Environmental drivers of sardine (*Sardina pilchardus*) in the Catalan Sea (NW Mediterranean Sea).

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Funding

This study was supported by the European Commission through the H2020 Research and Innovation Action 'MINOUW: Science, technology and society initiative to minimize unwanted catches in European fisheries', contract n° 634495.

Journal: Marine Biology Research

Abstract

In the area surrounding the Ebro Delta, similar to the rest of the north-western Mediterranean Sea, the sardine (*Sardina pilchardus*), one of the most exploited small pelagic fishes, has suffered a decreasing trend in abundance and biomass in the last decade, with low values in evidence since 2007. The dependence of this species on environmental factors makes it vulnerable to environmental changes; consequently, the abundance of the species is highly variable. Using segmented regression, we evaluated the presence of discontinuities in the temporal pattern of the seasonally adjusted landings per unit effort (LPUE), which was used as a proxy of abundance, between 2000 and 2013. The results suggested a sudden increase in mid-2005, followed by a sharp decrease starting in 2006. A generalized additive mixed model (GAMM), incorporating the linear correlation structure, was used to identify relationships between the seasonally adjusted LPUE and trends of the Western Mediterranean Oscillation index (WeMOI), Sea Surface Temperature (SST), Salinity (SAL) and the Zonal and Meridional Currents (ZC and MC, respectively). The variance inflation factors (VIFs) were calculated between all environmental variables to avoid high-dimensional collinearities. The final GAMM, selected using the Akaike information criterion, indicated that positive WeMOI values, which favour the productivity of the area, along with SAL (at ca.38) and a northward-flowing MC, favoured LPUE. Our results, obtained by applying a method in which variation due to season, non-linearity, autocorrelation and collinearity of the covariates was taken into account, provided further evidence of the dependence of the sardine population upon specific hydrographic variables.

Keywords: Sardine, landing, purse seine, GAMM, WeMOI, NW Mediterranean Sea.

Introduction

Small pelagic fishes are an important component of marine ecosystems due to their role in energy transfer from lower to higher trophic levels (Cury 2000; Palomera et al. 2007). Globally distributed, they support important fisheries around the world (Alder et al. 2008). Early maturation, a short life span, and rapid and drastic responses to changes in the ocean climate (Checkley et al. 2009) characterize their biology.

Large fluctuations in the population abundance of these species in different parts of the world have been associated with shifts in biological and physical processes that particularly affect the recruitment phase (Agostini & Bakun 2002) due to the vulnerability of the species to changing oceanographic conditions during early life stages. Moreover, changes in environmental conditions also influence the adult populations and consequently affect fisheries' production by directly influencing the spatial distribution of fish or their availability to fishing fleets and by indirectly influencing adult mortality (Palomera et al. 2007; van Beveren et al. 2016).

The effects of climatic components on the variability of small pelagic resources have been studied across various marine ecosystems (e.g. Checkley et al. 2009). Despite the differences encountered across the ecosystems, such as the importance of an environmental factor in one area but not in another area (e.g. in the Mediterranean sea between the Strait of Sicily, where the Atlantic-Ionian Stream was identified as a main driver; Patti et al. 2004; and the Aegean Sea, where the main drivers were depth and river flow; Giannoulaki et al. 2005), patterns of physical mechanisms, summarized as the 'ocean triads' concept, can generally be identified (Agostini & Bakun 2002). In fact, even if small pelagics inhabit distinguishable areas characterized by different oceanographic characteristics (e.g. circulation patterns, bathymetry, rivers influences), their distribution patterns seem to be driven by environmental processes, which, although specific to each ecosystem, lead to conditions capable of enhancing and maintaining food availability (Bonanno et al. 2014).

Small pelagics dominate the catches in the Mediterranean sea; in particular, European anchovy *Engraulis encrasicolus* (Linnaeus, 1758) and European sardine *Sardina pilchardus* (Walbaum, 1792) represent the main species landed (Stergiou et al. 2016). Similar to other Mediterranean fish stocks, sardine spawning stock biomass and age at the time of capture have shown a progressive decrease in the last two decades (Vasilakopoulos et al. 2014).

Since the mid-1990s, sardine and anchovy landings have demonstrated a continuous decreasing trend in the NW Mediterranean Sea (Catalan sea and Gulf of Lions; Van Beveren et al. 2016). This trend has also been observed in the rest of the Mediterranean in recent decades and is consistent with the decline in population biomass in almost all areas where small pelagic stocks are assessed (GFCM 2015; STECF 2015).

In the Catalan sea, sardine reproductive success is enhanced by productivity mechanisms during the spawning season, which occurs from the autumn to spring, with a peak in the winter (January and February; Olivar et al. 2001, 2003; Sabatés et al. 2007). Spawners' abundance is mainly high in inshore waters, where sardine eggs are concentrated in water < 100 m deep (Olivar et al. 2001, 2003). During winter vertical mixing, which is mediated primarily by wind stress, an increased homogenization of the water column enhances biological primary productivity. This condition favours the survival of sardine in their early life stages, which is directly linked to increased landings (Lloret et al. 2004). However, extreme wind speeds can negatively affect sardine populations by increasing larvae mortality via reduced feeding success due to the dispersal of food and larvae to unfavourable locations (Borges et al. 2003; Lloret et al. 2004).

In addition to the wind mixing index, significant positive relationships were found with the Western Mediterranean Oscillation index (WeMOI, Martin-Vide & Lopez-Bustins 2006; Martín et al. 2012), a good proxy for regional atmospheric conditions in this area. Finally, although less significant, negative correlations were found in relation to sea surface temperature (Martín et al. 2012).

