




## Trends and drivers of marine fish landings in Portugal since its entrance in the European Union

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Marine landings in Portugal have decreased at a higher rate than fishing effort in the last 20 years. Identifying the variables driving the quantity and composition of landings is pivotal to understand the dynamics of the fisheries sector, which entails complex social and environmental aspects. In this study, we investigate the main drivers of marine fish landings in continental Portugal between 1989 and 2014. To identify common trends in time series, and quantify the importance of environmental factors, we applied a dynamic factor analysis considering four regions and three types of gear (trawling, purse-seine, and a multi-gear fishery). Our results show the importance of fishing effort as the most relevant factor driving marine landings in Portugal, both at the long and short terms. In addition, the effect of environmental factors such as the winter river discharge and the spring East Atlantic Teleconnection index should not be neglected, probably through mechanisms affecting coastal productivity. We provide a comprehensive amount of information that permits to improve our understanding of the trends of the most important commercial species in Portugal during the period of study.

**Keywords:** fisheries, landings, landings per unit effort, Portugal, purse-seine, trawling

### Introduction

In terms of their contribution to food supply, marine fish and shellfish landings are the world's most important provisioning marine ecosystem service, with estimates by the Food and

Agriculture Organization of the United Nations of captures worth over 80 billion dollars annually (United Nations, 2010; FAO, 2018). Although total reported catch has been relatively static since the late 1980s (~85 million tonnes; FAO, 2018), analyses

based on temporal trends of proportional catch relative to maximum catch (the stock status plot; see [Kleisner et al., 2013](#) and references therein) indicate that ~40% of the world stocks were over-exploited or had collapsed by 2005 ([Kleisner et al., 2013](#)). Furthermore, the build-up of the proportion of collapsed stocks since the 1970s is not compensated by the stocks that have recovered or entered the fisheries ([Froese et al., 2009](#)). In this way, overfishing has been identified as the trigger of regime shifts in many regional seas ([Daskalov et al., 2007](#)).

While the relationship between fish abundance and catch is still subject of debate ([Pauly et al., 2013](#)), stock status estimates are largely dependent on landings data (especially in countries lacking the technical expertise or financial resources to conduct formal assessments of stock biomass, requiring age-size distribution information and independent scientific surveys). Landings, however, are a poor index of population abundance and structure because of market regulations, changing levels of effort associated with quota restrictions, adjustments of taxonomy affecting reported species names, technological progress that influences fish catchability, or unreported catch ([Pauly et al., 2002, 2013](#)). Standardizing landings per effort expended [landings per unit effort (LPUE)] can reduce the effects of sources of bias (market regulations, quota restrictions) associated with bulk landings. It also provides an index of the relative abundance of the stock that can be used in models for stock assessment ([Campbell, 2015](#)), and in the study of the effect of environmental factors on population abundance ([Wang et al., 2003](#)). However, the use of LPUE or catches per unit effort (CPUE) is also problematic, not least because of the validity of CPUE or LPUE as an abundance index depending on randomized search effort. Thus, for example, the fact that fishers tend to concentrate their effort in areas of higher abundance can lead to CPUE providing an overoptimistic view of stock status and trends. Hence, because of interactions among spatial distributions of fish aggregations (aggregations distributed over a smaller area as population size decreases) and fishers' behaviour, fish catch (proportion of the population fished per unit effort) can be independent of population size ([Harley et al., 2001](#)). In many fisheries, CPUE actually increases as population size decreases because fishers concentrate on known remaining patches, resulting in a non-linear relationship between fish abundance and CPUE that may convey the erroneous perception that population density remains unaffected in spite of decreases in population size ([Winters and Wheeler, 1985](#); [Crecco and Overholtz, 1990](#); [Rose and Leggett, 1991](#)). Despite the limitations of landings as an index of the status of a stock, or as a proxy for the abundance of exploited species, landings remain the only available statistics to analyse general trends in fisheries production in many regional seas ([Pauly et al., 2013](#)). Landings also provide a measure of what is delivered for human consumption, that is the benefit that is derived from the ecosystem ([Maes et al., 2014](#)), and are commonly used in global and regional assessment studies for this purpose (e.g. [FAO, 2018](#)).

Fishing is one of the most important social and economic maritime activities in Portugal, currently involving >4100 boats and 17 500 fishers and being an important employer in coastal communities often with limited job opportunities ([Pita et al., 2010](#)). This sector has seen tremendous changes during the last 50 years. Reported landings reached maximum levels exceeding 300 000 tonnes in the 1960s and dropping to 250 000 tonnes by the end of the 1980s and <200,000 tonnes in 2009 ([Leitão et al., 2014b](#)). On the other hand, a steady decrease in fishing capacity started

during the mid-1980s, with drops of 75% and 50% in the number of boats and fishers, respectively, during the last 30 years ([Leitão et al., 2014b](#)). These latter changes have been mostly driven by the measures put into force under the European Union Common Fisheries Policy (EU-CFP) since its implementation in 1983, in the form of increasingly strict entry limitations and provision of decommission subsidies with a view to permanently reduce fleet capacity ([Guyader et al., 2007](#); [Khalilian et al., 2010](#)).

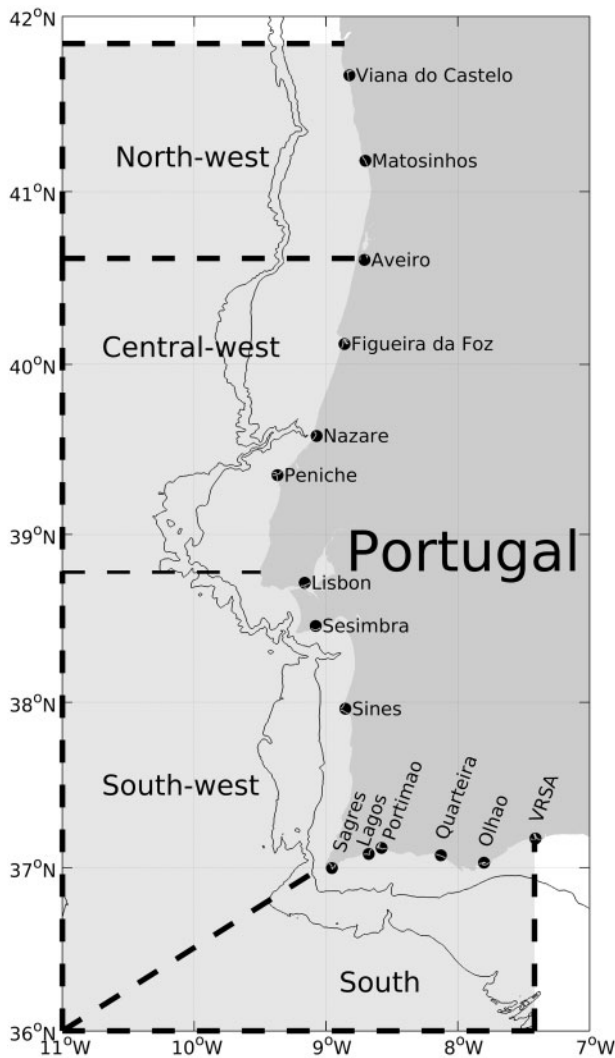
Several studies have analysed the relationship between marine fisheries production and environmental variables in Portugal. These analyses, however, have been directed to understand particular segments of the coast (south coast: [Erzini, 2005](#); central-west coast: [Gamito et al., 2015](#)) or particular species groups (elasmobranchs: [Correia and Smith, 2003](#); flatfishes: [Teixeira and Cabral, 2009](#); small pelagics: [Teixeira et al., 2016](#); climate-sensitive species: [Teixeira et al., 2014](#)). A recent study ([Gamito et al., 2013](#)) analysed trends in landings of different fleet components from a 16-year period ending in 2009. Most of these studies analysed trends in biomass landed per unit of effort [except [Correia and Smith \(2003\)](#) and [Erzini \(2005\)](#), who analysed total landings] and found that different combinations of sea surface temperature (SST) ([Teixeira and Cabral, 2009](#); [Teixeira et al., 2014, 2016](#); [Gamito et al., 2015](#)), the North Atlantic Oscillation (NAO) ([Gamito et al., 2015](#); [Teixeira et al., 2016](#)) and river discharge ([Erzini, 2005](#)) influenced landings. These studies also highlighted regional compositional changes in landed biomass, with increasing incidence of subtropical species in the south ([Gamito et al., 2013](#)) and increases in the ratio of warm temperate to cold temperate species ([Teixeira et al., 2014](#)).

