showed a declining trend in catch rates between 1998 and 2003, followed by a sharp rise in 2004 (Fig. 7c). Fishing sets were more or less evenly distributed among the years of the study, except 1998, during which less than 100 fishing sets were monitored ($n = 99$).

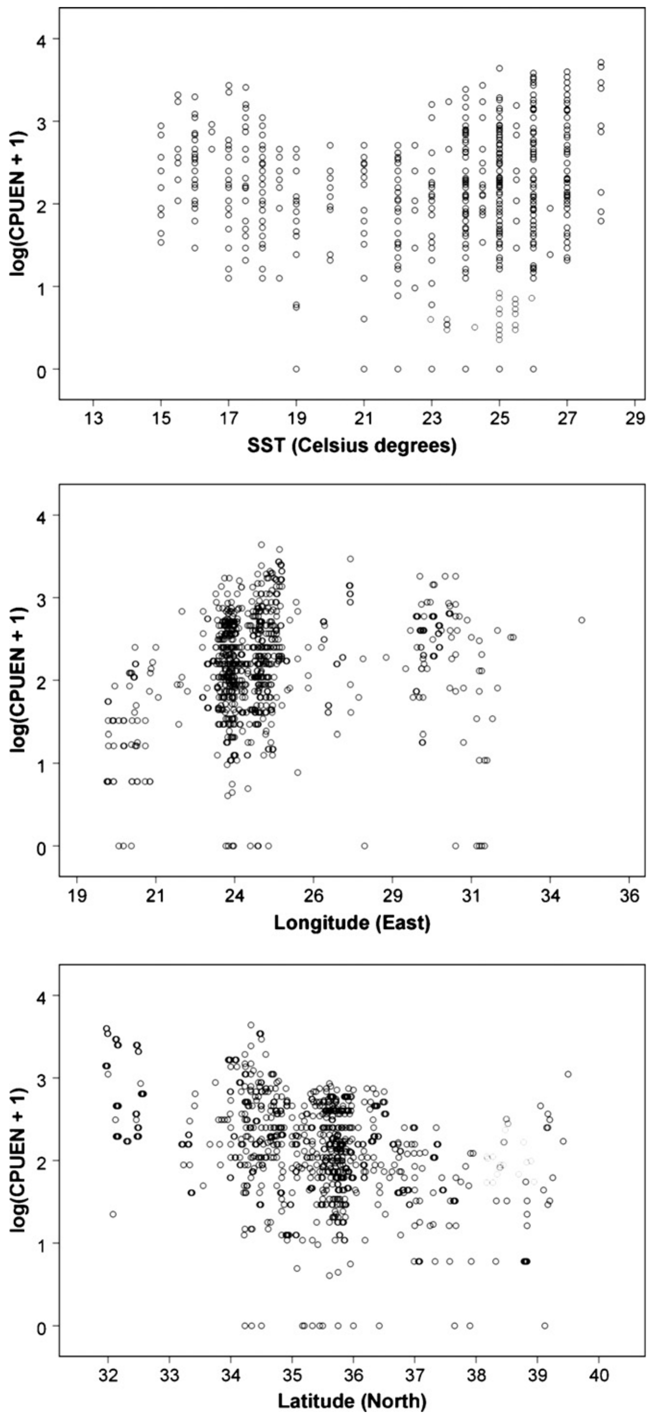

Fig. 4. Scatterplots of the dependent variable (log-transformed catch per unit effort) vs. three independent variables (SST, Longitude, Latitude) for swordfish catch rates in the eastern Mediterranean (1998–2004).