These significant relationships (Lloret et al. 2004; Martín et al. 2012) demonstrated that environmental changes influenced sardine population variability by presumably acting principally on the early life stages. However, the results of these analyses were strongly based on correlative or linear models; there is evidence that the relationships between the fisheries' catches (or landings) and the information available on environmental and climate factors can be better modelled using non-linear relationships (Borges et al. 2003). Generalized additive models (GAMs) are a modelling framework well suited to describing this kind of relationship by means of non-linear specification of the dependence of the response variable (Wood 2006); hence, the data allow for the determination of the nature of the relationship rather than the assumption of some form of parametric relationship (Guisan et al. 2002). Furthermore, in cases in which residual autocorrelation is significant (i.e. violation of independence), as in the analysis of time series, generalized additive mixed models (GAMMs) can be used to explicitly model autocorrelation (Wood 2006).

Environmental variability can alter fish distributions over short time-scales and can persist as long as environmental conditions remain unfavourable for fish survival, growth and reproduction, significantly affecting fishery by varying resource availability (Fréon et al. 2005). Thus, in the present study, a characterization of sardine landings in terms of trend and breakpoints was performed to evaluate the presence of marked temporal changes. Then, using GAM and GAMM, we investigated the relationships between the decrease in sardine landings and a combination of potential climate drivers in the Catalan Sea in order to assess their influence.

MATERIALS AND METHODS

General characteristics of the Study Area

The fishing area is situated off the Ebro delta (NW Mediterranean Sea) between 40°56’ N and 41°16’ N latitude and 0°80’ E and 1°72’ E longitude (Figure 1 (a)). This area, which is part of the so-called Ebro shelf, is marked by a drastic change in shelf width, evolving from ca. 15-20 km in the northern part to ca. 70 km in the southern part, and by the presence of a steep slope (Figure 1 (a)). A shelf-slope density front separating the less dense continental influenced waters and the denser open sea waters (Font et al. 1998) and the presence of a quasi-permanent geostrophic slope current (Northern Current, NC) flowing south-westward (Millot 1999; Salat et al. 2002) characterize the Ebro shelf.

The study area receives an important amount of continental fresh water from the Ebro river. On average, its annual water discharge rate ranges from 300 and 600 m^3 s^{-1} with maximum discharge in the spring and autumn (Salat 1996). The seasonal evolution of the stratification is clear in the area. The water column, in fact, is almost homogenous in the winter (13-14° C at all depths) while it is characterized by a defined thermocline between the early spring and late autumn (Salat 1996). Consequently, the river outflow plays an important role, especially immediately before the stratified season, by providing nutrients and enhancing surface productivity during this season (Salat 1996; Palomera et al. 2007).

The sea surface is dominated by winds coming from the north-northwest, which are strong and more frequent in the winter (60-100 km/h). These winds are associated with vertical mixing along the coast, contributing to the formation of the surface mixed layer during the stratified season (Salat 1996). Furthermore, the north westerly wind predominance, together with the specific features of the shelf, are involved in the intrusion processes of the shelf edge flow into the shelf, allowing the development of anticyclonic eddies (Salat 1996; Xing & Davies 2002), which are important structures for the spawning and reproduction of the small pelagic populations (Bakun 2006). Given these features, the Ebro river continental shelf is considered one of the most important spawning areas for clupeids in the western Mediterranean Sea (Palomera 1992; Palomera et al. 2007).

Data

The monthly data of landings (kg) and the number of fishing days (a measure of fishing effort) (Figure 1 (b)) for purse seine vessels were obtained for the two harbours of the study area with a small pelagic fleet, Tarragona and L'Ametlla del Mar, in the South of Catalonia, from 2000 to 2013 (Figure 1(b)). The selected ports produce 20-30% of the total landings of sardine in the geographical subarea GSA06 (STECF, 2015 p. 110 shows 9-10,000 t in GSA06 in 2012-2103, from 17-20,000 in 2002-2004), while in south Catalonia, production was ca. 6,000 t annually in the early 2000s and has been down to ca. 1000 t in recent years. The fleet was composed of 20 purse seiners in 2013 with the following characteristics: 16-24 m LOA, 30-65 GT and 127-450 kW engines. This purse seine fleet has decreased in the number of vessels (STECF, 2015 p. 109), similar to the other fleets in the Mediterranean Sea, in the last two decades due to poor profitability of fisheries and EU-funded subsidies for the decommissioning of vessels (STECF, 2015 p. 111, 140 vessels in GSA06 in 2013, i.e. our fleet is approximately 15% of the total fleet).

As an index of sardine fishery productivity, the monthly average LPUE (Y_t) was obtained by dividing the landings per month by the sum of the days when fishing operations were carried out by the fleet (LPUE in kg/day).

The environmental monthly time series were derived from satellite datasets, which are commonly used in studies of fisheries data due to their consistent space-time coverage and their ability to highlight the main ocean processes that determine the dynamics of fish populations dwelling near the surface (e.g.

