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Title: A multi-model approach to evaluate the role of environmental variability and fishing pressure in sardine fisheries

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Abstract

Understanding the fluctuations in population abundance is a central question in fisheries. Sardine fisheries are of great importance to Portugal and are data-rich and of primary concern to fisheries managers. In Portugal, sub-stocks of *Sardine pilchardus* (sardine) are found in different regions: the Northwest (IXaCN), Southwest (IXaCS) and the South coast (IXaS-Algarve). Each of these sardine sub-stocks is affected differently by a unique set of climate and ocean conditions, mainly during larval development and recruitment, which will consequently affect sardine fisheries in the short term. Taking this hypothesis into consideration we examined the effects of hydrographic (river discharge), sea surface temperature, wind driven phenomena, upwelling, climatic (North Atlantic Oscillation) and fisheries variables (fishing effort) on *S. pilchardus* catch rates (landings per unit effort, LPUE, as a proxy for sardine biomass). A 20-year time series (1989-2009) was used, for the different subdivisions of the Portuguese coast (sardine sub-stocks). For the purpose of this analysis a multi-model approach was used, applying different time series models for data fitting (Dynamic Factor Analysis, Generalised Least Squares), forecasting (Autoregressive Integrated Moving Average), as well as Surplus Production stock assessment models. The different models were evaluated, compared and the most important variables explaining changes in LPUE were identified. The type of relationship between catch rates of sardine and environmental variables varied across regional scales due to region-specific recruitment responses. Seasonality plays an important role in sardine variability within the three study regions. In IXaCN autumn (season with minimum spawning activity, larvae and egg concentrations) SST, northerly wind and wind magnitude were negatively related with LPUE. In IXaCS none of the explanatory variables tested was clearly related with LPUE. In IXaS-Algarve (South Portugal) both spring (period when large abundances of larvae are found) northerly wind

and wind magnitude were negatively related with LPUE, revealing that environmental effects match with the regional peak in spawning time. Overall, results suggest that management of small, short-lived pelagic species, such as sardine quotas/sustainable yields, should be adapted to a regional scale because of regional environmental variability.

Key-words: *Sardina pilchardus*; time series analyses; catch rates; sub-stocks regional variability; recruitment hypothesis; ICES IXa sub-division

1. Introduction

Understanding the factors that control variations in population abundance is a central question in fisheries and is of particular importance to management. The search for environmental controls of recruitment has been an important component of fisheries research at least since the work of Helland-Hansen and Nansen (1909), Hjort (1914) and more recently Houde (2008). These early works have led to many hypotheses that are still discussed in the fisheries ecology literature, e.g. such as the phenological processes such as match–mismatch hypothesis (Cushing, 1975), mesoscale features, the optimal environmental window hypothesis (Cury and Roy, 1989) and the stable ocean hypothesis (Lasker, 1978), advocating that stable physical and biological ocean conditions, are important for the survival of young fish larvae and their future recruitment. These environment-fisheries scientific studies have been compiled and reviewed by Peck et al. (2013), who centered the work on discussion of the intrinsic and extrinsic factors driving match-mismatch dynamics during the early life history of marine fishes. More recently, recruitment or population variability in fish stocks have been explained by theories based on ocean-scale, long-

term climatic models of variability (Chavez et al., 2003; Rocha et al., 2013). In most marine systems and for many fish populations, relationships between environment and recruitment have been proposed, but they have often been contested or have failed when retested with new and longer sets of observations (see Myers, 1998). The multiplicity and complexity of the environmental controls limit our ability to adequately understand and model environment–recruitment relationships (Planque and Buffaz, 2008). Studies showed that a variety of environmental and oceanographic variables (local scale effects, such as SST) affect the same species (and or species stocks) differently across inter and intra geographical scales (Planque and Frédou, 1999; Ullah et al., 2012; Baptista and Leitão, 2014; Baptista et al., 2014; Teixeira et al., 2013). Variability in the distribution, abundance, and size of populations of pelagic fish may also in some cases be better explained by hydrographic properties, such as currents and geographical features of the coast and bottom (Checkley et al., 2009). The underlying mechanisms for population variability of small pelagic fish have also been described and discussed in regard to future climate variability (Bernal et al., 2007; Borges et al., 2003; Cury et al., 2000; Porteiro et al., 1996; Ramos et al., 2009; Silva et al., 2006; Lloret et al., 2004).

Sardina pilchardus is a well-studied commercially important small pelagic species with a distribution in the NE Atlantic from the North Sea to Senegal and throughout most of the Mediterranean Sea (Parrish et al., 1989). In Portugal *S. pilchardus* is the main target species of the purse seine fleet, contributing around 98% of the landings in division IXa (ICES WGHANSA, 2012). The area with the highest share of landings is the Northwest coast of Portugal (subdivision IXa – Central North). Although the broad seasonal pattern of spawning activity is the same across regions, differences in the intensity and duration of spawning are observed in all Portuguese ICES IXa sub-division (Stratoudakis et al., 2003). The spawning

season for sardine in the western and southern Iberian Peninsula is long, with a single peak that shifts from a spring to a winter maximum with decreasing latitude. Further south (central and southern Portugal), the high probability of spawning activity starts earlier (October/November–Autumn) and extends to April, leading to a wider spawning period. Such biological differences are associated to different environmental condition in spawning grounds. According to most theoretical expectations, sardine spawning is driven locally by the seasonal cycle of water temperature, assuming preferences for spawning at 14–15°C and avoidance of temperatures below 12°C and above 16°C, with spawning tolerance to higher temperatures progressively increasing with decreasing latitude. However, it is not only temperature that influences spawning behaviour. Sardine major spawning events take place outside the upwelling season (Santos et al 2007). This discrepancy could be an adaptive mechanism for avoiding offshore transport in upwelling areas (advection effect) and associated loss of larvae from the coastal habitat (Parrish et al., 1981).

S. pilchardus studies on the linkages between sardine early life history stages, recruitment and fisheries are numerous, but are mostly concentrated on the Iberian northwest coast and the Bay of Biscay and do not consider analyses of environmental drivers on a regional scale (Silva et al., 2009; Santos et al., 2001, 2005, 2007; Garrido et al., 2007, 2008; Chicharo et al., 1998; Borges et al., 2003; Chicharo et al., 2003). In fact, most studies related to environmental driver effects on sardines deal with metadata (e.g. ICES division or stock analyses) rather than subdivision (sub-stock) analyses. *S. pilchardus* is suggested to be particularly sensitive to sea temperature changes (Coombs et al., 2006) and recruitment success was also related to offshore wind, wind mixing, river flow and NAO (Lloret et al., 2004; Porteiro et al., 1996; Santos et al., 2005; Solari et al., 2010). In Portugal, several factors have been reported to influence *S. pilchardus* recruitment and

abundance. For instance, in the Northwest coast of Portugal, the survival of *S. pilchardus* larvae has been associated with the timing and intensity of upwelling events and the related sea surface temperatures, with different response of sardine to oceanographic conditions varying according to season (Santos et al., 2005). Sardine stocks are generally associated with upwelling systems and upwelling is one of the main environmental drivers of sardine abundance in the world oceans (Lluch-Belda et al., 1992; Santos et al., 2001, 2007, 2012; Cury et al., 2000; Checkley et al., 2009).

