Global Environmental Change 69 (2021) 102288

Contents lists available at ScienceDirect

Global Environmental Change

journal homepage: www.elsevier.com/locate/gloenvcha

# International politics must be considered together with climate and fisheries regulation as a driver of marine ecosystems

Gustavo F. de Carvalho-Souza [a,b], María Ángeles Torres [a], Carlos Farias [a], Juan José Acosta [a], Jorge Tornero [a], Ignacio Sobrino [a], Fernando Ramos [a], Marcos Llope [a,*]

[a] Instituto Español de Oceanografía, Centro Oceanográfico de Cádiz, Puerto Pesquero, Muelle de Levante s/n, 11006, Cadiz (Andalusia), Spain
[b] CAPES Foundation, Ministry of Education of Brazil, 70040-020, Brasília, Brazil

ARTICLE INFO

*Keywords:*
Gulf of Cadiz (GoC)
Integrated ecosystem assessment (IEA)
Integrated trend analysis (ITA)
Ecosystem-based fisheries management (EBFM)
Sustainable fisheries partnership agreements (SFPA)
Regime shifts

ABSTRACT

Seafood is an essential source of protein globally. As its demand continues to rise, balancing food security and the health of marine ecosystems has become a pressing challenge. Ecosystem-based fisheries management (EBFM) has been adopted by the European Union (EU) Common Fisheries Policy (CFP) to meet this challenge by accounting for the multiple interacting natural and socio-economic drivers. The CFP includes both the implementation of regulatory measures to EU stocks and the establishment of bilateral fisheries agreements with neighbouring countries, known as sustainable fisheries partnership agreements (SFPAs). While the effects of fisheries management regulations are well acknowledged, the consequences of the SFPAs on EU ecosystems have been commonly overlooked. Here we investigate the development of the Gulf of Cadiz marine ecosystem over the last two decades and found evidence of the impact of both policy interventions. Our findings reveal the effectiveness of regulatory measures in reverting a progressively degrading ecosystem, characterised by high fishing pressure and dominance of opportunistic species, to a more stable configuration, characterised by higher biomass of small pelagics and top predators after 2005. Knock-on effects of the EU-Morocco SFPA and climate effects were detected before 2005, resulting in increased purse seine fishing effort, lower biomass of pelagic species and warmer temperatures. This southern EU marine ecosystem has been one of the latest to introduce regulations and is very exposed to fishery agreements with neighbouring Morocco. Our study highlights the importance of taking into consideration, not only the effects of in situ fisheries regulations but also the indirect implications of political agreements in the framework of EBFM.

## 1. Introduction

Marine ecosystems provide us with valuable services, contributing to nutrition, economic and socio-cultural well-being. Commercial fishing (alone) captures about 90 million tonnes of biomass per year, providing an essential source of protein to more than 3.1 billion people worldwide (FAO, 2016). But fishing is also a top pressure on marine ecosystems. Fish stocks decline together with habitat loss, pollution and climate change are compromising these ecosystem services (Halpern et al., 2008; Hoegh-Guldberg and Bruno, 2010; Lam et al., 2016; Pauly and Zeller, 2016).

The United Nations Convention on the Law of the Sea (UNCLOS, UN, 1982) delineated the area of national rights over marine resources, known as exclusive economic zones (EEZs). Consequently, each country is responsible for sustainable fishing and sea-dependent-sectors potential impacts within their EEZs.

In the EU, a number of directives aim at harmonising efforts in order to achieve sustainable fisheries and healthy ecosystems. The most important are the Common Fisheries Policy (CFP, EC, 2013) and the Marine Strategy Framework Directive (MSFD, EC, 2008). These directives as well as higher-level environmental policies and obligations, such as the resolutions of Regional Sea Conventions, the Convention on Biological Diversity (CBD, 2005) or the United Nations Food and Agriculture Organization (FAO) call for ecosystem-based fisheries management (EBFM) as the optimal framework to implement these policies. Quoting Patrick and Link (2015) EBFM recognizes “the combined physical, biological, economic, and social tradeoffs for managing the fisheries sector as an integrated system, specifically addresses competing objectives and cumulative impacts to optimize the yields of all fisheries in an ecosystem”.

---

* Corresponding author.
*E-mail address:* marcos.llope@ieo.es (M. Llope).

https://doi.org/10.1016/j.gloenvcha.2021.102288
Received 6 July 2020; Received in revised form 27 April 2021; Accepted 7 May 2021

Components of EBFM are being adopted in compliance with the CFP, which foresees regionalization of decision structures, multi-annual plans, discard plans and establishment of stock recovery areas. But countries also hold responsibility beyond their EEZs since their flag vessels and fleets operate on other EEZs (Sumaila et al., 2015; McCauley et al., 2018).

Several EU countries have negotiated access agreements, through sustainable fisheries partnership agreements (SFPAs), for their fishing fleets, particularly in waters off neighbouring developing countries (Le Manach et al., 2013; Mallory, 2013). The number of SFPAs notably increased after the implementation of the CFP in 1983 (Le Manach et al., 2013). These agreements affected around 266 EU vessels and generated about 31,500 jobs (including processing) for EU and third-country nationals. SFPAs production amounts to 45% of EU vessels total catches (Goulding, 2016). The number of active SFPAs has oscillated largely over the last two decades because of difficulties to approve (e.g., Morocco and Micronesia), renew agreements (Mauritius and Senegal) or due to political instabilities (Guinea suspended in 2009) (EC, 2009; Le Manach et al., 2013).

The entry into force (or suspension) of SFPAs results in displacement of entire fishing fleets, which can significantly release (or increase) fishing pressure within the home ecosystem. While the ecosystem effects of regulation measures taken under CFP guidelines are commonly acknowledged and investigated, those that are consequence of SFPAs are not often considered. Yet, EBFM should consider all human activities impacting the marine ecosystem, be these direct or indirect. For these reasons, integrated ecosystem assessments are recognised as useful tools in support of EBFM (Levin et al., 2009, 2014). Using the Gulf of Cadiz as an illustrative case study we here show evidence of the impact of both EU/national fisheries management regulations and bilateral political decisions on a particular ecosystem.

The Gulf of Cadiz (GoC) is the southernmost European Atlantic shelf sea, between Europe (Portugal, Spain) and Africa (Morocco) (Fig. 1). It is a relatively young ecosystem in terms of policy implementation and regulations; for instance, the first total allowable catch for anchovy and the first marine protected area were set in 2004 (BOE, 2004; BOJA, 2004). Fishing fleets are highly diversified and target a number of species: anchovy, sardine, hake, rose shrimp, prawn or Norway lobster (Jiménez et al., 2004; Coll et al., 2014). At the same time, its proximity to Morocco's EEZ makes its fisheries dynamics dependent on the status of the SFPA with that country.

By using a comprehensive dataset consisting of abiotic drivers (environmental and human pressures) and biotic (state) variables we investigate how the different components of the GoC ecosystem have changed over the last two decades (1993–2015) and relate them to major changes in the natural, anthropogenic and political settings. Understanding the interplay between these driving factors and the state and structure of marine ecosystems is crucial to implementing ecosystem-based management.

## 2. Material and methods

### 2.1. Data collection

We compiled all available data featuring the GoC ecosystem (Spanish waters) over the period 1993–2015. Data on biotic, abiotic (including oceanographic and climatic variables) and human pressures were obtained from various sources (Fig. 1, Table S1 in Supplementary Material 1).

### 2.1.1. Biotic data

*2.1.1.1. Sampling and classification.* Yield per species was obtained from a bottom trawl survey program (15 to 800 m depth) carried out in spring between 1993 and 2015 (IEO, 2018; http://www.ices.dk/marine-data/data-portals/Pages/DATRAS.aspx). The time series comprised a total of 876 hauls (around 40 per year), carried out during daylight hours at a mean towing speed of 3.0 knots, using Baka 40/60 trawl gear with a 43.6 m footrope and a 60.1 m headline (details are given in Silva et al., 2011). In each haul, samples were sorted and individuals were counted and weighted. Individual species biomass was standardized to one square km (kg/km$^2$) and classified into thirty functional groups (Table S1). The functional groups were chosen based on ecological similarities from a previous Ecopath model developed with the same database (Torres et al., 2013). A review and update of the species assigned to each group was performed and the complete species list is given as Supplementary Material (SM 2). Among others, these groups included: polychaetes, crabs and lobsters, sharks, skates, two groups of