An overall assessment of the effects of fishing effort and environmental drivers on landings of commercially important species during the last few decades is still lacking at the scale of continental Portugal. In the present study, we investigate the most important variables driving marine fish landings by analysing regional trends in the period between 1989 and 2014, separately for the three main components of the fleet (trawling, purse-seine, and multi-gear) and considering four separate geographical regions along the Portuguese coast. We use dynamic factor analysis (DFA), a technique for data reduction appropriate for short multivariate time series ([Zuur et al., 2003](#)), to estimate underlying common patterns, evaluate interactions between response variables (fish landings) and determine the effects of explanatory variables (environmental and effort variables) on response variables.

## Material and methods

### Landings data

Official data on landings of fish and shellfish at the different ports of mainland Portugal ([Figure 1](#)) from 1989 to 2014 were obtained from the Direção Geral de Recursos Naturais, Segurança e Serviços Marítimos (DGRM). The period of the study starts at the beginning of the standardized digital data compilation by Portuguese authorities (DGRM), after the major vessel decommissioning period, and ends right before the beginning of the implementation of the European fish discard ban ([Borges, 2015](#)). These data reported the species, port of landing, year, weight in kilograms, days-at-sea, and type of gear considering three categories: purse-seine, trawling, and multi-gear. While purse-seine constitutes a homogeneous type of gear targeting small pelagic fish and catching small volumes of accessory species, the trawling and multi-gear fleets deploy a diverse array of gears targeting a



**Figure 1.** Map of Portugal with the regions and ports considered. The bathymetry shown corresponds to 200 and 1000 m.

diverse group of species. The trawling category includes two different techniques, i.e. pelagic and demersal trawling, with the latter targeting fish or crustaceans depending on mesh size. Multi-gear is the most diverse category and includes gill nets, trammel nets, surface long lines, bottom long lines, shelter traps, cage traps, and a few others. DGRM data do not allow further disaggregation of landings by specific gear type. We eliminated all fluvial and estuarine ports and species (mainly bivalves) from the analysis.

Our analysis was focused on the most important species and ports of continental Portugal. The first 6% of the most landed species in all the ports was considered separately for purse-seine, trawling, and multi-gear. The subset of ports used in the analysis consisted of 20 most important ports for purse-seine and trawling and 40 most important ports in the case of the multi-gear. This method retained 15 species out of 243 (accounting for 97% of total landings in the period) in the case of the purse-seine, 18 species out of 310 (accounting for 79% of total landings in the period) in the case of trawling, and 21 species out of 359 (accounting for 62% of total landings in the period) in the case of

multi-gear fisheries. These criteria enabled us to consider only the most important species and ports, while also reflecting the diversity of species targeted by the different gears in the different ports (see [Supplementary File 1](#) for the time series of landings, in tonnes, of the species considered in this study). To analyse the effect of fishing effort changes on the number of landed species, however, we used the full list of species landed by each gear type.

### Identification of temporal and spatial trends in landings

To identify general patterns of landings variability over space and time, we used the log-transformed landings from 1989 to 2014 for the species and ports selected. We generated a three-dimension data matrix for each gear type (species  $\times$  years  $\times$  ports), which was then decomposed into three different modes: species mode (ports  $\times$  year), temporal mode (port  $\times$  species), and the spatial mode (year  $\times$  species). Then, a parametric multi-dimensional scaling analysis (MDS) was used to analyse each mode separately, based on a similarity matrix constructed with the Bray–Curtis coefficient ([Quinn and Keough, 2002](#)). MDS is a multivariate technique that attempts to reproduce, in the reduced ordination space, the rank of the pairwise distances separating objects in the original space. Therefore, MDS is not affected by deviations from assumptions about the linearity of trends in species abundances along environmental gradients, which were present in the data and resulted in a strong “arch effect” when ordination methods based on principal components analysis were applied.

This exploratory analysis ([Supplementary Figure S1](#)) indicated clear geographical patterns and temporal shifts in landings, as well as groups of species that appeared to change coherently across space and time. According to this, the continental Portuguese margin was divided into four main geographic regions ([Figure 1](#)) with the purpose of describing temporal patterns of fish landings. The north-west coast, comprising the area between the Minho river and the estuary of Aveiro (40.62–41.86 N), contains the ports of Viana do Castelo, Matosinhos, and Aveiro. The central-west area starts south of Aveiro and extends until Cabo da Rocha (38.77–40.62 N), with the ports of Figueira da Foz, Nazaré, Peniche, and Lisbon. The south-west region includes the ports of Sesimbra and Sines and extends from Cabo da Rocha to the Sagres Canyon (37.01–38.77 N). Finally, the south region comprises the south-facing coast from the Sagres Canyon to the Guadiana river (35.7–37.01 N), including the ports of Sagres, Lagos, Portimão, Quarteira, Olhão, and Vila Real de Santo António. These regions are also broadly coincident with well-known oceanographic patterns in coastal waters of continental Portugal ([Relvas et al., 2007](#); [Aristegui et al., 2009](#)). The whole west coast is characterized by seasonal upwelling; the north west has a wide continental shelf and an extensive retention zone; the central west has a wide continental shelf and is mostly a divergence zone; the south-west coast has a narrow continental shelf and is a divergence zone; and along the south coast of Portugal (Algarve’s south coast), upwelling events are rare.

### Time series of landings and explanatory variables

The ports and species selected were used to construct time series of bulk annual landings per species, geographical region, and gear type, by summing the landings of each species over the ports of a region. A database of time series of fishing and environmental



variables was also assembled, to test their effects as predictors of fish landings. These were the fishing effort, the NAO index, the Atlantic Multidecadal Oscillation (AMO) index, the Eastern Atlantic Teleconnection (EAT) index, the inshore SST, the offshore SST, the SST anomaly (see definitions below), the upwelling index, the river input to the coastal ocean, and the precipitation. The fishing effort series were prepared separately for each region-gear combination. The inshore and offshore SST, SST anomaly, upwelling, river input, and precipitation time series were prepared separately for each region. The time series of the remaining variables were considered as universal. The time series of landings and explanatory variables are available in [Supplementary Files 1 and 2](#), respectively (for units of the explanatory variables see below). The selection of these variables was related to their potential influence on primary and secondary productivities, with likely impacts on the population dynamics of the main oceanic species of Portugal.

Fishing effort for each gear category was calculated as the total number of days-at-sea from the DRGM data. Days-at-sea may not be an optimal proxy for effective fishing effort because of changes in technology and gear efficiency along the time series, variability in boat size or horsepower, disparity of fishing gears aggregated into each category, or unreliable reporting of fishing data ([Stewart et al., 2010](#); [Anticamara et al., 2011](#)). However, days-at-sea is the most consistent standardized variable available for the entire time series.