Fisheries stock assessment involved as it is with the analysis of large population units, has not focused on local level phenomena, such as the changes in behavior and distribution of local populations associated with the collapse of a stock that are so often described by fishermen. The focus of fisheries science on system-wide characteristics has left it without historical parameters that allow the interpretation of fine-scale changes in stock distribution, behavior, or migration patterns over time. Consequently, management has lacked the ability to detect or interpret fine scale changes in abundance (Ames, 2001). In this work we analysed the effect of environment drivers on Iberian sardine sub-populations, under the assumption that sub-stock components of small pelagic fish species exhibit different life history traits and thus can show differences in productivity and vulnerability to fishing pressure (Harma et al., 2012) and environmental conditions (Santos et al., 2005, 2007; Cury et al., 2000; Checkley et al., 2009; Porteiro et al., 1996; Santos et al., 2005; Solari et al., 2010).

Although Hjort's pioneering work has stimulated research on recruitment for a century, and despite the number of available theories and hypotheses proposed to relate inter-annual fluctuations in fish abundance to variations in environmental conditions, it appears that environmental controls on fisheries are likely to exist but the factors are difficult to identify,

numerous and their respective importance may change with time (Myers, 1998). To elucidate the relative importance of hypotheses about environmental drivers control, a multi-inference model and information theoretic approach may be used (Hilborn and Mangel, 1997; Johnson and Omland, 2004; Loots et al., 2010). Such an approach allows successfully comparing several models reflecting various hypotheses of control over LPUE (landings per unit effort as a proxy of biomass) and including the model accuracy based on model predictions and observations. Hypotheses underlying the selected set of reasonably good models can thus be inferred to represent the dominant controls (Loots et al., 2010). In fact, even the same data tested with different model approaches may show different results that are open to discussion. Therefore, data analyses should try to isolate each hypothesis (regional and seasonal) from the others, for the sake of clarity, and mainly because it is only when the hypotheses regarding the effect of explanatory variables on response variables are clearly and strictly defined that they can be discussed and challenged in an objective manner (see Planque et al., 2011). Otherwise we could come out with several candidate hypotheses for interpreting the observed patterns of explanatory variables over the response variables (catch rate trends). The present study aims to identify the dominant environmental and fishing control factors influencing sardine landings in the different oceanographic divisions of the Portuguese coast using a multi-model approach. Data was lagged according to sardine fishing recruitment age under the assumption that fisheries catch rates depend on larvae recruitment.

2. Material and Methods

2.1. Study area

The effect of climatic variability and fishing pressure on sardine catch rates was evaluated across three biogeographic areas off the Portuguese coast with distinct oceanographic regimes (Bettencourt et al., 2004; Cunha, 2001): the northwestern, southwestern and south Atlantic coast of Portugal (Fig. 1). The three areas match the ICES IXa subdivisions areas for Portugal and hereafter will be designated as IXaCN (North coast), IXaCS (South coast) and IXaS-Algarve (Algarve coast).

2.2. Sardine data (response variables)

Landings and fishing effort monthly data from 1989 to 2009 were obtained from the Portuguese Direcção Geral das Pescas e da Aquicultura (Directorate-General of Fisheries and Aquaculture – DGPA). These data include monthly detailed information regarding the sardine fishery, namely effort and landed catches per boat (kg), for each fishing port along the Portuguese coast. The landings and effort data by boat and port were pooled (cumulative contribution) into three distinct areas (Fig.1), IXaCN, IXaCS and IXaS-Algarve. Monthly and yearly landings per unit effort (LPUE) were estimated dividing the total landings per year/month by the total number of fishing events of the year/month (LPUE units: kg per fishing day/event). Herein, LPUE is considered a proxy of sardine biomass production or a biomass index based on landings.

2.3. Explanatory variables (environmental and fisheries data)

The information on yearly river discharge (RD), January–December, was used for testing the effect of hydrology on catch rates and consisted in the cumulative monthly contribution

(discharge volumes in cubic decameters, dam^3) of the main Portuguese rivers or Basins (Fig. 1), including i) IXaCN (North coast: Cávado, Lima, Douro, Vouga, Mondego, ii)), IXaCS (South coast): Tejo, Sado, Mira and iii) IXaS-Algarve (Algarve coast) Guadiana river and minor inputs from three smaller river systems (Seco, Alportel and Almargem). The monthly hydroclimatic series of freshwater that is discharged into coastal areas was collected from the Instituto Nacional da Água (INAG, Portuguese Institute of water - online data base, SNIRGH: <http://snirh.pt/>). All data were collected from the same hydrological stations located nearest the coast.

A coastal Upwelling index (Units: $\text{m}^3/\text{s}/100\text{m}$ of coastline), calculated based on Ekman's theory of mass transport due to wind stress, was obtained from the Pacific Fisheries Environmental Laboratory (PFEL web page: <http://www.pfeg.noaa.gov>). The average annual Upwelling (UPW) index was estimated based on the monthly average. Upwelling data were obtained for each fishing port and averaged for each subdivision and for the entire coast.

Monthly satellite data on easterly (u) and northerly (v) wind components (m/s) was derived according to Atlas et al. (2011, <http://podaac.jpl.nasa.gov>). The geostrophic wind satellite data is broken into its two horizontal components. The "u" component represents the east-west component of the wind while the "v" component represents the north-south component. The vector geostrophic wind velocity from satellite data is expressed with two components: the East-west component is u (positive for flow from west, westerly) and the North-south component is v (positive for flow from south, southerly). The latter wind components were used to estimate the wind magnitude [WMag: $\text{SQRT}(u^2 + v^2)$] that was used in the statistical models in addition to both wind u and v data.

Sea surface temperature (SST) data were obtained from summary imagery data obtained from Modis-Aqua 4km satellite available on the NASA Ocean Color Giovanni website, (<http://gdata1.sci.gsfc.nasa.gov>). To cope with the lack of some satellite data (cloud effect) close to the shore, the coastal oceanographic data considered the range of depths from the Mean High Water Line to territorial sea limits per port jurisdiction (Fig. 1). SST, UPW and wind related variables data were averaged for each geographic area.

The North Atlantic Oscillation (NAO) often influences other environmental conditions in the North Atlantic, such as wind strength, precipitation, strength of westerly winds, SST, salinity and wave height (Hurrell, 1995; Brunel, 2007). Because it indirectly affects other oceanographic and environmental variables, both the NAO and the NAO winter (December–March) indexes were compiled (<http://www.cgd.ucar.edu/jhurrell/nao.html>, last accessed 2010; Hurrell, 1995).

The fishing effort (FE) estimator for sardine was the total number of fishing events and/or fishing days and was also grouped by area.

2.4. Data analyses

2.4.1. Experimental design and assumptions for modeling

Recruitment of small pelagic and most marine fish (Cushing, 1975) is highly variable and does not relate clearly to the abundance of the parental stock (spawning stock biomass) because of (among other factors) high and variable rates of mortality during the early life stages, which are thought to be strongly affected by environmental processes (Santos et al., 2012). *S. pilchardus*

exemplifies the life history strategy of small pelagic fish around the world, with a short life, fast growth, high fecundity and long spawning season extending over the whole year (Stratoudakis et al., 2007). For the purpose of this study we assumed that sardine larvae are highly sensitive to environmental changes and that larval mortality rate will affect fish recruitment to fishery and consequently affect sardine biomass in the short term. *S. pilchardus* is a short-lived species, commonly reaching maturity at the age of one year old (99%), with most sardines being caught during the first year of life (ICES WGWISE, 2012). Since sardines recruit to the seine fishery in the 1+ year class, environmental variables with the lag of one year were also included in the analyses.

Synchronous effects of more than one variable were tested in the models to evaluate the relationship with LPUE. We always started with simple models and if more than one variable was significant, these variables were combined. Given the different environmental conditions of each of the three areas, we postulated that at any given time, the survival rate of larvae will vary according to local or regional seasonal environmental marine conditions. The seasons considered were winter (Win), spring (Spr), summer (Sum) and autumn (Aut) with: (1) winter (January to March); (2) spring (April to June); (3) summer (July to September); and (4) autumn (October to December).

