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Environmental Conditions Affect Striped Red Mullet (*Mullus surmuletus*) Artisanal Fisheries

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Abstract: The influence of environmental variables (oceanographic and climatic) on the catch rates of striped red mullet (*Mullus surmuletus*) by artisanal fishery was investigated using different time series models (Dynamic Factorial Analyses; Min-Max Factorial Analyses and Generalized Least Square models). Climatic and oceanographic survey data were collected at different areas of the Portuguese coast (Northwestern, Southwestern and South-Algarve) with distinct oceanographic regimes. Time series analyses reveal an effect of fishing effort in catch rates in Southwestern areas. Variability in *M. surmuletus* catch rates was associated to regional environmental multi-controls. Upwelling and westerly winds were the main drivers of catch rates variability across the three areas but the type of relationship varied among them. A consistent relationship between catch rates and environment factors was identified during the peak period of seasonal recruitment (spring to summer) in Southwest and South-Algarve coast, with Upwelling-summer and Sea surface temperature-spring affecting short term (lag 2 years) catch rates. In South-Algarve the increase in SST in summer, during peak of spawning, was correlated with the catch rate increase with a lag of two years. Environmental effect on catch rates reveals that fisheries management needs to accommodate the regional effect of environment variables on species biology to better define future assessment plans (catch limits).

Keywords: recruitment; oceanographic features; times series models; population dynamics; regional scale analyses

Citation: Leitão, F. Environmental Conditions Affect Striped Red Mullet (*Mullus surmuletus*) Artisanal Fisheries. *Oceans* **2023**, *4*, 220–235. https://doi.org/10.3390/oceans4030015

Academic Editors: Gualtiero Basilone and Diego Macías

Received: 1 March 2023
Revised: 19 June 2023
Accepted: 27 June 2023
Published: 29 June 2023

1. Introduction

Fish stocks are constantly adapting to fluctuations in the environment and to fishery disturbance; therefore, it is difficult to determine the partial effects of each type of forcing on catch rates. In fact, commercial fisheries' time-series models contain noisy and mixed information on the respective effects of climate and environmental variability, population dynamics, and exploitation (Durand and Mendelssohn 1998 [1]; Santos et al., 2001 [2]; Lehodey et al., 2006 [3]). Recent work has demonstrated that such effects are not simply additive, but rather interact (Levi et al., 2003 [4]; Pinnegar et al., 2013 [5]) with fisheries' time series resulting from a combination of different processes containing signatures of global and local influences, long-term trends, and seasonality (Durand and Mendelssohn 1998 [1]). Therefore, assessing and understanding environmental change effects on fisheries is one of the challenges for the sustainable management of marine ecosystems.

The concern with environmental effects on fisheries, mostly related to stock recruitment, has been an important issue since early 1990. These hypotheses consider that physical and biological ocean conditions are important to the survival of fish larvae (Lasker 1975 [6]; Cury and Roy 1989 [7]; Cushing 1996 [8]). The works in the field of stocks–recruitment relationships have led to the development several theories discussed in fisheries ecology literature, such as phenological processes (e.g., match–mismatch theory, Cushing 1996 [8]), mesosclale features, or the optimal environmental window (Cury and Roy 1989 [7]) and stable ocean (Lasker 1975 [6]) hypotheses, advocating that physical and biological ocean conditions are important for the survival of fish larvae and their future recruitment. For instance, variability in the sea surface temperature, upwelling, winds, tidal currents and oceanic circulation, precipitation, and river runoff are known to affect changes in the timing of reproduction, population dynamics, abundance, distribution, and inter-specific relationships at both regional and oceanic scales (Santos et al., 2001 [2]; Ottersen et al., 2001 [9]; Lehodey et al., 2006 [3]). However, the multiplicity and complexity of the environmental controls limit our ability to adequately understand and model environment–recruitment relationships in marine systems, and, for many fish populations, the relationships between environment and recruitment estimations vary when retested with new and longer sets of observations (Myers 1998 [10]). Analyzing the patterns of variations in fish species in contrasting environments and subject to a variety of fishing pressures is, thus, expected to shed light on the relative effects of these factors and/or the way they interact.

The striped red mullet (*Mullus surmuletus*) is a major target species in many Mediterranean and North Sea demersal fisheries (Levi et al., 2003 [4]; Pinnegar et al., 2013 [5]). *M. surmuletus* exhibits a life strategy with a short spawning season and fast-growing pelagic larvae, taking one year to reach maturity (ICES 2010 [11]; Bentes 1996 [12]; Arslan and İşmen 2013 [13]; Mahé et al., 2013 [14]). There are few references regarding the reproductive biology of *M. surmuletus* in the Portuguese Iberian coast (Bentes 1996 [12]). Species spawning is variable from the North Atlantic to the temperate Atlantic/Mediterranean waters, with a spawning peak occurring from April to May in the Northern Aegean Sea/Mediterranean (Arslan and İşmen 2013 [13]), and May to June in the English Channel and southern North Sea (Mahé et al., 2013 [14]). *M. surmuletus* abundance increased in the North Sea, coinciding with increased temperatures after 1995 (Pinnegar et al., 2013 [5]). Climate change effects on *Mullus barbatus* fisheries, a congeneric warm-water *Mullus* spp., were also detected around the UK, as species increased catches due to ocean warming (Cheung et al., 2012 [15]). Moreover, fish biomass distribution response to anomalies in environmental factors (salinity and temperature) in Mullus spp. have been recorded in the Spanish Mediterranean coast, with *M. barbatus* showing affinity for low salinity waters (García–Rodríguez et al., 2011 [16]). *M. surmuletus* shows a positive correlation with warmer waters in the Strait of Sicily, as higher recruitment levels corresponded to above-average sea surface temperatures (SST) during the early life stages. (Levi et al., 2003 [4]).

In 1989, FAO reported an 8434 t total *M. surmuletus* catch, which continuously increased to 12,783 t by 2009 (ICES 2010). In Portugal, accordingly to Direcção-Geral das Pescas e Aquacultura (DGPA) statistic fisheries office from 1989 to 2009, the minimum, medium and maximum landings of *M. surmuletus* were 85, 144 (± 38 standard deviation) and 249 tonnes. Artisanal fleet sector accounted for 62% of the total Portuguese Mainland *M. surmuletus* landings (source: DGPA). In Portugal, the artisanal sector (boasts length < 9 m) includes mostly (85.9%) fiber glass open-deck local boats (<7 m long) that can operate between 3 to 6 miles (allowed to boat with a UHF radio) from the coast. This fleet accounts for about 80% of the Portuguese fleet (Gaspar and Pereira 2014 [17]) and uses static/passive gears, namely, gillnets, trammel nets, pots and traps, and hook and line gears (Leitão et al., 2014 [18,19]). Therefore, since ancient times, artisanal fisheries have played an important social–economical role in Portuguese coastal communities (Leitão et al., 2016, 2018, 2020 [20–22]). Understanding coastal marine resources' variability is crucial for fisheries management, namely, artisanal fisheries. Presently, Portuguese coast management measures include the minimum landing size; however, no seasonal, spatial closures and TAC or quotas are enforced for the Portuguese fleet (UE 2022 [23]). This study analyzes the influence of environmental variables (oceanographic and climatic) and fishing efforts on the catch rates of striped red mullet *Mullus surmuletus* exploited by Portuguese artisanal fisheries in distinct areas along the Portuguese coast (different oceanographic regimes), using different time-series models.

