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ORIGINAL ARTICLE

The role of environmental and fisheries multi-controls in white seabream (*Diplodus sargus*) artisanal fisheries in Portuguese coast

Francisco Leitão · Vânia Baptista · Maria Alexandra Teodósio · Samantha Jane Hughes · Vasco Vieira · Luís Chícharo

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Abstract Evaluating the effects of fishing and environmental factors on fish populations are fundamental tenets of fisheries science. In this study, we assess associations between environmental variables (sea surface temperature; North Atlantic Oscillation index; upwelling; wind magnitude; westerly winds; northerly winds; river discharge) and fishing variables (fishing effort) in *Diplodus sagus* catch rates accounting for regional analyses (northwest coast; southwest coast and Algarve—Algarve south coast). Different time series models for data fitting (multi-model approach) were used. The models were lagged, according to species fishing recruitment age based on the hypothesis that fisheries catches depend on larvae recruitment and survivorship. *D. sargus* catch rates across areas were unrelated to fishing effort but correlated to environmental variables, with seasonal events explaining much of the variability in trends. On the northwestern coast, the catch rates were mainly set by sea surface temperature (SST) and wind magnitude; however, southwestern coast catch rates were set by NAO winter. On the south coast, only one statistical model (SST, upwelling and westerly winds) associated spring conditions with *D. sargus* catch rates. The multi-model approach revealed autumn, winter and spring seasonal effects to be related with northwest, southwest and Algarve coastal catch rates, respectively, indicating a possible coastal longitudinal gradient related with given periods of spawning and larval availability. The metadata analysis yielded different results from the regional analyses. In summary, marine resource management should take regional environment characteristics and variability into account when determining sustainable catch rates in given areas for species with high habitat site fidelity.

Keywords Fish-environment relationships · Portuguese coast · Regional analyses · Min/max autocorrelation factor analysis · Dynamic factor analyses · Generalize least squares

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F. Leitão (✉) · V. Baptista · M. A. Teodósio
Centro de Ciências do Mar, Universidade do Algarve,
Campus de Gambelas, 8005-139 Faro, Portugal
e-mail: fleitao@ualg.pt

V. Baptista
e-mail: vania_bap@hotmail.com

M. A. Teodósio
e-mail: mchichar@ualg.pt

S. J. Hughes
Centre for Research and Technology of Agro-Environmental
and Biological Sciences (CITAB), University of Trás-os-Montes
e Alto Douro, Quinta dos Prados, 5001-801 Vila Real, Portugal
e-mail: shughes@utad.pt

V. Vieira
MARETEC, Instituto Superior Técnico, Universidade Técnica
de Lisboa, Av. Rovisco Pais, 1049-001 Lisbon, Portugal
e-mail: vasco.vieira@ist.utl.p

L. Chícharo
Centre for Marine and Environmental Research (CIMA),
University of Algarve, Campus de Gambelas,
8005-139 Faro, Portugal
e-mail: lchichar@ualg.pt

Introduction

Community structure varies in space and time in response to a complex array of physical and biological factors. The extent to which these different factors influence ecosystem function is one of the fundamental issues of ecosystem ecology and coastal fisheries. Environmental change such as sea temperature, upwelling, wind and currents can affect productivity at both regional- and large-scale areas (Planque and Frédou 1999; Baptista et al. 2014; Baptista and Leitão 2014). In recent decades, major attention has been given to climate drivers that affect the life cycle of small fish such as pelagic species (Santos et al. 2001; Fréon et al. 2005; Lehodey et al. 2006; Ullah et al. 2012). More recently, fisheries studies have highlighted environmental effects on other commercial groups such as demersal long-lived species (Ottersen and Sundby 1995; Planque and Frédou 1999; Solow 2002; Gröger and Fogarty 2011), cephalopods (Zuur and Pierce 2004; Ullah et al. 2012), bivalves (Baptista et al. 2014; Baptista and Leitão 2014) and crustaceans (Herraiz et al. 2009).

Coastal areas are some of the most productive ecosystems in the world, with a crucial role as nursery grounds for the immature phases of economically important fish such as sparids as well as invertebrate species. Seabreams (Sparidae), namely the genus *Diplodus*, are found in coastal waters worldwide and sustain important recreational and commercial fisheries (Fischer et al. 1987). *Diplodus sargus* (Linnaeus 1758) is an abundant species, found on the continental shelf and in the lagoons and estuaries of the Portuguese coast (Gonçalves 2000; Gomes et al. 2001; Sousa et al. 2005; Ribeiro et al. 2006). This species occurs across a wide variety of marine habitats ranging from rocky to sand bottoms and at depths ranging from 0 to 500 m, although they tend to be more common in coastal areas less than 150 m deep (Abecasis et al. 2008) and are mostly fished at depths of approximately 30 m (Erzini et al. 1996).

Both *D. sargus* and *D. vulgaris* contribute greatly to the total fish abundance (in number) in southern European rocky infralittoral zones, representing up to 56 % of total abundance in the NW Mediterranean Sea (Garcia-Rubies 1997). These two species account for 40 % of overall resident artificial reef fish assemblages and 20 % of the overall artificial reef fish assemblage at 20 m depth (Leitão et al. 2008) along the Algarve coast of southern Portugal. *D. sargus* has pelagic larval stages; young recruits concentrate mainly in near shore coastal areas on rocky bottoms and coastal lagoons (Monteiro et al. 1990). Subadult and adults move toward deeper waters in response to ontogenic changes in habitat choice (García-Rubíes and Macpherson 1995; Harmelin-Vivien et al. 1995). *D. sargus* has high site fidelity and is categorized as a resident rocky areas species (Santos et al. 2005; Leitão et al. 2007, 2009).

The Portuguese coastal fishing fleet is divided into inshore (local or artisanal), coastal and long-distance fleets along the coast (Fig. 1). The local/artisanal fishery is of considerable socioeconomic importance for the local population which has increased along the coast over the last decades. The fishing effort of the multi-gear fleet on many fisheries resources is very intense, involving large numbers of fishermen. In Portugal, *D. sargus* is mainly caught by the multi-gear (artisanal) fishing sector. National data bases (Direção-Geral de Recursos Naturais, Segurança e Serviços Marítimos; DGRM) between 1989 and 2009 reveal that multi-gear fishing contributed to 57 % of the overall species landings on average (73 % of fishing effort, units: fishing days.boats), followed by trawling (19 %) and seine netting (24 %). In certain areas such as the south—southwest coast of Portugal, hook and line multi-gear fleet fisheries can directly target sparid species (Erzini et al. 2001). In south Algarve coast, multi-gear fishing account for 78 % of the total landings while in northwestern and southwester 66 and 43 % (Source: DGRM data between 1989 and 2009). *D. sargus* is a highly prized species that reaches high prices at auction (7, 5 and 10 € kg^{-1} average, minimum and maximum auction price between 1989 and 2009: Source DGRM). In the multi-gear sector, this species is not normally discarded, therefore landings can be assumed as directly proportional to catches based on this sector while in other sectors (seine and trawl) the species is accidently caught, although in low percentages (Fernandes et al. 2007; Gonçalves et al. 2008).