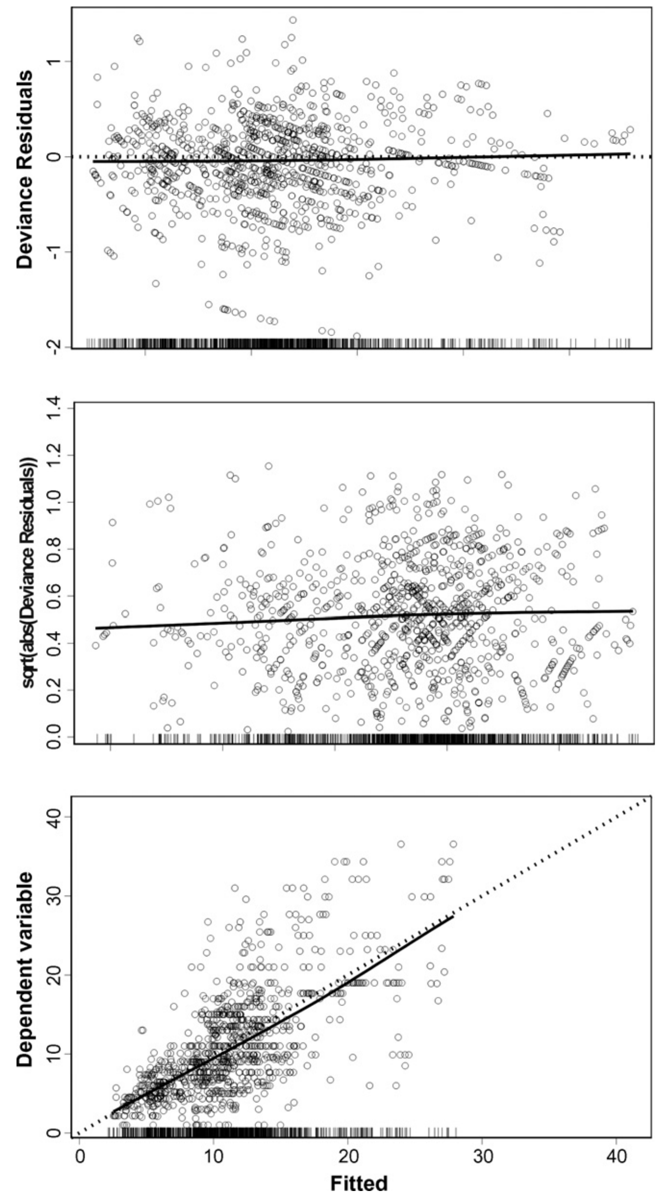

Fig. 5. Diagnostic plots for the goodness-of-fit of a Gamma model for swordfish catch rates in the eastern Mediterranean (1998–2004). Standardized residuals vs. the fitted values (top), the square root of the absolute values of the standardized residuals versus the fitted values (middle) and the observed versus the fitted values (bottom). Solid lines are loess smoothers through the plotted data.

Abundance related to SST (Fig. 7d) fluctuated throughout the temperature range studied, however higher CPUE values were observed in temperatures from around 17 °C to greater than 26 °C. More than 35% of the fishing sets were deployed during these temperature ranges.

The spatial predictor Longitude explained 6.0% of total deviance. The GAM plot (Fig. 8a) suggests a longitudinal constituent in the presence of swordfish as catches increase in an easterly direction with a slight drop beyond 30°E. The effect of Longitude east of 30°E (East Levantine) is unclear because the reduced density of data points leads to greater standard error ranges.

Regarding Latitude, the plot showed a distinct region of higher abundance (Fig. 8b), and elevated CPUE values observed in the lower latitudes (<34°N) corresponded to the area off the North African coast. North of the 37th parallel the variable became insignificant due to the absence of sufficient data points.

Lunar index was the penultimate statistically significant factor identified in our GAM analysis. Elevated catches were more noticeable when the lunar disc was illuminated at a percentage of more than 50% of the whole disc (Fig. 8c).