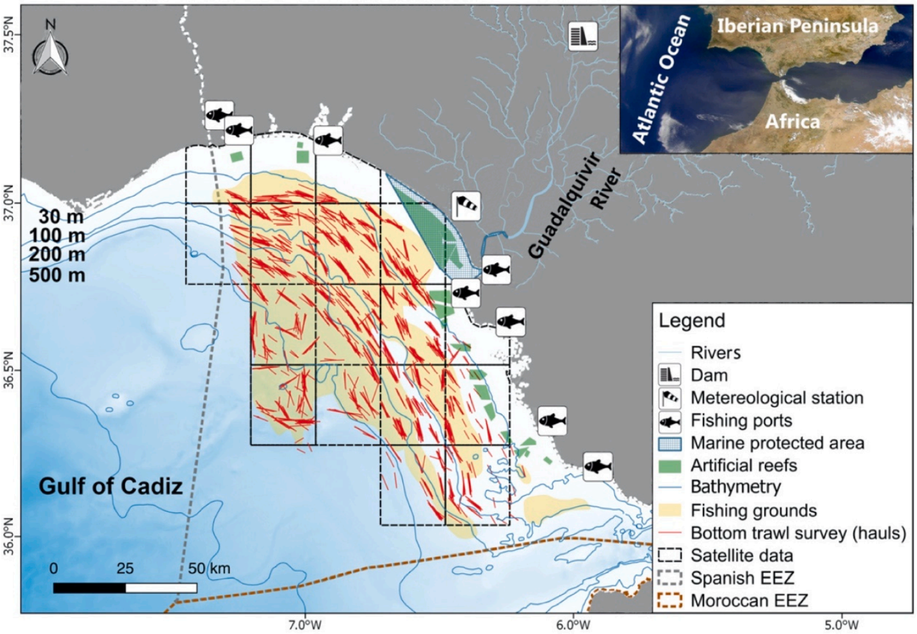

**Fig. 1.** Map of the Gulf of Cadiz showing the location of the various data sources. Satellite squares, bottom trawl hauls, fishing ports, Guadalquivir River dam as well as some other important features of the ecosystem, like the Guadalquivir mouth fishing reserve, are illustrated.

cephalopods (benthic and benthopelagic) or benthic invertebrates, the latter also separated into two categories according to their feeding preferences: carnivores and filter-feeders/detritivores/suspensivores (F/D/S invertebrates). Eleven of those thirty functional groups correspond to commercial species (or genus) and were considered separately: anchovy, blue whiting, hake, horse mackerels, mackerels, mullets, sardine, mantis shrimp, Norway lobster and rose shrimp (Table S1).

Time series of comparable length were not available for nekton (e.g. acoustics surveys started in 2004). However, we included some pelagic species (anchovy and horse mackerels), which are known to have vertical diurnal migrations (feed on the bottom during the day) and are relatively well-sampled by bottom trawls (ICES, 2014; Ramos, 2015).

### 2.1.2. *Abiotic data*

*2.1.2.1. Satellite data.* Daily sea surface temperature data (SST, °C) matching the biotic time series described above (1993–2015) were obtained from the satellite-based Advanced Very High Resolution Radiometer (Pathfinder v5; see SI 1) of the National Oceanic & Atmospheric Administration (http://www.ncdc.noaa.gov/oisst; Reynolds et al., 2007). Grid cells of 0.25° x 0.25° resolution (overlapping the area of biotic samplings, see Fig. 1) were generated with QGIS 2.18.2 – L. Palmas de Gran Canaria (http://qgis.org) – and averaged to annual values. The latter were validated with in-situ measurements.

Daily Chlorophyll (Chl, mg/m$^3$) and Particulate Organic and Inorganic Carbon (POC, PIC, mol/m$^3$) were obtained from the GlobColour project (European Space Agency, http://globcolour.info) (Maritorena et al., 2010). Annual averages were calculated similarly to SST data.

*2.1.2.2. Other environmental data.* Precipitation (total rainfall, l/m$^2$; 1993–2015) was acquired from "El Palacio" meteorological station (http://icts.ebd.csic.es/datos-meteorologicos). Sea surface height (SSH; 1996–2015) was obtained from a buoy moored off the coast of Cadiz (36.48°N, 6.96°W; maintained by the Spanish State Port Agency ("Puertos del Estado", http://www.puertos.es/).

*2.1.2.3. Climate indices.* The North Atlantic Oscillation (NAO; http://www.esrl.noaa.gov/psd/data/climateindices/list/) (Hurrell and Dickson, 2004), the unsmoothed Atlantic Multidecadal Oscillation (AMO; http://www.esrl.noaa.gov/psd/data/correlation/amon.us.long.data) (Enfield et al., 2001) and the annual Gulf stream index (GSNW; http://www.pml-gulfstream.org.uk/data.htm) (Taylor, 1995; 1996) were included as climate indices.

### 2.1.3. *Pressures*

*2.1.3.1. Fisheries.* Harvest rate of commercial functional groups/species (anchovy, blue whiting, hake, horse mackerel, mackerel, mullets, piscivores, sardine, mantis shrimp, Norway lobster and rose shrimp) was calculated as proportion of estimated total biomass over landings (tonnes) (FAO, 2003). Landings from the fishing ports shown in Fig. 1 and fishing effort (fishing days/year) were obtained from official fishery statistics 1993–2015 (IEO Database; http://datos.ieo.es/geonetwork/srv/eng/catalog.search#/home).

*2.1.3.2. River runoff.* Freshwater discharges (hm$^3$) from the "Alcalá del Río" dam (Fig. 1) were provided by the Regional River Authority ("Confederación Hidrográfica del Guadalquivir"; http://www.chguadalquivir.es/saih/DatosHistoricos.aspx).

*2.1.3.3. Marine litter.* Anthropogenic debris items (size greater than 25 mm) were collected by the bottom trawl survey and classified following the master list of categories of the guidance document of the MSFD Common Implementation Strategy (Galgani et al., 2013). Densities of marine litter were standardized similarly to the benthos data (number of items/km$^2$).

## 2.2. *Statistical methods*

A total of 55 variables (Table S1) characterizing the biota (30 functional groups), natural drivers (9 abiotic variables) and human pressures (16 variables) were used in the analyses. To reduce complexity and help trend visualisation a panoply of multivariate and plotting techniques, traditionally utilized for integrated trend analysis (Diekmann and Möllmann, 2010), was used (Table 1). Before-hand, missing values were replaced by the average of the neighbouring 2 years (or 4-year in the case of 2 consecutive missing years). Subsequently, data were log-transformed [ln (x + 1)] to both reduce skewness and normalize variances. Pairwise correlations are presented in Figure S1 (SM 1). These techniques included:

*i) Principal Component Analysis (PCA).* This dimension-reduction technique is commonly used to extract the major modes of variability (principal components, PC) in a data set on an ordination plot (Legendre and Legendre, 1998) but see also Planque and Arneberg (2018). Yearly scores of the first two principal components (PC1 and PC2) are usually plotted over time to visualize temporal trends and ecosystem shifts (Beaugrand et al., 2001, 2003). The trajectory of the system can be illustrated by placing the years in a scatter plot where the PC1 and PC2 define the × and y-axes (Link et al., 2002; Kenny et al., 2009; Möllmann et al., 2009; Lindegren et al., 2012; Möllmann et al., 2013).

*ii) Sequential t-test analysis of regime shifts (STARS).* The STARS algorithm (Rodionov, 2004; 2006) is commonly applied on time-series of PCs scores to detect abrupt changes or regime shifts (see details in Möllmann et al., 2009). We ran STARS on the 1st and 2nd PCs of the previous analysis. In addition, STARS was used to identify statistically significant shifts in mean values in each time series separately (Table S2). Cumulative Regime Shift Indices (RSI) (Rodionov, 2004) were also estimated and are given in Table S2 (SI 1). The RSI represents a cumulative sum of normalized deviations and used to detect the time of an abrupt change.

*iii) Min/max autocorrelation factors analysis (MAFA).* MAFA is a multivariate statistical method, similar to PCA, that extracts common trends from multiple time series (Shapiro and Switzer, 1989). One of the

**Table 1**
List of statistical techniques used for integrated trend analysis including advantages (pros) and disadvantages (cons) of each method.

| Method | Pros | Cons |
|---|---|---|
| PCA | - Great reduction of dimensionality.- Identification of variables most related to the PCs.- Widely used and available.- It allows for system's trajectory inspection. | - It can't handle missing values.- Shortest time series limits the analysis.- Selection of variables may affect results.- Sensitive to the presence of autocorrelation and non-stationarity in the times series. |
| STARS | - Simple and easy to apply.- It can be applied to mean or variance, on raw series or PCs. | - Sensitive to parameters' tunning (type 1 error). |
| MAFA | - Reduces complexity by selecting the most continuous indicators.- Focus on autocorrelation rather than variance. | - Not so widely used as PCA or CC and, hence, a bit more difficult to interpret. |
| CC | - Widely used and available.- Identification of periods of similar characteristics. | - Does not indicate which variables are drivers (less able to infer causality). |
| TLP | - Intuitive (colour-coded).- Visualisation of general trends, patterns.- It can handle missing values. | - Magnitude of change not assessed (same scale, quintiles).- Not information about causality.- Sensitive to transformations and sorting. |
| Anomalies | - Visualisation of single trends.- No assumptions need to be met.- Very little transformation of the data (almost raw). | - As it is not a joint analysis dimensionality is not reduced.- Better in combination with other methods. |

key differences between PCA and MAFA is that the latter maximizes the temporal autocorrelation structure rather than the variance. As with PCA, MAFA provides a series of orthogonal factors (MAFs) of decreasing autocorrelation that are continuous in time (see details in Woillez et al., 2009; Doray et al., 2018). The MAF analysis consists of 3 steps: (1) an initial selection of indicators based on the one-lag variogram of each indicator, scaled to the indicator variance and ranked. Since the number of variables cannot exceed the number of years, we selected the 17 most continuous variables following the pattern displayed by the variogram and the approach taken by Woillez et al. (2009); (2) MAFs are calculated on this reduced set of variables; (3) a continuity index is computed based on the loadings and one-lag variogram values of the first 2 MAFs. Subsequently, a selection of indicators is carried out based on this continuity index, aka MAF-based indicator selection procedure (Doray et al., 2018).