The theory of "ocean triads" (processes of enrichment, concentration and transport/retention of larvae) has been a source of important discussions on environmental effects on fish recruitment (Santos et al. 2007). However, understanding the processes that influence recruitment is a fundamental objective of fisheries biology. Recruitment of small pelagic and most marine fish (Cushing 1996) is highly variable with no clear links with parental stock abundance levels (spawning stock biomass). This is because of high and variable mortality rates during the early life stages (among other factors) that are thought to be strongly affected by environmental processes (Santos et al. 2012). Environmental controls of recruitment have been an important component of fisheries research for at least a century (Helland-Hansen and Nansen 1909; Hjort 1914) resulting in the development of many hypotheses that are still actively discussed in the environment-fisheries literature (Lasker 1975; Cury and Roy 1989).

Evidence that environmental factors (hydrological and oceanographic) cause long-term, large-scale variability in fish stocks is growing although it is mistaken to assume that the effects of fishing are less important. These associations have not yet been clearly demonstrated or integrated into sustainable coastal fisheries management (Fréon et al. 2005). Hypotheses underlying sets of

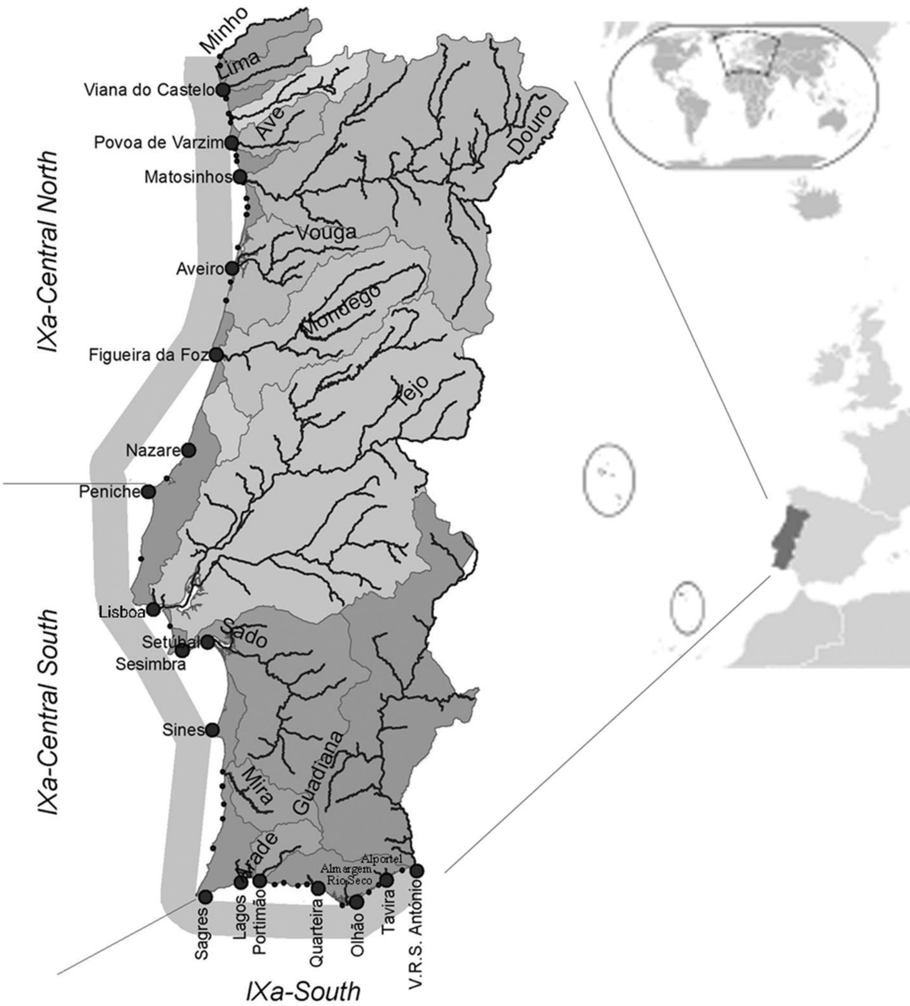

Fig. 1 Location of the rivers and ports of Portuguese coastal study areas: Northwest (IXaCN). Southwest (IXaCS) and south (IXaS-Algarve)

representative models can be used to make inferences about dominant factors controlling fisheries (Loots et al. 2011). A multi-inference model theoretic approach can be used to determine environment-fisheries links and evaluate model "predictive" capabilities, rather than data fitting performances (Johnson and Omland 2004). Studies on climate effects on benthopelagic species such as sparids are scarce. This study seeks to determine the potential role of climate factors and artisanal fisheries pressure on *D. sargus* catch rates, across different regions of the coast (different fishing and oceanographic regimes), using a multi-model approach, that can provide important information for fisheries managers.

Materials and methods

Study area

The effect of climatic variability and fishing on *D. sargus* catch rates was evaluated across three biogeographic areas situated off the Portuguese coast, namely the northwest, southwest and South Atlantic coast of Portugal (Fig. 1). Each of these areas has distinct oceanographic regimes (Cunha 2001; Bettencourt et al. 2004). The three areas match the International Council for the Exploration of the Sea (ICES): IXa subdivision area for Portugal and are hereafter designated as northwest coast (IXaCN), southwest coast (IXaCS) and Algarve south coast (IXaS-Algarve).