Tugores et al. 2011; Bonanno et al. 2013). The environmental variables selected were as follows; Sea Surface temperature (SST in °C), Sea Surface Salinity (SSS), the Meridional Component of the water current (MC in m s^{-1}, positive northward), and the Zonal Component of the water current (ZC in m s^{-1}, positive eastward), which were retrieved from the Myocean Project with a spatial resolution of 1/16° x 1/16° (5.2 x 7.0 km, approximately). The first variables mentioned were useful because they were linked to the population dynamics of small pelagic fishes in the NW Mediterranean Sea (e.g. Lloret et al. 2001, 2004; Martín et al. 2008; Maynou et al. 2014) as well as in other locations around the Iberian peninsula (Guisande et al. 2001; Borges et al. 2003; Guisande et al. 2004; Santos et al. 2012). The latter two variables (MC and ZC) were selected because they are indicative of the circulation patterns upon the Ebro shelf, which is characterized principally by a current flowing south-westward (Northern Current) and interrupted by clockwise eddies (structures supporting high level of biological activities; Bakun 2006) and periods of current reversal (i.e. current flowing northward; Font et al. 1990; Salat et al. 2002; Lorente et al. 2015). Furthermore, the monthly Western Mediterranean Oscillation index (WeMOI), resulting from the difference of the standardized atmospheric pressure values in San Fernando-Cadiz (South western of Spain) and Padua (North eastern Italy) (Martin-Vide & Lopez-Bustins 2006), was used as an additional explanatory variable encompassing the overall atmospheric climatology in the area.
All environmental variables (X_t) were averaged over the entire study area (Figure 1 (a)) and examined using statistical modelling to explore their temporal trends and whether they are possible explanatory variables of sardine LPUE. The study area was delimited considering the area fished by the fleet, which was based in the 2 study harbours and the bathymetric range from 35 to 200 m depth (Lleonart & Maynou 2003). The fishing range of the vessels was local because the fleet was obliged to return to port daily, and the boats had to be tied up for a minimum of 12 hours daily (Martín et al. 2012).

The LPUE dataset contained irregularities in terms of missing data in the winter months and in the different number of trips where fishing operations were carried out (Table I, Figure 1 (b), Figure 2). This was due to the annual closure of the purse seine fishery in the area for 2 months to protect anchovy recruitment. The closure occurs usually in December and January, but may be advanced to mid-November or delayed until mid-February for ad hoc reasons.

Statistical analyses

Because the objective of the analysis was to relate trends in the environmental variables to the temporal variation observed in sardine fisheries productivity, to avoid any influence of the monthly cycle (Figure 2), the LPUE series was seasonally adjusted (SaY_s) as follows:

$$(SaY_t) = Y_t - \mu_s$$

where the calculation of the monthly averages (μ_s) using the data from all years was used to correct the time series by subtracting these values from each cycle subseries (months) (Figure 3). This simple seasonal adjustment was chosen because we were not interested in imputing missing LPUE data, which is a requirement for many decomposition methods since they do not allow 'internal' missing values.

The decomposition and extraction of temporal trends in the data series were performed according to 'the seasonal and trend decomposition procedure based on loess' (STL) (first designed by Cleveland et al. 1990) (Figure 4). The STL is an empirical, non-parametric filtering procedure that decomposes a time series (X_t) into three unobservable components using an iterative procedure (inner and outer loop) based on successive smoothing (for more details see Cleveland et al. 1990), resulting in a trend (t_t), seasonal (s_t) and residual or short -term variation (e_t) and is as follows:

$$(X_t) = (t_t) + (s_t) + (e_t)$$

Overall, the STL includes six parameters that determine the degree of smoothing in trend and seasonal components: n_p (Number of observations in each cycle of the seasonal component), n_i (Number of iterations of the inner loop), n_o (Number of iterations of the outer loop), n_l (Smoothing parameter for the low pass filter), n_s (Smoothing parameter for the seasonal component), and n_t (Smoothing parameter for the trend component). The smoothing parameters of the seasonal component were selected using the visual diagnostic method described by Cleveland et al. (1990), while the trend smoothing parameters using the smallest odd integer number that satisfies the following equation:

$n_t \geq \frac{1.5\, n_p}{1 - 1.5 n_s^{-1}}$ (Cleveland et al. 1990).

The seasonally adjusted LPUE (Figure 3) showed relatively stable values around the zero mean until approximately 2007 and decreasing values from 2008 onwards, indicating the possible presence of a change in the trend around the mid-2000s. This change in trend suggests that a better description of the seasonally adjusted LPUE may be provided by segmented regression. The selection of the best explanatory segmented regression was achieved by comparing linear and non-linear (second order polynomial) models and choosing the model with the lowest Akaike Information criterion (AIC). The AICs were the minimum values obtained during the process of the selection of the optimum breakpoint performed for each regression model. The selection of this point, indicating a marked change (in this case on LPUE over time), was performed by doing a search grid throughout a time range starting from the beginning of 2001 to the end of 2012 (ca. 90% of the data) and choosing the break that produced the model that minimized the AIC (Crawley 2007). Because the objective was not to test the null hypothesis of no effects, no correction for autocorrelation was attempted.

To assess the influence of exogenous factors on the decrease of sardine landings, the environmental trends extracted by the STL procedure were included as explanatory variables in the Generalized Additive Model approach (GAM, Hastie & Tibshirani 1990; Wood 2006) using the seasonal adjusted LPUE as the response variable. The cubic regression spline was used as a one-dimensional non-parametric smoothing function and a double penalty was applied to the penalized regression to reduce the chance of over fitting. As error distribution, the Gaussian with the identity link function was applied, and the restricted maximum likelihood estimation (REML) was used.

To detect possible high-dimensional collinearities, the variance inflation factors (VIFs) between all environmental variables were calculated. The covariates with the highest VIFs were removed from the model until the highest VIF value was <5 (Zuur et al. 2007).