2. Material and Methods

2.1. Study Sites

Portugal is located on the western coast of the Iberian Peninsula, having a continental shelf area of 28,000 km^2, with a variable width of 150 km in the north to 25 km in the south.

The Portuguese coast is oriented North–South along the meridian 90° W in average and around the latitude 40° N. The oceanographic conditions along the western Iberian Peninsula ecosystems are variable throughout the year, from north to south, and more unstable than previously thought (Relvas et al., 2007 [24]). The effect of environmental variability on *M. surmuletus* catch rates was separately evaluated for the northwest, southwest and south Atlantic coasts of Portugal (Figure 1) because each area has distinct oceanographic regimes (Bettencourt et al., 2004 [25]). These three areas match the International Council for the Exploration of the Sea (ICES) IXa subdivisions areas for Portugal and are hereafter designated as Northwest coast (IXaCN), Southwest Coast (IXaCS) and Algarve, South Coast (IXaS-Algarve).

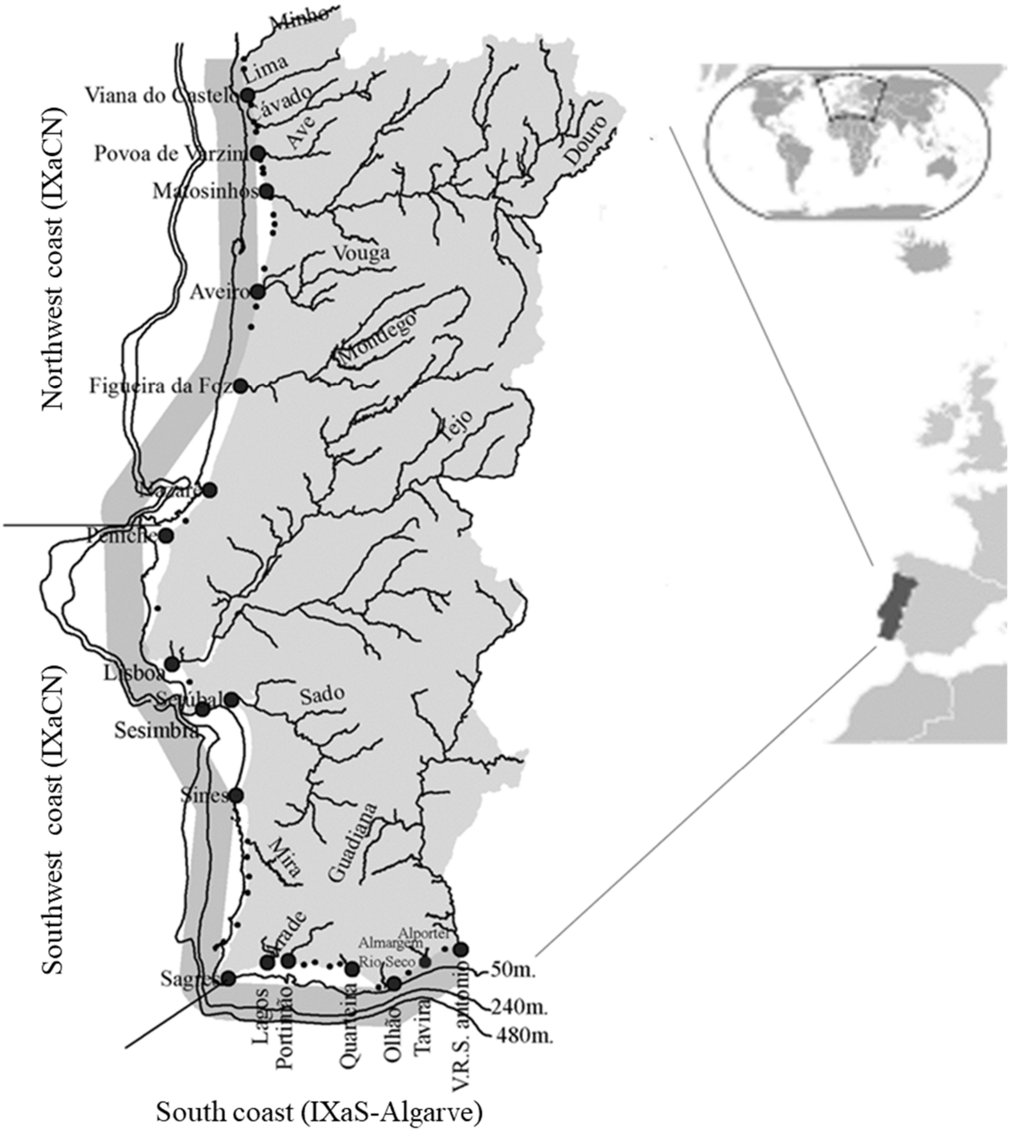

Figure 1. Portuguese coastal study areas: northwest (IXaCN), southwest (IXaCS), and south Algarve (IXaS-Algarve) coasts. Large dots are main ports, while small dots are secondary ports. Lines in the coastal area denoted 50, 240, and 480 m bathymetry/depth.

2.2. Data Acquisition

Landing (kg) and fishing effort data (FE: boats.days) for artisanal fleet sector for the period 1989–2009 were obtained from DGPA Portuguese fisheries office. Fishing data were grouped into annual periods and per area (using individual port data). Annual Landings Per Unit Effort (LPUE or catch rates) were used as a proxy for *M. surmuletus* biomass production (biomass index proxy). Landings Per Unit Effort is a good species biomass proxy and direct proportionality with catches can be assumed from the fact that in multi-gear fisheries this species is not discarded due to their high commercial value. Landings Per Unit Effort (response variable) were estimated by dividing total annual landings (kg) by the FE that include total number of fishing boats.days (LPUE units: kg per fishing boats.days).

North Atlantic Index (NAO) affects marine environment. Thus, NAO effect on fisheries recruitment has received increase attention, namely regarding the inter-annual fluctuation effects on important marine resources such as bivalve's, cephalopods, flatfishes and fast growth short live pelagic Atlantic species and demersal Mediterranean fish species (Solow 2002 [26]; Ullah et al., 2012 [27], Maynou 2011 [28]; Baptista & Leitão 2014 [29]; Leitão et al., 2014 [19]; Baptista et al., 2022 [30]). Thus, NAO was used as a climatic explanatory variable (http://www.cgd.ucar.edu/jhurrell/nao.html (accessed 10 on October 2010), Hurrell 1995 [31]). The NAO is a climatic phenomenon characterized by fluctuations in the difference of atmospheric pressure (measured at sea level) between the Icelandic low and the Azores high. Positive values are typically associated with stronger-than-average western winds over the middle latitudes and more intense weather systems over the North Atlantic. Addition, during positive NAO phase warmer Atlantic temperatures are observed while during negative NAO cooler temperatures prevail.