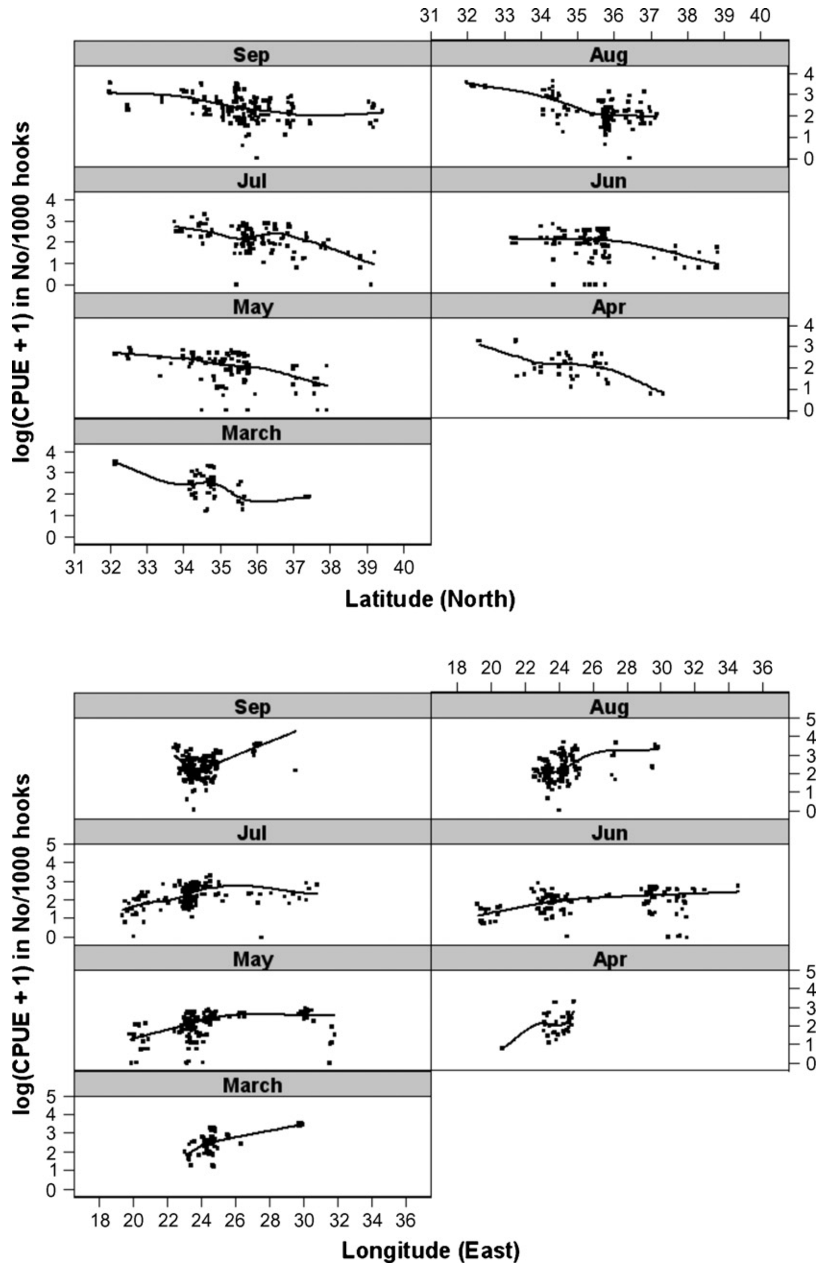

Fig. 6. Loess plots of log-transformed swordfish catches against Latitude and Longitude by Month, in the eastern Mediterranean (1998–2004).

Finally, Bathymetry, explained no more than 1.0% of the total deviance, and when plotted against the dependent variable (CPUE) indicated that lower catch rates were more likely to occur in shallow waters (Fig. 8d). More than 33% of the fishing effort was conducted in depths of less than 1000 m, while only 8% in depths greater than 3000 m.

4. Discussion

Swordfish distribution and abundance is known to be influenced by a series of factors such as: availability of prey, marine currents, thermal fronts, latitude and longitude, time of day, season, sea surface temperatures, bottom depth and topography, light levels, lunar phases, dissolved oxygen concentration and wind velocity (Carey and Robison, 1981; Nakamura, 1985; Draganik and Cholyst, 1987; Sakagawa, 1989; Podesta et al., 1993; Holts et al., 1994; Bigelow et al., 1999; Sedberry and Loefer, 2001; Seki et al., 2002; Fritsches et al., 2005). However, several authors reported that fishery dependent swordfish catch rates are largely dependant on fishing gear, its configuration (setting depth, hook size, bait type) and the skipper's experience (Broadhurst and Hazin, 2001; Stone and Dixon, 2001; Tserpes and Peristeraki, 2003; Bigelow et al., 2006). In this paper, we provide a new perspective of the east Mediterranean swordfish fishery by examining how a selection of environmental, spatial, temporal and operational parameters was linked to swordfish catch rates. We proceeded in two stages: (1) applying a simple general linear model (GLM) to sketch a general outline of the

