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

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Abstract :

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

1 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 (FAO, 2018; United Nations, 2010). Although total reported catch has been relatively static since the late 1980s (around 85 million tons; FAO, 2018), analyses based on temporal trends of proportional catch relative to maximum catch (the Stock Status plot; see Kleisner et al., 2012 and references therein) indicate that roughly 40% of the world stocks were over-exploited or had collapsed by 2005 (Kleisner et al., 2012). Furthermore, the build-up of the proportion of collapsed stocks since the 1970’s 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 which lack 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; Pauly et al., 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 CPUE (catches per unit effort) is also problematic, not least because the validity of CPUE or LPUE as an abundance index depending on randomised 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 (Crecco & Hoverholtz, 2011; Rose & Leggett 2011; Winters & Wheeler, 2011). Despite the limitations of landings as an index of the status of a stock, or as a proxy for 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 more than 4,100 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 t in the 1960s, dropping to 250,000 t by the end of the 1980s, and to less than 200,000 t in 2009 (Leitão et al., 2014a). On the other hand, a steady decrease of 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., 2014a). 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 & Smith, 2003; flatfishes: Teixeira & 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 & Smith, 2003 and Erzini, 2005, who analysed total landings), and found that different combinations of sea surface temperature (Teixeira & Cabral, 2009; Teixeira et al., 2014; Gamito et al., 2015; Teixeira et al., 2016), the North Atlantic Oscillation (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), in order 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.

2 MATERIALS AND METHODS

2.1 Landings data

Official data on landings of fish and shellfish at the different ports of mainland Portugal (Fig. 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 kg, 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 wide group of species. The trawling category includes two different techniques: 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. On the other hand, the subset of ports consisted on the 20 most important ports for purse-seine and trawling, and on the 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 Information File, SIF, 1 for the time series of landings, in tons, 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.

2.2 Identification of temporal and spatial trends in landings

In order 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 × years × ports), which was then decomposed into three different modes: species mode (ports × year), temporal mode (port × species), and the spatial mode (year × 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 & 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 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 Information Document, SID; Fig. SID1) 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 (Fig. 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 to 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 to 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 to 38.77 N). Finally, the South region comprises the south-facing coast from the Sagres Canyon to the Guadiana river (35.7 to 37.01 N), including the ports of Sagres, Lagos, Portimão, Quarteira, Olhão, and Vila Real de Santo António (VRSA). These regions are also broadly coincident with well-known oceanographic patterns in coastal waters of continental Portugal (Relvas et al. 2007; Arístegui 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.

2.3 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 any region. A database of time series of fishing and environmental variables was also assembled, in order to test their effects as predictors of fish landings. These were the fishing effort, the North Atlantic Oscillation (NAO) index, the Atlantic Multidecadal Oscillation (AMO) index, the Eastern Atlantic Teleconnection (EAT) index, the inshore Sea Surface Temperature (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 of explanatory variables are available in the SIF 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 productivity, 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). 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 (ºC) were obtained from the Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA) database (ghrsst-pp.metoffice.com/pages/latest_analysis/ostia.html), which uses satellite data provided by international agencies via the Group for High Resolution SST (GHRSST) Regional/Global Task Sharing (R/GTS) framework (Donlon et al., 2012). OSTIA data are corrected for sensor bias and provided at a 0.05º 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 11 to 12º 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 ($m^3\ s^{-1}\ km^{-1}$) were obtained from the Instituto Español de Oceanografía (IEO, http://www.indicedeafloramiento.ieo.es/afloramiento_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.

In order to obtain a proxy for freshwater input to the coastal ocean ($m^{-3}\ s^{-1}$) we used a combination of monthly data available from the website of the Sistema de Informação Nacional de Recursos Hídricos (snirh.pt), which compiles data from the network of measurement stations of the Ministério do Ambiente, and supplied by EDP - Energias de Portugal SA, 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 both lie close to the limit between the Central-west and the 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 10 pairwise correlation coefficients were positive and significant at the 5% level, with 5 of the coefficients above 0.75 and the remaining above 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, 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).

In order to obtain a measure of rainfall for the coastal ocean we used the accumulated rainfall (L m^{-2} $year^{-1}$) 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.

2.4 Dynamic factor analysis

Dynamic Factor Analysis (DFA) is a multivariate time-series analysis technique used for non-stationary time series analysis allowing 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 & Pierce, 2004; Erzini 2005; Erzini et al., 2005; Leitão et al., 2016a; 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 greater than 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 (MARSS) 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, in order to facilitate the interpretation of factor loadings and canonical correlations.

3 RESULTS

3.1 Exploratory analysis of the time series

The MDS analysis (SID “Exploratory analysis of the time series”; Fig. SID1) 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 1989-2014 (Fig. 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 (Fig. 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 (Fig. 2), although the general trend was decreasing in the Central-west and South-west and increasing in the South (Table 1). Considering the 3 most important species in each region-gear combination (SID “Landings evolution of the three most important species per region and gear”; Fig. SID2) 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 more than 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 in the 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% (Fig. 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 of fishing effort, decreasing almost 50% during the period, while effort by trawling and the multi-gear fishery decreased by about 20%. Trawling effort decreased more slowly after 2005 in all regions except in the South-west, where a 4-fold increase was registered. On the other hand, multi-gear effort (which accounts for more than 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 (Fig. 2 and Table 1).