Annual averages of the standardized NAO, AMO, and EAT atmospheric circulation modes were obtained from the website of the National Oceanic and Atmospheric Administration (NOAA, [www.esrl.noaa.gov](http://www.esrl.noaa.gov)). We also used time series of seasonal averages of these indices calculated from the monthly values published at the NOAA website, by defining seasons as winter (December–February), spring (March–May), summer (June–August) and autumn (September–November).

SST data ( $^{\circ}\text{C}$ ) were obtained from the Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA) database ([ghrsstpp.metoffice.com/pages/latest\\_analysis/ostia.html](http://ghrsstpp.metoffice.com/pages/latest_analysis/ostia.html)), which uses satellite data provided by international agencies via the Group for High Resolution SST (GHRSSST) Regional/Global Task Sharing (R/GTS) framework ([Donlon et al., 2012](#)). OSTIA data are corrected for sensor bias and provided at a  $0.05^{\circ}$  resolution. For each geographical region, annual and seasonal (seasons defined as above) average inshore SST series were calculated over an area delimited by the coast and by a line 20-km offshore. This limit was based on [Relvas et al. \(2007\)](#), who show consistent negative temperature anomalies due to summer upwelling along this coastal strip. Offshore annual and seasonal SST series were calculated on the range of  $11\text{--}12^{\circ}\text{W}$  in each region, and SST anomaly series were then calculated as the difference between SST inshore and SST offshore. This SST anomaly time series is expected to be a more direct proxy of upwelling than the wind-based upwelling index (larger negative anomaly with stronger upwelling).

Monthly upwelling indices ( $\text{m}^3 \text{s}^{-1} \text{km}^{-1}$ ) were obtained from the Instituto Español de Oceanografía ([http://www.indicedeafloreamiento.ieo.es/afloreamiento\\_en.html](http://www.indicedeafloreamiento.ieo.es/afloreamiento_en.html)) and used to calculate time series of annual and seasonal average values. These upwelling indices are calculated using wind speed measurements from different weather stations in the database. In the present case, the stations of Aveiro, Cabo da Roca, Sines, and Algarve were assigned to the north-west, central-west, south-west, and south regions, respectively, and seasons were defined as above.

To obtain a proxy for freshwater input to the coastal ocean ( $\text{m}^{-3} \text{s}^{-1}$ ), we used a combination of monthly data available from the website of the Sistema de Informação Nacional de Recursos Hídricos ([snirh.pt](http://snirh.pt)), which compiles data from the network of measurement stations of the Ministério do Ambiente, and supplied by Energias de Portugal SA (EDP), a company that operates most of the hydroelectric power plants in Portugal. None of these data sets provides information on the outflow to the ocean but rather on the effluent flux at the dam or measurement station. The rivers (and dams/stations) selected were the Douro (Crestuma, on the main river) in the north-west region, the Guadiana (Pulo do Lobo, on the main river) in the south region, and the joint input of the Tagus (Fratel, on the main river, plus Castelo de Bode, on the Zêzere, the main tributary downstream of Fratel) and the Sado (Torrão, on the main river), which lie close to the limit between the central-west and south-west regions and were used as representing the freshwater inputs to both these two regions. Correlations among the time series of average monthly flux at the dams/stations showed a strong spatial consistency among watersheds and databases (all ten pairwise correlation coefficients were positive and significant at the 5% level, with five of the coefficients  $>0.75$  and the remaining  $>0.50$ ). Given that the EDP data for the Douro and the Tagus covered the entire time scope of the present study, and the generally high correlations among watersheds, the EDP data were chosen as representative of the freshwater outputs from the Douro and the Tagus and the EDP Tagus data were used to model the monthly missing values from the Sado and the Guadiana (using linear regression; correlations were 0.79 and 0.69, respectively, and the percentage of missing values was 14 in both cases). Based on the reconstructed time series of monthly values, we generated time series of average annual values (using the hydrologic year from October to September), and of average seasonal fluxes (with seasons defined as above).

To obtain a measure of rainfall for the coastal ocean, we used the accumulated rainfall ( $\text{l m}^{-2} \text{year}^{-1}$ ) at Porto (north west), Aveiro (central west), Sines (south west), and Faro (south). This information was downloaded from the Pordata website (<http://www.pordata.pt>) and is based on data provided by the Instituto Português do Mar e da Atmosfera.

### Dynamic factor analysis

DFA is a multivariate time series analysis technique used for non-stationary time series analysis allowing us to estimate underlying common patterns, evaluate interactions between response variables (fish landings) and determine the effects of explanatory variables (environmental and effort variables) on response variables ([Zuur et al., 2003](#); [Zuur and Pierce, 2004](#); [Erzini, 2005](#); [Erzini et al., 2005](#); [Leitão et al., 2016](#); [Zimmermann et al., 2019](#)). In DFA, the response time series are modelled in terms of a linear combination of common trends, explanatory variables, a level parameter, and a noise component. The common trends, which are independent of one another, represent the underlying common patterns of variation along time. In a DFA framework it is possible to select the number of common trends and explanatory variables to include in the model for each time series, which is done by examining the loadings and canonical correlations among common trends, dependent variables, and explanatory variables. Synchronous effects of more than one variable were tested in the models to evaluate the relationship with fish landings. For each

region–gear combination, a set of models were compared. These models comprised all the possible combinations of 0, 1, 2 or 3 common trends and 1 or 2 explanatory variables (23 variables in total). A diagonal and unequal error covariance matrix was used for the models, and the corrected Akaike information criterion (AICc) was used to compare the models (Zuur *et al.*, 2003). The canonical correlations between the time series of response variables and trends and response variables and explanatory variables were used to indicate either a positive or negative relationship (correlations with an absolute value of  $>0.5$  indicate a significant relationship between variables; 24 degrees of freedom at 1% similarity). The variables included (in addition to the common trends) in the models with the lowest AICc were considered as drivers of variability of the response variables at the short term, while the variables correlated to the common trends are interpreted as potential drivers of the landings on a longer time scale (trends) (Zuur *et al.*, 2003). DFA was performed using the multivariate autoregressive state-space R-package 3.4, considering 5000 iterations for each model.

Because species landings and explanatory variables are expressed in different units and show large differences in variability, the data were standardized by subtracting the mean and dividing by the standard deviation of the annual values before applying the DFA, to facilitate the interpretation of factor loadings and canonical correlations.

## Results

### Exploratory analysis of the time series

The MDS analysis (Supplementary Figure S1) shows that a gradual change in the species composition of the catch occurred over the years of study, affecting the three fleet components. Overall, landings have decreased by 52% in mainland Portugal during the period of 1989–2014 (Figure 2, and see Table 1 for a detailed analysis of each region–gear combination). Two main periods can be recognized in landings from the three fisheries. Trawling landings stabilized in 2005 after an initial decrease, mainly driven by the patterns in the north-west and central-west regions. The single region where trawling landings increased was the south west (Table 1). Purse-seine landings in the west coast saw an increase after 2007, although still far from the values registered up to 1995 (Figure 2). The only observed increase occurred in the south-west coast (Table 1). Multi-gear landings increased in all regions after 2003 to values around or above those verified during the first part of the series (Figure 2), although the general trend was decreasing in the central west and south west and increasing in the south (Table 1). Considering the three most important species in each region–gear combination (Supplementary Figure S2) enables further analysis. The stabilization of trawling landings after 2005 was driven by a stabilization of landings of *Trachurus trachurus*, which was the dominant species; the effort increase in the south west resulted in a strong increase in the landings of this species and of *Micromesistius poutassou*. On the other hand, the decrease in landings of the purse-seine fishery was driven by the decrease in sardine, *Sardina pilchardus*, which represented  $>90\%$  of landings in the north-west and central-west regions. In the southern regions, however, it seems that a replacement of *S. pilchardus* by the Atlantic chub Mackerel (*Scomber colias*) has happened, masking the decrease in purse-seine landings. The multi-gear landings were the most variable in composition given the nature of this fishery. However, two clear patterns occurred in