The residuals of the full model were checked using variography, and violations of the independence assumption were detected (Figure 5 (a)). Consequently, to avoid a Type I error, the generalized additive mixed model (GAMM), which is capable of accounting for dependence between observations by adding a correlation structure to the additive model, was used (Wood 2006). Following Pinheiro & Bates (2000) and Zuur et al. (2009), we selected the linear residual correlation based on the minimization of the AIC by comparing models with the same fixed component (i.e. the full model with all the covariates) and different correlation structures. Furthermore, to assess the adequacy of the linear correlation structure, we investigated the sample semi-variogram for the normalized residuals (Figure 5 (b)). The general form of the GAMM used in the analysis has the following structure:

$$y = \beta_0 + \sum_{j=1}^{p} f_j\left(X_j\right) + \varepsilon_j$$

$$corr(\varepsilon_{js}, \varepsilon_{jt}) = \begin{cases} 1 \; if \; s = 0 \\ h(s,d) = 1 - \left(\frac{s}{d}\right) \; if \; 0 < s < d \end{cases}$$

where β_0 is the intercept, X_j are the covariates, f_j the cubic spline smoothing function for each covariate and ε_j are the error terms, which are normally distributed with mean 0 and variance σ^2. In the independence assumption, residuals from different time points were not allowed to covary. Next, we modelled the dependence between the residuals of different time points (ε_{js}, ε_{jt}) by the introduction of the linear correlation structure (second equation), where $h(\cdot)$ is the correlation function, s is the temporal distance between ε_j and ε_{jt} and d is the range, which represents the time distance at which residuals are no longer correlated.

The likelihood ratio test (ML) was used to obtain the optimal fixed model formulation, and the final combination of variables was refitted using REML (Zuur et al. 2009).

All analyses were performed with R v. 3.1.2, and the mgcv library was used to implement the generalized additive and mixed models (Wood 2006).

Results

Sardine LPUE exhibited the lowest values in the winter, while the highest LPUE occurred between the spring and fall (Figure 2). Figure 3 shows the seasonally adjusted LPUE and the fitted breakpoint regression. Landings underwent a decreasing trend during the whole period, with higher values between 2000 and 2004, followed by a slow decrease between 2004 and 2006 and a more accentuated decline starting in 2006.

The values of the AIC when comparing the different models suggested that the trend in LPUE was better modelled by dividing the data into two blocks rather than assuming a constant variation over time. The first block was best described with a linear function, while the second was best represented by using a second order polynomial regression. The profile of the AIC indicated that the optimum break was in 2005, and specifically, in June of that year. The seasonally adjusted LPUE decreased linearly and more slowly before the break and was characterized by large fluctuations, followed by a jump in mid-2005 to a higher LPUE. The second block was characterized by a strong LPUE decrease and slight intra and inter-annual variations, with the minimum values of LPUE almost constant at the end of the series (Figure 3).

Table II shows the parameters used for the STL decomposition of the environmental variables. The trend components obtained from the environmental series are shown in Figure 4. Salinity showed two clear increasing trends during 2000-2006 and 2009-2013 and for a period between 2006 and 2009 where the values reached those observed in 2000; overall, the values at the end of the study period were notably higher than those at the beginning of the period (ca. 37.7 vs ca. 38.2) (Figure 4 (a)). Temperature showed a slightly increasing trend with fluctuations during the whole period, although less marked than salinity (from 18.8 at the beginning of the period to 19.0 °C, approximately) (Figure 4 (b)). Figure 4 (c) shows the WeMOI trend, which was characterized by a decrease from 2000 to 2006, followed by stabilization at negative values; the highest positive values were observed between 2000 and 2003 (Figure 4 (c)). Both the Meridional and the Zonal currents showed a decreasing trend from mainly positive values to mainly negative ones starting from the end of 2009. Both currents presented a peak of positive values in 2009, indicating a higher northward flow in the case of the Meridional current and a higher eastward flow for the Zonal current (Figure 4 (d), Figure 4 (e)).
The calculation of VIFs to determine variables of high collinearity indicated a value of 5.67 for the Zonal current, and hence, this variable was not included in the model. The other variables showed a maximum VIF of 3.73 and were utilized because they did not introduce major bias in the analyses.

The GAMM formulation, with the incorporation of the linear residual correlation structure, was selected because the semi-variogram on the residuals compared with the GAM full model showed temporal independence (Figure 5) and because it minimized the AIC compared to the GAM formulation. The optimal fixed model formulation of the GAMM included Salinity, WeMOI and the Meridional current and explained 47% of the deviation. The parameter estimates of the GAMM are shown in Figure 6 and in Table III. Significant negative effects on the LPUE were present in relation with WeMOI for negative values between ca. -0.5 to ca. -0.2, while positive values higher than ca. 0.2 positively correlated with abundance. Although not particularly evident, a positive effect was present for WeMOI values lower than ca. –0.8 (Figure 6 (a)). The non-linear relationship with salinity is shown in Figure 6 (b). Negative significant effects were found for values lower than ca. 37.5, followed by values not affecting abundance until ca. 38. After this value, significant positive effects were recognized and were characterized by a local peak at ca. 38.1, which was followed by a negative non-significant effect (Figure 6 (b)). The meridional current negatively affected LPUE when flowing southward and positively at the opposite direction, with the shape of the relation presenting a local positive peak between 0.01 to 0.02 m/s, and anything above the positive effect started a decrease (Figure 6 (c)).

Discussion

The highly productive waters surrounding the Ebro river represent one of the few exceptions in the essentially oligotrophic coasts of the Mediterranean Sea; they are influenced by the two principal enrichment processes characterizing this semi-enclosed sea: nutrient intake by large river discharge and exposure to strong winds, allowing water mixing (Salat 1996; Salat et al. 2002; Lloret et al. 2004).