Table 1. Trends and significances of linear regressions between landings, effort, and LPUE for the period of study. Significances are represented as follows: **** $P < 0.0001$, *** $P < 0.0001$, ** $P < 0.01$, * $P < 0.05$.

Gear	Region	Landings trend	p-val.	Effort trend	p-val.	LPUE trend	p-val.
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	****

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

In order to further investigate the relationship between effort and the compositional change of 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 (Fig. 3). This relationship was only significant in the case of purse-seine during the complete time series (Fig. 3B; $p=4.92 \times 10^{-5}$), and in the case of trawling during the second half of the time series (Fig. 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. (Fig. 3C).

3.2 Dynamic Factor Analysis

Before using the explanatory variables to interpret landings patterns we used canonical correlations in order to detect collinearity among them and reduce their numbers to a tractable set (SIF 3, units as described in section 2.3). 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.

The DFA allowed us to identify the common trends of the time series of landings of fish characterizing each region-gear combination (Table 2, Fig. 4), as well as the explanatory variables contributing to the models with lowest AICc values (Table 2, SIF 4). The common trends identified by the DFA indicated some degree of geographical consistency within each type of fishery (Fig. 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 SIF 5. In this respect, the analysis for trawling detected consistent patterns of 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 3 common trends were chosen as the most representative (although we finally considered the model with 3 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 3 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 2 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) (SID “Sensitivity analysis of the DFA”; Table SID1). This sensitivity analysis showed that the results of the DFA were very robust, with a probability of obtaining an AICc value less than or equal to the correct value $p<<0.01$ 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 Information File 4). 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 3 trends). We also retained this in the final analysis and highlighted in dark grey.

Gear	Region	Model 1	AICc 1	Model 2	AICc 2	Model 3	AICc 3
Trawling	North-west	3 trends + effort	1040	3 trends	1053	2 trends + effort	1059
	Central-west	3 trends	1080	3 trends + SST spring	1094	3 trends + anomaly spring	1100
						3 trends + precipitation	1100
						3 trends + effort	1100
	South-west	3 trends + effort	895	3 trends + effort + NAO autumn	913	3 trends + effort + EAT autumn	916
	South	3 trends	1224	3 trends + effort	1225	3 trends + river winter	1226
		3 trends + effort + river winter	1224				
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	1328	3 trends + anomaly spring	1334	3 trends + effort	1337
						3 trends + SST spring	1337
	Central-west	3 trends + effort	1312	3 trends + effort + EAT winter	1314	3 trends	1315
	South-west	3 trends + effort	1188	3 trends	1206	3 trends + effort + SST winter	1212

	South	2 trends + effort + river winter	1271	2 trends + effort	1272	3 trends + effort	1276

3.3 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, SIF 6; and SID “Relationship between species-specific landings per region and gear and the environmental variables”, Tables SID2, SID3 and SID4), 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 SIF 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 (Fig. SID2). 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 SIF6 and Table SID2 show that the relationship between the dominant species in each region are 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* (Fig. SID2), which are positively correlated with fishing effort (SIF 6, Table SID2), although a substitution by *S. colias* is perceibed in the last years of the time series (Fig. SID2). 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 (Fig. SID2). On the other regions, a variety of species dominated the landings (Fig. SID2). Fishing effort in the South-west and South is related to the corresponding dominant species: *Lepidopus 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.

4 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., 2016a). The period of study 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 d y^{-1}, a 23.3% decrease. However, in the same period, total landings decreased by 52%, from 197,000 to 94,700 tons. The steeper drop of landings in comparison to effort implies a fall in landings per unit effort (LPUE) a trend that, interestingly, was not found at the regional scale when considering each gear separately (Fig. 3, 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: 1) the amount of species for which they exist is limited, 2) stock assessments are ussually made based on the entire area ICES IXa (comprising Portugal and other regions of Spain whose landings represent a high proportion compared to Portugal), 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 loose 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 dynamic factor analysis (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 SIF 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 (SIF 5). The fit of the selected models to the observations of landings per species (SIF 7) was good and capture 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 ($p<<0.01$; Table SID1) due to effective relationships between landings and the explanatory variables retained. Below, we will discuss in more detail the meaning of these findings.

4.1 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 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 (SIF 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 t, until 2014 at 119,000 t, 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 of 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 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* (Fig. 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 of 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 of 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 of regime also seems to be apparent in the middle of this time series, together with an increase of effort. Hence, in the beginning, there was a decrease of the number of species followed by a decrease of effort, but in a period of 4-5 years, an increase of 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.

4.2 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, SIF 6, Tables SID2, SID3, SID4). 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^2 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 SIF 6, Table SID3, and Bergeron et al., 2010), while the relationship was found to be negative for other more bentho-pelagic species such as *S. colias* and *T. picturatus* (SIF 6, Table SID3). 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. Rubio et al., 2016; Meng et al., 2016; Brunel and Boucher, 2007; Stige et al., 2006) 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 affects 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, SIF 4). Interestingly, the correlations between these indices and the common trends extracted by the DFA (SIF 5) were not significant, but instead they were correlated to the time series of the landings of sardine (SIF 6), indicating that they could be behind low frequency temporal variations of landings of sardine than to long cycles of variation of landings by this *métier*. More specifically, as shown in SIF 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 (Pingreen & 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), but 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.