The annual and seasonal mean Sea Surface Temperature—SST (source: NASA: http://gdata1.sci.gsfc.nasa.gov (accessed on 10 October 2010)), upwelling index—UPW (source: Pacific Fisheries Environmental Laboratory web page: http://www.pfeg.noaa.gov (accessed on 10 October 2010) both easterly winds—u-wind and northerly winds—v-wind components (Source: PO.DAAC: http://podaac.jpl.nasa.gov/dataset/CCMP_MEASURES_ATLAS_L4_OW_L3_5A_MONTHLY_WIND_VECTORS_FLK?ids=&values= (accessed on 10 October 2010; Atlas et al., 2011 [32])) were used as oceanographic explanatory variables. The monthly geostrophic wind data and SST, available from the Modis-Aqua satellite at 4 km spatial resolution, was extracted using the Marine Geospatial Ecology Tools (MGET, Roberts et al., 2010 [33]). The "u-wind" wind component represented the east-west component (a positive u was wind from the west) while the "v-wind" component represented the north-south component (a positive "v" was wind from the south). Wind magnitudewas modeled using u- and v-wind components [WMag: SQRT($u^2 + v^2$)].

The satellite oceanographic data was obtained in raster format and needed to be conjugated with the port/fishing landing data (N = 62 ports, Figure 1), in tabular format. Therefore, the following procedure was adopted:

(1) due to the lack of satellite data near the coast, the ports/harbors coordinates were moved 6 nautical miles into the territorial sea where most mullet artisanal fishery occur (Gaspar and Pereira 2014 [17]);
(2) a buffer with a radius of 36 km was created around each port (polygon shapefile);
(3) the raster values contained within each polygon for a given period of time and port were averaged using the "isectpolyrst" tool of Geospatial Modeling Environment (http://www.spatialecology.com/gme/isectpolyrst.htm (accessed on 10 October 2010));
(4) the data was averaged by fishing area (IXaCN, IXaCS, IXaS-Algarve) using port data (Figure 1).

The upwelling index was obtained from Pacific Fisheries and Environmental Laboratory website (www.pfeg.noaa.gov (accessed on 10 October 2010)). Pacific Fisheries Environmental Laboratory (PFEL) coastal upwelling indices are calculated based upon Ekman's theory of mass transport due to wind stress. Ekman mass transport is defined as the wind stress divided by the Coriolis parameter (a function of the earth's rotation and latitude). The depth to which an appreciable amount of this offshore transport occurs is termed the surface Ekman layer, and is generally 50 to 100 m deep. Positive values of upwelling index are the result of equatorward wind while negative values imply downwelling, the onshore advection of surface waters accompanied by a downward displacement of water.

2.3. Time-Series Analyses (Statistical Models and Assumptions)

Time-series Time series models were used to test relationships between catch rates (response variable) and explanatory variables (climatic: NAO; oceanographic: SST, Wind, Upwelling; and fishing pressure: Fishing Effort) trends. In this study we test hypothesis based on the assumption that fisheries catch rates mainly depend on larval recruitment, which in turn is affected by local/regional and seasonal environmental variability. Focusing the hypothesis on larval recruitment requires a lag in the statistical models in order to avoid results to be interpreted as "behavioural" response to environmental conditions. Accordingly, the environmental (explanatory) variables were centered on species gear recruitment age/size (that is when or how long ago the fish of a given size in the catch where in the larval stage), to allow inferences about the impact of environmental variables on catch rates.

In artisanal fisheries *M. surmuletus* is generally caught by gill nets ranging between 53 mm and 90 mm mesh sizes (Bentes 1996 [12]; Rueda et al., 2011 [34]; Gaspar and Pereira 2014 [35]). However, yields are higher and/or more frequent for exploitation regimes with mesh sizes between 53 and 60 mm (Bentes 1996 [12]; Rueda et al., 2011 [34]; Gaspar and Pereira 2014 [17]). For larger mesh sizes the size distribution of the catches varied between 17 and 30 mm with the mode being 23 mm (Rueda et al., 2011 [34]), which mean that most fishes are caught with 2 years old accordingly biological studies (ICES 2010 [11]; Bentes 1996 [12]; Arslan and İşmen 2013 [13]; Mahé et al., 2013 [14]; Santos et al., 2007 [36]). Moreover, Portuguese scientific selectivity surveys experiments showed large contribution from size classes comprised between 21-26 cm and with large size class retention being 22.6 cm (Mendes et al., 2004 [37]), that is 2 years old fish. Therefore, for time series statistical analysis models a 2 year lag was used. Fishing effort also indirectly affects spawning stock biomass which is targeted by the fishery (by removing adult fish) and recruitment in the following years. To accommodate this effect fishing effort was also lagged two years. *Mullus surmuletus* has a short spawning season, from spring to summer (Cherif et al., 2007 [38]). Therefore, environmental data were also assigned according to the timing of spawning season and grouped by: spring (April to June) and summer (July to September).

In this study it was assumed that landings of *M. surmuletus* are directly proportional to catches. This direct proportionality with catches can be assumed for the artisanal sector, as this species is not discarded due to their high commercial value (Santos et al., 2007 [36]; Leitão et al., 2018 [22]). Catch per unit effort (CPUE), or catch rates, from commercial fisheries has been used to derive indices of relative abundance for many world fisheries (Yimin et al., 2001 [39]). However, such abundance or estimating fishing effort indices requires standardization to consider changes in the ability to catch fish, and fleet composition, and to adjust catch rate estimates for specific factors that may affect the catch rates (Hilborn & Walters, 1992 [35]). Trends in CPUE, which are assumed to be proportional to biomass, are many times used for search evidence of stock depletion (King 1995 [40]). Thus, it was assumed that landings were directly proportional to catches and that catch rates (LPUE as biomass proxy index) are indicative changes in species available biomass.

Separate models were produced for each region and explanatory variable. Therefore, each hypothesis was analyzed separately, according to region and season, independent from the others. This approach was adopted for the sake of clarity, as it is only when the hypotheses regarding the effect of explanatory variables on response variables are strictly defined that they can be discussed and challenged in an objective manner.