For statistical purposes the landings per unit effort (LPUE) was the explanatory variable while effort and environmental variables were the response variables. We decided to include fishing effort (FE) in the models as an explanatory variable after collinearity between LPUE and FE was

tested with pairs plots and was found to be absent (correlations between sardine LPUE and FE: IXaCN = 0.04, IXaCS = 0.36, IXaS-Algarve = 0.40).

2.4.2. Time-series analyses (statistical models)

All data series were first tested for normality (Quantile-Quantile plots -QQ-plots) and collinearity (pairs plots) following Zuur et al. (2010). In the case of both yearly sardine LPUE and explanatory variables no transformation was applied. Since collinearity occurred between yearly northerly wind (VW) and wind magnitude (WMag), these variables were not combined in the same model.

A multi-model approach was used including Dynamic Factor Analysis (DFA), Generalised Least Squares (GLS), and Autoregressive Integrated Moving Average (ARIMA) models. Models were used to evaluate the importance of different environmental variables on LPUE rather than to forecast LPUE. Thus, results of the fitting and prediction models should be regarded as complementary. Since different analyses might reveal different results, a selection criterion (decision-tree) was adopted, aiming to highlight those variables with higher probability of explaining changes in LPUE. The best candidate variables were model-based and probability was defined according to the number of models that highlighted the same explanatory variable. This simple selection criterion allows classifying the variables with high (the variable is highlighted in more than one model) or low probability of affecting LPUE.

Dynamic Factor Analysis (DFA)

Trend analyses of the effect of environmental and fishing variables on catch rates of *S. pilchardus* were done independently for each region, by means of Dynamic Factor Analysis (DFA), a multivariate technique that can be used for non-stationary time series analysis, to estimate underlying common patterns, evaluate interactions between response variables (LPUE) and determine the effects of explanatory variables (environmental and fisheries variables) on response variables (Zuur et al., 2003a, 2007). A separate DFA univariate time series model/analysis was used for each region in order to account for the different environmental conditions and spatial independence among regions (Ullah et al., 2012; Baptista and Leitão, 2014; Baptista et al., 2014). Models were fitted with a diagonal covariance matrix and the Akaike's information criterion (AIC) was used to compare models. The t -values resulting from estimation of regression parameters were used to indicate either a positive or negative relationship between explanatory variables and the response variable (t -values with an absolute value greater than 3 indicate a strong relationship). DFA analyses were carried out using the Brodgar software package (<http://www.brodgar.com>). Both response and explanatory variables were standardized before running the DFA models as advised by Zuur et al. (2003a,b). The standardisation method used for converting data into the same dimensional scale was normalisation, that consists in centering all variables around zero ($X_i = (Y_i - \hat{Y}) / \sigma_y$), where \hat{Y} is the sample mean, Y_i the value of the i th sample and σ_y the sample standard deviation.

Generalised least square (GLS)

A prerequisite for basic linear mixed-effects models is often an independent random distribution of the within-group errors and a constant variance (Zuur et al., 2007). As in fisheries time-series

this is likely not to be the case, the univariate statistical method GLS is a strong method to use. GLS is an extended linear mixed-effect model in which errors are allowed to be correlated and/or have unequal variance (Lloret et al., 2001; Pinheiro and Bates, 2000). Several GLS models were applied without autocorrelation and with an autoregressive process imposed on the error components that allows errors to have unequal variance (Zuur et al., 2007). Thus, errors were specified to follow an autoregressive process of degree 1 or p that was determined using the partial autocorrelation function and the goodness of fit of an ARMA model. The correlation structure of the errors, autoregressive process of order 1 was used, as it is applicable to most regular spaced datasets (Zuur et al., 2007), assuming that the autocorrelation is highest between following years. Alternatively, a continuous autoregressive process was applied. Therefore, the GLS models with and without different autocorrelation structures were compared using the lowest AIC as the decision criterion and only the best GLS models are presented. For the explanatory variables a significance level of $p < 0.05$ was used. Herein, the strength of the relationship in GLS, between the explanatory and response variables, is evaluated by the value of the slope (the mean amount of change in LPUE when environment variables increase by 1 unit).

Multivariate autoregressive integrated moving average (ARIMA)

ARIMA is a standard time series method, which is based on the assumption that the time series is stationary. In time series data that is measured monthly, the main part of the variation may be related to seasonal fluctuation. The seasonal decomposition procedure removes periodic fluctuations from time series, such as annual or seasonal highs or lows. It is used primarily as a preliminary tool when attempting to analyse trends in such series (Prista et al., 2011). Thus prior

to ARIMA a set of pre-analyses of the data were done. To visualise the general pattern in the LPUE time series, the time series were decomposed by a LOESS smoother (Cleveland, 1993) into trend, seasonal and irregular components (as required for ARIMA). All the LOESS curves show a cyclical pattern, which is also captured by the mean value of the smoothing curves.

ARIMA models were fitted using the IBM SPSS Expert Modeler tool (IBM SPSS, 2011). This available tool automatically estimates the best-fit ARIMA model and allows incorporating explanatory variables. Only the best candidate explanatory variables are shown in the final model. The Expert Modeler routine for forecasting time series analyses tests the best potential transformation for the data. Examination of the autocorrelations and partial autocorrelations of the time series is therefore used by the Expert Model time series analyses toolbox to determine the underlying periodicity. To cope with outliers data errors were also considered to be additive, thus not providing a constant seasonal component along all the time period and thus preventing the analysis of its evolution. The stationary R-squared value was used as the measure of goodness of fit. In addition, the residuals of the ARIMA models were also used as a proxy of model fitness and the Ljung-Box statistic, also known as the modified Box-Pierce statistic, was used to indicate whether the model with explanatory variables is correctly specified ($P > 0.05$).

Surplus production models - SPM

Conventional Surplus Production Models are fitted to the data without any environmental variables. However, for relatively short-lived species, the models often do not give adequate fits. The CLIMPROD (Fréon et al., 1993) software allows including biological information as well as one environmental variable in the models. The *S. pilchardus* time series were analysed using

annual landings and FE plus one environmental variable at a time. The selection of the environmental variable to include in the models was based on the results of the other model approaches (DFA, GLS, ARIMA). The purpose of SPM analyses was to understand how the fisheries landings are affected by both fishing effort (E) and environmental variables (V). The models that include one environmental variable (V) were compared to the initial conventional models without environmental explanatory variables. Different type of models are provided in CLIMPROD: i) Conventional models $LPUE = f(E)$; ii) Simple regression models $LPUE=f(V)$; iii) Mixed models affecting abundance $LPUE=f(E, V)$. Different SPM conventional models, $LPUE = f(E)$, were initially fitted directly to the FE data. Thereafter, for the application of the mixed models (with environmental variables) it was assumed that the environmental variables influence the abundance (LPUE) rather than the catchability of the gears. The best model was selected according to the highest R^2 value. A cut-off value of $R^2 > 40\%$ is proposed by CLIMPROD software for the model to be accepted.

3. Results

3.1. Trends in environmental variables

The environmental variables for the time period 1989 to 2009 clearly show differences among subdivisions (Fig. 2; the mean seasonal environmental variables values are presented in Table 1). Area-independently, clear positive anomalies were observed in the years 1996-1997 for the variables RD, SST, UW and VW. At the same time negative anomalies were recorded for NAO. RD peaked in 1996-1997 for all areas (Fig. 2a). In IXaCN and IXaCS a second peak can be observed in 2001, namely at IXaCN reaching higher values than in 1996. In IXaS-Algarve minor

oscillation in RD, below the mean, were observed from 1999 to 2009. For SST, negative anomalies were recorded between 1991 and 1995, thereafter remaining around the mean, with the exception of two peaks above the mean in the year 1997 and 2006 (Fig. 2b).