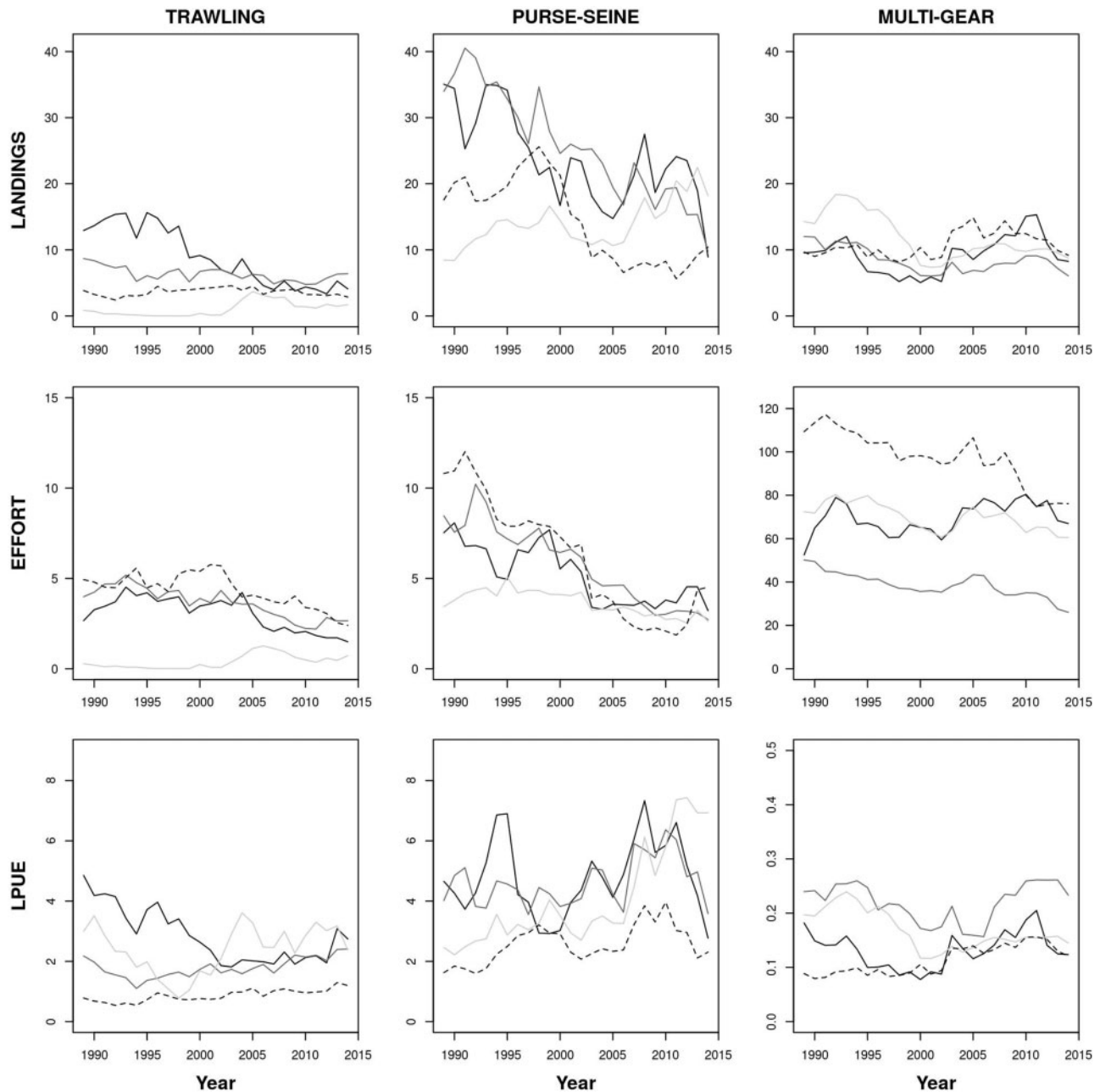
the north-west and central-west regions. In the former, most of the variability in total landings was due to variations in sardine landings, which represented up to 40% of the total. In the latter, variability of total landings was controlled by changes in landings of the silver scabbard fish, *Lepidopus caudatus*, until 1999, which represented up to 25% of the total during this period but disappeared in the region subsequently. Fishing effort, on the other hand, decreased in mainland Portugal during the period of study by 23.3% (Figure 2), and this was also the case in 10 out of 12 region–gear combinations evaluated (Table 1). Considering all regions together, purse-seine was the fishery that registered the greatest reduction in fishing effort, decreasing  $\sim 50\%$  during the period, while effort by trawling and the multi-gear fishery decreased by  $\sim 20\%$ . Trawling effort decreased more slowly after 2005 in all regions except in the south west, where a fourfold increase was registered. On the other hand, multi-gear effort (which accounts for  $>90\%$  of the total fishing effort in Portugal in time at sea) tended to decrease in all regions with exception of the north west, where a slight increase was observed (Figure 2 and Table 1).

Considering these values of landings and effort, we estimated the LPUE for the different region–gears (Figure 2 and Table 1), determining that LPUE values increased in 6 out of 12 region–gear combinations and decreased in two of them. The most significant increments were found for the purse-seine, with increasing trends in all the regions except of north west. From Figure 2, it also becomes apparent that LPUE values are generally higher in the northern regions, and consistently lower in the south coast.

To further investigate the relationship between effort and the compositional change in landings, we evaluated the relationship between the total number of species landed and the fishing effort of each *métier*, computed through the four regions of Portugal (Figure 3). This relationship was only significant in the case of purse-seine during the complete time series (Figure 3B;  $p = 4.92 \times 10^{-5}$ ), and in the case of trawling during the second half of the time series (Figure 3A;  $p = 0.0014$ ). For the multi-gear fishery, this relationship was not clear, and it seems that the drop in effort occurred during the most recent years was followed by an increase in the number of taxa landed. (Figure 3C).

### Dynamic factor analysis

Before using the explanatory variables to interpret landings patterns, we used canonical correlations to detect collinearity among them and reduce their numbers to a tractable set (Supplementary File 3, units as described in the “Time series of landings and explanatory variables” section). In all regions, seasonal time series for SST, upwelling, atmospheric mode indices and river outflow were often significantly correlated among themselves and with the annual time series. Therefore, we disregarded the annual time series in our analysis to avoid redundancy. Also, because of significant correlations, we excluded the upwelling time series, which was correlated with the SST anomaly (we consider the SST anomaly a more direct proxy of upwelling), and the offshore SST time series, which was correlated with the inshore SST time series. In the last case, offshore SST, and not inshore SST, was discarded because fishing in Portugal is mostly concentrated on the shelf. Thus, finally, the explanatory variables retained in were seasonal inshore SST, seasonal SST anomaly, seasonal NAO, annual AMO, seasonal EAT, annual precipitation, seasonal river discharge, and fishing effort.



**Figure 2.** Time series of total landings of fish in continental Portugal (thousands of tonnes, top row), fishing effort (thousands of fishing days, middle row) and LPUE (bottom row) between 1989 and 2014, according to gear type (trawling, purse-seine, and multi-gear) and region (north west, central west, south west, and south). Note the different scale of the Y-axis of the effort and LPUE plots for the multi-gear case. North west: black solid line; central west: medium grey solid line; south west: light grey solid line; south: dashed line.