Several time series models were used for yearly data analyses, including Min/max autocorrelation factor analysis (MAFA), Dynamic Factor Analysis (DFA) and Generalized Least Squares (GLS) models. Min/max autocorrelation factor analysis and DFA were used because these smoothing techniques can be used for analyzing short, non-stationary time series, with the ability to identify patterns in fisheries data and environmental variables as well as interactions between time series of response (e.g., catch rates) and explanatory variables (Zuur et al., 2007 [41]). The MAFA analyses that best fitted to the available data considered only a single MAFA trend (autocorrelation time lag 1 year) for each region (see: Baptista et al., 2014 [29]). Cross correlations between MAFA axes and explanatory variables were estimated, allowing significant relationships between trends and explanatory variables to be identified (Zuur et al., 2007 [41]). The DFA univariate time series analysis was used to assess the role of explanatory variables over catch rates trends (see: Baptista et al., 2014 [29]; Ullah et al., 2012 [27]). Dynamic Factor Analysis (DFA) models were fitted with a symmetric non-diagonal matrix and the Akaike's Information Criterion (AIC) was used to compare models with and without explanatory variables (Zuur et al., 2003 [42,43]). To deal with serial correlation due to long-term data fluctuations, we also fitted linear models using the Generalised Least Squares (GLS) method. Generalised Least Squares is an extended linear mixed-effect model in which errors are allowed to be correlated and/or have unequal variance (Zuur et al., 2007 [41]). Therefore, the GLS models with (simple models) and without different autocorrelation structures [autoregressive process of order 1 using the partial autocorrelation function and the goodness of fit of an autoregression (AR) analysis and moving average (MA) model (ARMA) was tested, allowing the errors to have unequal variance, as advise for regular spaced datasets such as yearly data] were also performed (Zuur et al., 2007 [41]). The AICs value was used to compare GLS models. If the difference in AIC values of two models (simple and autocorrelation models) is smaller than 2, general statistical consensus dictates using the simpler linear model (Zuur et al., 2007 [41]). For the explanatory variables a significance level of $p < 0.05$ was used.

Since different analyses might reveal different results, a selection criterion was adopted following (Leitão et al., 2014 [18]): the best candidate explanatory was defined according to the number of models that highlighted the same explanatory variable. This selection criterion allows classifying the variables with high (the variable is highlighted in more than one model) or low probability of affecting catch rate. All environmental data series were first tested for normality (Quantile-Quantile plots—QQ-plots) and collinearity (Pair-Plots). In the case of both yearly *M. surmuletus* 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. Second, whenever more than one variable was highlighted we tested the significance of the relationship (in DFA and GLS analyses), accounting for combining fisheries and environmental data series effects by surrogate testing. Both response and explanatory variables were standardized—i.e., N (0,1)—before running models as advised by Zuur et al., (2003) [42,43]. All statistical analyses were done using Brodgar software package that uses R version 3.0.1 (http://www.brodgar.com (accessed on 10 December 2018)).

3. Results

3.1. Ancillary Data

Most of the *M. surmuletus* catches occur in South-Algarve coast (62.4%), followed by Northwestern (23.3%) and southwestern (16.2%) coasts (Source: DGPA). The minimum, mean (±standard deviation) and maximum landings between 1989 and 2009 were: 12.39, 20.1 (±4.5) and 31.437 tonnes for IXaCN; 27.05, 14.68 (±6.04) and 29.028 tonnes for IXaCS; and 22.38, 55.65 (±27.06) and 12.17 tonnes for IXaS-Algarve.

In all areas the variation of the catch rates (LPUE) throughout the time series followed similar patterns to landings (Figure 2). In IXaCN LPUE and landing intra-annual values oscillated around the mean, with no particular trend. In IXaCS landings and LPUE increase until 1991 and 1992, respectively, decreasing oscillatory thereafter with trend values dropping below the average after 1998. In IXaS-Algarve LPUE and landing intra-annual values showed a slightly downward oscillatory trend until 2003–2004 with LPUE values increasing afterword. In IXaCN and IXaCS LPUE followed a similar trend to FE (boats.days) (Figures 2 and 3). In IXaS-Algarve FE varied around the mean with higher anomalies in the period of 1993–1997, when LPUE increased.

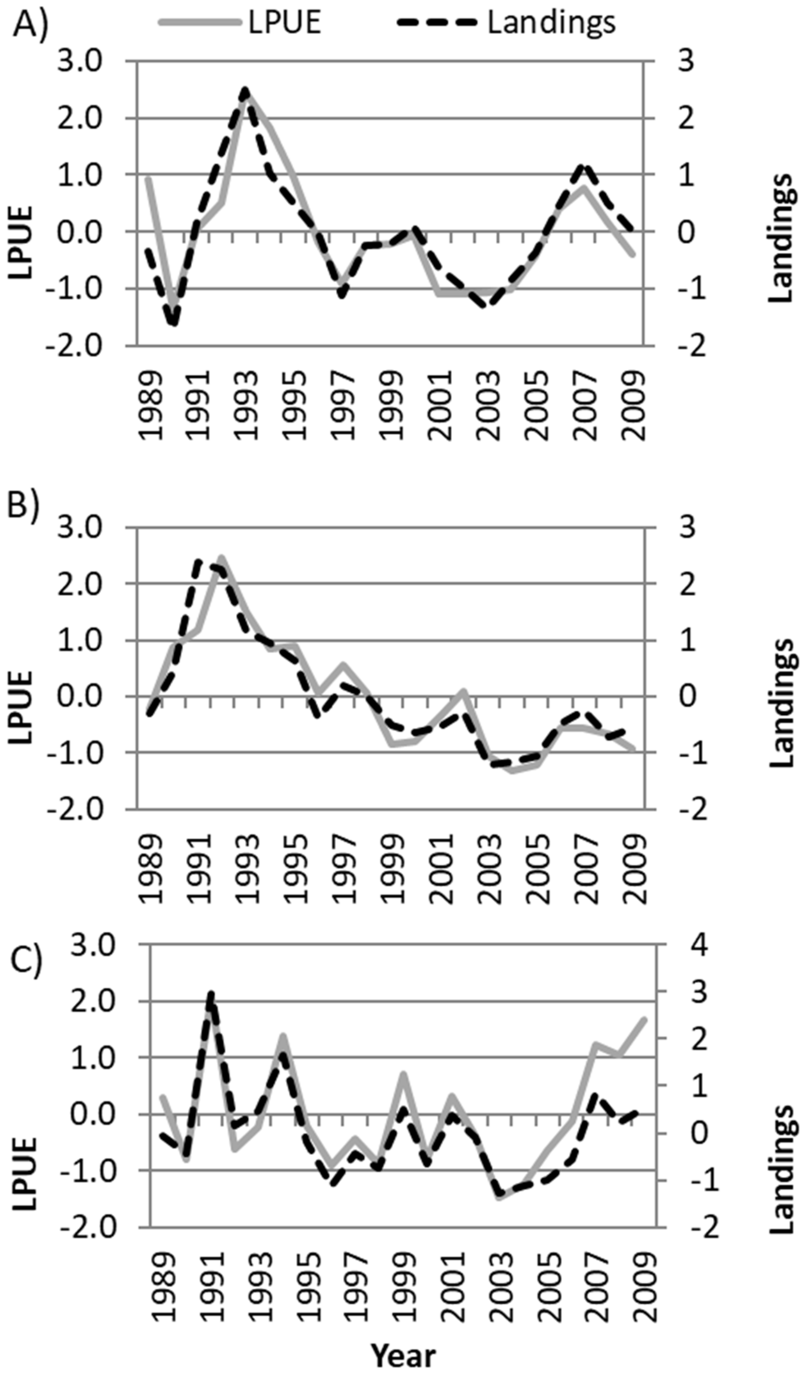

Figure 2. Standardized landings (dotted line) and Landings Per Unit Effort (LPUE—landing per unit effort/catch rates) (continuous line) for the three areas: (**A**) northwestern IXaCN, (**B**) southwestern IXaCS, and (**C**) south IXaS-Algarve from 1989 to 2009.