The NAO index shows positive anomalies until 1995, declining markedly thereafter with a negative peak in 1996 (Fig. 2b). Afterwards the NAO index oscillates around and below the mean. In subdivision IXaS-Algarve the upwelling index increases until it peaks in 1996, afterwards declining until 2001 to negative anomalies. For IXaCN and IXaCS upwelling values oscillate around the mean, dropping in 1997 and peaking afterwards in 1998-1999, 2006 and 2008 (maximum values), while reaching the lowest values in 2002 in IXaNC. The upwelling values increase steadily from negative to positive anomalies in all areas after 2002 (Fig. 2c).

The trends of UW show an increase until 1996 to positive anomalies (westerly winds increase). After 2005 an increase in UW was recorded (Fig. 2d). The VW trend is oscillatory, with the largest negative anomalies in 2008 (southerly) (Fig. 2e). The wind magnitude also oscillates around the mean, peaking in 2008 to higher positive values (Fig. 2f).

3.2. Trends of *S. pilchardus* LPUE and fishing effort

In IXaCN LPUE values dropped below the average after 1995 (Fig. 3.a). In IXaCS an oscillatory LPUE trend was observed with an increase of values between 1990 and 1995, declining in 1999-2000 and peaking again in both 2003 and 2009. The lowest LPUE values in IXaCS were recorded between 1989 and 1991, at the beginning of the time series (Fig. 3.a). In IXaS-Algarve *S. pilchardus* LPUE peaked in 1996, decreasing thereafter over time with LPUE values dropping below the mean in 2000 (Fig. 3a). A clear decline of FE is observed over time for the three areas

(Fig. 3.b). The FE declined until the mid 90s, peaked in 1998 and declined thereafter, reaching values below the mean after 2001.

For all the areas a clear seasonal LPUE trend is shown (seasonal trend of LOESS after seasonal decomposition, Fig. 4). In general, the monthly LPUE data for the different areas follow a similar trend to that observed for yearly data (Fig. 3a).

3.3. Effects of explanatory variables

The explanatory variables that were found to be significantly related to *S. pilchardus* LPUE by each model approach (DFA, GLS, ARIMA and SPM) are given in Table 2. In Appendix 1 all numerical data is provided regarding each model results.

Portuguese Northwest coast (IXaCN)

A combined model with the autumn variables (SST, VW, WMag) resulted in the best DFA model (Table 2). In the latter DFA model the SST was negatively related with LPUE while wind magnitude (WMag) and northerly wind component (VW) were positively related with LPUE. For IXaCN the GLS analyses gave similar results, with SST-autumn and VW-autumn both being negatively related to the LPUE, while WMag-autumn and NAO-winter are positively related to the LPUE. ARIMA highlighted SST, NAO, VW and WMag as significant predictors of LPUE. The seasonal ARIMA revealed that UPW-spring and SST-summer were significant predictors of LPUE (Table 2).

Overall results of all model approaches for data fitting (DFA, GLS) and predictive models (ARIMA) results showed that SST and SST-autumn have high probability of being negatively related to *S. pilchardus* LPUE time series. SST was also shown to greatly increase the model fit of the SPM. Other environmental variables that were highlighted by most of the models to be strongly related to sardine trends in IXaCN were the northerly wind component (VW-autumn) and the wind magnitude (WMag-autumn).

Portuguese Southwest coast (IXaCS)

According to the DFA models only NAO-winter was found to be positively related to the *S. pilchardus* LPUE time series. The GLS models indicates a significant negative relationship between FE and LPUE while UW and SST-autumn are positively related to the LPUE. SST and UPW were found to be significant ARIMA predictors. Additionally, SST-spring and SST-summer were significant LPUE predictors in the seasonal ARIMA models.

For the Southwest coast, the present multi-models selection approach found none of 8 explanatory variables identified by individual model-based analyses to have a high probability to be related with *S. pilchardus* trends (no variable is related in more than one model with the LPUE).

Portuguese South Coast (IXaS-Algarve)

According to DFA, the northerly wind component (VW and VW-Spring), NAO and RD were negatively related with sardine LPUE trends. WMag (spring and summer) and FE were positively related to the LPUE. The best DFA model includes both VW-spring and WMag-spring

(Tab. 2). For the GLS analysis LPUE is positively related to the FE, the westerly wind component (UW-summer) and WMag (WMag-summer and WMag-winter), while VW-spring is negatively related to the LPUE. For ARIMA, SST, RD and WMag were significantly related to LPUE. When testing ARIMA models with quarterly environmental data, three significant models were observed with all models including SST. The first model includes SST-spring, the second SST-autumn and NAO-autumn and the last SST-winter as LPUE predictors. In IXaS-Algarve the SPM models without environmental variables resulted in a good model fit, above the threshold ($R^2=42\%$). All the variables that have been highlighted at least once as significant for DFA, GLS or ARIMA also increased SPM fitness. The best SPM model predictions were achieved with WMag-summer ($R^2=71\%$), WMag-winter ($R^2=71\%$), VW-spring ($R^2=61\%$) and SST-autumn ($R^2 = 56\%$, Appendix 1).

Overall for DFA, GLS and ARIMA, 3 variables, FE, WMag-summer and VW-spring were significantly related to the LPUE in more than one model, suggesting high probability of a relationship with *S. pilchardus* LPUE.

4. Discussion

The results of this study show that *S. pilchardus* LPUE along the Portuguese coast are affected by different factors that underlie regional and seasonal differences. Since different statistical methods indicate that different environmental variables affect LPUE, herein we concentrate the discussion on variables that were selected in more than one model (high probability of influencing LPUE). As SPM, without explanatory variables, with the exception of IXaS-Algarve were not very convincing (low R^2) in explaining relationships between the LPUE and FE, SPM results were not considered for the multi-model approach. Nevertheless, overall the SPM results

clearly showed that by adding environmental variables the amount of variability predicted by the models can increase significantly (see appendix 1).

Northwestern coast (IXaCN)

In IXaCN a/the change in the sardine trend in the autumn season was related to SST and both VW (northerly wind component) and wind strength (WMag.). Autumn corresponds to the season when minimum spawning activity is recorded (Stratoudakis et al., 2003). So results indicate that even in low activity periods and/or larval availability, environmental variability can be detrimental to sardine fishing recruitment to fishery in the following year (data was lagged 1 year).