During the period of 2000 to 2013, the declining trend of sardine LPUE was characterized by two striking events: the sudden increase in mid-2005, followed by an abrupt decrease until the year 2010, where it stabilized at a lower value for the rest of the investigation period.
The breakdown of the seasonal adjusted LPUE agrees with the findings of Tugores et al. (2010), who, with the use of acoustic surveys, described a general decreasing trend in abundance from 2003 to 2006 with signals of recovery during the year 2005 in the area surrounding the Ebro. Since sardines in the NW Mediterranean Sea spawn from November to March (e.g. Lloret et al. 2004; Palomera et al. 2007), during the early summer, the fished sardine population is mainly composed of adults that are 1 and almost 2 years old (Lloret et al. 2004). The discontinuity observed in the summer of 2005 might have occurred due to more suitable environmental conditions during the spawning season between the late autumn of 2003 and the winter of 2004 compared with the other spawning periods preceding the breakpoint. In particular, temperature during this period was on average relatively low and had small variability (low standard deviation compared to other years) which could indicate a completely broken thermocline in mid-autumn. This homogeneous water column likely allowed optimal environmental conditions in terms of nutrient supplies that lasted the whole spawning season and therefore increased food availability for sardine early life stages. Although this was only a small recovery, which formed part of the general decreasing trend observed in the area, it could have led to an expansion of the area

occupied by this fish and the formation of more dense patches (in areas with favourable environmental conditions), which became more susceptible to fishing pressure (Barra et al. 2015).

The second characteristic event of this period, occurring between 2010 and 2013 and consisting of the stabilization at the lowest values, is in accordance with the findings in the nearby Gulf of Lions (NW Mediterranean Sea), where sardine landings in the same period became even lower than those during the period before the 1960s (Van Beveren et al. 2016).

A part of the landings variation, which are only an approximation of fish abundance, could be explained by a change in fishing effort (Figure 1 (b)), but sudden changes, such as the LPUE shift observed, emphasize the fact that the fluctuations can also be due to variation in the availability of the species to the fishing gear due to environmental conditions, thus leading to low productivity (Cushing 1995; Van Beveren et al. 2016). Furthermore, when looking at the estimated summer biomass from 2010 to 2013 from scientific acoustic surveys (MEDIAS) in the whole GSA 06, its average was almost three and a half times higher than their respective annual landing estimates (STECF 2015). In these estimates, sardine seems to maintain high biomass regardless of the preceding fishing pressure, and consequently, it seems unlikely that the recent LPUE changes were caused by overexploitation alone. Instead, a combination of overexploitation and an unfavourable environment for the species would better explain these trend changes. On the other hand, the likely increase in the catchability of modern purse seiners, as seen with other fleets in Europe (García-Carreras et al. 2015), may contribute to the problem of decreasing abundance of sardine due to excessive fishing mortality.

The aim of this study was to test the environmental drivers that best explained the variation of sardine LPUE, and to do so we used GAM and GAMM, which are useful tools to describe relationships between biological and environmental variables (e.g. Bellido et al. 2008; Martín et al. 2008; Giannoulaki et al. 2011; Carpi et al. 2015).

In our study, in the final GAMM obtained, the drivers that better explain the LPUE dynamic are WeMOI, SSS and MC. The influences of the WeMOI on fish populations were indirect, with its effects mediated through relationships with local environmental factors (Martín et al. 2012). In fact, during the positive WeMOI, which positively affected LPUEs, the low pressures in the Gulf of Genoa and the high pressure over the Azores (Martin-Vide & Lopez-Bustins 2006) led to two phenomena: one, the prevailing winds affecting the study region came from the northwest (García-Sellés et al. 2010) and two, an augment of the river's discharge rate volume due to an increase in rainfall in the head of the Ebro drainage basin in north Spain (Martín et al. 2012).

When north westerly winds and river discharge are simultaneously propitious, wind pushes the continental and more productive waters across the shelf and causes these waters to be mixed and trapped in the mesoscale eddy structure, which takes form offshore of the Ebro mouth (Font 1990; Xing & Davies 2002; Salat et al. 2002). Furthermore, wind stress allows a rise in the mixing and increases the turbulence in the surroundings of the river mouth, widening the mixing area and thus reducing the salinity gradient (Sierra et al. 2002). The resulting waters become more productive and have salinity values more typical of the shelf-water (ca. 38), which was observed in our results and are positively related with LPUEs.

These favourable, high nutrient conditions enhance phyto- and zooplankton production (Salat 1996; Salat et al. 2002; Lloret et al. 2004) and allow the sardine population to increase in abundance and consequently yield high LPUE (Agostini & Bakun 2002; Lloret et al. 2004; Sabatés et al. 2007; Palomera et al. 2007). Our findings are congruent with those of other studies in the Mediterranean Sea (Lloret et al. 2004; Ganias 2009; Martín et al. 2012) as well as in other areas and for other species of sardine (e.g. Pacific sardine in Emmett et al. 2005), where the positive relationships between sardine and primary and secondary production, the latter being enhanced by wind and continental water inputs, are described.

The negative values of the WeMOI, which are characterized by an onshore wind flowing from the South (S) and Southeast (SSE), lead to warmer conditions and enhance rain events in the area (Martin-Vide & Lopez-Bustins 2006) and do not allow the discharge water of the river to extend offshore (Xing & Davies 2002); instead, it remains confined to the north and northwest of the Ebro mouth (Mestres et al 2003), probably decreasing primary production. These conditions negatively affect sardine LPUE. Negative relationships are also found with low values of salinity, suggesting that less saline waters or meteorological parameters that lead to a reduction in the salinity of the coastal waters (i.e. rainfall enhanced by WeMOI) are not a suitable environment for this small pelagic fish. As described by Palomera et al. (2007), sardine in early life stages, contrary to anchovy, can be distributed in a wide salinity range and appear to have a lower tolerance to low salinity waters.