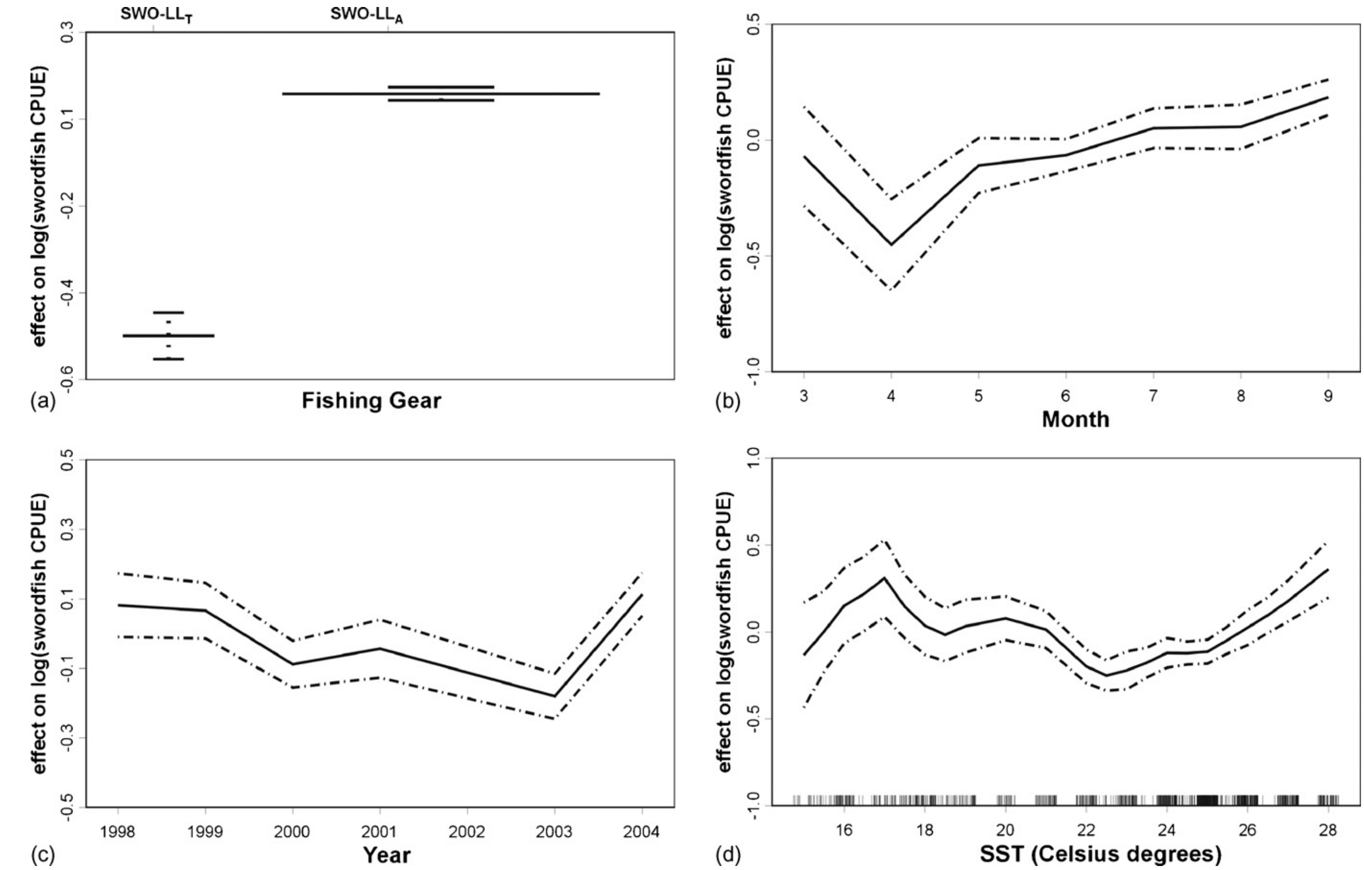

Fig. 7. Generalized additive model (GAM) derived effects of (a) Fishing gear type, (b) Month, (c), Year and (d) SST on the log-transformed swordfish catch rates. Dashed lines (or upper and lower brackets) indicate 95% confidence bands (levels). Relative density of data points is shown by the 'rug' on the *x*-axis.

relations, and (2) after non-linearities were identified for some factors, we used a non-linear generalized additive model (GAM) analysis. GAM was an improvement over the linear approach (GLM), not only for the reason that it explained an additional 10% of the variance, but mostly because of its' superior explanatory ability and predictive power, as the cross-validation method confirmed.

Our results indicated that operational (Fishing gear type), temporal (Month, Year), and spatial factors (Longitude, Latitude), as well as thermal preference (SST) played the most significant role in the model substantially affecting catches, while the remaining features: Lunar index and Bathymetry, were subsequent constituents.

4.1. Operational variables affecting catches

Fishing gear type was the strongest explanatory variable in predicting fishery performance (nominal CPUE). The effect of the operational variables on swordfish catch rates has already been documented in the northern Pacific Ocean and was ascribed to the number of hooks deployed and number of light-sticks per hook (Bigelow et al., 1999). The variables probably reflect the vulnerability of swordfish rather than their actual abundance. The higher catches of the "American type" swordfish longline when compared to the traditional one (Fig. 7a) could be attributed to four major characteristics defining the gear: (1) chemical light-sticks as fish attractants; (2) thicker and more resilient line, minimizing the possibility of a fish cutting the line and escaping; (3) setting depth, SWO-LL$_A$ targets fish in a greater part of the water column, often below 50 m, while SWO-LL$_T$ depth ranges rarely exceed 20 m; (4) bait type, SWO-LL$_A$ hooks are usually baited with squid (*Todarodes* sp., *Illex* sp.), while SWO-LL$_T$ with mackerel (*Scomber* sp.). Broadhurst and Hazin (2001) compared bait (squid and mackerel) and how this affected catches of an artisanal sub-surface longline fishery off Northeastern Brazil.