Acquisition of environmental and fisheries data

Landing and fishing effort data for the artisanal fleet (responsible for most landings across the regions) for the period 1989–2009 where obtained from the Direção-Geral de Recursos Naturais, Segurança e Serviços Marítimos (DGRM). The database includes information on fisheries practices such as monthly effort (number of fishing days.-boats and/or fishing events) and monthly landings per boat per month. Fishing data were then amalgamated into annual periods. Landings per unit effort (LPUE or catch rates) were used as a proxy for fish biomass production (abundance index proxy). LPUE (response variable) were estimated by dividing total annual landings by fishing effort (FE; fishing days.boats) (LPUE units: kg per fishing days.boats). The aggregations for spawning for this species in late winter/beginning of spring are well known by the recreational fishermen (anglers) in same locals of IXaCS and IXaS-Algarve coast. In these areas, recreational fisheries catches for the species can reach meaningful values regarding commercial fisheries: Forty-four percentage of the total catches by number and 48 % by mass (Veiga et al. 2010). However, this study is on commercial fisheries only and does not include the recreational fisheries data which is unreported (Leitão et al. 2014a).

The annual and seasonal mean sea surface temperature (SST; °C), annual and seasonal upwelling index (UPW), and yearly and seasonal u-wind and v-wind components were used as oceanographic explanatory variables. Geostrophic wind in satellite data is broken into its two horizontal components: The "u" component (UWIND; m/s) represents the east–west wind components while the "v" component (VWIND; m/s) represents north–south winds. SST data were obtained from summary imagery data obtained from Modis-Aqua 4 km satellite available on the NASA Ocean Color Giovanni website, (http://gdata1.sci.gsfc.nasa.gov). The upwelling index was obtained from Pacific Fisheries and Environmental Laboratory website (www.pfeg.noaa.gov). Wind components (u- and v-) were obtained from NASA Jet Propulsion Laboratory California Institute of Technology—Physical Oceanography Distributed Active Archive Center—PODAAC (http://podaac.jpl.nasa.gov/dataset/CCMP_MEASURES_ATLAS_L4_OW_L3_5A_MONTHLY_WIND_VECTORS_FLK?ids=&values=) (Atlas et al. 2011). Wind magnitude (WMAG; m/s) [WMAG: SQRT(u2 + v2)] was modeled using u- and v-wind components. Coastal oceanographic data were used to derive a range of depths from Mean High Water Line to 200 m (Fig. 1), in order to compensate a lack of some near shore satellite data (cloud effect). Therefore, SST, UPW, WMAG, UWIND and VWIND data are averaged means for the geographical area.

Yearly river discharge data (RD; dm^3) from January to December was used to test the effect of hydrology on catch rates. RD comprised cumulative monthly contribution (discharges volumes in cubic decameters, dam^3), of the principal Portuguese rivers or Basins (Fig. 1), including (1) northwest coast: Cávado, Lima, Douro, Vouga, Mondego, (2) southwest coast: Tejo, Sado, Mira and (3) Algarve south coast: Guadiana river and minor inputs from three smaller river systems (Seco, Alportel and Almargem). The monthly hydroclimatic date series of freshwater discharged into coastal areas were downloaded from Agencia Nacional do Ambiente (APA online data base, SNIRH: http://snirh.pt/). All data were collected from the same hydrological stations located nearest the shore.

The North Atlantic Oscillation (NAO and NAO winter (December–March)) indices were used as climatic explanatory variables (http://www.cgd.ucar.edu/jhurrell/nao.html, last accessed 2010; Hurrell 1995). NAO indices are the difference between sea level atmospheric pressure located at the Azores and Iceland, respectively. These phenomena influence precipitation, temperature and wind regimes over most of the northwestern Europe (Witbaard et al. 2005).

Time series analyses (statistical models)

We used catch rates (LPUE) as the response variable for statistical purposes while effort and environmental variables were the explanatory variables. We assumed that fishing recruitment variability would be largely determined by survival during the larval stages. Hypotheses can be postulated that link larval fish survival (affecting recruitment into the fisheries) with environmental and fishing conditions during the larval stage. Therefore, the hypothesis applied in this study is that larvae recruitment is influenced by regional environmental and fisheries factors that affect larval mortality rate and recruitment to the fishery and consequently short-term catch rates. *D. sargus,* a long-lived species that can live for up to 25 years, commonly reaches maturity at 2-year old (Erzini et al. 1996, 2001, 2003; Morato et al. 2003). The adult stage becomes available to the fishery when individuals reach the minimum landing size of 15 cm, a proxy of the age of first maturity. Environmental variables lags of 2 years were applied for the analyses, since *D. Sargus* recruitment to fishery occurs in the 2nd year class. The analysis is based on the assumption that landings per unit effort are directly proportional to biomass (catch rate as biomass proxy) and that landings are directly proportional to catches. This is the case for *D. sargus* for multi-gear sector: Direct proportionality with catches is assumed since this species is residually discarded due to their high commercial value. Fishing effort can also affect spawning biomass (adults) and recruitment in subsequent years. To accommodate this effect, environmental data and FE (number of fishing days.boats) were manipulated using a 2-year time lag to reflect temporal change. We also included FE in the models as an explanatory variable after collinearity between catch rate and FE was tested with pair plots and was found to be absent (collinearity between catch rate and FE: IXaCN = 0.01; IXaCS = 0.64; IXaS-Algarve = 0.14; Total = 0.21).

We hypothesized that the larval survival rates would vary according to seasonal environmental marine conditions. We considered winter (January–March), spring

(April–June), summer (July–September) and autumn (October–December) seasons. Finally, we assumed that *D. sargus* fisheries are affected by distinct environmental conditions on the coast; therefore, separate models were produced for each region, to each explanatory variable. Nevertheless, data were also evaluated taking into consideration all Portuguese area (ICES IXa) (metadata analyses or total area). For metadata analyses, fishing data and RD were pooled (cumulative contribution) while other environmental data (e.g., SST) was averaged across areas.

A complementary multi-model results approach was used including min/max autocorrelation factor analysis (MAFA), dynamic factor analysis (DFA) and generalized least squares (GLS) models. Since different analyses might give different results, a selection criterion was adopted to identify variables with a 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 identified the same explanatory variable. This simple selection criterion allows classification of variables with either a high (the variable is highlighted in more than one model) or low probability of influencing catch rate.