Moreover, another environmental variable (i.e. current flowing towards the coast) that contributed to the explanation in the landing per unit effort variability was the meridional current flowing northward, which was positively related with LPUE. This northward current, resulting from the interaction between the cross shelf flow and the topographic structure of the Ebro shelf, which displaces the coastal flow eastward (Lorente et al. 2015), is described as being essential for the generation of the mesoscale anticyclonic eddies along the Catalan coast (Garreau et al. 2011). These structures allow the surface waters and particles to converge in the centre of the anticyclonic circulation, increasing food availability (Bakun 2006) and influencing sardine aggregations.

Overall, with respect to previous studies in the area, our results constitute a step forward by applying a more complex methodology where variation due to the seasonality, non-linear relationships, autocorrelation in the data and collinearity of the environmental covariates were considered and thus provided further evidence of the dependency of sardine LPUEs upon specific hydrographic variables. The study stresses the importance of the additive and non-linear effects on sardine landings production in Catalan Sea via the WeMOIand the local environmental variables (i.e. salinity and northward current). Although LPUEs are only an approximation of the population abundance, they are a function of fishing efforts and stock dimension (Santos et al. 2012); therefore, the environmental influences encountered can also be expected to affect the sardine population in the area.

Sardine landings along the Catalan Coast have been characterized by cyclical fluctuations for the last 40 years (Martín et al. 2012), and the analysed period is part of the long decreasing trend starting from the mid-90s. In the studied area and the whole GSA06, this decreasing trend reached the lowest values of the historical series during the last years of the series. Given the overexploited status of sardine stock and the nonstationary nature of the relationships between the physical factor and the populations' functional response (Schmidt et al. 2014), which may have changed over time, unexpected patterns such as the downfall of cyclic fluctuations may arise and prolong the period of low abundance. The environmental conditions that can be expected in the western Mediterranean Sea, under the current climatic change, is a considerable decrease in rainfall and wind, warmer surface waters and a prolonged stratification period (Calvo et al. 2011). These conditions are in line with the second half (i.e. 2006 and later) of the time series environmental data analysed here. If these trends continue in future decades, a likely scenario of decreased primary productivity and lower sardine fisheries production can be anticipated.

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Tables

Table I. Sum of landings in tons and number of fishing operation for each month subseries

	jan	feb	mar	abr	may	jun	jul	aug	sep	oct	nov	dec
Landings (Tons)	0	1090.72	2815.35	3865.54	4677.89	3463.29	3236.93	4100.31	3868.99	4501.23	2497.49	1094.84
N of trips	0	1335	3034	3160	3050	2246	2615	2710	2439	2558	2039	1289

Table II. STL decomposition parameters. n_p = Number of observations in each cycle of the seasonal component, n_i = Number of iterations of the inner loop, n_o =Number of iterations of the outer loop, n_l = Smoothing parameter for the low pass filter, ns = Smoothing parameter for the seasonal component, n_t = Smoothing parameter for the trend component

	Decomposition Parameters					
Environmental Variables	n_p	n_i	n_o	n_l	n_s	n_t
Temperature	12	2	0	13	29	19
Salinity	12	2	0	13	21	19
WeMOI	12	2	0	13	27	19
Meridional Current	12	2	0	13	25	19
Zonal Current	12	2	0	13	21	19

Table III. Final GAMM model with the analysis of deviance of the covariate (WeMOI = Western Mediterranean oscillation index; Sal = Salinity; MC = Meridional current). Edf = estimated degree of freedom. DVe = explained deviance.

	edf	**F**	**p-value**	**DVe**	**R^2**
s(WeMOI)	2.878	5.898	< 0.01	47%	0.43
s(Sal)	5.06	5.144	< 0.01		
s(MC)	3.1	5.24	< 0.01		

Figure captions

Figure 1. a) The study area limited by the 35 m and 200 m of the isobaths and the two fishing ports; b) landings in tons per month and sum of the days per month in which fishing operations were carried out by the fleet. Note the missing data in the winter due to the annual closed season; c) Annual landings in tons from the two ports starting from the year 1993.

Figure 2. Seasonal cycle of the sardine LPUE. The bold lines indicate the median, while bold points are the mean LPUE values.

Figure 3. Variation in seasonal adjusted LPUE series (points) and segmented regression (lines) fitted to identify the possible presence of breaks.

Figure 4. Main graphs: Trend components of the environmental drivers obtained by the STL decomposition (SAL = Salinity; SST = Sea surface temperature, WeMOI = Western Mediterranean oscillation index; ZC = Zonal Current; MC = Meridional current). Small graphs: monthly mean of each covariate.

Figure 5. a) Experimental variogram of the residuals obtained by applying a GAM with all environmental trends. Note that there is evidence that the independence assumption is violated. b) Experimental variogram of the normalized residual using the GAMM with the linear correlation structure. The horizontal axis *(h)* in each graph represents the time distance.

Figure 6. Final GAMM of the seasonal adjusted LPUE in relation to the trend of the environmental variable. The y-axis indicates the smoothers for significant effects of a) Western Mediterranean oscillation index, b) Salinity and c) Meridional current. Shaded areas show 95% confidence limits for the smoothers.