*iv) Chronological Clustering (CC)*. CC was used as another ordination technique, independent and complementary to PCA, STARS and MAFA. CC is based on a Euclidean distance matrix and was carried out to identify the years in which the largest shifts in the mean value of the time series occurred. This standardized method builds a hierarchy from the sequential years based on a time-variable matrix (Legendre and Legendre, 1998).

*vi) Traffic Light Plot (TLP)*. A TLP was generated to visualize overall systematic patterns based on single time series (Link et al., 2002; Möllmann et al., 2009). The raw values of each variable are categorized into quintiles and each one of these is assigned a specific colour: red for the lowest (0–20%), green for the highest (80–100%) and a gradation of colours in between. The variables were then sorted by the 10-year standardized average and plotted against years. The use of the first PC loadings to sort variables on the y-axis was intentionally avoided in order to make the arising patterns independent of PCA. The code to produce the TLP was provided by Diekmann et al. (2012).

*vii) Temporal anomalies*. Temporal anomalies were calculated for the main functional groups or drivers detected by PCA, MAFA and TLP.

All analyses were carried out in R version 3.5.0 (R Development Core Team 2018) with the R packages "vegan" (Version 2.5–5; Oksanen et al., 2019), "factoextra" (Version 1.0.5; Kassambara and Mundt, 2017), "ggplot2" (Version 3.2–0; Wicham and Chang, 2019) and "gridExtra" (Version 2.3; Auguie and Antonov, 2017).

## 3. Results

### 3.1. Principal components analysis (PCA)

The first two PCs of the PCA on the full dataset (biotic and abiotic variables and pressures) described 60% of the total variance (Fig. 2A). The variable loadings (i.e. the length and orientation of vectors on the biplot) show the degree of correlation with the corresponding PC (Fig. 2A). The variables that correlated the most with the main mode of variability (PC1; 37%) are those arrows more or less parallel to the horizontal axis coloured in red/orange. Those showing positive correlations were anchovy, horse mackerels, sharks, skates, hake, and mullets. By comparison, demersal trawl effort, marine litter, carnivore benthic invertebrates, crabs & lobsters and polychaetes presented negative correlations with PC1. The variables that contributed the most to PC2 (23%) were: benthopelagic and benthic cephalopods, purse-seine effort and AMO all showing negative correlations. No clear-cut associations could be identified on the positive side of PC2 (Fig. 2A).

In terms of time trajectories, the first PC was characterized by minor variations during the first decade, followed by an abrupt increase in the period 2005–2006 (Fig. 2B) and showed little variation thereafter. On the other hand, PC2 showed a steep decline at the end of the 1990 s followed by moderate fluctuations (Fig. 2B). STARS analyses on PC1 and PC2 detected jumps in 1998–1999 and 2005–2006 (Fig. 2B) (RSI = 0.87 and 1.32, respectively).

The system trajectory over time (Fig. 2C) described a progressive drop within the left quadrant between 1993 and 1998, followed by a less marked downward trend towards the lower-left corner until 2004. This period (1993–2004) was mainly driven by changes in the second PC, which turned from positive to negative. The most remarkable change happened between 2005 and 2006 when the system jumped to the right side of the plot to describe a somewhat circular pattern for the remaining decade (2006–2015). This abrupt change was primarily driven by the first PC which turned positive in 2006, while PC2 showed little variation, oscillating around zero.

### 3.2. Min/max autocorrelation factor analysis (MAFA)

A normalized one-lag variogram was computed across the dataset and the 55 variables were ranked according to their variance (Fig. 3A). Based on this variogram, the 17 most continuous indicators to be

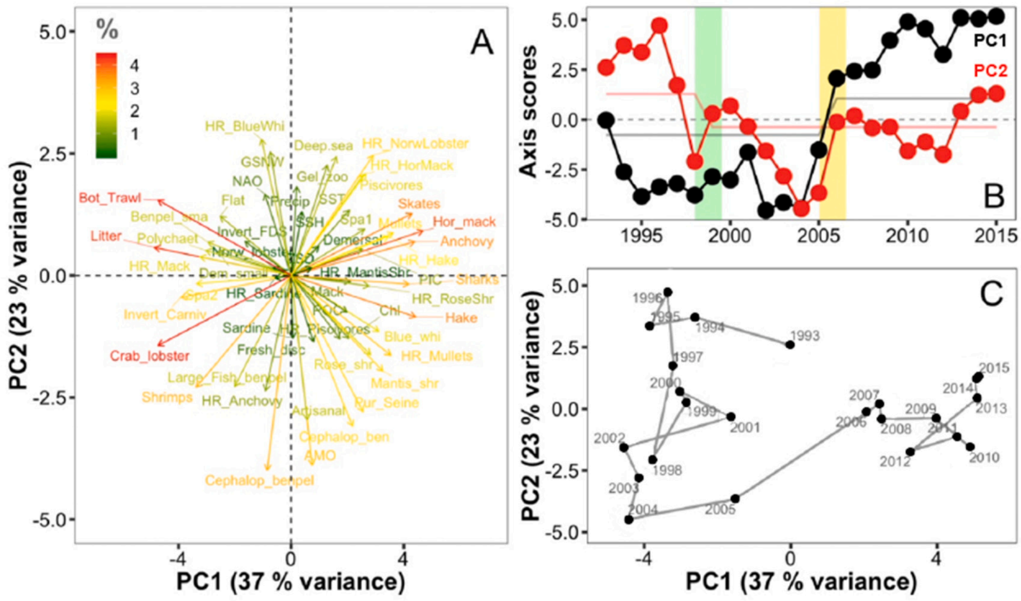

**Fig. 2.** Principal Component Analysis (PCA). Panel A shows the loads of each variable with the respective PC (variable acronyms are spelled out in Table S1). Variable contributions to the principal axes are colour-coded as shown in the legend (from green to red). Panel B shows the temporal trends of PC1 and PC2 scores (black and red lines, respectively). Transparent black and red straight lines show the results of STARS on the Principal Components. Vertical green and yellow shades mark the periods of shift. Panel C displays the trajectory of PCA biplot (PC1 and PC2). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

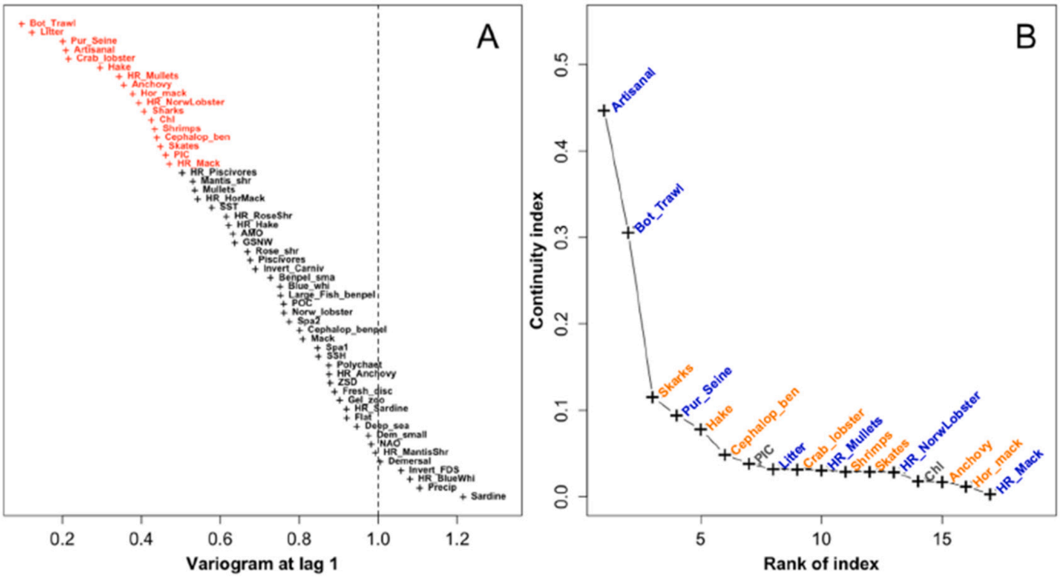

**Fig. 3.** Min/max Autocorrelation Factor Analysis (MAFA). Panel A shows the normalized one-lag variogram. Indicators with a normalized one-lag variogram values <=1 are considered as sufficiently continuous (vertical line). The most continuous indicators here selected (<0.5) are coloured in red and were retained for the next step. Panel B presents the indicators ranked according to their continuity index on the first two MAFs. Variables are colour coded: orange is used for biotic variables, grey for abiotic variables and blue for pressures. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

included in the MAF computation were selected. The continuity index (Fig. 3B) showed that the most continuous, and hence most representative, indicators were: fishing pressure (artisanal, bottom trawl and purse-seine) and two functional groups (sharks and hake). Indeed, fishing pressure went down, from high to low values, over the studied period while sharks and hake showed the opposite trend (Fig. 7).