3.2. Brief Description of the Oceanographic Features in the ICES IXa Subdivisions

The Portuguese Peninsula Iberian coast is characterized by colder SST in the Northwest and Southwest regions than in the Southern region, including in spring and summer seasons (Figure 4). Yearly average downwelling prevail in IXaCN and IXaS-Algarve while in IXaCS UPW prevail year around. In spring and summer upwelling events prevails in all areas being higher in summer in IXaCN and IXaCS. Moreover, the intensity of the UPWindex is much higher in both IXaCN and IXaCS than in IXaS-Algarve (Figure 4).

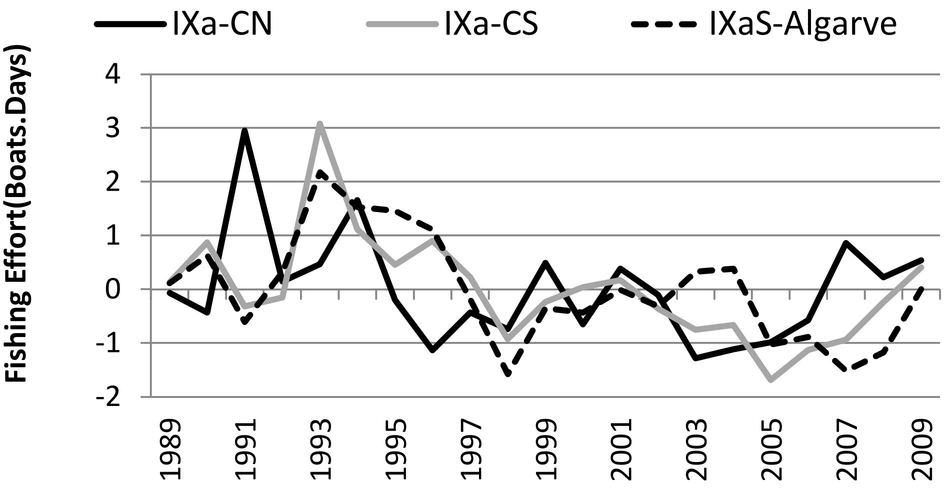

Figure 3. Standardized fishing effort (FE: boats.days) for the three areas: northwestern (IXaCN), southwestern (IXaCS), and south coast (IXaS-Algarve) from 1989 to 2009.

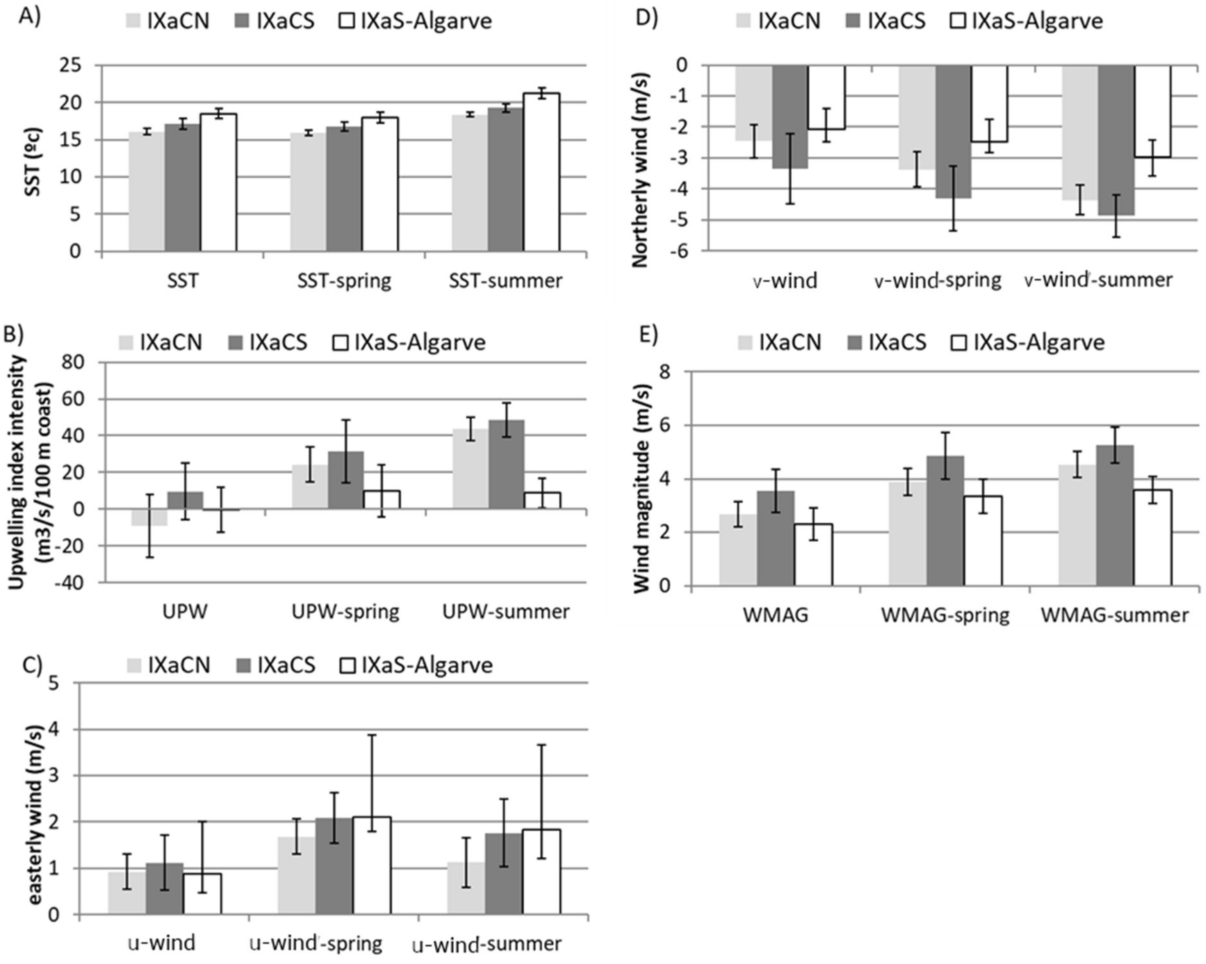

Figure 4. Average and seasonal time series values for study environmental variables; (**A**) SST—sea surface temperature, (**B**) UPW—Upwelling index, (**C**) u-wind—easterly winds, (**D**) v-wind—northerly winds, (**E**) WMAG—Wind magnitude for the time period 1989–2009 in IXaCN—Northwestern Coast; IXaCS—Southwestern coast and IXaS-Algarve—South coast.