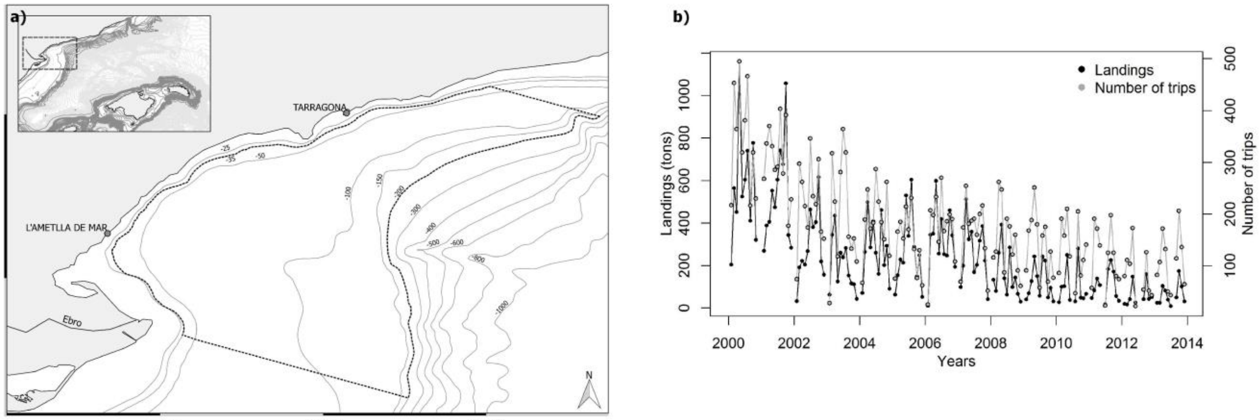
a)
TARRAGONA
L'AMETLLA DE MAR
Ebro
41°6′
40°48′
0°54′
1°12′
1°30′
N
b)
Landings
Number of trips
Landings (tons)
Number of trips
Years
0
200
400
600
800
1000
100
200
300
400
500
2000
2002
2004
2006
2008
2010
2012
2014

FIG. 1

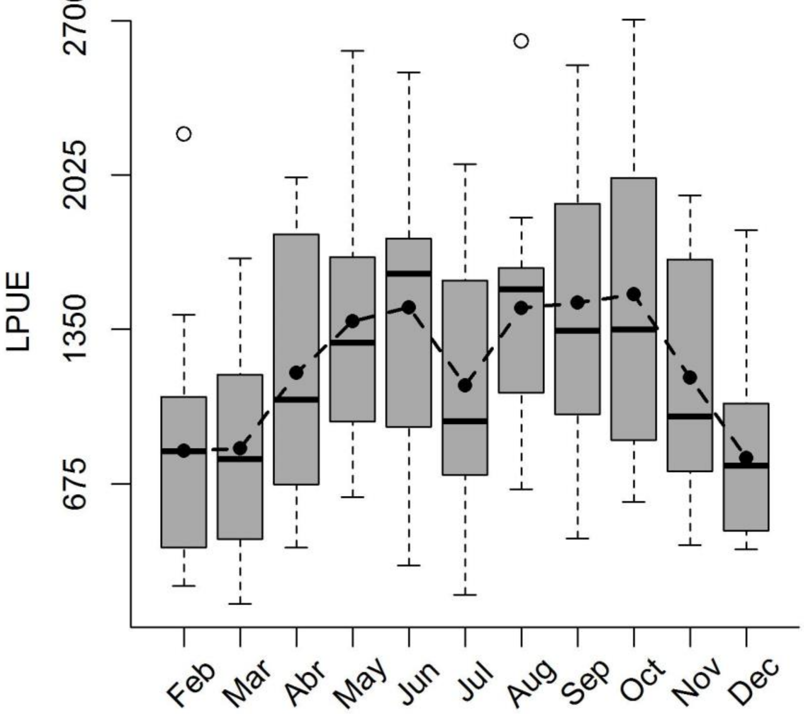
LPUE
2700
2025
1350
675
Feb
Mar
Abr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

FIG. 2

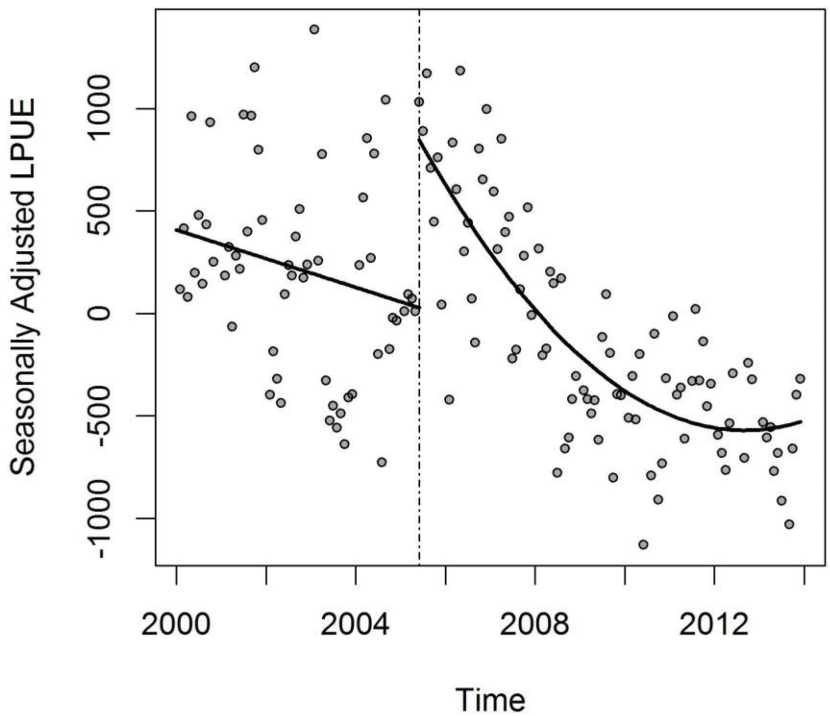
Seasonally Adjusted LPUE
-1000
-500
0
500
1000
2000
2004
2008
2012
Time