The DFA allowed us to identify the common trends of the time series of landings of fish characterizing each region-gear combination (Table 2 and Figure 4), as well as the explanatory variables contributing to the models with lowest AICc values (Table 2 and Supplementary File 4). The common trends identified by the DFA indicated some degree of geographical consistency within each type of fishery (Figure 4). Hence, in the case of trawling, Trend 1 decreased, in general, in all regions through time, while Trends 2 and 3 were less consistent over regions. For purse-seine, Trend 1 decreased through time in the two northern regions and showed a distinctive peak between 2000 and 2005 in

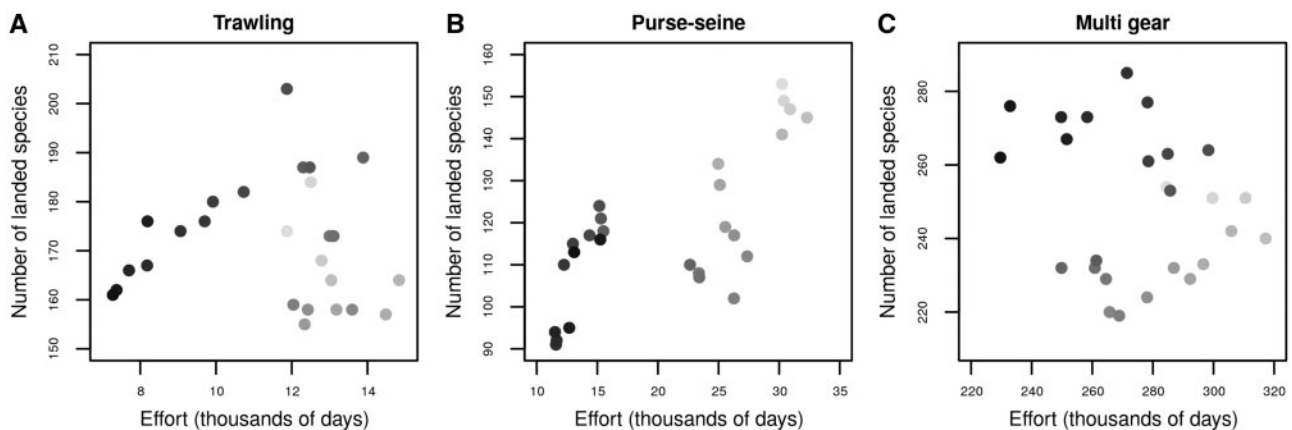
the two southern regions; Trend 2 showed peaks in the early part of the time series in all the regions except of the north west, while Trend 3 peaked in the end of the time series. Regarding the multi-gear fishery, Trend 1 decreased in the two northern regions and increased in the two southern regions, while Trend 2 followed, in general, opposite trends than Trend 1. Finally, Trend 3 was more variable and only significant in the three northern regions.

The relationship between the common trends and the explanatory variables is shown in Supplementary File 5. In this respect, the analysis for trawling detected consistent patterns of

**Table 1.** Trends and significances of linear regressions between landings, effort, and LPUE for the period of study.

Gear	Region	Landings trend	p-Value	Effort trend	p-Value	LPUE trend	p-Value
Trawling	North west	Decreasing	****	Decreasing	****	Decreasing	****
	Central west	Decreasing	***	Decreasing	****	Increasing	***
	South west	Increasing	***	Increasing	***	Not significant	0.156
	South	Not significant	0.700	Decreasing	****	Increasing	****
Purse-seine	North west	Decreasing	****	Decreasing	****	Not significant	0.448
	Central west	Decreasing	****	Decreasing	****	Increasing	*
	South west	Increasing	****	Decreasing	****	Increasing	****
	South	Decreasing	****	Decreasing	****	Increasing	**
Multi-gear	North west	Not significant	0.109	Increasing	*	Not significant	0.397
	Central west	Decreasing	***	Decreasing	****	Not significant	0.948
	South west	Decreasing	****	Decreasing	****	Decreasing	**
	South	Increasing	*	Decreasing	****	Increasing	****

Significances are represented as follows: \* $p < 0.05$ , \*\* $p < 0.01$ , \*\*\* $p < 0.0001$ , \*\*\*\* $p < 0.0001$ .

**Figure 3.** Relationship between the total number of taxa landed and fishing effort for each métier computed through the four regions of Portugal. Years are coded from light to dark grey along the time series. Note the differences in the scales of both axes.

co-variability, between the third common trend and fishing effort in the four regions, with significant relationships between annual AMO and the three common trends in the north and south west. In the case of purse-seine, fishing effort was correlated to different trends in each region and more variables such as winter NAO, annual AMO, or river summer discharge among others were related to the common trends. Finally, in the case of the multi-gear fishery, the first common trend was correlated with the annual AMO in the north-west, central-west, and south regions, while other environmental variables were also related to the first and second common trends obtained. In the case of fishing effort, correlations were obtained with the common trends in all the regions.

Regarding the variables captured by the models with the lowest AICc, a consistency among the regions and gears was also found (Table 2). In the case of trawling, the unique variable adding significant explanatory power to the models was fishing effort, both in the north-west and south-west regions. On the other hand, in the central west and south, the models with only three common trends were chosen as the most representative (although we finally considered the model with three common trends, effort, and winter river discharge; see below). For the purse-seine, the best model in the north west considered fishing effort and the

spring EAT as explanatory variables; in the central and south-west regions, no variable was chosen besides the three common trends, while in the south, both fishing effort and the river discharge in winter were selected by the best model with three common trends. In the case of the multi-gear fishery, no variable was chosen for the model in the north and central-west regions, while fishing effort was retained in the south west and south. Nevertheless, as in the case of trawling, we finally chose the model considering two trends, fishing effort and winter river discharge. The final selection of the models considering winter river discharge in the south over more simple models was made on the basis that it provides an environmental explanation for fish landings besides fishing effort. A sensitivity analysis for the selection of the models based on their AICc was carried out by fitting the models of interest to a randomized set of landings time series (100 randomizations for each region-gear) (Supplementary Table S1). This sensitivity analysis showed that the results of the DFA were very robust, with a probability of obtaining an AICc value of less than or equal to the correct value  $p \ll 0.01$  in all cases. Therefore, the models obtained were not caused by statistical artefacts of the DFA and their selection (based on AICc) did not rely on wrong computational results.



**Table 2.** The three best models according to AICc values for each region and gear type (AICc values in [Supplementary File 4](#)).

Gear	Region	Model 1	AICc 1	Model 2	AICc 2	Model 3	AICc 3
Trawling	North west	3 trends + effort	1 040	3 trends	1 053	2 trends + effort	1 059
	Central west	3 trends	1 080	3 trends + SST spring	1 094	3 trends + anomaly spring	1 100
						3 trends + precipitation	1 100
						3 trends + effort	1 100
	South west	3 trends + effort	895	3 trends + effort + NAO autumn	913	3 trends + effort + EAT autumn	916
South	3 trends	1 224	3 trends + effort	1 225	3 trends + river winter	1 226	
	3 trends + effort + river winter	1 224					
Purse-seine	North west	3 trends + effort + EAT spring	723	3 trends + effort + NAO spring	727	3 trends + effort + AMO	728
	Central west	3 trends	850	3 trends + effort	851	3 trends + effort + EAT summer	852
						3 trends + EAT summer	852
	South west	3 trends + effort	892	3 trends	893	3 trends + NAO winter	898
	South	3 trends + effort + river winter	806	3 trends + effort	821	3 trends + effort + river summer	822
Multi-gear	North west	3 trends	1 328	3 trends + anomaly spring	1 334	3 trends + effort	1 337
	Central west	3 trends + effort	1 312	3 trends + effort + EAT winter	1 314	3 trends + SST spring	1 337
						3 trends	1 315
	South west	3 trends + effort	1 188	3 trends	1 206	3 trends + effort + SST winter	1 212
	South	2 trends + effort + river winter	1 271	2 trends + effort	1 272	3 trends + effort	1 276

When different models had AICc values with less than three points of difference, the principle of parsimony was applied to identify the most relevant model, which is shown in light grey. In the south region, models with winter river discharge had the lowest AIC in the case of purse-seine and multi-gear fisheries but not for trawling (tied with the model with only three trends). We also retained this in the final analysis and highlighted in dark grey.