Southerly and southwesterly winds dominate off the NW Iberian coast from October to March (Relvas et al., 2007), helping to develop the Iberian Polward Current (IPC), which is related to the generation of convergence zones over the shelf (Frouin et al., 1990) that can act as retention areas for eggs, larvae, and their food (Santos et al., 2001, 2005, 2007). However, we cannot exclude that detrimental effects on recruitment can also occur during the juvenile phase due to school-mix feedback, predator pit (Bakun et al., 2010). Nevertheless, off the Northern Portuguese coast, spawning is mainly restricted to the coastal continental shelf (Cunha et al., 1989). In autumn, the northerly wind (VW), causing coastal upwelling, is negatively related to LPUE. Thus, VW winds blowing towards the south, parallel to the Portuguese west coast can indirectly cause an offshore transport of surface waters, which can lead to an unfavorable dispersion of *S. pilchardus* eggs and larvae (Kohut, 2002; Santos et al., 2001). Upwelling events and mesoscale features regulate offshore transport and retention of fish eggs and larvae in

various areas of the Mediterranean and Iberian coast and can thus determine recruitment success (Santos et al., 2004; Santos et al., 2007; Lafuente et al., 2005). In fact, this mechanism is likely to occur since Borges et al., (2003) found that during winter (when sardine spawning season activity is also high), northerly winds that favour upwelling led to unfavorable conditions for egg and larval survival in IXaCN

In this study autumn wind magnitude (WMag) was found to positively affect *S. pilchardus* LPUE, mostly at the Northwest coast. Here, the wind magnitude can be related to wind mixing, generating turbulences and thus leading to nutrient input in surface waters (Cury and Roy, 1989). Wind mixing can lead to a higher nutrient concentration in the upper water column, enhancing plankton growth and hence providing better feeding conditions for *S. pilchardus* larvae (Silva et al., 2006). Consequently, as already suggested by (Lloret et al., 2004), wind mixing can be positively correlated with *S. pilchardus* spawning, as feeding conditions are of major importance for larvae and determine the survival and recruitment success (Chícharo, 1998; Palomera et al., 2007). Such a mechanism is likely to occur as studies report high sardine larval condition, and potential survival, during winter upwelling in the northwest coast of Portugal. In fact during winter the upwelling plume (Western Iberian Buoyant Plume) is advected offshore within a shallow Ekman layer and interacts with the slope-current. This induces meridional elongation and retention close to the upper slope, in this process, low mixing with offshore mixed-water layers due to stratification, guaranteeing the conservation of static stability to a level necessary for phytoplankton growth, high copepod egg production and vertical retention of sardine larvae in excellent nutritional condition (Chicharo et al. 2003).

Moreover, it was found that the SST (SST, SST-autumn) is strongly negatively related to the LPUE at the IXaCN. *S. pilchardus* spawning activity is temperature-dependent, with an optimum

range at the Portuguese coast between 14 - 15°C (Coombs et al., 2006). Along the Portuguese Northwest coast, the yearly mean SST in the studied time series (1989-200) varied between 15.25 – 17.21 °C, being highest in summer (18.34°C). If the temperature is likely to be at the upper limit or above the optimum for *S. pilchardus* spawning, such as in autumn (>16°C) when spawning is likely to start, then sardine spawning can be affected. A similar negative relation between changes in mean SST during spawning season (winter) and *S. pilchardus* biomass was also reported for the South Catalan Sea (Palomera et al., 2007).

Southwestern coast (IXaCS)

The multi-model approach did not identify any variable to be clearly related to LPUE. According to Najjar et al. (2000), the impacts of environmental variables on coastal regions will have a regional signature. IXaCs comprises an area between the North (cool and rough sea conditions) and South (fair and warm weather, with Mediterranean influence), with both the latter representing the max./min. limits of many of the environmental variables (e.g. SST). For instance the Iberia Poleward Current mostly affects the Northwestern coast, from Cabo da Roca to Vigo, effecting local oceanographic conditions and fisheries yield (Sherman, 1994). An important consideration in this study was the extent to which regional landing profiles were affected by the same environmental variables. For instance, ARIMA highlighted SST in spring and summer to be related to LPUE in IXaCS, but the sign of the effect of explanatory variables was contradictory. Therefore, variations in sardine catches seemed determined by seasonal upper and lower environmental regional limits. Regional temperature changes have been observed to have an inverse effect on Atlantic cod populations, with recruitment being linked to inter-annual fluctuations in temperature in such a way that there is a negative relationship between stocks and

warm water and a positive relationship between stocks and cold water, and no discernible relationship for stocks located in the mid-range of the temperatures (Planque and Frédou, 1999).

For the Southwest coast very nearshore distributions of sardine larvae were more frequently observed than in other coastal areas (Borges et al., 2007). So the "member vagrant" hypothesis (Sinclair 1998) and especially the "Ocean triads" (Agostini and Bakun, 2002) hypothesis, where larvae fate depends on: a) enrichment processes- upwelling, mixing, buoyant plumes; b) concentration processes- convergence, frontal formation, water column stability; c) retention processes within, or drift towards, appropriate habitats, may determine recruitment success. These theories may be used to explain the results, because retention in more productive habitats very close to the shore is less dependent on offshore coastal oceanographic features.

Algarve Coast (IXaS-Algarve)

In the South coast, spring conditions were relevant for *S. pilchardus*, matching with the regional peak in spawning (Stratoudakis et al., 2007). In IXaS-Algarve, the northerly wind in spring is negatively related with *S. pilchardus* LPUE. In a region of wind-induced coastal upwelling, the relationship between recruitment success of pelagic fish and the intensity of upwelling is likely to be dome-shaped (Cury and Roy 1989). In the Algarve coast, however, the dome-shaped association with sardine is not found (Reis et al., 2001). Here, upwelling frequency and turbulence reach significantly higher values in spring than in summer, when eggs and larvae are very abundant (Ré et al., 1990). The dynamics of the subtropical front and the Azores high-pressure center (Dias et al., 1996) lead to the intensification and steadiness of northerly winds along the west coast between July and September, and westerly winds off the Algarve coast

between April and August. This suggests that recruitment in the Algarve coast may be defined primarily by the occurrence of calm weather conditions during spring, which can explain why northerly winds negatively affect catch rates. Extreme turbulence and mixing of the surface layer can disperse food and larvae patches, thereby increasing mortality rates (Peterman and Bradford 1987). This results are in agreement with the “Stability of water column” hypothesis (Lasker 1975) for coastal upwelling areas, where it is hypothesized that relaxation of storm winds and intense upwelling results in a stable, vertically stratified ocean, where fish larvae and their prey coincide, promoting larval nutrition and survival.

As indicated by the results of the multi-model approach for *S. pilchardus* larvae, the impact of wind magnitude is highest in summer, when the water column is homogenous and nutrients only become available at the surface when induced by strong winds (Salat, 1996). Therefore, in the Algarve, the wind magnitude in summer, when calm sea conditions prevail, can be related to wind mixing, generating turbulence that leads to a nutrient input in surface waters (Cury and Roy, 1989). Wind mixing allows a higher nutrient concentration in the upper water column, enhancing plankton growth and hence providing better feeding conditions for *S. pilchardus* larvae (Silva et al., 2006) and consequently wind mixing can be positively related with *S. pilchardus* (see also Lloret et al., 2004).

On the South coast, the FE was positively related with LPUE of *S. pilchardus*. Portugal joined the EU in 1985 and since this period ICES group have been responsible for assessment of sardine. In the last two decades reductions of FE have been advised (ICES WGWIDE, 2012). The trend in FE is similar across areas, with a decrease over time. Such results might suggest that during the time of this study control measures have kept the FE at a level allowing environmental variables to become a significant cause for sardine variability. In fact, FE was only identified to

affect sardine LPUE (lag 1 year) in IXaS-Algarve, the region of Portugal with the strongest decline in sardine (lowest spawning stock biomass), due to lower recruitment and a low spawning biomass, particularly since 2006 (ICES WGWIDE, 2012).

General remarks

Overall, wind conditions in spring (when larvae abundance is higher) and autumn (when larvae abundance is lower) are related with *S. pilchardus* catch rates. Yearly peaks in sardine recruitment are generally found in winter (1985–2000; Stratoudakis et al., 2003) but general models did not identify seasonal relationships in this season to be detrimental to sardine fisheries. Other studies showed that *S. pilchardus* recruitment is linked to local winter wind conditions that can have both positive and negative effects on larvae survival (Santos et al., 2011; Porteiro et al., 1996; Ramos et al., 2009) and recruitment of pelagic species (Bakun and Parrish, 1991; Lloret et al., 2004), suggesting that larvae survivorship is closely related to vertical mixing and, consequently, to wind stress as a contributing mechanism to fisheries. Strong changes in the yearly relative proportion of spawning components can be observed in small pelagics (Harma et al., 2012). This suggests that life-cycle diversity in herring stocks and other small pelagics (such as sardine) may confer resilience to potential climate-induced changes.