The pattern of the wind varied accordingly to areas and seasons. Northerly winds (v-wind) have a dominant North-South direction (negative values) with higher values in summer regardless of the area (Figure 4). The v-wind was higher in IXaCS followed by the IXaCN and IXaS-Algarve coasts. Westerly winds (u-wind) have a dominant east-west component (positive values). Annual u-wind values are higher in IXaCS. However, in spring and summer u-wind values are higher in IXaS-Algarve followed by IXaCS and IXaCN. Wind magnitude (WMag) blows with higher strength in IXaCS, followed by IXaCN and IXaS-Algarve, independently of the season (Figure 4).

3.3. Environmental–Fisheries Relationship

The multi-model approach revealed the environmental variables that affect *M. surmuletus* catch rates varied accordingly area and season (Table 1, Figure 5; Supplementary Table S1). Until 2002 UPW in IXaCN varied around the mean. From 2002 to 2005, strong negative anomalies in UPW were recorded matching with the decrease trend in both landings and catch rates (LPUE). The trend in yearly UPW in IXaCN match catch rates variability. Therefore, of all environmental variables tested, yearly UPW index was the only variable that relates with catch rates (positively), being highlighted in all statistical models applied.

Table 1. Resume table with results for Dynamic factor analysis (DFA), Generalised Least Square (GLS) and Min/max autocorrelation factor analysis (MAFA), including explanatory variables that related to *M. surmuletus* LPUE in the Northwest (IXaCN), Southwest (IXaCS) and South (IXaS-Algarve) regions. For DFA the − and + sign indicates estimated *t*-values with a negative and positive relationship; For GLS the relationship between explanatory variables and LPUE are given by the slope of regression coefficient (− and + signs) and $p < 0.05$ refers to significant relationship models between environmental variables and LPUE). Details on all models statistical fitting are provided in Supplementary Table S1. u-wind—easterly winds; UPW—Upwelling index; SST—Sea Surface Temperature; FE—Fishing Effort (boats.days).

		Northwestern (IXaCN)		
	DFA	**GLS**	**MAFA**	**Probability**
UPW	sig. (+)	sig. (+)	sig. (+)	high
		Southwestern (IXaCS)		
FE	sig. (+)	sig. (+)	sig. (+)	high
u-wind	sig. (−)	sig. (−)	sig. (−)	high
UPW-summer	n.s.	sig. (−)	sig. (−)	high
UW-spring	sig. (−)	n.s.	n.s.	low
		South Algarve (IXaS-Algarve)		
SST	sig. (+)	n.s.	n.s.	low
SST-spring	n.s.	sig. (+)	n.s.	low
SST-summer	sig. (+)	sig. (+)	sig. (+)	high
u-wind	sig. (−)	sig. (−)	sig. (−)	high
UPW-summer	sig. (−)	n.s.	n.s.	low

The UPW-summer and UW (westerly winds) trends in IXaCS increased until 2004 dropping thereafter to values around the mean (Figure 5). In the same period, the landings and catch rates of *M. surmuletus* as well as FE decrease continuously across years (Figures 2 and 3). Therefore, in IXaCS, the multi-model statistical analyses revealed that fishing effort was positively related with catch rates whereas yearly u-wind and UPW-summer were negatively related with catch rates (Table 1). In IXaCS one single model (DFA) highly u-wind in spring to relate with *M. surmuletus* catch rates.

The trend in SST-summer and u-wind were highly variable in IXaS-Algarve with no clear upward or downward trend for overall period. All time series models revealed that in IXaS-Algarve, SST-summer was positively related with catch rates revealing that oscillation in SST-summer has high probability to affect catch rates. In IXaS-Algarve yearly SST and SST-spring were also highlighted by one statistics analysis (DFA) to relate positively with catch rates. Westerly wind (u-wind) was also negatively related with catch rate that is the increase in U-wind leads to low catch rate values. The relationship between u-wind and catch rates were strong as all statistical models highly u-wind as a driver of catch rates. UPW-summer trend was also related negatively with catch rates trend in IXaS-Algarve but this explanatory variable was solely highlighted by a single statistical model (DFA).