### Species-specific influence of trends and explanatory variables

Considering the weights of the different common trends and explanatory variables for each species in the different region-gear combinations (Table 2, [Supplementary File 6](#), and [Supplementary Tables S2–S4](#)), the DFA allowed to reconstruct the landings of the species considered during the period of study. The fit between the model predictions and observations is shown in [Supplementary File 7](#), demonstrating that both the general trends and the short-term variation of the time series of most of the species were satisfactorily captured.

The best models describing the landings of trawling in Portugal included three common trends (Table 2), being accompanied by fishing effort in the north west and south west, or by fishing effort and the river winter discharge in the south. The most important species for this fishery was *T. trachurus*, which dominance decreased from north to south ([Supplementary Figure S2](#)). Other species, such as *Parapenaeus longirostris* and *M. poutassou*, reached important landing values in the south, where a specific fishing segment is dedicated (crustacean bottom trawling). The correlations shown in [Supplementary File 6](#) and [Supplementary Table S2](#) show that the relationship between the dominant species in each region is positively related to fishing effort.

Regarding purse-seine, models with three common trends were the ones with lowest AICc as well (Table 2). Fishing effort was included in the models for the north west and south, being accompanied by spring EAT in the north west and by the winter river discharge in the south. These time series are very strongly dominated by landings of *S. pilchardus* ([Supplementary Figure S2](#)), which are positively correlated with fishing effort

([Supplementary File 6](#) and [Supplementary Table S2](#)), although a substitution by *S. colias* is perceived in the last years of the time series ([Supplementary Figure S2](#)). Interestingly, the spring EAT time series is negatively correlated with the landings of all species in the north west (not always significantly) except of *Scomber scombrus*. On the other hand, in the south, the winter river discharge is only positively correlated to the landings of *S. pilchardus*.

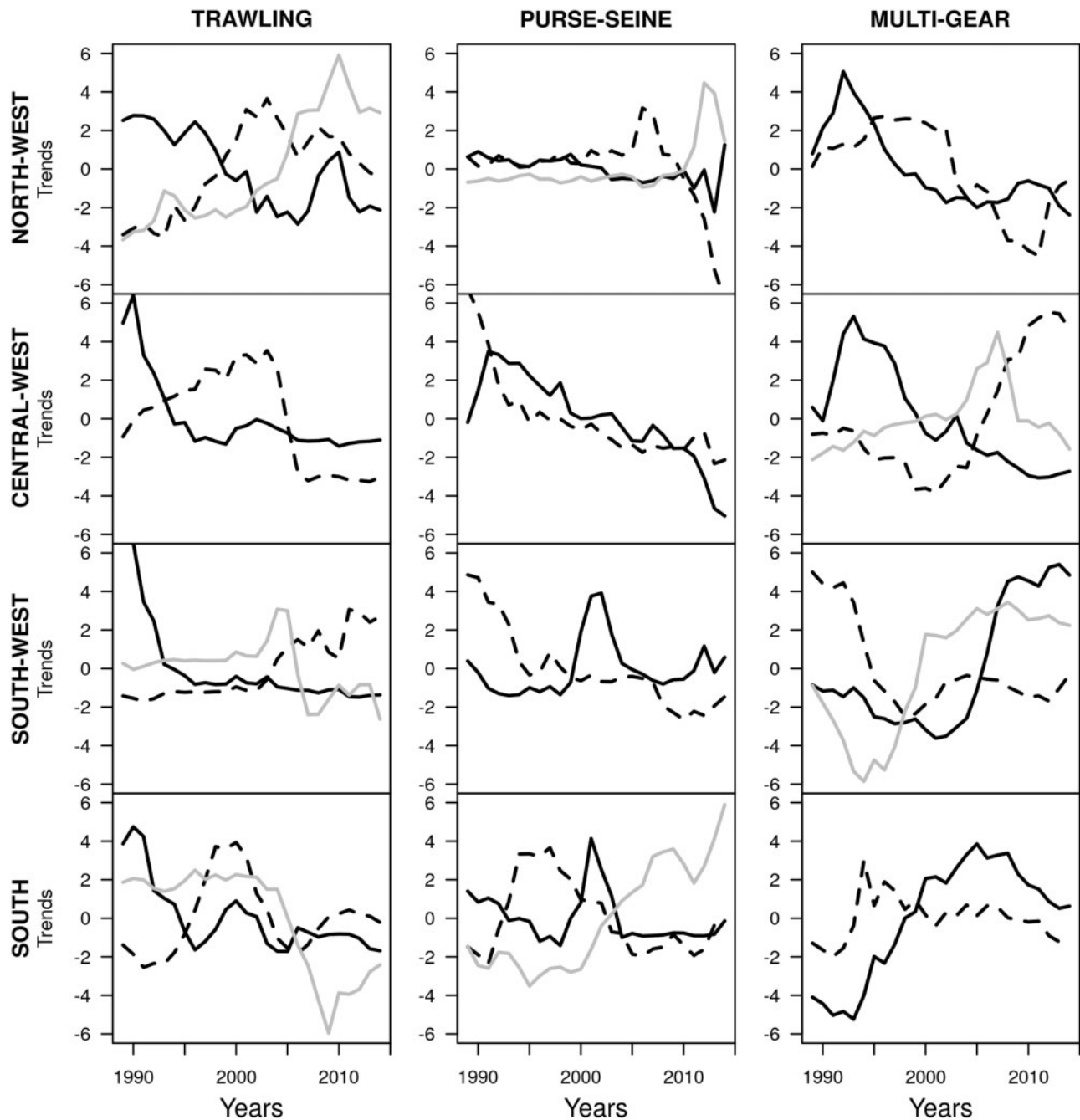
For the multi-gear fishery, the variables improving the models are fishing effort in the south-west and south regions, plus the winter river discharge in south (Table 2). In the north west, landings have been dominated by sardine in recent years, although other species such as *Trisopterus luscus* and *T. trachurus* have been constantly important ([Supplementary Figure S2](#)). On the other regions, a variety of species dominated the landings ([Supplementary Figure S2](#)). Fishing effort in the south west and south is related to the corresponding dominant species: *L. caudatus* and *Aphanopus carbo*, and Octopodidae and *S. colias*, respectively, while the winter river discharge appeared to be related to Istiophoridae and *Makaira indica* landings.

### Discussion

This is the first attempt to provide a comprehensive overview of the drivers of marine fish and shellfish landings in Portugal considering the entire continental coast and the three main types of commercial fisheries: trawling (comprising pelagic and demersal trawling), purse-seine, and multi-gear (which includes a wide variety of small-scale techniques).