4.3 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. There are some synthesis capturing the fishing policy actions in the Portuguese coast after entrance in the European Union (EU) in middle 1980s: i) a notable decrease in fishing effort in terms of number of boats, thereafter balanced by technological advances and increase the increase of engine power (Baeta, 2009; Hill and Coelho 2001; Leitão et al., 2014b) ii) loss of third countries agreements that did not affect the national fleet activity (Leitão et al., 2016b); iii) the ban of discards after 2015 (Leitão et al., 2016b).

Concerning the decrease in effort policies (see Fig. 2, 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 (Fig. 2), and with few technological changes (Baeta, 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 in order to control quota limits. TACs of seine are divided into quotas by the fishermen Production Organization (OP) that should reduce fishing effort since 1997. However, rules for decreasing effort and manage quotas are enforced by the fisheries department (DGRM) and applied evenly across areas and OPs.

The 2012 revision of the EU Common Fisheries Policy (CFP) led to the implementation of a discard ban in European waters (Borges, 2015). The time series here analysed goes from 1989 to 2014 and so the discard potential effect is not biasing analyses. Similarly, the definition of marine protected areas (MPA's) was still not finished during the period of study, and so there was not yet loss of fishing areas, making 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 catches 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 et al., 2016b). Further investigation would help to clarify these questions.

4.4 Policy considerations: fisheries statistical datasets

The low resolution of the available data in terms of type or sub-type 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*).

4.5 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 (Fig. 3). Trawling has a documented impact on the ecological integrity of the seafloor (Morais et al., 2007; Ramalho et al., 2017; Hiddink 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 licenses 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 in order to support sustainable activities of cleaning of the ocean and environmental awareness, which would maintain the subsidy money in the community.

5 CONCLUSIONS

In this paper, we have carried out a comprehensive analysis of the drivers of marine fish landings in continental Portugal for the period 1989-2014. This analysis considered four different regions and three gears: trawling, purse-seine, and a multi-gear fishery. Using a Dynamic Factor Analysis, 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 the long term. 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.

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BIBLIOGRAPHY

- Anticamara, J. A., Watson, R., Gelchu, A., & Pauly, D. (2011). Global fishing effort (1950-2010): trends, gaps, and implications. Fisheries Research, 107, 131–136.
- Arístegui, J., Barton, E. D., Álvarez-Salgado, X. A., Santos, A. M. P., Figueiras, F. G., Kifani, S., et al. (2009). Sub-regional ecosystem variability in the Canary Current upwelling. Progress in Oceanography, 83, 33–48.
- Baeta, F., Costa, M. J. & Cabral, H. (2009) Changes in the trophic level of Portuguese landings and fish market price variation in the last decades. Fisheries Research, 97: 216-222.
- Bergeron, J.-P., Delmas, D., & Koueta, N. (2010). Do river discharge rates drive the overall functioning of the pelagic ecosystem over the continental shelf of the Bay of Biscay (NE Atlantic)? A comparison of two contrasting years with special reference to anchovy (*Engraulis encrasicolus* L.) nutritional state. Journal of Oceanography, 66, 621–631.
- Borges, M. F., Santos, A., Crato, N., Mendes, H., & Mota, B. (2003). Sardine regime shifts off Portugal: a time series analysis of catches and wind conditions. Scientia Marina, 67 (Suppl 1): 235–244.
- Borges, L. (2015). The evolution of a discard policy in Europe. Fish and Fisheries, 16: 534-540
- Brunel, T., & Boucher, J. (2007). Long-term trends in fish recruitment in the north-east Atlantic related to climate change. Fisheries Oceanography 14(4): 336-349.
- Bueno-Pardo, J., Ramalho, S. P., García-Alegre, A., Morgado, M., Vieira, R. P., Cunha, M. R., & Queiroga, H. (2017). Deep-sea crustacean trawling fisheries in Portugal: quantification of effort and assessment of landings per unit effort using a Vessel Monitoring System (VMS). Scientific Reports 7: 40795.
- Campbell, R. A. (2015) Constructing stock abundance indices from catch and effort data: Some nuts and bolts. Fisheries Research 161: 109-130.
- Correia, J., & Smith, M. (2003). Elasmobranch landings for the Portuguese commercial fishery from 1986 to 2001. Marine Fisheries Review, 65; 32–40.
- Corte-Real, J., Qian, B., & Xu, H. (1998). Regional climate change in Portugal: precipitation variability associated with large-scale atmospheric circulation. International Journal of Climatology, 18: 619-635.