MAF1 exhibited positive values at the beginning of the series (1993–2004) and negative ones from 2005 to 2015 (Fig. S2A), displaying an almost linear decrease. The temporal autocorrelation of MAF1, as shown by its variogram (Fig. S2B), has a period of around 20 years. Two indicators contributed the most to MAF1; bottom trawl effort and litter (positive loadings) (Fig S2C). The high contribution of these indicators (similarly to PCA) indicates the importance of these two variables in driving the ecosystem in the past (Fig. 3B) as well their reduced contribution in recent times (Table 2).

MAF2 displayed negative values from 1993 to 1997 (Fig. S2D), became positive from 1998 until 2007, turned again to negative around 2008–10 and decreased constantly thereafter. MAF2 temporal autocorrelation has a period of 9–10 years (Fig. S2E). As before, two indicators contributed the most to MAF2; artisanal fisheries and sharks (positive loadings) (Fig S2F).

**Table 2**
List of the 17 most continuous indicators (MAFA ordering) indicating the (positive and negative) effect of each of the drivers on the state of the ecosystem (degraded or stable).

| Type | Variable | Driver | State |
|---|---|---|---|
| Pressure | Bot_Trawl | – | Degraded |
| Pressure | Litter | – | Degraded |
| Pressure | Pur_Seine | – | |
| Pressure | Artisanal | – | |
| Biotic | Crab_Lobster | – | Degraded |
| Biotic | Hake | + | Stable |
| Pressure | HR_Mullets | – | |
| Biotic | Anchovy | + | Stable |
| Biotic | Hor_mack | + | Stable |
| Pressure | HR_NorwLobster | – | |
| Biotic | Sharks | + | Stable |
| Abiotic | Chl | + | |
| Biotic | Shrimps | – | Degraded |
| Biotic | Cephalop_ben | + | |
| Biotic | Skates | + | Stable |
| Abiotic | PIC | – | |
| Pressure | HR_Mack | – | |

### 3.3. Chronological clustering (CC)

The CC broke the time series into two periods: 1993–2005 and 2006–2015, being 2005–2006 the major breakpoint (Fig. 4). Surprisingly, the changes detected in the late 1990 s by the previous analyses did not show up as significant at this detection level (Cophenetic coefficient = 0.57).

### 3.4. Traffic light plots (TLP)

The temporal development of the GoC is shown in Fig. 5 in the form of a traffic light. Those variables that increased towards the end of the studied period are located in the upper half of the TLP. These were hake, anchovy, horse mackerels, skates, sharks and mullets. It can be appreciated how they turned from red (low values) to green (high values) after 2005. The lower half of the plot gathered those variables that showed the opposite pattern, turning from green to red after 2005. Here, we found demersal trawl effort, marine litter, carnivore-benthic invertebrates, benthopelagic small fishes, polychaetes, F/D/S invertebrates, crabs & lobsters, Norway lobster and shrimps. All these groups decreased after 2005.

### 3.5. Sequential regime shift analysis (STARS)

Sequential regime shift analysis (STARS) carried out on individual time series (Table S2) revealed that most of the significant changes occurred at the end of the 1990 s and around the mid/late 2000 s. The RSI identified 1994–2000 and 2002–2006 as potential periods of shifts.

Specifically, 5 out of 7 environmental variables (SST, precipitation, NAO, AMO, GSNW) and most of the harvest rates (10/16) displayed abrupt changes in the 1990 s. The 2000 s' change was observed in a few but important pressures, such as the demersal trawl effort or the abundance of marine litter. The 28 biota components showed a more

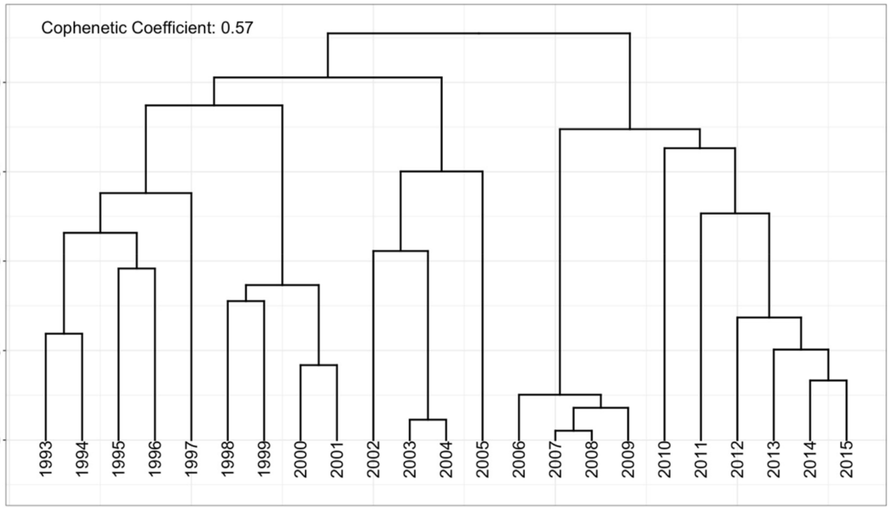

**Fig. 4.** Chronological clustering analysis (CC). The dendrogram suggests two distinct periods marked by breakpoints in 1993–2005 and 2006–2015.

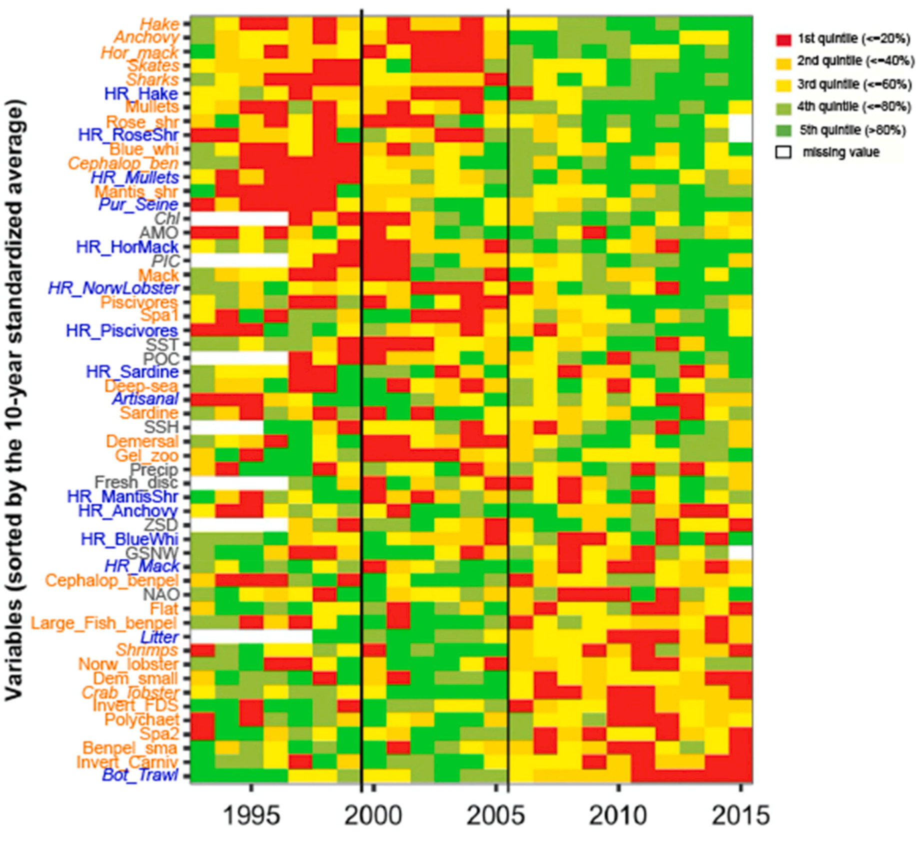

**Fig. 5.** Traffic light plot (TLP). Time series were transformed to quintiles, colour coded and sorted in numerically according to the average of their first 10 years. Red represent low values while green represent high values of the corresponding variable (acronyms are spelled out in Table S1). Superimposed vertical translucent bars mark the shifts detected by STARS on PC1 and PC2. Variables are colour coded orange for biotic variables, grey for abiotic variables and blue for pressures. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

balanced distribution of changes, with 9 functional groups showing shifts in the 1990 s (e.g. F/D/S benthic invertebrates, polychaetes, mantis shrimp, sharks) and 11 in the 2000 s (e.g. hake, anchovy, skates, crabs & lobsters). A few groups (hake, rose shrimp) depicted drastic changes in both periods.

## 4. Discussion

This article presents the first holistic assessment of the Gulf of Cadiz marine ecosystem over the last twenty years, with a focus on the impact of policy on its temporal development. Our results, arising from a number of visualisation and multivariate techniques, reveal two main periods of change: (1) a discontinuity, regime shift-like type of change, in 2005 and (2) an earlier but secondary, more progressive, change in the late 1990 s. Interestingly, these changes coincided with the enforcement of two policy events: the implementation of the CFP regulation in 2004 and the halt of the SFPA with Morocco in 1999.

1) Effort regulation and spatial closure – The 2005 shift

The first change divided the time series in two halves: (1) before 2005 and (2) after 2006.

(i) *The 1993–2005 period*

The initial state (1993–2005) was characterized by low biomasses of target and big species, such as hake, anchovy, sharks or skates. At the same time, less commercially important species, like crabs & lobsters, carnivorous invertebrates or polychaetes were found in high abundances. This ecosystem configuration is represented in Fig. 6A.