Upwelling intensity can affect *S. pilchardus* recruitment off the NW Iberian Atlantic both positively (food availability) and negatively (larvae offshore transport) . The UPW impact is likely to depend on the exact timing, intensity and frequency of upwelling events (Santos et al., 2001). In this study UW and VW were related to LPUE. Wind conditions affect UPW, but the UPW index itself was not related to the *S. pilchardus* LPUE. Such findings highlight the

importance of the use of different variables while searching for environment-fisheries relationships.

However, contradicting several studies on the importance of river discharge for coastal small pelagics, no relationship was found between sardine trends and river discharge in any sub-division. The effect of terrestrially enriched river discharge seems to be most noticeable in oligotrophic seas (Lloret et al., 2001) and in semi-enclosed systems (Daskalov, 1999), favorably influencing biological processes (i.e. growth, survival and recruitment) and fisheries production (Grimes, 2001; Lloret et al., 2004) rather than in open coastal Atlantic waters, such as the Portuguese west coast. However, in nearshore areas where higher larvae productivity occurs (such as in IXaCS) attempts to explain catch rate variability (LPUE), due to recruitment, with oceanographic conditions fail. That is, favorable and somewhat stable physical and biological ocean conditions are less relevant for fluctuations in sardine populations in areas where larvae are spawned in inshore coastal areas, and are therefore less dependent on coastal oceanographic features dynamics.

Despite oceanography studies that separate Portuguese coast according to hydrological characteristics, fisheries data collection, advice and management have traditionally been based on a single-stock basis (ICES WGwide, 2012). Since 2012 sardine quotas have been established, that are distributed according to producers' organizations (DRMA, 2012). FE has been reduced since the early 90s across areas, following ICES advice, but in IXaS-Algarve sardine biomass has declined at a higher rate than in IXaCS and IXaCN (ICES WGwide, 2012). The evaluation of the impacts of environmental change on exploited stocks is crucial for adequate management of the fisheries sector and for the conservation of resources and the marine ecosystem since this is known to be one of the main causes of sardine variation rather than FE.

Improved knowledge on environmental-fisheries interactions and their integration into stock-assessment models can increase our ability to manage resources more successfully. Although SST along the Portuguese coast is increasing, UPW intensity and wind are decreasing, but distinct trends across regions are predicted (Santos and Miranda, 2006), being more marked at the South-Algarve coast (IPCC, 2001). Therefore, management of small short-lived pelagic species, such as sardine quotas/sustainable yields, under the scope of climate variability, should be adapted to a regional scale.

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Tables and Figures

Figure 1. Location of the rivers and main ports (large circles) and secondary ports (small circles) from the three ICES IXa sub-regions where sardine is fished. The dashed area along the coast represents the territorial sea (12 nautical miles).

Figure 2. Standardised time series of the yearly environmental variables, River discharge (a), sea surface temperature - SST and North Atlantic Oscillation -NAO index (b), Upwelling index (c), easterly winds - UW (d), northerly winds - VW (e) and Wind magnitude (f), for the time period 1989-2009 in subdivisions: IXaCN – Northwestern Coast; IXaCS – Southwestern coast; IXaS-Algarve – South coast.

Figure 3. Standardised observed time series of a) yearly LPUE (Landings Per Unit Effort) and fishing effort (FE) for each subdivision (IXaCN – Northwestern coast; IXaCS – Southwestern coast; IXaS-Algarve – South coast) between 1989 and 2009

Figure 4. Seasonal decomposition of *S. pilchardus* LPUE (kg/fishing days) time series (1989-2009) into seasonal component, trend and remaining noise (Seasonal decomposition by LOESS smoother). The original time series was normalised.

Table 1. Mean and standard deviation values of seasonal environmental variables, for the time series 1989-2009 in subdivisions IXaCN, IXaCS and IXaS-Algarve: SST – Sea surface temperature ($^{\circ}\text{C}$); NAO index; UPW – Upwelling index ($\text{m}^3/\text{s}/100$ m coast), UW- Westerly wind (m/s), VW – Northerly wind (m/s), WMag – Wind magnitude (m/s), RD – River discharge ($\text{dm}^3 \times 10^4$).

Variables/Subdivisions	IXaCN	IXaCS	IXaS-Algarve
SST-Winter	13.88 (± 0.62)	15.06 (± 0.56)	16.06 (± 0.43)
SST-Spring	15.84 (± 0.75)	16.67 (± 0.61)	17.94 (± 0.5)
SST-Summer	18.34 (± 0.6)	19.2 (± 0.66)	21.23 (± 0.67)
SST- Autumn	16.05 (± 0.83)	17.25 (± 0.75)	18.71 (± 0.68)
NAO-W	0.34 (± 2.35)	0.34 (± 2.35)	0.34 (± 2.35)
UPW-Winter	-41.58 (± 36.89)	-12.2 (± 22.44)	-6.09 (± 26.82)
UPW-Spring	23.67 (± 14.43)	30.95 (± 15.52)	10.38 (± 9.24)
UPW-Summer	43.83 (± 11.45)	49.43 (± 13.71)	7.81 (± 7.46)
UPW-Autumn	-57.83 (± 47.57)	-26.63 (± 27.6)	-5.59 (± 25.54)
UW-Winter	0.73 (± 1.19)	0.42 (± 1.3)	-0.39 (± 1.67)
UW- Spring	1.76 (± 0.64)	2.16 (± 0.57)	2.17 (± 0.72)
UW- Summer	1.16 (± 0.4)	1.76 (± 0.31)	1.86 (± 0.59)
UW- Autumn	0.39 (± 1.26)	0.46 (± 1.41)	0.12 (± 1.51)
VW- Winter	-1.32 (± 1.24)	-2.56 (± 1.04)	-1.82 (± 0.75)
VW- Spring	-3.38 (± 1.08)	-4.34 (± 1)	-2.52 (± 0.65)
VW- Summer	-4.36 (± 0.73)	-4.95 (± 0.73)	-3.06 (± 0.59)
VW- Autumn	-1.19 (± 2.1)	-1.97 (± 1.65)	-1.31 (± 1.23)
WMag-Winter	2.07 (± 0.97)	2.96 (± 0.86)	2.56 (± 0.53)
WMag-Spring	3.94 (± 0.78)	4.91 (± 0.85)	3.39 (± 0.66)
WMag-Summer	4.52 (± 0.67)	5.32 (± 0.64)	3.68 (± 0.55)
WMag-Autumn	2.63 (± 1)	2.76 (± 1.25)	2.27 (± 0.79)
RD- Winter	1313.21 (± 996.62)	417.04 (± 442.88)	114.72 (± 150.05)
RD- Spring	622.01 (± 268.56)	128.29 (± 65)	21.34 (± 17.83)
RD- Summer	279.58 (± 96.95)	94.79 (± 55.52)	8.1 (± 5.61)
RD- Autumn	856.66 (± 511.66)	292.31 (± 272.39)	69.25 (± 121.8)

Table 2. Resume table with results for Dynamic factor analysis (DFA), Generalised Least Square (GLS), Multivariate Autoregressive integrated Moving Average (ARIMA) and Surplus production models (SPM). For DFA the – and + sign indicates estimated t -values with a negative and positive relationship; -- or ++ indicates t -values larger than 3, indicating a strong relationship. For GLS the relationship between explanatory variables and LPUE are given by the slope of regression coefficient (– and + signs) with P -value < 0.02 being considered highly significant (-- and ++). For ARIMA the relationship between environmental variables and LPUE are given by the estimate parameter of ARIMA model for each explanatory variables (- or +). The strength of fitness of ARIMA model is given by the coefficient correlation (R^2) with R^2 higher than 0.5 (* - asterisk) being considered highly significant adjustment of the ARIMA model. The strength of fitness of ARIMA model with environmental variables were measured by the Ljung-Box statistic P -value and it was considered that for P -values > 0.4 the model with explanatory variables is highly correctly specified (see Appendix 1 for all details concerning numerical statistical results). For the SPM the explanatory variables are significant with a coefficient of determination (R^2) $> 40\%$. Environmental variables that increase the fit (R^2) of the initial SMP, without explanatory variables, are marked as “sig.”.