- Crecco, V., & Overholtz, W. J. (2011). Causes of density-dependent catchability for Georges Bank haddock *Melanogrammus aeglefinus*. Canadian Journal of Fisheries and Aquatic Sciences, 47: 385–394.
- Daskalov, G. M., Grishin, A. N., Rodionov, S., & Mihneva, V. (2007). Trophic cascades triggered by overfishing reveal possible mechanisms of ecosystem regime shifts. Proceedings of the National Academy of Sciences, 104: 10518-10523.
- Donlon, C. J., Martin, M., Stark, J., Roberts-Jones, J., Fiedler, E., & Wimmer, W. (2012). The Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA) system. Remote Sensing of Environment, 116: 140–158.
- Erzini, K., Costa, M. E., Bentes, L., & Borges, T. C. (2002). A comparative study of the species composition of discards from five fisheries from the Algarve (southern Portugal). Fisheries Management and Ecology, 9: 31–40.
- Erzini, K. (2005) Trends in NE Atlantic landings (southern Portugal): identifying the relative importance of fisheries and environmental variables. Fisheries Oceanography 14: 195-209.
- Erzini, K., Inejih, C., & Stobberup, K. (2005). An application of two techniques for the analysis of short, multivariate non-stationary time-series of Mauritanian trawl survey data. ICES Journal of Marine Science, 62: 353–359.
- European Commission (2008). Green Paper. Reform of the Common Fisheries Policy. Brussels, 22.4.2009, COM (2009) 163 final. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2009:0163:FIN:EN:PDF
- European Commission (2009). Marine Strategy Framework Directive. Brussels, 25.6.2008, DIRECTIVE 2008/56/EC. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32008L0056&from=en
- FAO (2018). The State of World Fisheries and Aquaculture 2018. Meeting the sustainable development goals. Food and Agriculture Organization of the United Nations. Licence: CC BY-NC-SA 3.0 IGO. Rome, Italy. 227 pp.
- Froese, R., Stern-Pirlot, A., & Kesner-Reyes, K. (2009). Out of new stocks in 2020: A comment on “Not all fisheries will be collapsed in 2048.” Marine Policy, 33: 180–181.
- Gamito, R., Teixeira, C. M., Costa, M. J., & Cabral, H. N. (2013). Climate-induced changes in fish landings of different fleet components of Portuguese fisheries. Regional Environmental Change, 13: 413-421.
- Gamito, R., Teixeira, C. M., Costa, M. J., & Cabral, H. N. (2015). Are regional fisheries' catches changing with climate? Fisheries Research, 161: 207–216.

- Glantz, M. H. (ed.) (1992) Climate variability, climate change and fisheries. Cambridge, UK: Cambridge University Press, 450 pp.
- Gomes, M. C., Serrão, E., & Borges, M. F. (2001) Spatial patterns of groundfish assemblages on the continental shelf of Portugal, ICES Journal of Marine Science, 58, 000-000.
- Guisande, C., Cabanas, J. M., Vergara, A. R., & Riveiro, I. (2001). Effect of climate on recruitment success of Atlantic Iberian sardine *Sardina pilchardus*. Marine Ecology Progress Series, 223: 243–250.
- Guisande, C., Vergara, A. R., Riveiro, I., & Cabanas, J. M. (2004). Climate change and abundance of the Atlantic Iberian sardine (*Sardina pilchardus*). Fisheries Oceanography, 13: 91–101.
- Guyader, O., Berthou, P., & Daures, F. (2007). Decommissioning schemes and capacity adjustment: a preliminary analysis of the French experience. Pp: 81-104. Eds: Curtis, R and Squires, D. Fisheries buybacks. Blackwell Publishing.
- Harley, S. J., Myers, R. A., & Dunn, A. (2001). Is catch-per-unit-effort proportional to abundance? Canadian Journal of Fisheries and Aquatic Sciences, 58: 1760–1772.
- Hiddink, J. G., Jennings, S., Sciberras, M., Szostek, C. L., Hughes, K. M., Ellis, N., et al. (2017). Global analysis of depletion and recovery of seabed biota after bottom trawling disturbance. Proceedings of the National Academy of Sciences, 114: 8301–8306.
- Hill L. & Coelho M. L. (2001). Portuguese fisheries in Portugal for the period 1950-1999. Comparison with ICES data. Part 3. South-eastern North Atlantic. In Zeller, D., R. Watson, and D. Pauly (eds.). Fisheries Impacts on North Atlantic Ecosystems: Catch, Effort and National/Regional Data Sets. Fisheries Centre Research Reports 9(3): 254 pp.
- ICES (2018). Advice on fishing opportunities, catch, and effort. Sardine (Sardina pilchardus) in divisions 8.c and 9.a (Cantabrian Sea and the Atlantic Iberian waters). DOI: 10.17895/ices.pub.4495.
- Joint, I., Groom, S. B., Wollast, R., Chou, L., Tilstone, G. H., Figueiras, F. G., et al. (2002). The response of phytoplankton production to periodic upwelling and relaxation events at the Iberian shelf break: estimates by the 14C method and by satellite remote sensing. Journal of Marine Systems, 32: 219–238.
- Khalilian, S., Froese, R., Proelss, A., & Requate, T. (2010). Designed for failure: A critique of the Common Fisheries Policy of the European Union. Marine Policy 34: 1178-1182.