The first GoC fishery management plan was not passed until 2004 (BOE, 2004) so that this first period was characterised by a relatively loose regulation and consequently heavy fishing pressure (Fu et al., 2015; Kleisner et al., 2015; Coll et al., 2016; Bundy et al., 2017). This is reflected in our analyses by the high values of demersal trawl effort (number of days) but also by the high abundance of marine litter. Marine litter is to a great extent associated with the fishing activity since 37% of the items were nets, pots, cables and lines.

We hypothesize that the heavy fishing intensity of this period could have been responsible for the observed high biomasses of opportunistic benthic species. Bottom trawling is the most widespread source of physical disturbance to the seabed habitats (Hiddink et al., 2017). High trawling can have a twofold positive effect on these groups. On the one hand, trawling is known to cause resuspension of sediments which increases food availability for these functional groups (Groenewold and Fonds, 2000; Hiddink et al., 2008). Detritus is an important source of food in the GoC and increases in this resource have been seen to have positive effects (via bottom-up) on most groups (Torres et al., 2013). Besides enhancing bottom-up processes heavy fishing can also act via top-down. Sharks, skates or hake are known to prey on these opportunistic groups (Torres et al., 2013). Hence, the high fishing mortality imposed on these big predator species, reflected in their low biomasses during this period, could have released benthic groups from top-down control. Alternatively, their opportunistic feeding behaviour could have benefited from scavenging on organisms that are damaged by the trawl (Groenewold and Fonds, 2000; Johnson et al., 2015).

(ii) *The 2006–2015 period*

In 2004 and following years, a number of fisheries management measures, in agreement with the CFP, were established by the Spanish Administration, entering into force at the end of 2004 (BOE 2004, see complete list in Table S3, SI 1). Briefly, these regulations set an upper limit on fishing effort (200 days per year) and established autumn–winter closures (45–90 days) in order to favour the recovery of stocks. The bottom trawl and purse seine fleets were particularly affected by these measures.

Another management milestone happened in 2004 with the establishment of the fishing reserve of the Guadalquivir River mouth (BOJA, 2004, IEO, 2005), due to its role as an essential fish habitat (Llope, 2017; de Carvalho-Souza et al., 2018). This Marine Protected Area (MPA) extends beyond the Guadalquivir mouth covering ~ 400 km2 of its area of influence (Fig. 1). The establishment of the Guadalquivir MPA resulted in bottom trawlers and purse seiners not being able to operate inside the MPA.

Our analyses detected the consequences of these regulations already in 2005 (Fig. 2B-C) and more clearly in 2006 (Figs. 4 & 5). This second (and current) ecosystem state is characterised by a marked increase in the biomass of target species (e.g. anchovy) and those that occupy higher trophic levels, e.g. hake, horse mackerels, anchovy, sharks, skates and mullets (Fig. 6B). This food web reconfiguration is likely to be a direct response to the decrease in fishing effort and the establishment of the Guadalquivir MPA described above.

2) International politics and climate – The late 1990 s

In 1997, the purse-seine (small pelagics) fleet voluntarily agreed to introduce a fishery closure every year from December to February (ICES 2014). This self-regulatory measure was suddenly interrupted in 1999. That year, the UE-Morocco SFPA, which had been in place since 1995, was not renewed (García-Isarch et al., 2012). As a consequence, the Spanish purse-seiners that would fish for anchovy in Moroccan waters had to come back, increasing the fishing pressure in the GoC.

The anchovy and horse mackerels very low values detected in the early 2000 s (Fig. 5, and Fig. 7A, F) could be a consequence of this increase in fishing pressure. Unfortunately, we lack comparable information for other pelagic components (e.g. zooplankton) to be able to track cascading effects across trophic levels, as seen in other ecosystems (Lynam et al., 2017; Doray et al., 2018).

Local (SST, precipitation) and large-scale hydro-climatic forcing (NAO, AMO, GSNW) variability could have also played a role in the late 1990 s. Most of the changes detected in these variables are concentrated around this period (see STARS analyses in Table S2) plus, these variables

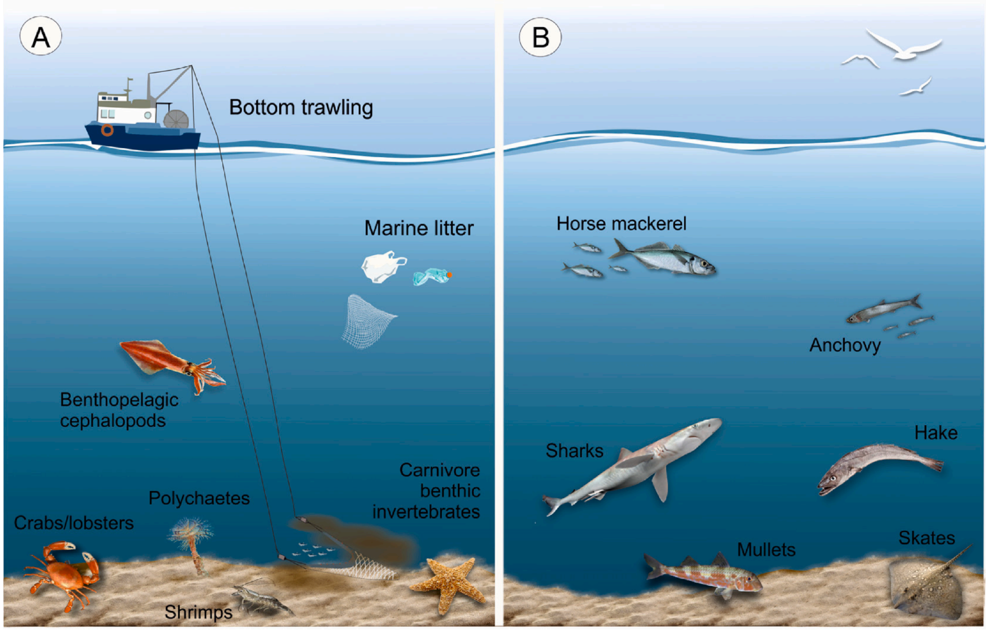

**Fig. 6.** Diagrammatic representation of the two main configurations. Panel A shows the initial state (1993–2005), with high fishing pressure, poor quality habitat and opportunistic species dominance. Panel B presents a more stable ecosystem (2006–2015), with an increase of target species occupying the higher trophic levels.

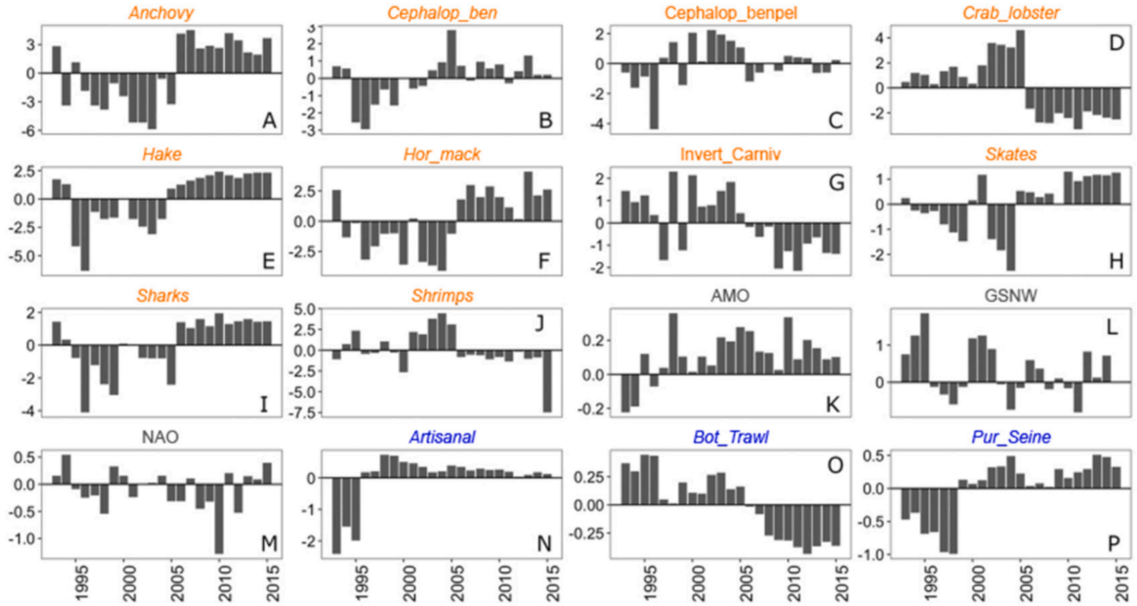

**Fig. 7.** Anomaly plots of biotic and abiotic factors, climatic indices and human pressures. Note that scales are logarithmic and adjusted to each variable's range of values. For acronyms, see Table S1. Variables are colour coded: orange for biotic variables, grey for abiotic variables and blue for pressures. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

were found to correlate with PC2 (Fig. 2).

Environmental effects have been previously reported as important drivers in this ecosystem (Sobrino et al., 2002; Báez and Real, 2011; Delgado et al., 2018) and the warm phase of the AMO after 1995 is known to have led to simultaneous changes in plankton and fish in the North Atlantic (Edwards et al., 2013).