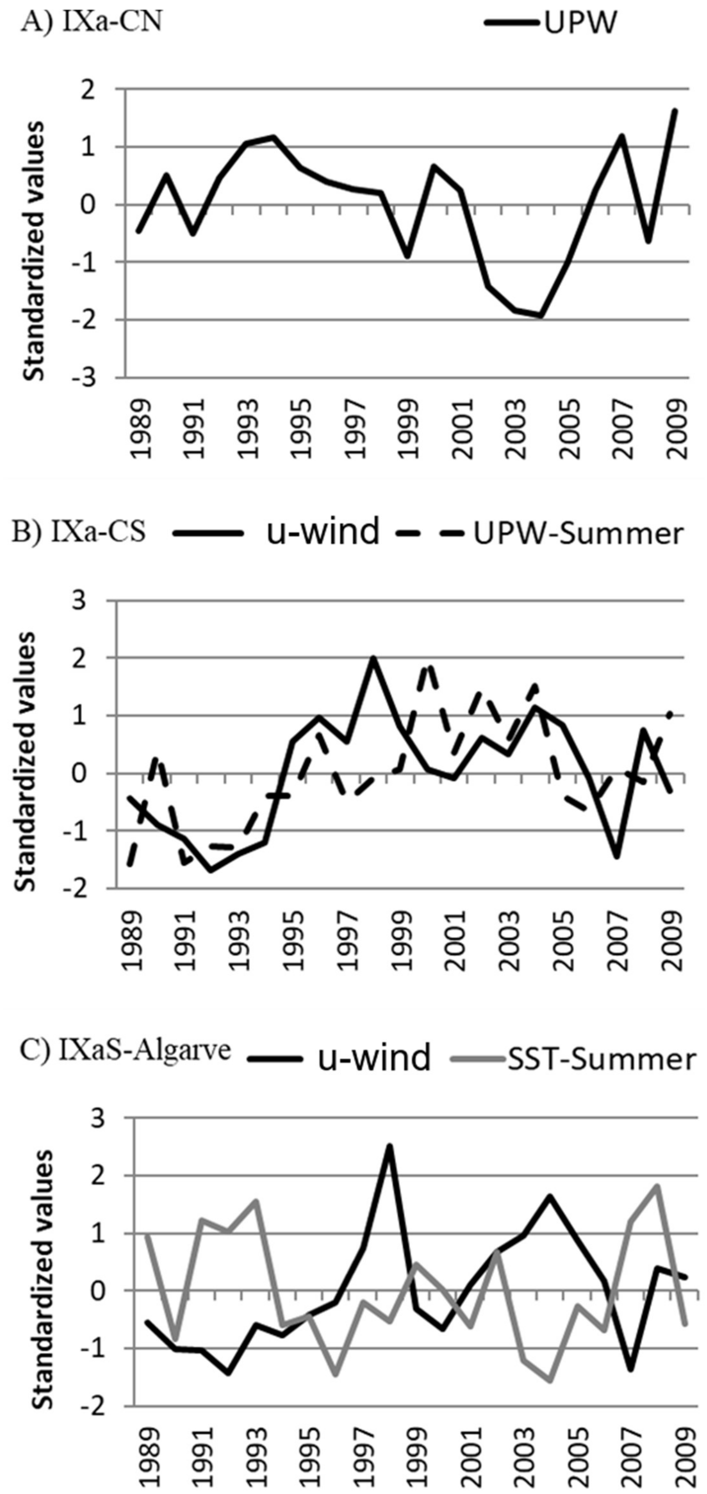

Figure 5. Standardized values for environmental variables (with a lag of two years) that have high probability to relate with LPUE (Ladings per unit effort) for the different oceanographic areas from 1989 to 2009 for (**A**) Northwestern (IXaCN), (**B**) Southwestern (IXaCS) and (**C**) South-Algarve (IXaS-Algarve) coast. u-wind—easterly winds; UPW—Upwelling index; SST—Sea Surface Temperature.

4. Discussion

The outcome of the different model approaches revealed that different explanatory variables affect catch rates. Independently the statistic model applied the type of relationship between explanatory variables and catch rate (negative or positive) were consistent across models. The main variables affecting *M. surmuletus* catch rates were environmental factors. For small and medium pelagics environmental variables have been described to affect fish stocks variability (Fréon et al., 1993 [44]; Borges et al., 2003 [45]). Environmental-fisheries relationships can be difficult to stablish for age-structured species with complex demographic processes governing their population dynamics (e.g., hake) at temporal and spatial scale besides the environmental influence on recruitment through larval survival. We believe therefore that the hypothesis "recruitment variability depends on the larval survival affected by the environmental variability" can be tested using LPUE in artisanal selective age-structured species such as *M. surmuletus* because large values of LPUE do not result from the combination of several age classes. That is, in *M. surmuletus* case high values of LPEU result from the combination of age classes 2 and thus LPUEs can provide peaks of high values at the age of maturation.

The spawning season of *M. surmuletus* (a demersal species) extends from May to June and largely coincides with the UPW regime along the Portuguese coast (May to August). Intermittent UPW events are observed during the winter (out of the peak season of the species), increasing in frequency, intensity and length towards the upwelling dominated summer (Figure 4; Relvas et al., 2007 [24]). In IXaCS UPW in summer was negatively related with catch rates, supporting the hypotheses that intensification of UPW during reproduction season can lead to larvae offshore movement (intense UPW are recorded in summer) and enhance mortality due to unfavorable conditions for larvae. On the contrary, yearly UPW in IXaCN was positive related with *M. surmuletus* catch rates. The yearly UPW average value in IXaCN is negative denoting downwelling predominance over the year (Figure 4) and poor nutrient water. However, the yearly UPW intensity is low compared to winter and autumn when strong downwelling values are recorded (Leitão et al., 2014 [19]). The larvae of *M. surmuletus* have the same forage ability and are able to undergo vertical migrations to forage area independently. Therefore, inshore-offshore water movement due to UPW waters becoming the main promising mechanism for explain *M. surmuletus* larvae survivorship accordingly comparison of both IXaCN and IXaCS results.

The meteorological conditions in the south are controlled by the northward position of Azores anticyclone. This is periodically broken by interactions with the polar front, origination pulses of north-easterly flows over the western Iberian Peninsula and very weak easterly winds over the Algarve area (Relvas et al., 2007 [24]; Oliveira et al., 2008 [46,47]). Despite peak situations, weak easterly winds prevail in the Algarve's atmospheric circulation. Without such winds Algarve coastal circulations seem to be predominantly westwards. Strong westerly winds along the Portuguese coast are associated with low barometric pressure and related with the passage of weather systems that affect turbulence of water column (Relvas et al., 2007 [24]; Oliveira et al., 2008 [46,47]). Westerly winds (u-wind) affect catch rates negatively in IXaCS and IXaS-Algarve. However, due to coast orientation u-winds affect differently oceanographic conditions in IXaCS and IXaS-Algarve. Westerly winds favor UPW in center and east IXaS-Algarve while in IXaCS increase turbulence in water mix column. This mixing of the surface water layer can disperse food and larvae patches, thereby increasing mortality rates (Peterman et al., 1987 [48]) depending on larvae swimming ability (Jenkins 2005 [49]). Moreover, at a given wind speeds, wind-driven mixing dominates the stabilizing effect of solar radiation on upper ocean structure (Peterman et al., 1987 [48]). The negative correlation between westerlies and catch rates in IXaCS supports the "stability of water column" hypothesis (Lasker 1975 [6]) regardless of the area: the relaxation of storm winds and favorable UPW regimes results in a stable, vertically stratified ocean, where fish larvae and their prey coincide, promoting larval nutrition and survival.

The study of Kermorvant et al. (2020) [50] indicates that the relationship between *M. surmuletus* seasonal LPUE with seasonal environmental covariates was not systematic and not spatially uniform. In the present study, the SST effects were not visible in all areas. These results are not unexpected as regional SST changes have been observed to have an inverse effect on Atlantic cod populations. For these species recruitment was linked to inter-annual fluctuations in temperature in such a way that there was a negative relationship between stocks and warm water and a positive relationship between stocks and cold water, with no discernible relationship for stocks located in the midrange of the temperatures (Planque and Frédou 1999 [51]). However, in IXaS-Algarve the increase in SST in summer, during peak of spawning, was correlated with the catch rate increase with a lag of two years. Along the Algarve south coast (IXaS), the summer wind is predominantly weaker with westerlies winds inducing an offshore Ekman transport and force subsurface waters to upwell (Relvas et al., 2007 [24]). Therefore, the relaxation of west winds during summer favors warmer waters in the south coast, where annual mean SST is higher than in western Iberian regions (IXaCN and IXaCS). Larvae hatching during periods when water temperature is more favorable will show faster growth and will have higher survival rates (Pepin 1991 [52]) consequently affecting catch rates increase. A tropicalization effect was observed for several species in Portuguese coast due to SST including demersal species (Teixeira et al., 2014 [53]), such as *M. surmuletus*. A study using 2001 and 2010 data set (Maltby et al., 2020 [54]; English Channel, Celtic Sea, the Bristol Channel and parts of the southern North Sea) predict climate projections to be associated with increase in SST, that would affect *M. surmulletus*. Thus, results show that the environmental variables, such as SST, will exert similar effects on the species regardless of the geographic range and time window datasets.