FIG. 3

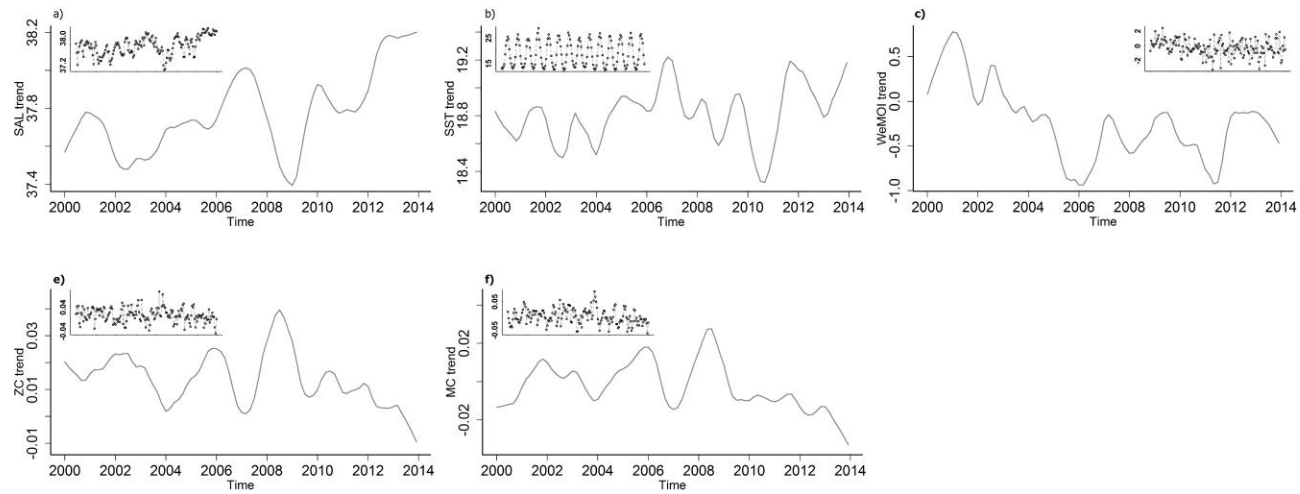
a)
SAL trend
37.4
37.8
38.2
b)
SST trend
18.4
18.8
19.2
c)
WeMOI trend
-1.0
-0.5
0.0
0.5
e)
ZC trend
-0.01
0.01
0.03
f)
MC trend
-0.02
0.02
2000
2002
2004
2006
2008
2010
2012
2014
Time

FIG. 4

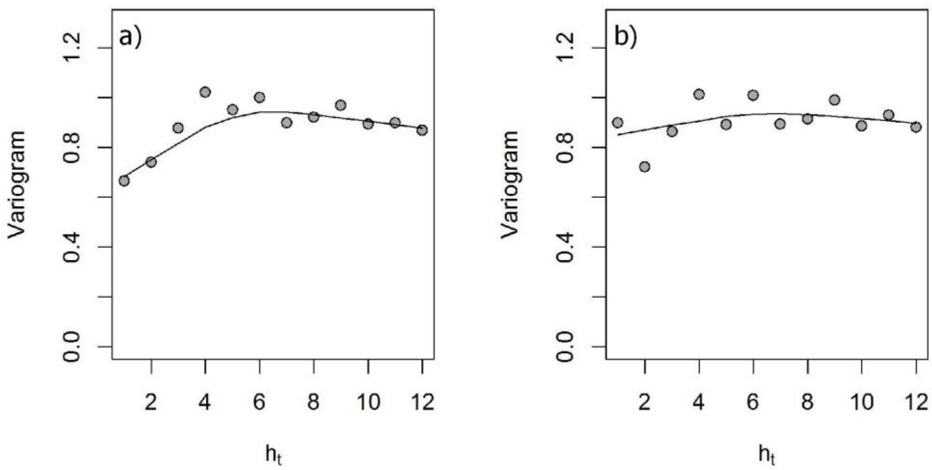

FIG. 5

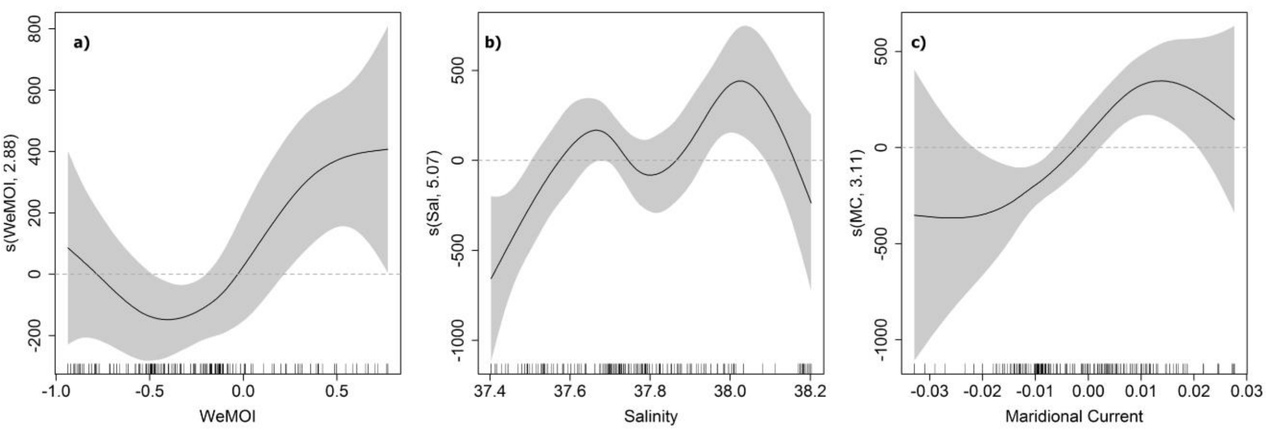
a)
s(WeMOI, 2.88)
WeMOI
b)
s(Sal, 5.07)
Salinity
c)
s(MC, 3.11)
Maridional Current

FIG. 6