- Kleisner, K., Zeller, D., Froese, R., & Pauly, D. (2012). Using global catch data for inferences on the world’s marine fisheries. Fish and Fisheries, 14: 293–311.
- Leitão, F., Baptista, V., Zeller, D., & Erzini, K. (2014a). Reconstructed catches and trends for mainland Portugal fisheries between 1938 and 2009: implications for sustainability, domestic fish supply and imports. Fisheries Research, 155: 33–50.
- Leitão, F., Baptista V, Erzini K., Iritanu, D., & Zeller, D. (2014b). Reconstruction of mainland Portugal fisheries catches 1950-2010. Working Paper Series. Fisheries Centre, University of British Columbia, 08: 1-29.
- Leitão, F., Baptista, V., Teodósio, M.A., Hughes, S.J., Vieira, V., & Chícharo, L. (2016a). The role of environmental and fisheries multi-controls in white seabream (*Diplodus sargus*) artisanal fisheries in Portuguese coast. Regional Environmental Change, 16: 163-176.
- Leitão F, & Baptista V. (2016b). The discard ban policy, economic trends and opportunities for the Portuguese fisheries sector. Marine Policy, 75: 75–83.
- Maes, J., Teller, A., Erhard, M., Murphy, P., Paracchini, M.L., Barredo, J.I., Grizzetti, B., Cardoso A., et al. (2014). Mapping and assessment of ecosystem and their services. indicators for ecosystem assessments under Action 5 of the EU Biodiversity Strategy to 2020. Publications office of the European Union, Luxembourg.
- Martins, M. M., Skagen, D., Marques, V., Zwolinski, J., & Silva, A. (2013). Changes in the abundance and spatial distribution of the Atlantic chub mackerel (*Scomber colias*) in the pelagic ecosystem and fisheries off Portugal. Scientia Marina, 77: 551-563.
- Meng, K. C., Oremus, K. L., & Gaines, S. D. (2016). New England cod collapse and the climate. Plos ONE. DOI:10.1371/journal.pone.0158487.
- Morais, P., Borges, T. C., Carnall, V., Terrinha, P., Cooper, C., & Cooper, R. (2007). Trawl-induced bottom disturbances off the south coast of Portugal: direct observations by the “Delta” manned-submersible on the Submarine Canyon of Portimão. Marine Ecology 28, Suppl. 1, 112-122.
- Pauly, D., Christensen, V., Guénette, S., Pitcher, T. J., Sumaila, U. R., Walters, C. J., et al. (2002). Towards sustainability in world fisheries. Nature, 418: 689–695.
- Pauly, D., Hilborn, R., & Branch, T. A. (2013). Does catch reflect abundance? Nature, 494: 303–306.
- Pingreen, R. D., & Le Cann, B. (1990). Structure, strength and seasonality of the slope currents in the Bay of Biscay region. Journal of the Marine Biological Association of the UK, 70: 857–885.

- Pinsky, M. L., & Fogarty, M (2012). Lagged social-ecological responses to climate and range shifts in fisheries. Climatic Change, 115: 883-891.
- Pita, C., Dickey, H., Pierce, G.J., Mente, E., & Theodossiou, I. (2010). Willingness for mobility amongst European fishermen. Journal of Rural Studies 26: 308-319.
- Quinn, G., & Keough, M. (2002) Experimental design and data analysis for biologists. Cambridge University Press, United Kingdom.
- Ramalho, S., Lins, L., Bueno-Pardo, J., Cordova, E. A., Amisi, J. M., Lampadariou, N., Vanreusel, A., & Cunha, M. R. (2017). Deep-sea mega-epibenthic assemblages from the SW Portuguese Margin (NE Atlantic) subjected to bottom-trawling fisheries. Frontiers in Marine Sciences, 4: article 350.
- Reis, C.S., Lemos, R.T., Dornelas, M.A., & Santos, R.A. (2001). Fisheries, in: Santos, F.D., Forbes, K., Moita, R. (Eds), Climate Change in Portugal: Scenarios, Impacts and Adaptation Measures – SIAM Project. Gradiva, Lisboa, pp. 415-452.
- Relvas, P., Barton, E. D., Dubert, J., Oliveira, P. B., Peliz, Á., da Silva, J. C. B., & Santos, A. M. P. (2007). Physical oceanography of the western Iberia ecosystem: Latest views and challenges. Progress in Oceanogaphy, 74: 149–173.
- Rose, G. A., &Leggett, W. C. (2011). Effects of biomass–range interactions on catchability of migratory demersal fish by mobile fisheries: An example of Atlantic cod (*Gadus morhua*). Canadian Journal of Fisheries and Aquatic Sciences, 48: 843–848.
- Rubio, C. J., Macías, D., Camiñas, J. A., Fernández, I. L., & Báez, J. C. (2016). Effects of the North Atlantic Oscillation on Spanish catches of albacore, *Thunnus alalunga*, and yellowfin tuna, *Thunnus albacares*, in the North-east Atlantic Ocean. Animal Biodiversity and Conservation 39(2): 195-198.
- Santos, A. M. P., Borges, M. D. F., & Groom, S. (2001). Sardine and horse mackerel recruitment and upwelling off Portugal. ICES Journal of Marine Science, 58; 589–596.
- Santos, A. M. P., Peliz, Á., Dubert, J., Oliveira, P. B., Angélico, M. M., & Re, P. (2004). Impact of a winter upwelling event on the distribution and transport of sardine (*Sardina pilchardus*) eggs and larvae off western Iberia: a retention mechanism. Continental Shelf Research, 24: 149–165.
- Santos, M. B., Gonzalez-Quiros, R., Riveiro, I., Cabanas, J. M., Porteiro, C., & Pierce, G. J. (2012). Cycles, trends, and residual variation in the Iberian sardine (*Sardina pilchardus*) recruitment series and their relationship with the environment. ICES Journal of Marine Science, 69: 739–750.
- Schuhbauer, A., Chuenpagdee, R., Cheung, W. W. L., Greer, K., & Sumaila, U. R.

(2017). How subsidies affect the economic viability of small-scale fisheries. Marine Policy, 82: 114–121.