	IXaCN				
	DFA	GLS	ARIMA	probability	SPM
NAO	n.s.	n.s.	sig. (-)	Low	sig.
NAO-Winter	n.s.	sig.(+)	n.s.	Low	n.s.
SST	sig.(--)	sig.(-)	sig. (-)	High	sig.
SST-Summer	n.s.	n.s.	sig.(--)*	Low	n.s.
SST-Autumn	sig.(--)	sig.(--)	n.s.	High	n.s.
UPW-Spring	n.s.	n.s.	sig.(++)*	Low	sig.
VW	n.s.	n.s.	sig.(+)	Low	n.s.
VW-Autumn	sig.(--)	sig.(--)	n.s.	High	n.s.
WMag	n.s.	n.s.	sig.(-)	Low	n.s.
WMag-Autumn	sig.(++)	sig.(+)	n.s.	High	n.s.
SST + VW +WMag (Autumn)	sig(--), sig(+),sig(+)				
	IXaCS				
	DFA	GLS	ARIMA	probability	SPM
Effort	n.s.	sig.(--)	n.s.	Low	

NAO-Winter	sig.(+)	n.s.	n.s.	Low	sig.
SST	n.s.	n.s.	sig.--)	Low	sig.
SST-Spring	n.s.	n.s.	sig.--)	Low	n.s.
SST-Summer	n.s.	n.s.	sig.(++)	Low	n.s.
SST-Autumn	n.s.	sig.(+)	n.s.	Low	sig.
UPW	n.s.	n.s.	sig.(++)	Low	n.s.
UW	n.s.	sig.(++)	n.s.	Low	n.s.
IXaS-Algarve					
	DFA	GLS	ARIMA	probability	SPM
Effort	sig.(+)	sig.(++)	n.s.	High	sig.
NAO	sig.(-)	n.s.	n.s.	Low	sig.
OffDis	sig.(-)	n.s.	n.s.	Low	sig.
SST	n.s.	n.s.	sig.--)*	Low	sig.
SST-Spring	n.s.	n.s.	sig.(++)	Low	sig.
SST-Autumn	n.s.	n.s.	sig.(-)	Low	sig.
SST-Winter	n.s.	n.s.	sig.(-)*	Low	sig.
UW-Summer	n.s.	sig.(++)	n.s.	Low	sig.
VW	sig.(-)	n.s.	n.s.	Low	sig.
VW-Spring	sig.(-)	sig.--)	n.s.	High	sig.
WMag	n.s.	n.s.	sig.--)*	Low	sig.
WMag-Spring	sig.(+)	n.s.	n.s.	Low	sig.
WMag-Summer	sig.(+)	sig.(++)	n.s.	High	sig.
WMag-Winter	n.s.	sig.(++)	n.s.	Low	sig.
VW_Spring + WMag_Spring	sig(-), sig(+)				

Appendix 1. Resume table with results for Dynamic Factor Analysis (DFA), Generalised Least Squares (GLS), Multivariate Autoregressive Integrated Moving Average (ARIMA) and Surplus Production Models (SPM) with environmental variables. EV – Environmental variable; FE - fishing effort. Diff. AIC – difference between initial simple DFA model (only with LPUE trend) and DFA with LPUE trend plus explanatory variable.