Prior to the analyses, all data series were tested for normality (Quantile–Quantile plots—QQ-plots) and collinearity (pair plots) following Zuur et al. (2010). In the case of both yearly *D. sargus* catch rates and explanatory variables, no transformation was applied. First, we computed simple models and tested for the significance of the relationship without accounting for more than one variable. Whenever more than one variable was identified, we tested the significance of the relationship (in DFA and GLS analyses, see below), accounting for combining fisheries and environmental data series by surrogate testing. Since collinearity occurred between yearly northerly wind (VWIND) and wind magnitude (WMAG), these variables were not combined in the same models whenever they were both found to be statistically significant. Both response and explanatory variables were standardized before running the models as advised by Zuur et al. (2003a, b). The standardization method used for converting data into the same dimensional scale was normalization that consist in centering all variables around zero ($Xi = (Yi - \hat{Y})/\sigma y$), where $\hat{Y}$ is the sample mean, Yi the value of the ith sample and σy the sample standard deviation. All statistical analyses were made using Brodgar software package that uses R version 3.0.1 (http://www.brodgar.com).

Min/max autocorrelation factor analysis (MAFA)

MAFA is a type of principal component analysis (PCA) for short time series that can be used to extract common behavior trends of the original time series and for smoothing. A set of orthogonal linear combinations of the original time series (MAFs) of decreasing smoothness, measured by lag-one autocorrelation, are constructed (Solow 1994). The MAFA axes represent autocorrelation with lag 1; the first MAFA axis represents the main trend in the data, while the others represent the other less important trends (Solow 1994). Cross correlations between MAFA axes and explanatory variables can also be estimated, allowing significant relationships between trends and explanatory variables to be identified (Erzin 2005; Zuur et al. 2007). The MAFA analyses that best fitted to the available data (providing the data availability for the species) considered only a single MAFA trend (autocorrelation time lag 1 year) for each region.

Dynamic factor analysis (DFA)

Trend analyses of the effect of environmental and fishing variables on catches rates of *D. sargus* were carried out for each region using dynamic factor analysis (DFA). DFA is a multivariate technique used for non-stationary time series analysis to estimate underlying common patterns, evaluates interactions between response variables (LPUE) and determines 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 (Ullah et al. 2012; Baptista et al. 2014; Baptista and Leitão 2014; Leitao et al. 2014b). Models were fitted with a diagonal covariance matrix, and the Akaike 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 response variable (t values with an absolute value greater than 3 indicate a strong relationship among variables).

Generalized least square (GLS)

Generalized least squares (GLS) is an extended linear mixed-effect modeling method where errors are can be correlated and/or have unequal variance (Pinheiro and Bates 2000; Lloret et al. 2001). Several GLS models were applied without autocorrelation and with an autoregressive process imposed on the error components allowing errors to have unequal variance (Zuur et al. 2007). Thus, errors were specified to follow an autoregressive process of degree 1 that was determined using the partial autocorrelation function and the goodness of fit of an auto-regressive moving average (ARMA) model. This approach can be used for most regular spaced datasets (Zuur et al. 2007), assuming that autocorrelation is highest between consecutive years. Therefore, the GLS models with and without different autocorrelation structures were compared using the lowest AIC as decision criterion; only the best GLS models are presented. An important criteria into consider is whether the decrease in AIC is large enough to proceed with discarding the simple linear regression model in favor of a more complex GLS model. If the difference in AIC values of two models is smaller than 2, general statistical consensus dictates using the simpler linear model (Zuur et al. 2007). A significance level of $p < 0.05$ was used for the explanatory variables. The type of the relationship in GLS between the explanatory and response variables is evaluated by the sign (+ or −) of the slope.

Results

The SST revealed similar yearly trend variations among study regions (northwest, southwest and south coast of Portugal), peaking in 1989–1990, 1995, 1997 and 2006 (Fig. 2a). The SST was colder in the northwest and southwest regions than in the southern region (Table 1). The NAO index declined markedly until 1996 (Fig. 2b) and then varied although values below the mean became more frequent.

The UPW index revealed differing trends among study regions and marked oscillations over time (Fig. 2c). The northwest and southwest regions had higher UPW index values in 1992, 1999–2000, 2005 and 2007–2008. In the south region, UPW index values peaked in 1996 and 2009. Along the Portuguese coast, UPW was predominant in the spring and summer, particularly in the northwest region (Table 1).

The WMAG showed a similar pattern among study regions, oscillating around the mean value and peaking in 2008 (Fig. 2d). The WMAG was strongest on the southwest coast (Table 1). Seasonal WMAG varied considerably across the study areas with increasingly weaker seasonal oscillations in the south. WMAG tended to be stronger in the spring and summer. The easterly wind (UWIND) component showed an increasing trend oscillating around the mean (Fig. 2e). Values greater than the mean of UWIND (positive anomalies) were found in 1993–1997, 1998–2004 and 2006–2009. The northerly wind component (VWIND) trend oscillated around the mean over time, with values falling below the mean from 2004 reached the lowest values recorded for all-time series after 2006 (Fig. 2f).

Northwest and southwest RD presented similar trends, oscillating around the mean with positive peaks in 1996 and 2001 (Fig. 2g). RD peaked in 1989 and 1997 in the south region. Maximum RD volumes occurred during the winter and lowest RD volumes in the summer, independent of region (Table 1). RD was far higher in the northwest region regardless of season, followed by the southwest and the south, respectively. RD values were significantly lower in the south region compared to the other regions.

Standardized FE for *D. sargus* had similar pattern among different study regions (Fig. 3). FE remained at a steady state until 2004 and then increase markedly until 2009.

Catch rate trends of *D. sargus* varied among the three regions (Fig. 4). For total area, the LPUE trend increased rapidly, with peaks in 1994 and 1998, followed by a drastic decrease in 1999 and then a gentle increase (Fig. 4). In the northwest region, the catch rate trend increased until 1998, then decreased and remained close to the mean value (Fig. 4). For the southwest region, the catch rate showed an increasing trend with values increasing from below the average after 2002 (Fig. 4). In the south region, the catch rate was oscillatory. Standardized oscillation values varied between −1 and 1, indicating a low oscillation range and a steady state across time, except 1995, when the LPUE value peaked (Fig. 4).

Explanatory variables selected as significant in more than one model have a high probability of influencing *D. sargus* recruitment (Table 2). Summarized results of explanatory variables related with *D. sargus* catch rates for each region and statistical approach (MAFA, DFA and GLS) are given in Table 2 (for the detailed results of all model approaches see online supplement).

The MAFA model results showed no significant results in the northwest region. DFA and GLS results revealed a negative association between catch rate and autumn SST and a positive association with autumn WMAG. The spring WMAG was also negatively associated with catch rate in the GLS model. For this reason, the autumn SST (negative) and autumn WMAG (positive) were the environmental variables with a high probability of affecting *D. sargus* catch rate.