- Sobrino, I., Silva, L., Bellido, J. M., & Ramos, F. (2002). Rainfall, river discharges and temperature as factors affecting abundance of two coastal benthic cephalopod species in the Gulf of Cádiz (SW Spain). Bulletin of Marine Sciences, 71: 851-865.
- Sousa, P., Lemos, R. T., Gomes, M. C., & Azevedo, M (2007). Analysis of horse mackerel, blue whiting, and hake catch data from Portuguese surveys (1989–1999) using an integrated GLM approach. Aquatic Living Resources, 20: 105-116.
- Stewart, K. R., Lewison, R. L., Dunn, D. C., Bjorkland, R. H., Kelez, S., Halpin, P. N., & Crowder, L. B. (2010). Characterizing fishing effort and spatial extent of coastal fisheries. PLoS ONE, 5: e14451–8.
- Stige, L. C., Ottersen, G., Brander, K., Chan, K-S., & Stenseth, N. C. (2006). Cod and climate: effect of the NOrth Atlantic Oscillation on recruitment in the North Atlantic. Marine Ecology Progress Series 325:227-241.
- Sumaila, U. R., Lam, V., Le Manach, F., Swartz, W., & Pauly, D. (2016). Global fisheries subsidies: An updated estimate. Marine Policy 69: 189–193.
- Teixeira, C. M., & Cabral, H. N. (2009) Time series analysis of flatfish landings in the Portuguese coast. Fisheries Research 96: 252-258.
- Teixeira, C. M., Gamito, R., Leitão, F., Cabral, H. N., Erzini, K., & Costa, M. J. (2014). Trends in landings of fish species potentially affected by climate change in Portuguese fisheries. Regional Environmental Change, 14: 657–669.
- Teixeira, C. M., Gamito, R., Leitão, F., Murta, A. G., Cabral, H. N., Erzini, K., & Costa, M. J. (2016) Environmental influence on commercial fishery landings of small pelagic fish in Portugal. Regional Environmental Change, 16: 709-716.
- United Nations (2010). General facts regarding world fisheries. Resumed Review Conference on the Agreement Relating to the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks.
- Wang, J., Pierce, G. J., Boyle, P. R., Denis, V., Robin, J. P., & Bellido, J. M. (2003). Spatial and temporal patterns of cuttlefish (*Sepia officinalis*) abundance, and environmental influences – a case study using trawl fishery data in French Atlantic coastal, English Channel, and adjacent waters. ICES Journal of Marine Sciences, 60: 1149-1158.
- Winters, G. H., & Wheeler, J. P. (2011). Interaction between stock area, stock abundance, and catchability coefficient. Canadian Journal of Fisheries and Aquatic

Sciences, 42: 989–998.

- Zimmermann, F., Claireaux, M., & Enberg, K. (2019). Common trends in recruitment dynamics of north-east Atlantic fish stocks and their links to environment, ecology and management. Fish and Fisheries, 2019: 1-19.
- Zuur, A. F., & Pierce, G. J. (2004). Common trends in northeast Atlantic squid time series. Journal of Sea Research, 52: 57–72.
- Zuur, A. F., Tuck, I. D., & Bailey, N. (2003). Dynamic factor analysis to estimate common trends in fisheries time series. Canadian Journal of Fisheries and Aquatic Sciences, 60: 542–552.