4.2. Temporal variables affecting catches

Although a time series of 7 years is insufficient to reliably identify trends in annual catches or inter-annual variability, our results show a gradual decrease in catch rates during the 1998–2003 period, followed by an increase in 2004 (Fig. 7c). Annual variation of nominal swordfish CPUE compared to the GAM standardized CPUE differs moderately with the standardized indices being restricted to a narrower range of values. Only a decline in 2003 was statistically significant (Fig. 9).

Diminishing swordfish abundance indices may be influenced by fishing mortality. Average individual swordfish weight caught during our survey (unpublished data), revealed a gradual decline from 30 kg in 1998 down to 23 kg in 2004. If we consider size as a more sensitive indicator of swordfish stock status than catch rates

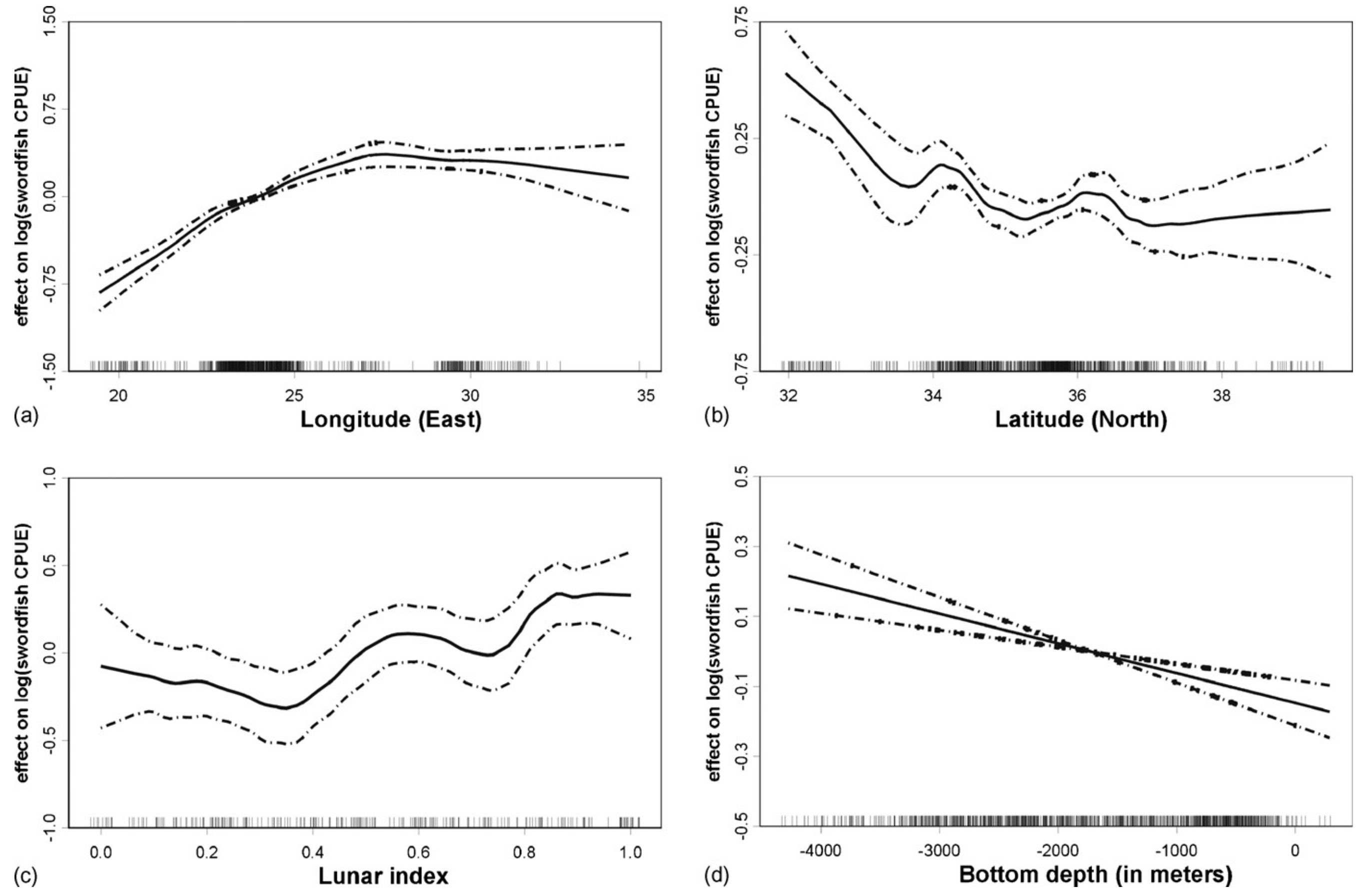

Fig. 8. Generalized additive model (GAM) derived effects of (a) Longitude, (b) Latitude, (c) Lunar index and (d) Bathymetry on the log-transformed swordfish catch rates. Dashed lines indicate 95% confidence bands. Relative density of data points is shown by the 'rug' on the *x*-axis.

(Ward et al., 2000), then this could be a sign that the population is under fishing pressure. De Metrio et al. (1999) studying trends of the swordfish fishery in an Italian port during 1978–1997 concluded that since 1980 average individual weight of fish caught has declined consistantly from 50 to 10 kg. However, the most recent stock assessments for Mediterranean swordfish conducted at the annual ICCAT meetings (ICCAT, 2004) suggest that the current exploitation pattern and level of exploitation are sustainable, at least in the short-term. Yet, the lack of sufficient historical data does not permit the determination of stock status relative to maximum sustainable yield (MSY). The Committee also noted the large catches of small size swordfish, i.e., less than 3 years old (many of which have probably never spawned) and the relatively low number of large individuals in the catches.

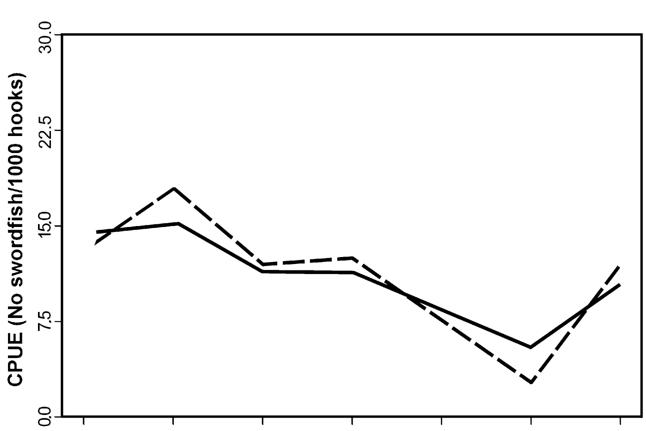

Fig. 9. Generalized additive model (GAM) standardized CPUE index of swordfish abundance (no swordfish/1000 hooks) as a function of Year compared with nominal CPUE as a function of Year (solid line: standardized CPUE, dashed line: nominal CPUE).