For the southwest coast of Portugal, the MAFA analyses showed that yearly FE and summer UWIND were positively related with catch rate. The winter SST, NAO winter index and yearly UWIND were related with catch rate in the DFA model; the former two variables had a negative relationship with catch rate while the latter was positively related with catch rate. Yearly and winter NAO indexes were negatively related with catch rate in GLS results, while spring UW and summer RD shared a positive relationship with catch rate. The NAO winter index was the only environmental variable with a high probability of affecting *D. sargus* catch rate.

Only DFA results identified variables associated with LPUE in the south region. This model revealed a negative

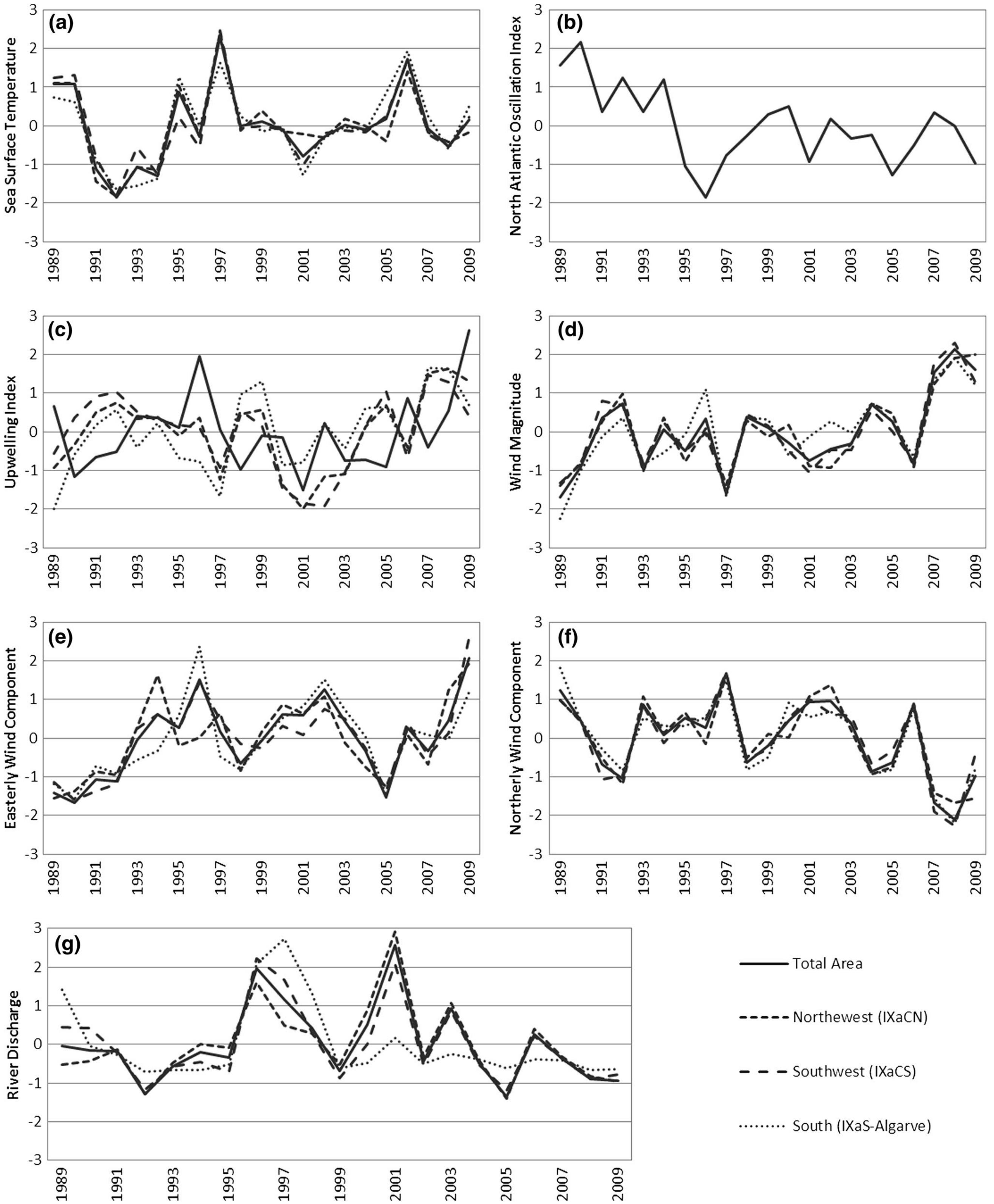

Fig. 2 Standardized time series of the yearly environmental variables, during the period 1987–2007 (for time series models the variables were lagged two years, therefore the data match the fisheries period 1989–2009) in the northwest (IXaCN), southwest (IXaCS) and south (IXaS-Algarve) regions, and total area (IXa) of Portugal: sea surface temperature (**a**), North Atlantic Oscillation index (**b**), upwelling index (**c**), wind magnitude (**d**), easterly wind component (**e**), northerly wind component (**f**) and river discharge (**g**)

Table 1 Means and standard deviations of annual and seasonal (winter, spring, summer and autumn) environmental variables, and total river discharge values, during the period 1987–2007 (for time series models the variables were lagged two years, therefore the data match the fisheries period 1989–2009) in the northwest (IXaCN), southwest (IXaCS) and south (IXaS-Algarve) regions, and total area (IXa) of Portugal