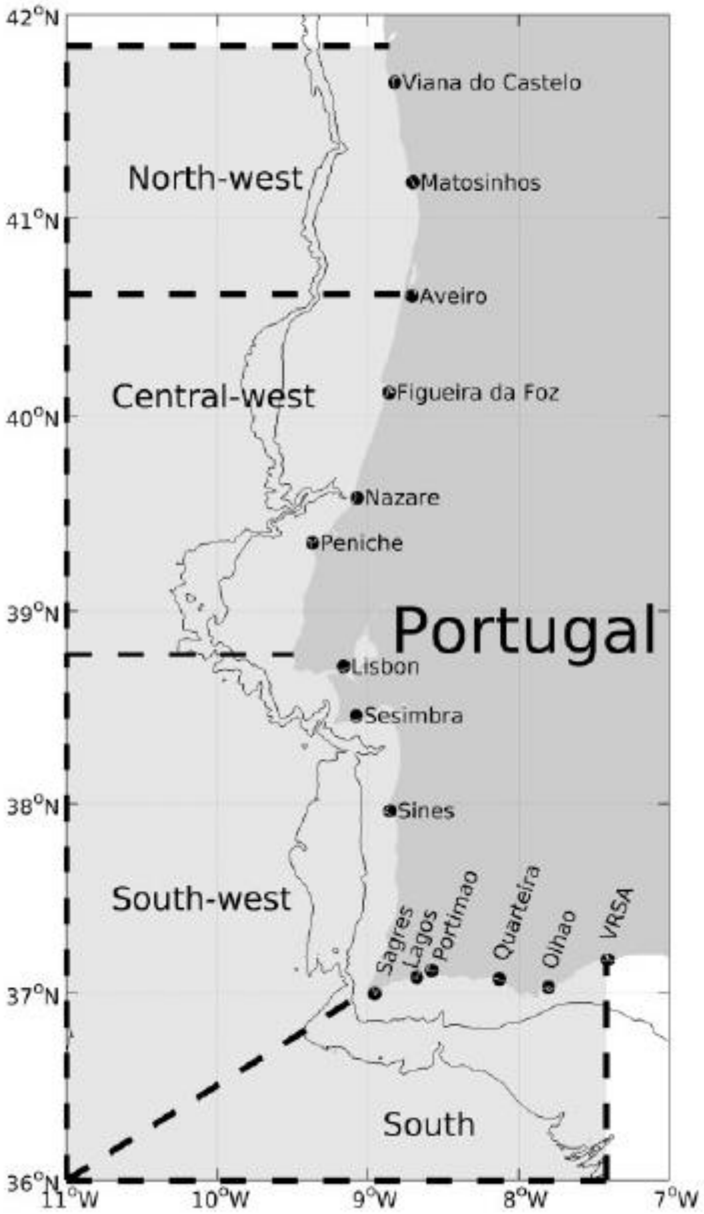

Figure 1. Map of Portugal with the regions and ports considered. The bathymetry shown corresponds to 200 and 1000 m.

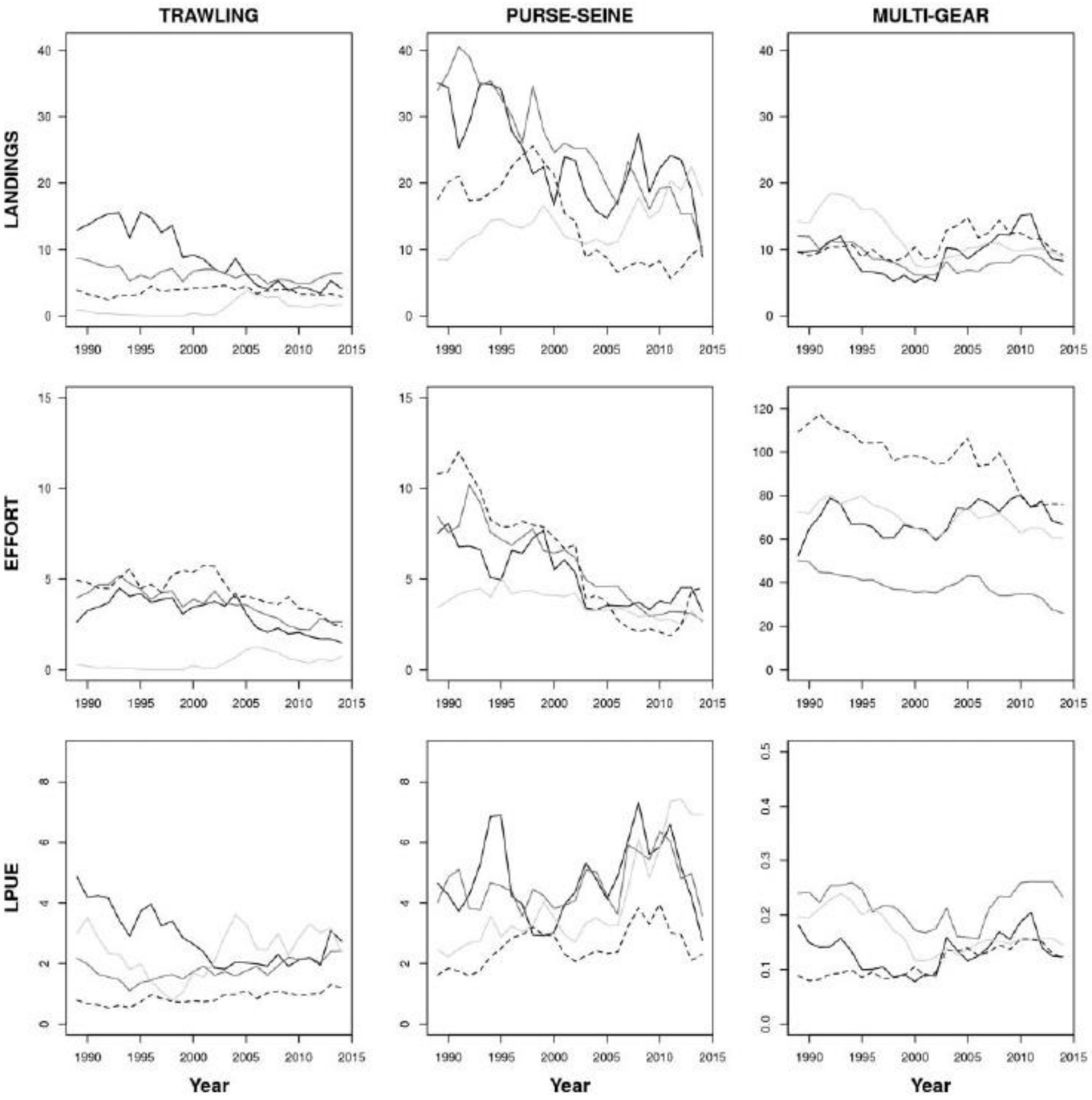

Figure 2. Time series of total landings of fish in continental Portugal (thousands of tonnes, top row), fishing effort (thousands of fishing days, middle row) and LPUE (bottom row) between 1989 and 2014, according to gear type (trawling, purse-seine, and multi-gear) and region (north west, central west, 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.