The effect of UPW on commercial species have been little addressed (Ullah et al., 2012 [27]; Baptista et al., 2014, 2022 [29,30]) compared to SST in Iberian coast (Gamito et al., 2013, 2015 [55,56]; Teixeira et al., 2014, 2016 [53,57]) for artisanal species. The results showed that the effects of upwelling in catch rates contrasted among the both IXaCN and IXaCS and IXaS-Algarve. Likewise, the effects of westerlies in catch rates contrasted among areas. These differences demonstrate that the effect on fisheries of a specific environmental factor, as the wind regime, is itself variable and dependent on other local conditions. Along the Algarve coast the oceanographic circulation is fairly different from that of the west coast due in part to its more southern latitude and also coastal bathymetry and water circulation (shoreline geography). In fact, there is a strong regional and seasonal dependence of the larvae transport due to wind, with average seasonal cycles of the percentage of eggs found in the shelf reflecting the anticipated effect of the seasonal north–south migration of the trade wind belt (Oliveira and Stratoudakis 2008 [46]). However, the geostrophic transport led to the attenuation of seasonal cycles and higher mean/maximum values in the probability of retention within the shelf. This increased capacity for retention even during strong upwelling conditions an aspect that seems to have been overlooked by theories aiming to describe the reproductive strategies of pelagic fish and understand recruitment dynamics based primarily on wind/UPW variability (Oliveira and Stratoudakis 2008 [46]). The reproductive strategies of many marine species are adapted to fit the prevailing currents, which serve for retention over the shelf and, furthermore, transport towards the coast. The way UPW (IXaCN), the u-wind (IXaCS) and the SST in IXaS-Algarve affect catch rates during spawning peak in different areas can be interpreted as different aspects of the same dispersion process which moves eggs, larvae, post-larvae and pre-recruits of striped red mullet offshore. This mechanism decreases the success of the recruitment of the species (see: Fiorentino et al., 2008 [58], stock-recruitment relationship of cogeneric *M. barbatus*). Therefore, in the case of *M. surmuletus* the "Ocean triads" (Agostini and Bakun 2002 [59] hypothesis, where larvae survivorship 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 and explain differences in catch rate variability among areas.

Statistical relationships were observed, using the multimodal approach, despite the intra-annual variability observed in environmental variables and catch rates time series.

Overall, results showed that *M. surmuletus* catch rates along the Portuguese coast are affected by different factors, emphasizing regional and seasonal differences. Biological literature on species spawning for each area is not available. Therefore, similar to other species (Leitão et al., 2014 [19]) we cannot exclude some spatial heterogeneity in the recruitment process to be found among areas. Consequently, seasonal effect and environmental influence on catch rates tested herein can be related to main pulse of recruitment occurred at a different time in the different areas.

The number of artisanal fleet boats along the Portuguese coast that target exclusively on the *M. surmuletus* is very small (Gaspar and Pereira 2014 [17]). Furthermore, it is difficult to know whether the *M. surmuletus* dataset covers periods encompassing overexploitation, underexploitation or optimal exploitation. In principle, landings will be a function of fishing effort and stock abundance. Therefore, we can also expect to be able to detect signals in the catch rate data, particularly if this is controlled by fishing effort. Only in IXaCS the fishing effort exhibited a conspicuous positive correlation with catch rates. Overall, results suggested that the vulnerability of this population to the artisanal fleet is reduced so far. In fact, the effort increase over the time did not lead to a catch decrease, as observed by the lack of negative relationships in all areas. Scientific reports (Marine Policy Framework Directive: DQEM 2014 [60]) showed moderate fishing pressure level for the red striped mullet fishery although such assessment did not consider environmental variability. It is conventionally accepted that negative relationships between effort and catch rates are an indicator of overexploitation in surplus production stock assessment models (Fréon et al., 1993 [44]). Therefore, the range of landings values within the period in study (for any area in study), within environmental conditions variability, seems to be a good reference for future catches. There is no evidence of decrease *M. surmuletus* catch rates with increasing fishing effort and thus values of landings in each area can be used as proxy to guide managers regarding fishery exploitation sustainable limits. The identification of environmental drivers that affect seasonal species—specific fisheries trends is also a key issue in fisheries science and the base for proceed with future selection of variables that can be predict climate change effect (Albo-Puigserver et al., 2022 [61], Bueno-Pardo et al., 2021 [62]).

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/oceans4030015/s1, Table S1. Resume table with results for Dynamic Factor Analysis (DFA), Generalised Least Squares (GLS) and Min/max autocorrelation factor analysis (MAFA), including all explanatory environmental variables related to *M. surmuletus* LPUE in the Northwest, Southwest and South-Algarve regions. Diff. AIC—difference between initial simple DFA model (only with LPUE trend) and DFA with LPUE trend plus explanatory variable. For DFA the − and + sign indicates estimated *t*-values resulting from estimation of regression parameters with a negative and positive relationship between explanatory variables and response variable (t-values with an absolute value greater than 3 indicate a strong relationship among variables); For MAFA the significance level for correlations (coefficient correlation—Corr. Coef.) of EV with MAFA trend were significant at 0.44 and single MAFA trend (Auto-correlation with time lag 1) explaining 0.59, 0.66 and 0.62 of the trend variability in IXaCN, IXaCS and IXaS-Algarve (all models with 1 MAFA trend were significant: $p < 0.04$). The asterisk (*) in GLS refers to models that were better fitter with AR model (1,0)—Autogressive model. FE—Fishing Effort; SST—Sea Surface Temperature; UW—Westerly Winds; VW—Northerly winds; WMAG—wind magnitude; UPW—Upwelling; NAO—North Atlantic Oscillation. Combined models were also performed but the results of simple models were overall better, thus they are not shown.

Funding: This study received Portuguese national funds from the: (1) FCT—Foundation for Science and Technology through projects UIDB/04326/2020, UIDP/04326/2020, and LA/P/0101/2020; (2) CLIMFISH project—a framework for assessing the vulnerability of coastal fisheries to climate change on the Portuguese coast, founded by Portugal 2020; n2/SAICT/2017—SAICT (Projetos de IC&DT: PTDC/ASP-PES/28518/2017; ALG-01-0145-FEDER-028518); and (3) the operational program MAR2020-FEAMP through project CLIMA-PESCA—Vulnerabilidade do Setor das Pescas às alterações climáticas: medidas de adaptação (MAR-01.03.02-FEAMP-0052). F.L. was funded by the FCT—Foundation for Science and Technology in the ambit of the contract program DL57/2016/CP1361 /CT0008 and FCT 2022.04803.CEECIND.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The author is grateful to the DGRM statistical office for providing the fisheries data.

Conflicts of Interest: The author declares no conflict of interest.

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