Intra-annual seasonality in catch rates was evident from the Month effect. Swordfish CPUE peaked during the start and end of the fishing period, and progressively increased after April (Fig. 7b). Stergiou et al. (2003), modeling and forecasting swordfish monthly landings in the eastern Mediterranean, ascribe the major summer peak to the higher fishing activity in summer, because of the prevailing favorable weather conditions, and the minor winter peak to the closed fishing season from October to January. Swordfish are known to exhibit rapid growth in their first year, reaching up to 90 cm of lower jaw fork length (∼15 kg) after 1 year (Ward et al., 2000). So, these peaks could be more realistically associated with the increased catches of juvenile swordfish (<age 2) that were born in June and July and began their recruitment during September and October (De Metrio and Megalofonou, 1987).

However, a more systematic examination of catches which incorporated supplementary aspects of the swordfish population like size, sex and maturity as well as possible migratory patterns and availability of food would clarify the temporal effect.

4.3. Spatial variables affecting catches

GAM analysis revealed that Longitude and Latitude were moderately explanatory for the nominal CPUE variance, with the area of increased abundance located in the Levantine basin (Fig. 8a and b). Certain latitudinal patterns – swordfish becoming more abundant in northern latitudes – have been described in the Pacific Ocean (de Sylva, 1962; Bigelow et al., 1999). According to Bigelow et al. (1999) this finding was ascribed to the presence of the Sub-arctic Frontal Zone in the northern Pacific plus the increased abundance of prey species during spring and summer. In the North Atlantic, swordfish adjust their spatial and temporal distribution according to their physiological needs, largely influenced by the latitudinal position of the path of the Gulf Stream, which in turn has been associated with temperature changes and abundant zooplankton (Mejuto, 2003). Commercial fisheries data suggest that swordfish are commonly found in certain thermal habitats and particularly along temperature fronts (Podesta et al., 1993). This behavior is thought to be a response to forage accumulation, migration cues, or spawning.