Variables	Total area (Ixa)		Northwest (IXaCN)		Southwest (IXaCS)		South (IXaS-Algarve)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
SST annual	17.20	0.37	16.02	0.46	17.04	0.38	18.51	0.33
SST winter	15.10	0.55	14.11	0.66	15.05	0.61	16.18	0.45
SST spring	16.88	0.57	15.88	0.71	16.68	0.61	17.98	0.48
SST summer	19.60	0.61	18.53	0.64	19.15	0.68	21.04	0.70
SST autumn	17.25	0.80	15.86	0.94	17.06	0.83	18.82	0.75
NAO annual	0.30	0.62	0.30	0.62	0.30	0.62	0.30	0.62
NAO winter	1.01	1.70	1.01	1.70	1.01	1.70	1.01	1.70
UPW annual	4.17	8.74	−4.66	17.80	13.20	9.80	−0.48	7.72
UPW winter	−16.23	21.74	−25.70	40.47	−4.24	22.65	−13.62	25.58
UPW spring	18.43	10.72	26.39	15.69	29.91	17.12	12.02	9.87
UPW summer	35.84	9.47	43.01	12.38	49.46	14.26	8.69	7.12
UPW autumn	−28.14	25.69	−48.60	53.20	−21.86	30.62	−3.29	28.14
WMAG annual	3.03	0.52	2.87	0.60	3.71	0.56	2.45	0.46
WMAG winter	2.45	0.64	1.93	0.93	3.11	0.88	2.48	0.54
WMAG spring	3.93	0.71	3.83	0.80	5.02	0.88	3.56	0.65
WMAG summer	4.60	0.53	4.46	0.70	5.34	0.65	3.75	0.58
WMAG autumn	2.48	0.97	2.69	1.03	2.78	1.29	2.25	0.82
UWIND annual	1.14	0.43	1.02	0.43	1.28	0.46	0.94	0.54
UWIND winter	−0.05	1.35	0.69	1.14	0.27	1.35	−0.83	1.74
UWIND spring	2.07	0.57	1.72	0.65	2.00	0.57	2.19	0.66
UWIND summer	1.70	0.33	1.35	0.36	1.81	0.29	2.02	0.58
UWIND autumn	0.19	1.32	0.18	1.29	0.29	1.43	0.20	1.49
VWIND annual	−2.61	0.55	−2.52	0.64	−3.21	0.60	−2.06	0.46
VWIND winter	−2.14	0.95	−1.25	1.27	−2.91	1.07	−1.90	0.74
VWIND spring	−3.63	0.88	−3.55	1.10	−4.45	1.04	−2.64	0.68
VWIND summer	−4.23	0.58	−4.41	0.76	−5.05	0.71	−3.21	0.55
VWIND Autumn	−1.77	1.62	−1.87	2.17	−2.13	1.67	−1.53	1.23
RD annual	42461.43	20461.42	27050.41	13363.74	6999.66	6348.43	1134.55	2417.12
RD winter	17782.92	16792.25	10799.63	11327.00	1772.88	4797.06	339.79	1592.59
RD spring	7631.91	3428.82	5443.01	2945.85	1092.84	633.51	140.97	135.77
RD summer	3760.61	1127.49	2775.88	760.97	777.55	485.12	74.64	58.58
RD autumn	13285.99	8973.27	6480.82	5486.53	2059.98	3039.32	317.86	1363.22

SST sea surface temperature (°C), *NAO* North Atlantic Oscillation index, *UPW* upwelling index, *WMAG* wind magnitude (m/s), UWIND easterly wind component (m/s), VWIND northerly wind component (m/s), *RD* river discharges (dam^3)

relationship between yearly and spring SST and LPUE while spring UPW and UWIND had a positive relationship. Thus, all tested significant environmental variables had a low probability of affecting *D. sargus* catch rate in the south regions.

For metadata analyses (Total IXa coast), the MAFA results showed that the summer SST was negatively related with *D. sargus* LPUE but positively related with the annual UWIND component. The DFA model had a negative relationship for yearly and summer SST, summer VWIND wind component and summer RD with LPUE while positive relationship for yearly and autumn UPW, yearly and summer WMAG wind magnitude and yearly, spring, summer and autumn UWIND. In GLS, summer VWIND was negatively related with LPUE and the yearly UWIND positively related with LPUE. Overall, the environmental variables with a high probability of influencing on *D. sargus* LPUE were summer SST (positive), yearly UWIND (negative) and summer VWIND (positive).

Discussion

Several factors affect survival of fish eggs and larvae, such as offshore winds that induce upwelling phenomena that transport eggs and larvae away from areas where they have a better chance of survival (e.g., Guisande et al. 2001; Landaeta and Castro 2002), predation (Bailey and

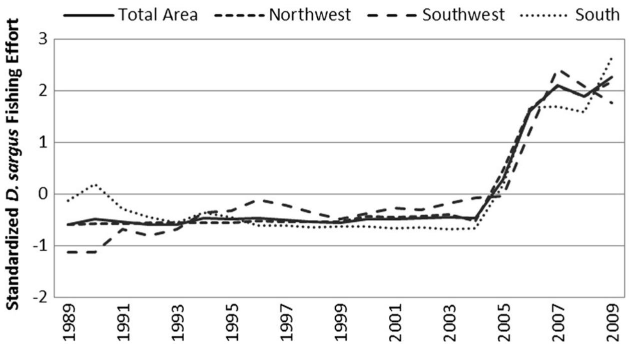

Fig. 3 Standardized yearly fishing effort (number of fishing days and boats) for *D. sargus* during the period 1989–2009 in the northwest (IXaCN), southwest (IXaCS) and south (IXaS-Algarve) regions, and total area (IXa) of Portugal

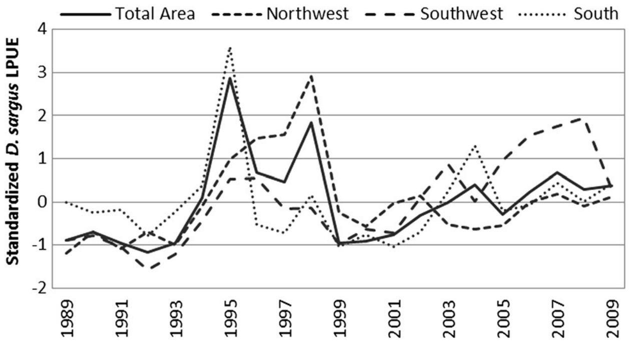

Fig. 4 Standardized *D. sargus* LPUE between 1989 and 2009 in the northwest (IXaCN). Southwest (IXaCS) and south (IXaS-Algarve) regions, and total area (IXa) of Portugal

Houde 1989), water temperatures outside the survival range (Rijnsdorp et al. 1995) and shortage of food (Cushing 1972; Houde 1987). Very few studies have addressed the role of fishing and environment effects on sparids, namely *D. sargus* fisheries (catch rates as a proxy of biomass index). FE remained in a relatively steady state until it began to increase in 2004, although this did not match an increase in catch rate. FE did not appear to be related to catch rate trends in any of the study areas. In most areas, except the Sagres area in the southwest region which has a hook and line fishery (Erzini et al. 1996, 1997, 1998, 2001, 2003), the fishery is not exclusively targeted on *D. sargus*. Given that *D. sargus* inhabits rocky coastal areas, this habitat preference might also reduce vulnerability to certain types of artisanal gears, such as trammel and gill nets (which not set in rocky areas due to the higher risk of gear loss and damage), that make up most of the artisanal fleet landings. However, results showed the effect of climate on catch rates varied between regions and that seasonal events were often caused short-term variation in catch rates.