Previous studies have provided information on specific gears (Erzini, 2005), regions (Erzini, 2005; Gamito et al., 2015) or on specific groups of fished species (Gomes et al., 2001; Sousa et al., 2007; Santos et al., 2012; Leitão et al., 2016). The period of study





**Figure 4.** Main common trends identified by DFA for each region and gear type (see Table 2). Trend 1: black solid line; Trend 2: black dashed line; Trend 3: grey solid line.

considered in this work (1989–2014) is coincident with the implementation of the Common Fisheries Policy of the European Union and other related policies looking for the sustainability of fisheries by decreasing fishing effort at the European level among other measures (European Commission, 2008, 2009). Accordingly, fishing effort dropped in continental Portuguese waters from 326 000 to 250 000 days year<sup>-1</sup>, a 23.3% decrease. However, in the same period, total landings decreased by 52%, from 197 000 to 94 700 tonnes. The steeper drop of landings in comparison to effort implies a fall in LPUE, a trend that,

interestingly, was not found at the regional scale when considering each gear separately (Figure 3 and Table 1). Also, it is important to keep in mind that the catching power varies both between and within different fleets and thus, using days-at-sea summed across all fleets can provide a misleading view of effort. In general, a fall in LPUE could imply a drop in fishing efficiency, which seems unlikely as “technological creep” tends to increase fishing efficiency over time, partially offsetting any reduction in days-at-sea. The more likely alternative is that target species abundance has fallen. Information from the available stock assessments could

throw some light on the relationship between fish stocks, landings, and effort. Albeit there exist stock assessments concerning the area and species under consideration, some methodological aspects obscure this comparison: (i) the amount of species for which they exist is limited, (2) stock assessments are usually made based on the entire area ICES IXa (comprising Portugal and other regions of Spain whose landings represent a high proportion compared to Portugal), and (3) the time series are not always coincident in time, or have important gaps. In addition, results from the stock assessments should be compared to landings and effort from the four regions and three *métiers* under comparison, implying to lose track of the different patterns here described.

To extract the common trends in landings time series and analyse the effect of other complementary variables, we used a DFA (Zuur *et al.*, 2003; Zuur and Pierce, 2004). This is a dimensionality reduction technique extracting the common trends (that are smoothing functions over time) from a set of time series and, allowing us to evaluate the relationships between time series, common trends, and explanatory variables. Besides the common trends, the variables selected by the different models in Table 2 are interpreted as the drivers of change over short time scales, while the variables found to be correlated with the common trends, shown in Supplementary File 5, are interpreted as likely drivers of longer-term variability (Zuur *et al.*, 2003). Hence, we have found that the variables capturing short-term variation in landings were fishing effort, river discharge in winter, and the spring EAT (Table 2), while the variables correlated with the common trends were fishing effort and the NAO, AMO and EAT indices (Supplementary File 5). The fit of the selected models to the observations of landings per species (Supplementary File 7) was good and captures some short-term variation in addition to the general trends of landings. The sensitivity analysis that we conducted indicated that these results are robust and very likely ( $p \ll 0.01$ ; Supplementary Table S1) due to effective relationships between landings and the explanatory variables retained. Below, we will discuss in more detail the meaning of these findings.

### Fish landings and effort

Albeit we cannot disregard the effect of overfishing and the fact that some important stocks are following an unequivocal dropping trend (e.g. ICES, 2018), our results suggest that landings in Portugal over the study period were primarily driven by fishing effort and secondarily driven by environmental variables. The fact that most of the models selected to describe fish landings consider fishing effort as explaining variable (Table 2) and that most of the common trends found in the time series were correlated with fishing effort (Supplementary File 5) is important, although fishing effort is not always selected by the best models (Table 2). Hence, while a causal relationship between landings and effort seems inevitable, the reality of the different fisheries is more complex. The fact that overall landings declined faster than overall effort suggests a coincidental relationship. For example, the biomass trajectory of the Iberian sardine in ICES areas 8.c and 9.a dropped in our study since 1993 at 967 000 tonnes, until 2014 at 119 000 tonnes, when it was close to a historical low (ICES, 2018). Fishing mortality in the 2000s is estimated to have been much higher than the sustainable level, pointing to an important role of overfishing on the decline in this stock (ICES, 2018).

We believe that the relationships between fishing effort and different social variables such as fuel price, unemployment rate, or the gross domestic product may also affect the complex relationship between fishing effort and landings and that it could vary significantly among the different regions of Portugal and for the different gears considered. Analysing these relationships is beyond the scope of this work but should be taken into account for future studies aiming at understanding the variation of fishing effort in relation to different social factors and landings.

Fishing effort, on the other hand, has not only an effect on landings quantity but also on landings composition, especially in the case of non-selective *métiers*. The DFA analysis captures the variation of the proportion of each species landed during the period of study, but it does not detect the entry of new species to a fishery because the number of taxa considered was fixed from the beginning (unless those species had reached an important percentage in the composition of landings, which was not the case). To understand the effect of effort on landings composition, we evaluated the relationship between the total number of species landed and the effort computed through the four regions of Portugal for each *métier* (Figure 3). The relationship was found to be significant and positive for purse-seine and partially significant (only during the second half of the time series) for trawling (which kept the spatial extent of activity more or less constant through time, Bueno-Pardo *et al.*, 2017). This means that the reduction in effort by purse-seiners over time effectively entailed a diminution of accessory species in the landings, while in the case of trawling, a possible change in regime occurred in the middle of the time series. This could be related to technological improvements, making fishing more efficient and/or to a real effect of the effort on landings composition, given that these are not selective gears. In the case of the multi-gear fishery, it is difficult to extract conclusions on this point because of the mixture of techniques and gears included within this category. However, a change in regime also seems to be apparent in the middle of this time series, together with an increase in effort. Hence, in the beginning, there was a decrease in the number of species followed by a decrease in effort, but in a period of 4–5 years, an increase in effort was associated with an increase in the number of species landed. Although it has been argued that the entry of subtropical species in northern waters due to climate change could have affected the composition of landings of non-selective fisheries such as trawling (Pinsky and Fogarty, 2012), it seems that in general, the number of landed species in Portugal decreased during the time series, accompanied by a decrease in fishing effort.

### Fish landings and environmental variables

Among the environmental variables driving marine fish landings in Portugal, the effect of the river discharge in winter was consistent in the south for the three gear categories under consideration (Table 2, Supplementary File 6, Supplementary Tables S2–S4). This phenomenon has been already described by Erzini (2005) for the purse-seine and multi-gear fisheries in southern Portugal and by Sobrino *et al.* (2002) for the octopus fishery in southern Spain. The Guadiana is the main river of the region and, despite its extensive catchment area of 67,000 km<sup>2</sup> shared between Spain and Portugal, has a relatively low discharge compared to other rivers on the west coast, which were not selected by the models in their respective regions (e.g. Douro in the north west, Tejo in the

central and south west). River discharge could benefit species spawning during winter/early spring (such as horse mackerel and sardine), by enhancing primary productivity or higher turbidity conditions that would increase larval and juvenile survival. In fact, we found a positive relationship between winter river discharge and purse-seine landings of pelagic fish (sardine, anchovy, the Atlantic mackerel, and Osteichthyes) in this region (see [Supplementary File 6](#) and [Supplementary Table S3](#), and [Bergeron et al., 2010](#)), while the relationship was found to be negative for other more benthic-pelagic species such as *S. colias* and *T. picturatus* ([Supplementary File 6](#) and [Supplementary Table S3](#)). In the west coast of Portugal, where upwelling events are more frequent and intense than in the south, the importance of river discharge as promoters of nutrient enrichment and primary production could be somehow masked and explain why that these factors were not chosen by the representative models in [Table 2](#).

Similarly, the spring EAT index was chosen by the best model for landings by purse-seine in the north west, with the second-best model considering spring NAO. Climatic cycles have been related to catches and recruitment fluctuations in very different fisheries all across the world (e.g. [Stige et al., 2006](#); [Brunel and Boucher, 2007](#); [Meng et al., 2016](#); [Rubio et al., 2016](#)) with mechanisms related to the enhancement of productivity driven by periodic environmental fluctuations. The NAO has been shown to influence the regime of winds and rainfall in continental Portugal ([Corte-Real et al., 1998](#)), which is finally related to the runoff and nutrient input to the sea ([Glantz, 1992](#)). In this manner, the mechanisms through which these indicators operate are related to the enhancement of productivity in coastal areas, in a similar way to river discharge affecting fish landings in the south during winter.