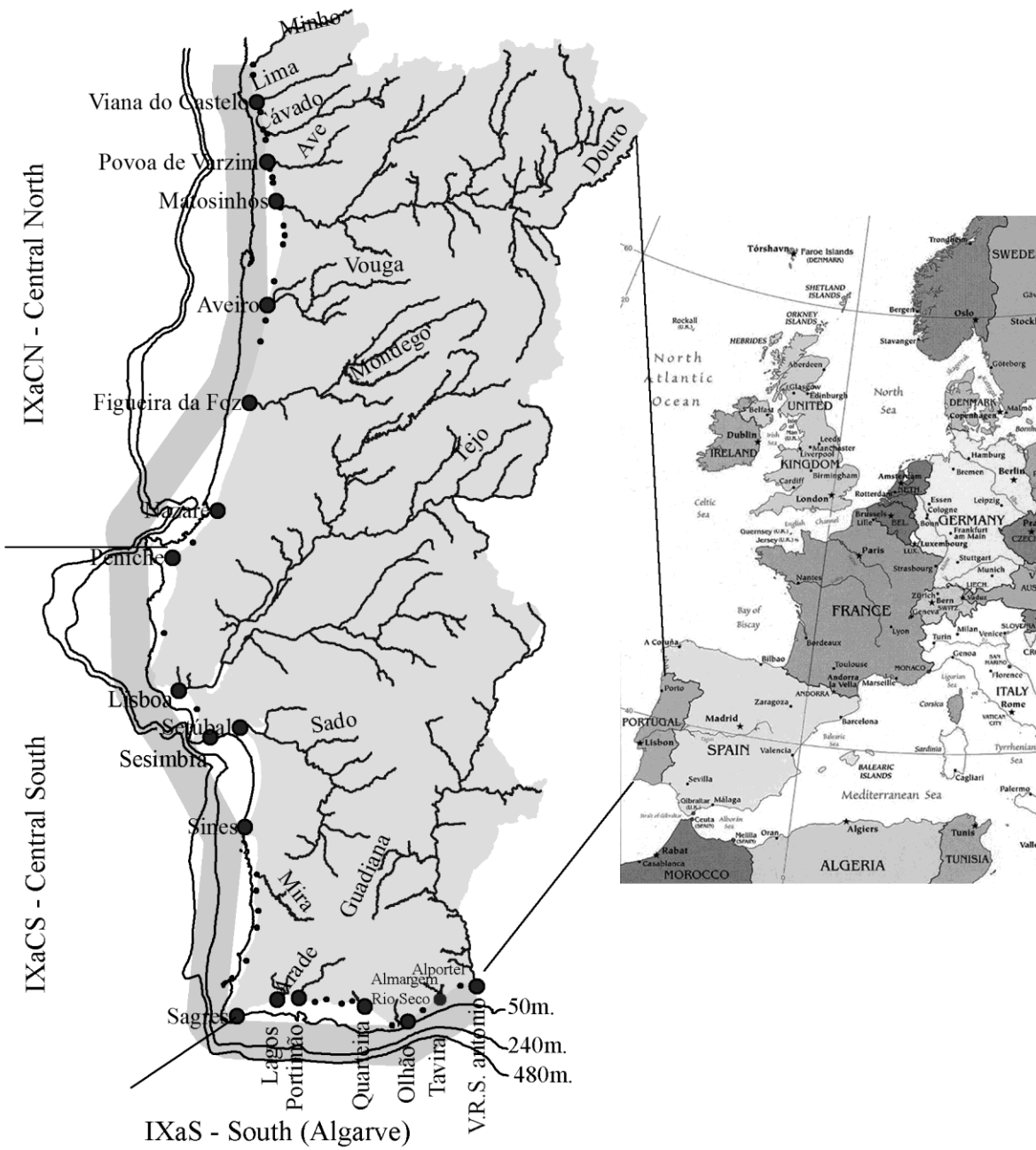


Figure 1

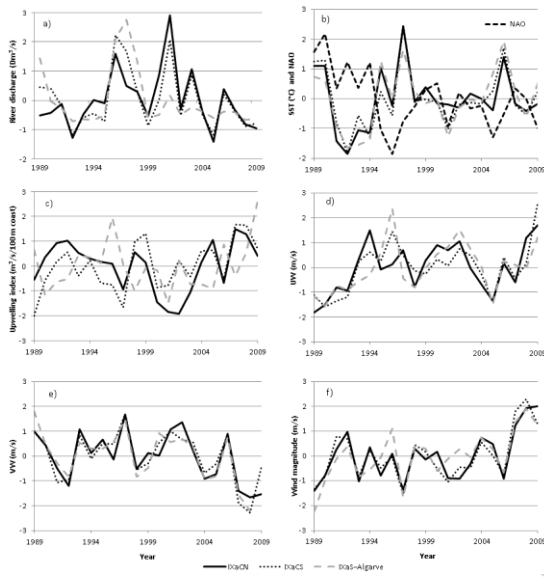


Figure 2

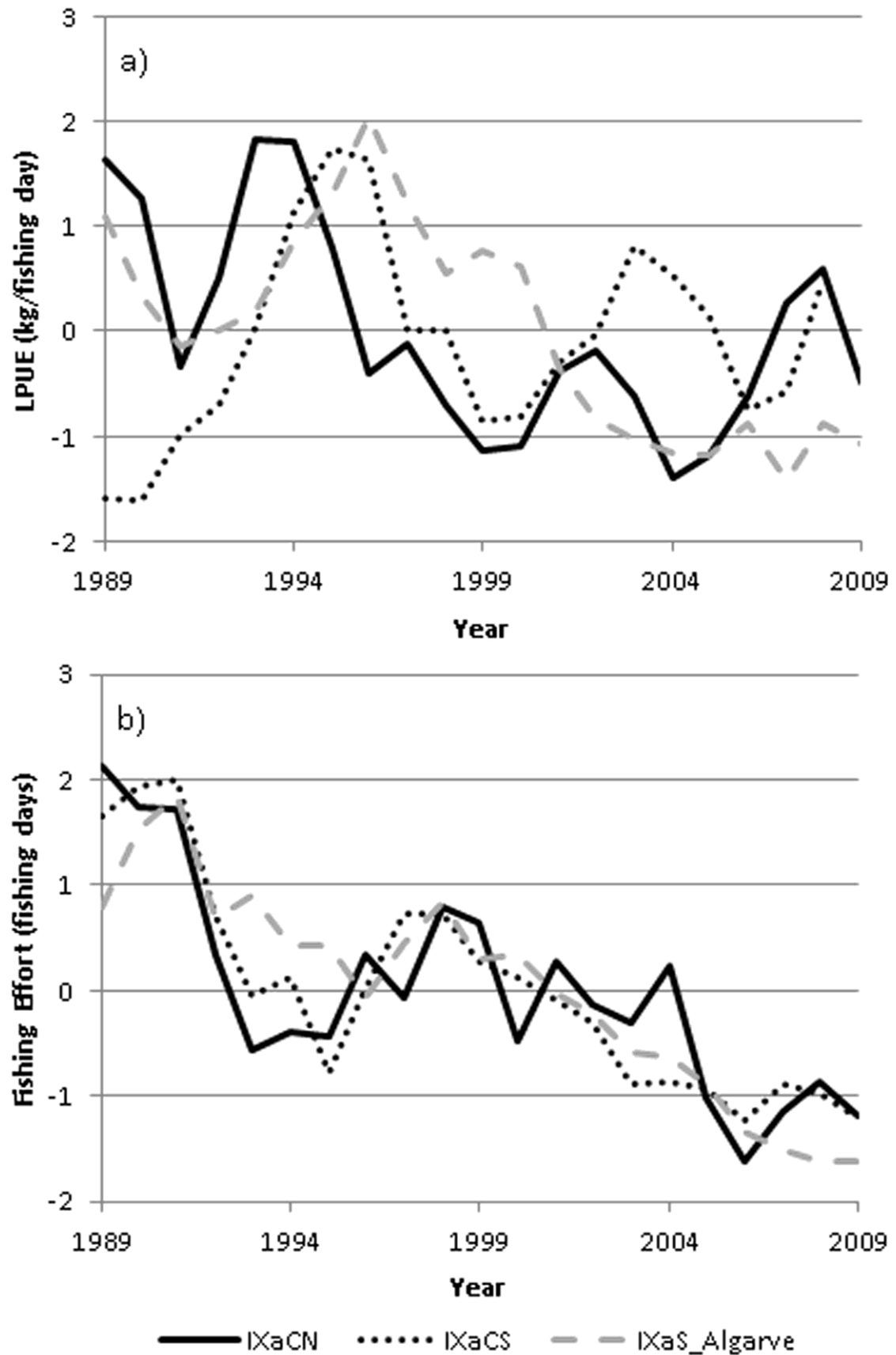


Figure 3

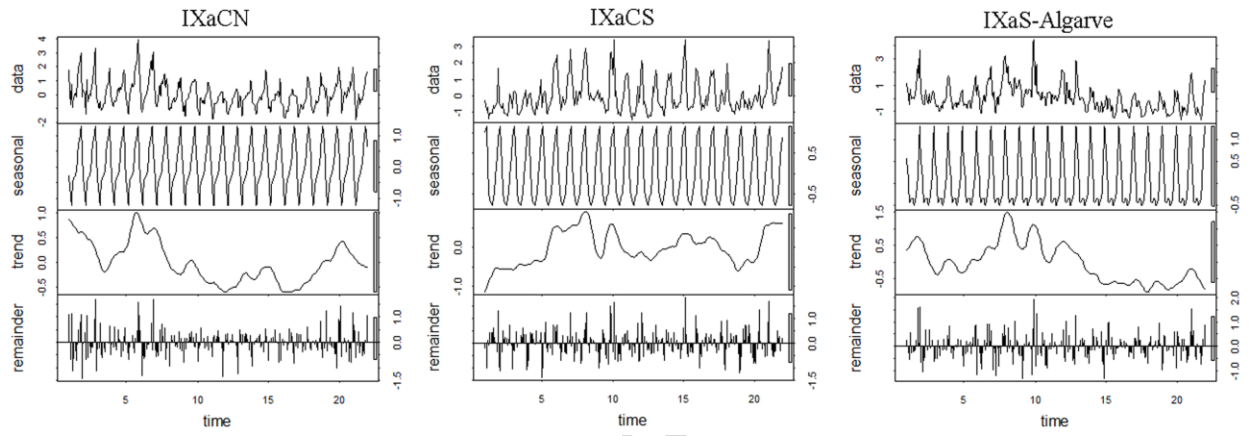


Figure 4

Highlights

- Fish recruitment (stock size) is affected by different environment variables and fishing pressure
- In ICES IXa sub-division three sardine sub-stocks are found (Northwestern, Southwestern and South)
- Catch rates of each sardine sub-stock was affected by regional environmental signature (abiotic factors)
- Seasonal (autumn and winter) wind driven effects plays an important role in catch rates variability, sub-stock independently
- Management of sardine (sustainable yields), under the scope of climate variability, should be adapted to a regional scale