Northwest coast (IXaCN)

D. sargus spawning occurs within an optimal range of 15–17 °C, with the onset and duration of the spawning season being influenced by sea water temperatures. As latitude decreases in the northern and southern hemispheres, the spawning season of *D. sargus* populations starts earlier and is more prolonged (Morato et al. 2003 and references therein).

Accordingly to Morato et al. (2003), the optimal range of SST in the northwest, southwest and Algarve occurred in autumn, winter and spring (Table 1). Thus, peaks in *D. sargus* spawning events differ across the regions, a phenomenon already recorded for other commercial species along the Portuguese coast (Gonçalves 2000; Stratoudakis et al. 2007). There are few studies on species spawning in northwest Portugal. However, changes in SST in the northwest can affect gametogenic activity by creating favorable conditions for early spawning in the autumn, compared to the southwest and south. The spawning season of *D. vulgaris*, a similar species that breeds from to autumn to winter, was found to vary inter-annually (Gonçalves 2000; Mouine et al. 2012) as a function of SST and the number of hours of direct sunlight, since the onset and duration of the spawning season is negatively correlated with these environmental parameters (Gonçalves 2000).

SST can affect larval survival since higher temperatures enhance larval growth rates and reduce the time interval between spawning and benthic settlement phases (Morato et al. 2003; Mouine et al. 2007; Vinagre et al. 2009). Since the eggs of *D. sargus* are spawned on the coast, larvae must be transported toward estuarine nurseries and shallow rocky coastal waters where *D. sargus* normally occurs (Harmelin-Vivien et al. 1995; Abecasis et al. 2009; Vinagre et al. 2009). This phase between spawning and successful arrival in the nursery areas is crucial for recruitment because high mortality rates can occur (Houde 1987). Thus, regional seasonal SST variations can affect recruitment into the fishery in different ways such as the timing of spawning/reproduction and larval availability. We found that autumn SST was negatively related with *D. sargus* catch rates with a 2-year time lag (the age fish recruit into the fishery as adults). In coastal areas the decrease of SST was related with UPW events (Santos et al. 2001) that are usually weak in autumn compared to other seasons, where UPW events bringing rich nutrient waters are essential required for larvae feeding. Although upwelling is more frequent between March and September, winds that favor this phenomenon are a recurrent feature on the Portuguese coast that can also occur in winter (Huthnance et al. 2002). Strong upwelling events, caused by north–south alongshore winds, can lead to offshore Ekman transport of

Table 2 Summary of results of relationship between *D. sargus* LPUE and explanatory (fishing and environmental) variables for min/max autocorrelation factor analysis (MAFA), dynamic factor analysis (DFA) and generalized least square (GLS) methods in the northwest (IXaCN), southwest (IXaCS) and south (IXaS-Algarve), regions and total area (IXa) of Portugal

	Explanatory variables	MAFA	DFA	GLS	Probability
Total area (IXa)	SST annual	n.s.	**sig.** (−)	n.s.	Low
	SST summer	**sig.** (−)	**sig.** (−)	**sig.** (−)	High
	UPW annual	n.s.	**sig.** (+)	n.s.	Low
	UPW autumn	n.s.	**sig.** (+)	n.s.	Low
	WMAG annual	n.s.	**sig.** (+)	n.s.	Low
	WMAG summer	n.s.	**sig.** (+)	n.s.	Low
	UWIND annual	**sig.** (+)	**sig.** (+)	**sig.** (+)	High
	UWIND spring	n.s.	**sig.** (+)	n.s.	Low
	UWIND summer	n.s.	**sig.** (+)	n.s.	Low
	UWIND autumn	n.s.	**sig.** (+)	n.s.	Low
	VWIND summer	n.s.	**sig.** (−)	**sig.** (−)	High
	RIVER summer	n.s.	**sig.** (−)	n.s.	Low
Northwest (IXaCN)	SST autumn	n.s.	**sig.** (−)	**sig.** (−)	High
	WMAG spring	n.s.	n.s.	**sig.** (−)	Low
	WMAG autumn	n.s.	**sig.** (+)	**sig.** (+)	High
Southwest (IXaCS)	EFFORT	**sig.** (+)	n.s.	n.s.	Low
	SST winter	n.s.	**sig.** (−)	n.s.	Low
	NAO annual	n.s.	n.s.	**sig.** (−)	Low
	NAO winter	n.s.	**sig.** (−)	**sig.** (−)	High
	UWIND annual	n.s.	**sig.** (+)	n.s.	Low
	UWIND spring	n.s.	n.s.	**sig.** (+)	Low
	UWIND summer	**sig.** (+)	n.s.	n.s.	Low
	RIVER summer	n.s.	n.s.	**sig.** (+)	Low
South (IXaS-Algarve)	SST annual	n.s.	**sig.** (−)	n.s.	Low
	SST spring	n.s.	**sig.** (−)	n.s.	Low
	UPW spring	n.s.	**sig.** (+)	n.s.	Low
	UWIND spring	n.s.	**sig.** (+)	n.s.	Low

For MAFA, the—sign indicates explanatory variables with a negative relationship, while + sign indicates a positive relationship. For DFA, the relationship between explanatory variables and LPUE are given by the estimated *t* values (− and + signs). For GLS, the relationship between explanatory variables and LPUE are given by the slope of regression coefficient (− and + signs)

Significant variables for each model are in bold (see online supplement)

surface water that can transport eggs and larvae away from the coastal nurseries, resulting in high mortality rates (Santos et al. 2001; Borges et al. 2003). This effect has not observed, providing the results found between SST *and D. sargus* catch rate in autumn when moderate upwelling conditions prevail.

The WMAG was positively related with species catch rates in autumn in northwester coast. Wind strength is low during both the winter and autumn compared to the spring and summer seasons (Table 1). However, increase in wind strength and direction (south–north predominant winds in this period), strongly affects coastal drift currents (Moita 1986; Melo 1989; Vila-Concejo et al. 2003) which are essential for food supply (Fernández et al. 1993; Santos et al. 2012) and larval transport and retention (Jager 2001; Vinagre et al. 2009), factors that influence larval settlement and growth. Wind strength also affects dispersal of river plumes, an important factor that influences the destination of larvae in rich estuarine waters (Tanaka 1985; Vinagre et al. 2007) as well as their retention in sheltered coastal areas (Borges et al. 2007). In the northwest coast, drift currents (indirect wind effect) tend to run parallel to the shore to depths of up to 40 m (Martinho 2006). Thus, when the autumn spawning season takes place (Gonçalves 2000; Mouine et al. 2012) an increase of WMAG can benefit *D. sargus* recruitment. Eggs are spawned on the coast and larvae undergo a complex transport process toward estuarine nurseries and rocky coastal areas that are crucial for successful recruitment (Houde 1987; Borges et al. 2007; Vinagre et al. 2009). In summary, upwelling has two major effects on fish recruitment: One is to trigger a productivity boom which is good for the larvae survivorship and the second is to transport the larvae away from the shore which could be negative to survival rates. The timing of each upwelling and spawning event is crucial for the balance of the effects.