The Levantine has some unique oceanographic characteristics, operating as an "engine" producing the deep dense waters of the Mediterranean Sea. Light, less saline Atlantic waters enter along the surface. Due to strong evaporation exceeding precipitation and river runoff, these become more saline and denser. Denser water masses descend and are exported back to the Atlantic as Levantine Intermediate Water, which is the most important component in the large-scale circulation of the Mediterranean. A system of cyclonic and anti-cyclonic gyres and fronts is present, with the Rodos gyre and the Ierapetra anticyclone being the most distinct oceanographic features (Zervakis et al., 2005). Nitrogen to phosphorus ratios are anomalously high in these two areas (>40) and although generally characterized as oligotrophic, locally and temporally high phytoplankton biomasses have been detected which account for an enriched mesozooplankton community (Siokou-Frangou et al., 2005). The reason for this relatively enhanced production is the input of nutrients from the lower layers as a result of the deep vertical mixing and the physical processes described previously (Souvermezoglou and Krasakopoulou, 2005).

Swordfish are perhaps becoming more abundant in the Levantine during late spring–early summer due to an optimal habitat that favors spawning at an earlier time of the year (De Metrio et al., 1988; Tserpes and Peristeraki, 2000).

4.4. Environmental variables affecting catches

SST was the fourth most significant factor identified during the fitting procedure of the GAM analysis. The GAM plot of catches in response to sea surface temperature (SST) detected two temperature intervals (16–18 and >26 °C) where swordfish were more frequently caught (Fig. 7d). These findings are in agreement with the observations of other studies in the Atlantic and Pacific oceans. Nakamura (1985) reports highest CPUE values between 18–22 °C, Draganik and Cholyst (1987) at 18 and 27 °C, and Bigelow et al. (1999) between 15 and 18 °C. Sedberry and Loefer (2001), using satellite telemetry techniques, state that swordfish prefer average temperatures as low as 10 °C during daytime and of up to 28 °C at night. Santos and Miguel (2000), in a review of the literature studying the environmental impact on fish behavior, cite that 63% of these found a relationship with sea surface temperature. In Fig. 10, a combined view of how fishing effort and CPUE varied with temperature (SST) and time (Week of Year) grouped by 1 °C and 1 week cells, implies that although effort was not heavily biased in favor of higher SSTs (Fig. 10, top), catches were more likely to be larger near or above the average seasonal SST (Fig. 10, bottom). What is also apparent from the graphs in Fig. 10 is that the extent of seasonal temperature ranges varied, being small during the start of the fishing period (minimum 15 °C to maximum 17 °C) and broadened in mid-summer (minimum 17 °C to maximum 28 °C). So, the elevated catches during fall (corresponding to higher temperatures on average) can be attributed to the increased numbers of juveniles due to recruitment (De Metrio and Megalofonou, 1987). Juvenile swordfish are more proliferate (>30% of catches) in the Greek swordfish fishery just before and after the winter months. A convincing illustration from a recent study conducted during 1998–2000 in the same study areas as ours, can be seen in Fig. 11 (Megalofonou et al., 2001). Such findings led to a swordfishing ban by Greece in 1987 for the winter period in order to reduce fishing mortality on immature swordfish.