Disentangling the effects of fishing and environmental forcing is always a challenge. Both effects seem to have partly overlapped in this period, with climate gaining importance as key driver towards the early 2000 s. This is when benthopelagic cephalopods increased (Fig. 7C) coinciding with a warm phase of the AMO and precipitation changes (Fig. 7K).

A recent global analysis revealed that cephalopod abundance has increased over the last decades in response to large-scale processes and declining fish populations (Doubleday et al., 2016), albeit casual mechanisms have not been identified. In the North Sea, climatic indices (AMO) and warming temperatures have also been associated with the increase of squids (van der Kooij et al., 2016).

3) Reconfiguration and stabilisation

Overfishing can entirely deplete fish stocks and permanently modify ecosystems, usually through trophic cascades. A classic example is the collapse of cod (*Gadus morhua*) in the Northwest Atlantic (Scheffer et al., 2005; Frank et al., 2005; Fogarty and Murawski, 1998). In the Gulf of Mexico, commercial and recreational fishing caused the depletion of red snapper (*Lutjanus campechanus*) at the end of the 20th century, which led to the design of a broad rebuilding plan (SEDAR, 2018). The collapse of abalone (*Haliotis* spp.) stocks off the southern coast of California is another example of how poor fisheries management associated with pollution and climate (El Niño) can affect entire ecosystems through habitat (kelp forest) alterations (Rogers-Bennett et al., 2002, 2013).

Ecosystem reorganisations triggered by a combination of fishing and environmental changes (e.g. warming, eutrophication) have been relatively common in Europe, like the regime shifts reported in the Black Sea (Daskalov et al., 2007; Llope et al., 2011), the Baltic Sea (Möllmann et al., 2009; Blenckner et al., 2015) or the Kattegat (Lindegren et al., 2012). Contrary to the GoC, all these coastal seas are semi-enclosed and are characterized by low biodiversity. Open and more diverse (~300 species) ecosystems, like the Cantabrian Sea in the southern Bay of Biscay have been seen to respond to fishing pressure in a more progressive fashion (Modica et al, 2014; Arroyo et al., 2017).

Apart from being an open and more diverse sea (~860 taxa, SI 2), the Gulf of Cadiz main change (2005) presents some differences from the previous examples: The first period (Fig. 5A) was a progressively degrading non-static state and did not constitute a proper regime in the sense that it quickly improved after intervention. The second period (Fig. 5B) constitutes an improvement over the former and seems to be fairly stable (Fig. 1C). The changes before and after 2005 are, however, very remarkable. For instance, hake and anchovy (Fig. 7E and 7A) doubled in the second regime (2006–2015) compared to the overall mean value (1993–2015), and so did horse mackerel (1.8 times; Fig. 7F), skates (1.5 times; Fig. 7H) and sharks (1.8 times; Fig. 7I). Similarly, artisanal fishing effort and shrimps decreased by a half (Fig. 7N/7J) and bottom trawl effort dropped by a third (Fig. 7O).

In Iberian waters, Atlantic and Mediterranean exploited fish stocks have been seen to show contrasting organizational properties (Hidalgo et al., 2017). In the Cantabrian Sea and Galicia (Atlantic Iberia) the 'rescue effect' from neighbouring areas together with the contribution of large fish renders quicker recovery times when compared to Mediterranean populations, which are more clustered and dependent on small-sized fish (Hidalgo et al., 2017; Fernandes et al., 2017). The quick recovery observed in the GoC would agree with this hypothesis.

4) Policy and its implications for marine ecosystems

Considering the ecosystem-wide consequences that not only fisheries management and climate but also, and most surprisingly, international politics has had on the GoC, we recommend that the implications of SFPAs should be taken into consideration. In particular on those EU fishing grounds that would be primarily affected by these agreements. This applies to the current EU-Morocco SFPA (the latest expired in July 2018) which has just been endorsed by the European Parliament. But this is not the only case, Côte d'Ivoire is in a similar situation with its SFPA expired since 2018. Others are in a dormant state (e.g. Mozambique, Equatorial Guinea and Guinea-Bissau, Cabo Verde and Sao Tomé e Principe) (EC 2017) while 3 are active: Mauritius, Senegal and Gambia (https://ec.europa.eu/fisheries/cfp/international/agreements_en). The direct and indirect effects of fishing effort translocations need to be considered in ecosystem-based fisheries management.

Another regulation whose impact would need to be considered in the near future is the CFP "landing obligation" (EC, 2013), which implies the landing of all catches of regulated commercial species. It is still quite unclear how this regulation will impact the Gulf of Cadiz (Gamaza et al., 2020). But the removal of previously discarded biomass from the ecosystem could in principle work in favour of the second configuration (2006–2015) described above, as it would be detrimental for the opportunistic trophic levels.

## 5. Conclusions

The Gulf of Cadiz is one of the youngest European marine ecosystems in terms of both monitoring and fisheries regulation enforcement. In the last twenty years it has shifted from a regime characterized by a progressive deterioration, due to weak fisheries regulation, climate sensitivity and knock-on effects of international politics, to a more stable configuration where top-down control has recovered importance. These findings showcase how timely regulation prevented an incipient regime shift and highlights the need to consider international politics if we are to manage ecosystems holistically.

## Author contributions

G.F. de C-S. carried out data compilation, analyses, interpretation of results and wrote the paper; M.A.T. provided the initial classification of functional groups, helped interpreting the results and co-wrote the paper; C.F. further contributed to classifying species into functional groups; J.J.A. provided access to landings data; J.T. provided access to acoustics data; F.R. contributed through ideas and interpretation of results. I.S. provided access to demersal survey data. M.Ll. designed the study, helped with interpretation of results and co-wrote the paper.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgments

We thank all scientists and technicians of IEO-Cadiz who initiated and maintained these long-term monitoring programs, which resulted in this valuable database. The European Maritime and Fisheries Fund (EMFF) co-funded the demersal trawl survey. We also thank AEMET, Confederación Hidrográfica del Guadalquivir, Consejería de Medio Ambiente, EBD/CSIC, NOAA, Plymouth Marine Laboratory and Puertos del Estado for climatic and oceanographic data. This work was conceived and started during a Marie Curie (re)Integration Grant (M.Ll., FP7-PEOPLE, ref: PERG05-GA-2009-247528) and is a contribution to OCAL-DILEMA project (ref: CTM2014-59244-C3-2-R) and the ICES Working Group on Ecosystem Assessment of Western European Shelf Seas (WGEAWESS). G.F. de C-S. thanks CAPES Foundation and the Science without Borders fellowship program (ref: 99999.013763/2013-00). This study helped make the case for including the Gulf of Cadiz as one of the case studies selected under the Specific Contract EASME/EMFF/2018/1.3.2.4/Lot2/SI2.818388-SC03, signed with the Executive Agency for Small and Medium-sized Enterprises (EASME) and funded by the European Union to study ecosystem-based approaches applied to fisheries management under the CFP.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloenvcha.2021.102288.

## References

Arroyo, N.-L., Preciado, I., López-López, L., Muñoz, I., Punzón, A., Österblom, H., 2017. Trophic mechanisms underlying bentho-demersal community recovery in the north-east Atlantic. J. Appl. Ecol. 54 (6), 1957–1967. https://doi.org/10.1111/jpe.2017.54.issue-610.1111/1365-2664.12879.

Auguie, B., Antonov, A. 2017. gridExtra. Miscellaneous Functions for "Grid" Graphics. R package version 3.2.0. https://cran.r-project.org/web/packages/gridExtra/gridExtra.pdf.

Báez, J.C., Real, R., 2011. The North Atlantic Oscillation affects landings of anchovy *Engraulis encrasicolus* in the Gulf of Cádiz (south of Spain). J. Appl. Ichthyol. 27 (5), 1232–1235. https://doi.org/10.1111/j.1439-0426.2011.01796.x.

Beaugrand, G., Ibanez, F., Lindley, J.A., 2001. Geographical distribution and seasonal and diel changes of the diversity of calanoid copepods in the North Atlantic and North Sea. Mar. Ecol. Prog. Ser. 219, 205–219. https://doi.org/10.3354/meps219189.

Beaugrand, G., Ibañez, F., Lindley, J.A., 2003. An overview of statistical methods applied to CPR data. Prog. Oceanogr. 58 (2-4), 235–262. https://doi.org/10.1016/j.pocean.2003.08.006.

Blenckner, T., Llope, M., Möllmann, C., Voss, R., Quaas, M.F., Casini, M., Lindegren, M., Folke, C., Chr. Stenseth, N., 2015. Climate and fishing steer ecosystem regeneration to uncertain economic futures. Proc. R. Soc. B Biol. Sci. 282 (1803), 20142809. https://doi.org/10.1098/rspb.2014.2809.

BOE. Official Spanish Gazette. 2004. Orden APA/3506/2004, de 25 de octubre, por la que se establece un Plan, de carácter urgente, para la conservación y gestión sostenible de la pesquería de cerco en el Caladero Nacional del Golfo de Cádiz. 35860-35861. https://www.boe.es/diario_boe/txt.php?id=BOE-A-2004-18545.

BOJA. Official Andalusian Gazette. 2004. Orden de 16 de junio de 2004, por la que se declara una reserva de pesca en la desembocadura del río Guadalquivir. num. 123. https://www.juntadeandalucia.es/boja/2004/123/3.