Southwestern coast (IXaCS)

Reproduction occurs mainly in winter and spring on the southwestern coast (Erzini et al. 2001). These periods were identified in single model analyses as being seasonally associated with catch rates. However, the multi-model approach only indicated NAO winter being strongly associated with catch rate. However, it is known that SST is highly correlated with NAO (Witbaard et al. 2005). The surface waters along the Portuguese shore are dominated by the Canary current, which brings a regular supply of cold water from the north (Bischof et al. 2003). In years, when the NAO is positive, the Canary current persists throughout all seasons. When the winter NAO is negative and strong, south and southwest winds predominate and the Canary current may be temporarily replaced by a poleward flow (Frouin et al. 1990) affecting temporal patterns of fish variation observed in Portuguese coast (Henriques et al. 2007). It is important to emphasize that the NAO index operates indirectly and at a broader spatial scale than the other environmental variables considered in this study. Environmental factors affected by NAO such as SST, wind velocity and wind strength, precipitation, water circulation and stratification patterns are expected to directly influence recruitment and growth (Witbaard et al. 2005), metabolic rates (Ottersen et al. 2001) and food availability (Carroll et al. 2009). During the positive NAO phase north winds predominate (Borges et al. 2003; Lehodey et al. 2006), causing cold dry weather in the Mediterranean regions, while the negative phase is characterized by warmer temperatures and increased precipitation (Lehodey et al. 2006). For *D. sargus* the NAO winter (spawning season; Erzini et al. 2001) indexes were negatively related to LPUE trends, i.e., years with a predominant NAO winter negative phase, warmer temperatures and wet conditions are favorable to species recruitment. Differences in the sensitivity of different species and populations to NAO winter are related to species biology. Ecological responses to NAO comprises changes in timing of reproduction, population dynamics, abundance, distribution and interspecific relationships such competition and predator–prey interactions (Ottersen et al. 2001; Baptista et al. 2014). Although the NAO exerts an effect at a higher spatial scale, it only influences the recruitment and catch rate of *D. sagus* in southwest coast. These finding shows that local effects can be driven by large-scale effects and that catch rate variability depends on a combined set of local/regional phenomena.

South coast, Algarve (IXaS-Algarve)

The multi-model approach did not identify any single particular variable as being more probable to affect catch rates. Compared to other regions, the eastern coast of the Algarve has the lowest level of rocky habitat availability. Sandy bottom habitats comprise a large part of the fishing grounds, especially in leeward region. For this reason, the deployment of artificial reefs has been considered essential to provide suitable habitats for *D. sargus* assemblages (Leitão et al. 2009). Moreover, south coastal lagoons and estuaries systems have also been identified as important larvae recruitment areas (Monteiro et al. 1990; Veiga et al. 2006). *D. sargus* larval abundance (in final larval stage development) and settlement density occur preferentially in shallow rocky areas and lagoons where *D. sargus* is considered a resident species due to high site fidelity (Harmelin-Vivien et al. 1995; Macpherson 1998; Vigliola and Harmelin-Vivien 2001; Abecasis et al. 2009; Leitão et al. 2009; Vinagre et al. 2009). Studies showing strong habitat selective preferences by *Diplodus* spp. (Ross, 1986) indicated that fish assemblage food segregation was the most important resource partitioned by species rather than habitat, space or time. Thus, egg and larval survival in shallow waters and nursery areas (lagoons, estuaries) depend less on offshore oceanographic condition and more on inshore local causes (river flow; Vinagre et al. 2009, 2010) such as the lack of suitable habitat for larvae. In fact, in the south area, LPUE was characterized by smooth trend in variability despite the fact that conditions for the fishery all year round generally allow higher number of fishing days than in western regions.

Conclusions

Metadata analyses revealed that total results (analyses for the coastal population) differed across the three study regions and emphasis the importance of stock analyses at sub-area or sub-stock levels (e.g., mackerel in IXa (e.g., ICES 2011). Little is known about the general population and sub-populations *of D. sargus* along the Portuguese coast (IXa division). Nevertheless, by ignoring subdivision analyses, only partial knowledge on resource status will be gained. For example, early stage larval recruitment is determined by regional climatic variability, therefore it is not expected that that SST in northwestern areas affects larval survivorship in south Algarve. Metadata containing the cumulative LPUE contribution of each area and its relationship with explanatory variables are sensitive to the effects of group-averaged data. For instance, a metadata approach erroneously indicates that the summer SST correlates with stock catch rates (a period of low spawning activity) when in fact summer SST did not show any such correlation within any area. Thus, stock assessment of species with high habitat fidelity should be based on regional analyses. For such species, the regional analysis can be considered conservative, because mobility tends to break up any spatial pattern (García-Charton and Péres-Ruzafa 2001). Taking this concept into consideration plus the fact that habitat is conservative over time habitat associated species can be a good indicator for regional analyses environmental and fisheries studies. The multi-model approach across areas revealed autumn, spring and summer environmental effects to be related with northwest, southwest and Algarve coast catch rates. This appears to indicate a longitudinal gradient related with spawning and larvae availability and regional environmental condition effects over species early life stages. These regional differences result in different biological responses of *D. sargus* life cycle processes. The magnitude of these impacts is determined by the "timing" of interactions between specific stages of the life cycle and local environmental conditions. According to the regional circulation models, the evolution of climate may differ from region to region along the Portuguese mainland, resulting in heterogeneous responses of some stocks (Sousa Reis et al. 2006). Since environmental variables fluctuate over time, management of marine resources should take into account regional environment characteristics in order to develop suitable management measures based on yearly sustainable catch rates at regional scale. However, considering the potential values of fish caught in same areas of the IXaCS and IXaS-Algarve, recreational fisheries should also be included in fisheries-environmental research management in the future.

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