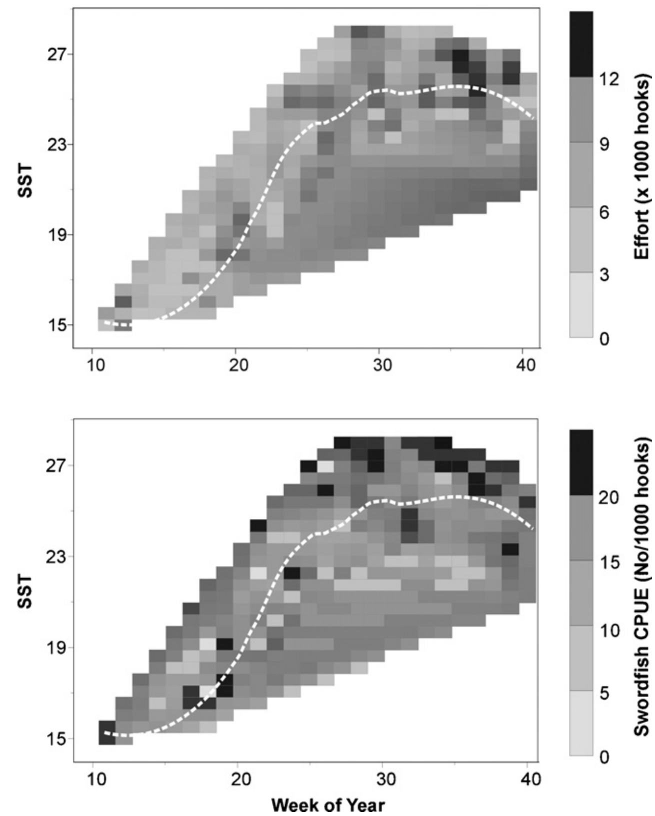

Fig. 10. Fishing effort and nominal CPUE in relation to week of year and SST. Each cell represents total effort or mean nominal CPUE by 1 °C and 1 week interval. SST annual trend is superimposed by a thick dashed white line.

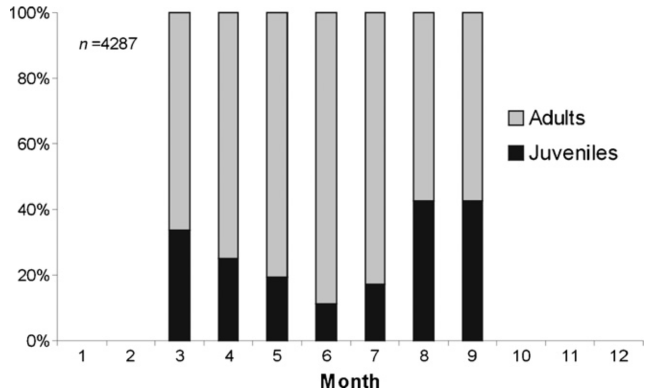

Fig. 11. Monthly percentages of juvenile swordfish in total catches of swordfish by the Greek fleet during 1998–2000 in the eastern Mediterranean Sea (taken from Megalofonou et al., 2001).

A more detailed analysis is required to fully understand the temperature effects including relating catches to certain features associated with SST such as thermal fronts, temperature gradients (thermal front energy) and isotherm movements (temporal change in SST).

Our analysis revealed that the Lunar index had an effect on swordfish, as the probability of catching a swordfish was positively correlated with the illumination of the lunar disc (Fig. 8c). Several authors provided similar findings investigating the influence of the moon on swordfish catches in the Atlantic and Pacific oceans (Draganik and Cholyst, 1987; Moreno et al., 1991; Bigelow et al., 1999; dos Santos and Garcia, 2005) as well as in the Mediterranean (de la Serna et al., 1992; di Natale and Mangano, 1995). Bigelow et al. (1999) postulated that lunar phases may in fact affect vulnerability to the fishing gear, since the fish either alter their vertical distribution or have more enhanced visual acuity.

Eastern Mediterranean swordfish appear to have a true pelagic nature, being more abundant in deeper waters away from the continental shelf (Fig. 8d). Carey and Robison (1981) suggested that swordfish responded to bottom topography and areas along the edge of the continental shelf were good places to find swordfish. Bigelow et al. (1999) partially confirmed this suggestion, observing a pronounced peak in catches in shallower waters, although catches at deeper waters were not insignificant. The latter has been attributed to the fact that the Hawaii-based swordfish fishery primarily fishes in a pelagic habitat. Sixty-six percent of our fishing sets were deployed in locations with bottom depths of >1000 m.

This study was an initial step towards understanding the effect of the environment on the Mediterranean swordfish population, which has been left out of the focus of the scientific community up to now. It was the first to examine how and to which extent environmental parameters affect the swordfish fishery of the eastern Mediterranean Sea, applying a generalized additive model analysis. The few studies so far (Tserpes and Peristeraki, 2003; Tserpes et al., 2003) dealt with the effect of area, time and gear applying linear models. We demonstrated non-linear relationships between swordfish catches in four of the significant factors studied. The eight variables included in the final model, ranked in order of their significance as follows: Fishing gear, Month, Year, SST, Longitude, Latitude, Lunar index and Bathymetry.

The outcomes of this study suggest that distribution and abundance of the eastern Mediterranean swordfish population was predominantly influenced by spatial and temporal factors, although significant associations with certain environmental parameters such as: SST, Lunar index and Bathymetry, were identified. However, it was clear that the study of certain oceanographic variables, such as SST, should be updated and studied in greater depth, as well as the partitioning of catches by sex and size will illuminate the effect of others such as: Latitude, Longitude and Month. Additional explanatory variables potentially exist such as salinity, primary productivity indices and prey abundance, which remain to be incorporated in the future.

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