Bundy, A., Chuenpagdee, R., Boldt, J.L., de Fatima Borges, M., Camara, M.L., Coll, M., Diallo, I., Fox, C., Fulton, E.A., Gazihan, A., Jarre, A., Jouffre, D., Kleisner, K.M., Knight, B., Link, J., Matiku, P.P., Masski, H., Moutopoulos, D.K., Piroddi, C., Raid, T., Sobrino, I., Tam, J., Thiao, D., Torres, M.A., Tsagarakis, K., van der Meeren, G.I., Shin, Y.-J., 2017. Strong fisheries management and governance positively impact ecosystem status. Fish Fish. 18 (3), 412–439. https://doi.org/10.1111/faf.12184.

CBD. 2005. Handbook of the Convention on Biological Diversity Including its Cartagena Protocol on Biosafety, 3rd ed. Montreal, Canada. Secretariat of the Convention on Biological Diversity. https://www.cbd.int/doc/handbook/ cbd-hb-all-en.pdf.

Coll, M., Carreras, M., Cornax, M.J., Massutí, E., Morote, E., Pastor, X., Quetglas, A., Silva, L., Sobrino, I., Torres, M.A., Tudela, S., Pauly, D., 2014. Closer to reality: Reconstruction total removals in mixed fisheries from southern Europe. Fish. Res. 154, 179–194. https://doi.org/10.1016/j.fishres.2014.01.013.

Coll, M., Shannon, L. J., Kleisner, K. M., Juan-Jorda, M. J., Bundy, A., Akoglu, A. G., Banaru, D., Boldt, J. L., Borges, J. L., Borges, M. F., Cook., Diallo, I., Fu, C., Fox, C., Gascuel, D., Gurney, L. J., Hattab, T., Heymans, J. J., Jouffre, D., Knight, B. R., Kucukavsar, S., Large, S. I., Lynam, C., Machias, A., Marshall, K. N., Masski, H., Ojaveer, H., Piroddi, C., Tam, J., Thiao, D., Thiaw, M., Torres, M. A., Travers-Trolet, M., Tsagarakis, K., Tuck, I., van der Meeren, G. I., Yemane, D., Zador, S. G., Shin, Y-J. 2016. Ecological indicators to capture the effects of fishing on biodiversity and conservation status of exploited marine ecosystems. Ecol. Indic. 60: 947–962. https://doi.org/10.1016/j.ecolind.2015.08.048.

Daskalov, G.M., Grishin, A.N., Rodionov, S., Mihneva, V., 2007. Trophic cascades triggered by overfishing reveal possible mechanisms of ecosystem regime. shifts. PNAS 104 (25), 10518–10523. https://doi.org/10.1073/pnas.0701100104.

de Carvalho-Souza, GF, González-Ortegón, E., Baldó, F., Vilas, C., Drake, P., Llope, M., 2018. Natural and anthropogenic effects on the early life stages of European anchovy in one of its Essential Fish Habitats, the Guadalquivir estuary. Mar. Ecol. Prog. Ser. Adv. View 617–618, 67–79. https://doi.org/10.3354/meps12562.

Delgado, M., Hidalgo, M., Puerta, P., Sánchez-Leal, R., Rueda, L., Sobrino, I., 2018. Concurrent changes in spatial distribution of the demersal community in response to climate variations in the southern Iberian coastal Large Marine Ecosystem. Mar. Ecol. Prog. Ser. 607, 19–36. https://doi.org/10.3354/meps12791.

Diekmann, R., Möllmann, C. Integrated ecosystem assessments of seven Baltic Sea areas covering the last three decades 2010. In ICES cooperative research report, Copenhagen, Denmark: ICES. p. 92. https://www.ices.dk/sites/pub/Publication%20Reports/Cooperative%20Research%20Report%20(CRR)/CRR302.pdf.

Diekmann, R., Otto, S., Möllmann, C. Towards integrated ecosystem assessments (IEAs) of the Baltic Sea: Investigating ecosystem state and historical development 2012. In: Climate impacts on the Baltic Sea: From Science to Policy", Reckermann, M., Brander, K., Mackenzie, B.R., Omstedt A. (eds.), Springer Earth System Sciences Series, Berlin, Heidelberg, pp. 161–201. https://doi.org/10.1007/978-3-642-25728-5_6.

Doray, M., Petitgas, P., Huret, M., Duhamel, E., Romagnan, J.B., Authier, M., Sanchez, F., Berger, L., Dorémus, G., Bourriau, P., Grellier, P., Massé, J., 2018. Monitoring small pelagic fish in the Bay of Biscay ecosystem, using indicators from an integrated survey. Prog. Oceanogr. 166, 15–29. https://doi.org/10.1016/j.pocean.2017.12.004.

Doubleday, Zoë.A., Prowse, T.A.A., Arkhipkin, A., Pierce, G.J., Semmens, J., Steer, M., Leporati, S.C., Lourenço, Sílvia, Quetglas, A., Sauer, W., Gillanders, B.M., 2016. Global proliferation of cephalopods. Curr. Biol. 26 (10), R406–R407. https://doi.org/10.1016/j.cub.2016.04.002.

Edwards, M., Beaugrand, G., Helaouët, P., Alheit, Jürgen, Coombs, S., Álvarez, I., 2013. Marine ecosystem response to the atlantic multidecadal oscillation. PLoS One 8 (2), e57212. https://doi.org/10.1371/journal.pone.0057212.

Enfield, D.B., Mestas-Nuñez, A.M., Trimble, P.J., 2001. The Atlantic multidecadal oscillation and its relation to rainfall and river flows in the continental US. Geophys. Res. Lett. 28 (10), 2077–2080. https://doi.org/10.1029/2000GL012745.

European Commission, 2008. Directive 2008/56/EC of the European Parliament and of the Council establishing a framework for community action in the field of marine environmental policy (Marine Strategy Framework Directive). Off. J. Eur. Union L164, 19–40.

European Commission. 2009. Green paper - Reform of the Common Fisheries Policy. Brussels (Belgium): European Commission. 27.

European Commission. 2013. European Council Regulation No 1380/2013 of the European Parliament and of the Council of 11 December 2013 on the Common Fisheries Policy, amending Council Regulations EC No 1954/2003 and EC No 1224/2009 and repealing Council Regulations EC No 2371/2002 and EC No 639/2004 and Council Decision 2004/585/EC. Official J. Eur. Union L, 354.

FAO. 2003. Measuring capacity in fisheries. FAO Fisheries Technical Paper. No. 445. Rome, FAO. 314p.

FAO. 2016. The State of World Fisheries and Aquaculture 2016. Contributing to food security and nutrition for all. Rome. 200.

Fernandes, P.G., Ralph, G.M., Nieto, A., García Criado, M., Vasilakopoulos, P., Maravelias, C.D., Cook, R.M., Pollom, R.A., Kovačić, M., Pollard, D., Farrell, E.D., Florin, A.-B., Polidoro, B.A., Lawson, J.M., Lorance, P., Uiblein, F., Craig, M., Allen, D.J., Fowler, S.L., Walls, R.H.L., Comeros-Raynal, M.T., Harvey, M.S., Dureuil, M., Biscoito, M., Pollock, C., McCully Phillips, S.R., Ellis, J.R., Papaconstantinou, C., Soldo, A., Keskin, Çetin, Knudsen, S.W., Gil de Sola, L., Serena, F., Collette, B.B., Nedreaas, K., Stump, E., Russell, B.C., Garcia, S., Afonso, P., Jung, A.B.J., Alvarez, H., Delgado, J., Dulvy, N.K., Carpenter, K.E., 2017. Coherent assessments of Europe's marine fishes show regional divergence and megafauna loss. Nat. Ecol. Evol. 1 (7) https://doi.org/10.1038/s41559-017-0170.

Fogarty, M.J., Murawski, S.A., 1998. Large-scale disturbance and the structure of marine systems: fishery impacts on Georges Bank. Ecol. Appl. 8 (Suppl. 1), S6–S22. https://doi.org/10.1890/1051-0761.

Frank, K.T., Petrie, B., Choi, J.S., Legget, W.L., 2005. Trophic cascades in a formerly cod-dominated ecosystem. Science 308, 1621. https://doi.org/10.1126/science.1113075.

Fu, C., Large, S., Knight, B., Richardson, A.J., Bundy, A., Reygondeau, G., Boldt, J., van der Meeren, G.I., Torres, M.A., Sobrino, I., Auber, A., Travers-Trolet, M., Piroddi, C., Diallo, I., Jouffre, D., Mendes, H., Borges, M.F., Lynam, C.P., Coll, M., Shannon, L.J., Shin, Y.-J., 2015. Relationships among fisheries exploitation environmental conditions and ecological indicators across a series of marine ecosystems. J. Mar. Syst. 148, 101–111. https://doi.org/10.1016/j.jmarsys.2015.01.004.

Galgani, F., Hanke, G., Werner, S., De Vrees, L., 2013. Marine litter within the European Marine Strategy Framework Directive. ICES J. Mar. Sci. 70, 1055–1106. https://doi.org/10.1007/978-3-319-13878-7_10.