The case of sardine deserves a separate comment because of its historical and cultural relevance in Portuguese marine landings. According to our analysis, purse-seine landings (the main source of sardine landings) are explained by models considering effort, spring EAT, and the winter river discharge ([Table 2](#)), while models considering other climatic indices such as spring NAO, summer EAT, annual AMO, or winter NAO had low AICc values too ([Table 2](#) and [Supplementary File 4](#)). Interestingly, the correlations between these indices and the common trends extracted by the DFA ([Supplementary File 5](#)) were not significant, but instead they were correlated to the time series of the landings of sardine ([Supplementary File 6](#)), indicating that they could be behind high frequency temporal variations of landings of sardine than to long cycles of variation of landings by this *métier*. More specifically, as shown in [Supplementary File 6](#), landings of sardine were found to be negatively correlated to annual AMO and autumn EA both in the north and central-west regions and positively correlated to the winter river discharge in the south, in concordance with the theory of a likely relationship between climatic indices promoting primary productivity in the sea (river runoff, increasing rainfall) with the landings of sardine in continental Portugal. Different studies, on the other hand, have explored the effects of different variables on sardine landings: sunspots (a proxy for solar irradiance; [Guisande et al., 2004](#)), the AMO and NAO indices ([Guisande et al., 2001](#); [Borges et al., 2003](#)), and the water column stability and seasonal upwelling ([Guisande et al., 2001](#); [Santos et al., 2001](#); [Borges et al., 2003](#)). Building on these results, it has been suggested ([Santos et al., 2004](#)) that convergence zones between the coast and offshore waters, associated with the Iberian Poleward Current ([Pingree and Le Cann, 1990](#)) during autumn

and winter, provide a retention mechanism that keeps sardine eggs and larvae in coastal waters that have been enriched by upwelling ([Joint et al., 2002](#)) and also that excessive upwelling during winter may increase mortality by advecting the larvae offshore into waters with decreased prey concentration. Nevertheless, as indicated by [Santos et al. \(2012\)](#), the conclusions on the causal relationships are frequently contradictory and the link between environmental variability during the critical larval period, abundance of recruits, and subsequent landed biomass is difficult to discern, requiring a partition of variability among effort and environmental factors, being effort, finally, the main driver of the sardine decline.

### Policy considerations: fishing effort

Fishing regulations are a major determinant of landings and LPUE with often strong and immediate effects. In this regard, our study included fishing effort as a proxy for the main management regulations. Subsequent to Portugal joining the European Union in the mid-1980s, important policy-related changes affecting marine fisheries in Portuguese coastal waters include: (i) a notable decrease in fishing effort in terms of number of boats, thereafter balanced by technological advances and the increase in engine power ([Hill and Coelho, 2001](#); [Baeta et al., 2009](#); [Leitão et al., 2014a](#)); (ii) loss of third country agreements that did not affect the national fleet activity ([Leitão and Baptista, 2016](#)); and (iii) the ban of discards after 2015 ([Leitão and Baptista, 2016](#)).

Concerning the decrease in effort policies (see [Figure 2](#) and [Table 1](#)), the multi-gear fishery has been the main component of coastal fisheries (in numbers of boats) with the highest proportional drop in effort ([Figure 2](#)) and with few technological changes ([Baeta et al., 2009](#)). Similarly, fishing seasons did not vary during the period of study, as they are linked to the species' spawning or recruitment periods. Restrictions regarding closed areas only occurred in the region for bivalve dredging under biotoxins events or for seine to control quota limits. Total allowable catches, of seine are divided into quotas by the fishermen's Production Organization (OP) that should have reduced fishing effort since 1997. However, rules for decreasing effort and manage quotas are enforced by the fisheries department (Direção-Geral de Recursos Naturais, Segurança e Serviços Marítimos, DGRM) and applied evenly across areas and OPs.

The 2012 revision of the EU-CFP led to the implementation of a discard ban in European waters ([Borges, 2015](#)). The time series analysed here runs from 1989 to 2014 so the data analysed are unlikely to have been affected by this. Similarly, the definition of marine protected areas (MPAs) was still not finished during the period of study, and so there was not yet any loss of fishing areas, making it possible to assume that fishing habitat was kept constant during the study period. The introduction of new technical regulations on fishing boats would effectively change catch composition and amount. However, there is still little understanding of the underlying socio-economic and institutional incentives that marine policy changes can cause at the fishery sector level ([Leitão and Baptista, 2016](#)). Further investigation would help to clarify these questions.

### Policy considerations: fisheries statistical datasets

The low resolution of the available data in terms of type or subtype of *métier* precludes a further disaggregation of the landings of marine fish in Portugal at the temporal and spatial scales



considered in the present study. This is of special relevance in the case of trawling where two well differentiated fleets are found (Erzini *et al.*, 2002), or for the multi-gear fishery, that includes a wide diversity of techniques and tools. This issue is further compounded by non-homogeneity of nomenclature between different public data sets (Bueno-Pardo *et al.*, 2017). These constraints are a critical obstacle to crossing different data sets and factors and prevent more detailed analysis, either here or elsewhere, of the factors that affect marine fisheries in Portugal. An improvement of the official reporting protocols in Portugal would be relatively easy to attain, by standardizing the classification of the *métiers* in every public data set, further disaggregating the trawling and multi-gear fisheries into subtypes, and updating and homogenizing the species nomenclature (containing several inaccuracies, ancient scientific names, or even scientific names changed during the period of study such as *Scomber japonicus*/*S. mediterraneus*).

### Policy considerations: a move for higher value, more sustainable fisheries

The present study shows that trawling is the *métier* that least contributed to total landings in Portugal during the whole time series and that applied the least effort (Figure 3). Trawling has a documented impact on the ecological integrity of the seafloor (Morais *et al.*, 2007; Hiddink *et al.*, 2017; Ramalho *et al.*, 2017), collects high amounts of accessory species (Erzini *et al.*, 2002) and generates the lowest first sale value of the landed fish in Portugal (e.g. Instituto Nacional de Estatística de Portugal, www.ine.pt). Purse-seine and, especially, multi-gear fisheries in Portugal, which generally are classified under the label of small-scale fisheries, employ many more fishers than trawling (>95% of the awarded licences in 2012–2014; Instituto Nacional de Estatística de Portugal, www.ine.pt). These *métiers* produce higher revenues per landed kilogram and are considered socially and economically more sustainable (Schuhbauer *et al.*, 2017). We suggest that public support to the fisheries sector in Portugal should progressively aim to eliminate unsustainable ecological fishing practices. As suggested elsewhere (Sumaila *et al.*, 2016), these savings could be directed to requalify fishers to support sustainable activities of cleaning of the ocean and environmental awareness, which would maintain the subsidy money in the community.

### Conclusions

In this article, we have carried out a comprehensive analysis of the drivers of marine fish landings in continental Portugal for the period of 1989–2014. This analysis considered four different regions and three gears: trawling, purse-seine, and a multi-gear fishery. Using a DFA, we have found that the drivers of fish landings vary among the region–gear combinations, although the effect of fishing effort was found to be significant in most of them, both at the short and long terms. Other variables such as the winter river discharge, or the spring East Atlantic Teleconnection index, were found to be relevant to explain the evolution of landings in the short term in some regions of Portugal. The mechanisms through which these variables control the landings of marine fish are discussed in detail. Finally, some advices on the methodology of the acquisition of data and on the control policy for trawling are provided.

### Supplementary data

Supplementary material is available at the ICESJMS online version of the manuscript.

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