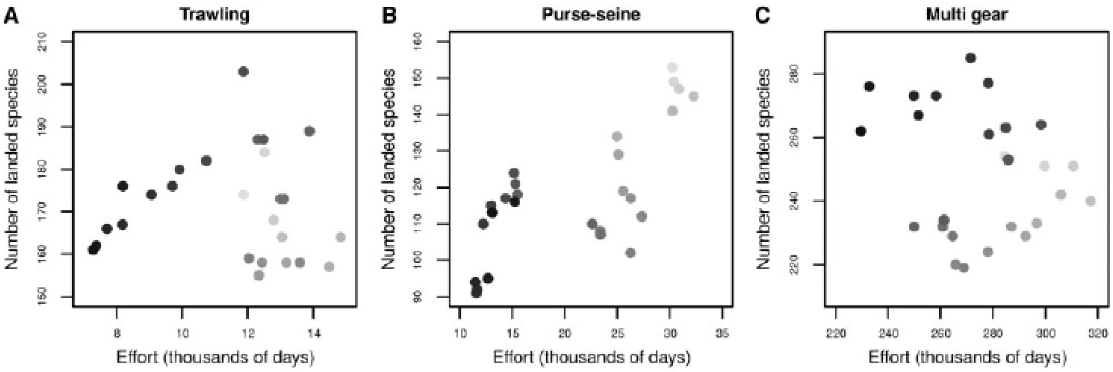

Figure 3. Relationship between the total number of taxa landed and fishing effort for each métier computed through the four regions of Portugal. Years are coded from light to dark grey along the time series. Note the differences in the scales of both axes.

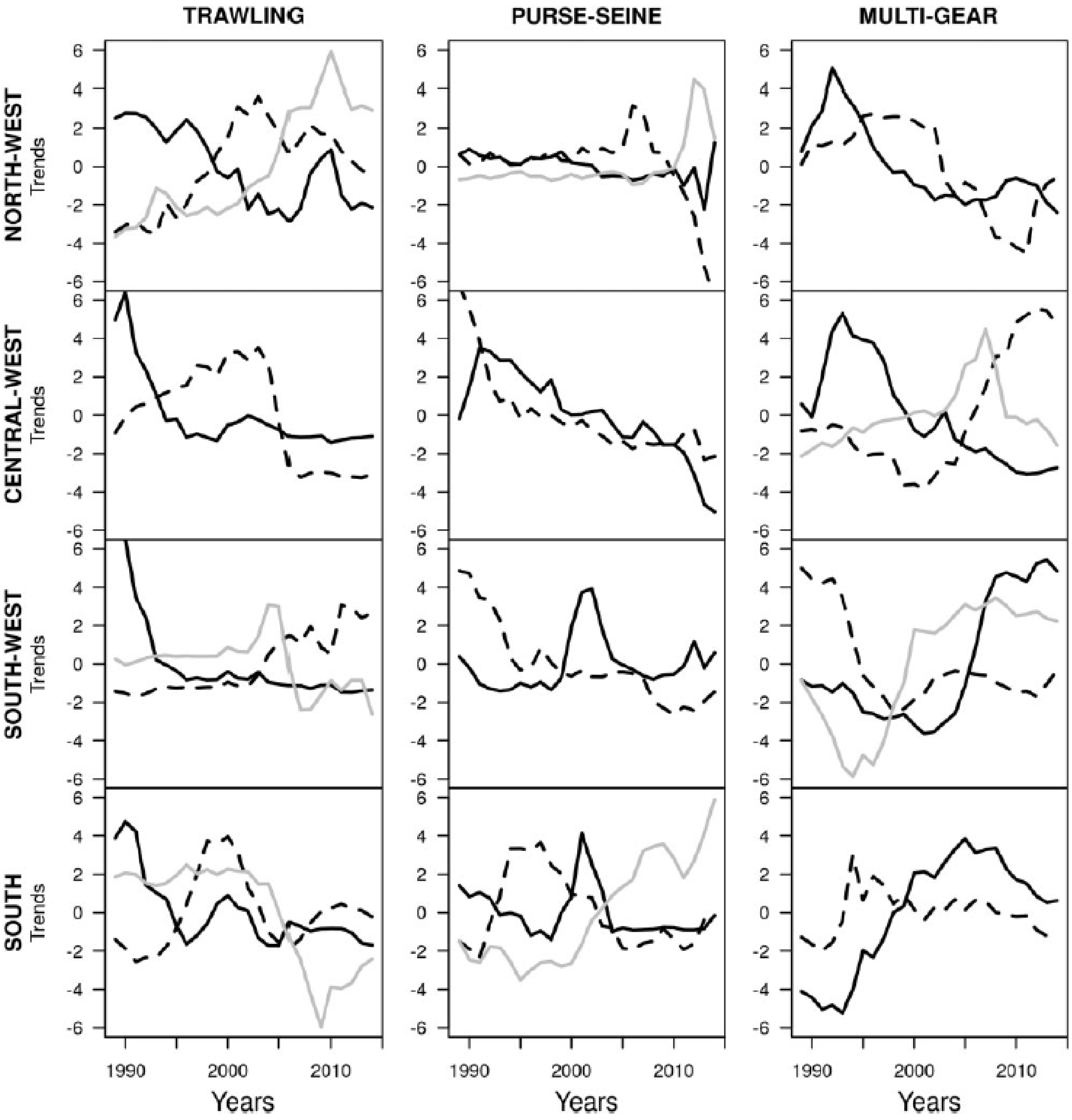

Figure 4. Main common trends identified by DFA for each region and gear type (see Table 2). Trend 1: black solid line; Trend 2: black dashed line; Trend 3: grey solid line.