Gamaza, M., Torres, M.A., Acosta, J.J., Erzini, K., Sobrino, I., 2020. Are we ready to implement a discard ban in the gulf of Cádiz? Stakeholders' perceptions. Mar. Policy 116, 103711. https://doi.org/10.1016/j.marpol.2019.103711.

García-Isarch, E., Millán, M., Ramos, F., Santamaría, M.T.G. Burgos, C. 2012. Recent past and present of the Spanish fishery of anchovy (Engraulis encrasicolus Linnaeus, 1758) in Atlantic Moroccan waters. In: S. Garcia, M. Tandstad and A.M. Caramelo (eds.). Science and Management of Small Pelagics. Symposium on Science and the Challenge of Managing Small Pelagic Fisheries on Shared Stocks in Northwest Africa, 11–14 March 2008, Casablanca, Morocco. FAO Fisheries and Aquaculture Proceedings. No. 18. Rome, FAO. 441–449.

Goulding, I. 2016. Research for pech committee - Impact of fisheries partnership agreements on employment in the EU and in third countries. Directorate-General for Internal Policies. Policy Department B: Structural and cohesion policies. 64. http://www.europarl.europa.eu/supporting-analyses.

Groenewold, S., Fonds, M., 2000. Effects on benthic scavengers of discards and damaged benthos produced by the beam-trawl fishery in the southern North Sea. ICES J. Mar. Sci. 57, 1395–1406. https://doi.org/10.1006/jmsc.2000.0914.

Halpern, B.S., Walbridge, S., Selkoe, K.A., Kappel, C.V., Micheli, F., D'Agrosa, C., Bruno, J.F., Casey, K.S., Ebert, C., Fox, H.E., Fujita, R., Heinemann, D., Lenihan, H.S., Madin, E.M.P., Perry, M.T., Selig, E.R., Spalding, M., Steneck, R., Watson, R., 2008. A global map of human impact on marine ecosystems. Science 319 (5865), 948–952. https://doi.org/10.1126/science:1149345.

Hidalgo, M., Quetglas, A., Ordines, F., Rueda, L., Punzón, A., Delgado, M., Gil de Sola, L., Esteban, A., Massutí, E., 2017. Size-spectra across geographical and bathymetric gradients reveal contrasting resilient mechanisms of recovery between Atlantic and Mediterranean fish communities. J. Biogeogr. 44 (9), 1939–1951. https://doi.org/10.1111/jbi.12976.

Hiddink, J.G., Rijnsdorp, A.D., Piet, G., 2008. Can bottom trawling disturbance increase food production for a commercial fish species? Can. J. Fish. Aquat. Sci. 65 (7), 1393–1401. https://doi.org/10.1139/F08-064.

Hiddink, J.G., Jennings, S., Szostek, C.L., Hughes, K.M., Ellis, N., Rijnsdorp, D., McConnaughey, R.A., Mazor, T., Hilborn, R., Collie, J.S., Pitcher, R., Amoroso, R., Parma, A.M., Suuronen, P., Kaiser, M.J., 2017. Global analysis of depletion and recovery seabed biota after bottom traling disturbance. PNAS 114, 8301–8306. https://doi.org/10.1073/pnas.1618858114.

Hoegh-Guldberg, O., Bruno, J.F., 2010. The impact of climate change on the world's marine ecosystems. Science 328 (5985), 1523–1528. https://doi.org/10.1126/science:1189930.

Hurrell, J. W., Dickson, R.R. Climate variability over the North Atlantic. N.C. Stenseth, G. Ottersen, J.W. Hurrell, A. Belgrano (Eds.), 2004. Marine Ecosystems and Climate Variation: The North Atlantic: A Comparative Perspective, Oxford University Press, Oxford.

ICES. 2014. Report of the Working Group on Southern Horse Mackerel, Anchovy and Sardine (WGHANSA), 20–25 June 2014, Copenhagen, Denmark. ICES CM 2014/ACOM:16. 599.

IEO. 2005. Estudio previo para la delimitación de una Reserva de Pesca en la Desembocadura del Guadalquivir. 215.

IEO. 2018. Informe de Campaña de Arrastre Región Sur-Atlántica - ARSA 0318. Centro Oceanográfico de Cádiz. Instituto Español de Oceanografía. 83.

Jiménez, M.P., Sobrino, I., Ramos, F., 2004. Objective methods for defining mixed-species trawl fisheries in Spanish waters of the Gulf of Cadiz. Fish. Res. 67, 195–206. https://doi.org/10.1016/j.fishres.2003.09.048.

Johnson, A.F., Gorelli, G., Jenkins, S.R., Hiddink, J.G., Hinz, H., 2015. Effects of bottom trawling on fish foraging and feeding. Proc. R. Soc. B Biol. Sci. 282 (1799), 20142336. https://doi.org/10.1098/rspb.2014.2336.

Kassambara, A., Mundt, F. 2017. factoextra. Extract and Visualize the Results of Multivariate Data Analyses. R package version 1.0.5, https://cran.r-project.org/web/packages/factoextra/factoextra.pdf.

Kenny, A.J., Skjoldal, H.R., Engelhard, G.H., Kershaw, P.J., Reid, J.B., 2009. An integrated approach for assessing the relative significance of human pressures and environmental forcing on the status of Large Marine Ecosystems. Prog. Oceanogr. 81 (1-4), 132–148. https://doi.org/10.1016/j.pocean.2009.04.007.

Kleisner, K.M., Coll, M., Lynam, C.P., Bundy, A., Shannon, L., Shin, Y.-J., Boldt, J.L., Borges, M.F., Diallo, I., Foz, C., Gascuel, D., Heymans, J.J., Jordá, M.J.J., Jouffre, D., Large, S.I., Marshall, K.N., Ojaveer, H., Piroddi, C., Tam, J., Torres, M.A., Travers-Trolet, M., Tsagarakis, K., van der Meeren, G.I., Zador, S., 2015. Evaluating changes in fisheries as a provisioning ecosystem service through comparative assessment of community degradation. Ecosyst. Serv. 16, 413–429. https://doi.org/10.1016/j.ecoser.2015.02.002.

Kooij, J., Engelhard, G.H., Righton, D.A., 2016. Climate change and squid range expansion in the North Sea. J. Biogeogr. 43 (11), 2285–2298. https://doi.org/10.1111/jbi.2016.43.issue-1110.1111/jbi.12847.

Lam, V., Cheung, W., Reygondeau, G., Sumaila, R., 2016. Projected change in global fisheries revenues under climate change. Sci. Rep. 6, 32607. https://doi.org/10.1038/srep32607.

Le Manach, F., Chaboud, C., Copeland, D., Cury, P., Gascuel, D., Kleisner, K.M., Standing, A., Sumaila, U.R., Zeller, D., Pauly, D., Hyrenbach, D., 2013. European Union's public fishing access agreements in developing countries. PLoS One 8 (11), e79899. https://doi.org/10.1371/journal.pone.0079899.

Legendre, P., Legendre, L. 1998. Numerical ecology, second English ed. Elsevier Science BV, Amsterdam, p. 853.

Levin, P.S., Kelble, C.R., Shuford, R.L., Ainsworth, C., de Reynier, Y., Dunsmore, R., Fogarty, M.J., Holsman, K., Howell, E.A., Monaco, M.E., Oakes, S.A., Werner, F. Guidance for implementation of integrated ecosystem assessments: A US perspective, ICES Journal of Marine Science, 71: 1198–1204. https://doi.org/10.1093/icesjms/fst112.

Levin, P.S., Fogarty, M.J., Murawski, S.A., Fluharty, D., 2009. Integrated ecosystem assessments: Developing the scientific basis for ecosystem-based management of the ocean. PLoS Biol. 7, 23–28. https://doi.org/10.1371/journal.pbio.1000014.

Lindegren, M., Blenckner, T., Stenseth, N.C., 2012. Nutrient reduction and climate change cause a potential shift from pelagic to benthic pathways in a eutrophic marine ecosystem. Glob. Change Biol. 18 (12), 3491–3503. https://doi.org/10.1111/j.1365-2486.2012.02799.x.

Link, J.S., Brodziak, J.K.T., Edwards, S.F., Overholtz, W.J., Mountain, D., Jossi, J.W., Smith, T.D., Fogarty, M.J., 2002. Marine ecosystem assessment in a fisheries management context. Can. J. Fish. Aquat. Sci. 59 (9), 1429–1440. https://doi.org/10.1139/f02-115.

Llope, M., Daskalov, G.M., Rouyer, T.A., Mihneva, V., Grishin, A.N., Chan, K.-S., Stenseth, N.C., 2011. Overfishing of top predators eroded the resilience of the Black Sea system regardless of the climate and anthropogenic conditions. Glob. Change Biol. 17, 1251–1265. https://doi.org/10.1111/j.1365-2486.2010.02331.x.

Llope, M. 2017. The ecosystem approach in the Gulf of Cadiz. A perspective from the southernmost European Atlantic regional sea. ICES Journal of Marine Science, 74: 382–390. https://doi.org/10.1093/icesjms/fsw165.

Lynam, C.P., Llope, M., Möllmann, C., Helaouët, P., Bayliss-Brown, G.A., Stenseth, N.C., 2017. Interaction between top-down and bottom-up control in marine food webs. PNAS 114 (8), 1952–1957. https://doi.org/10.1073/pnas.1621037114.

Mallory, T.G., 2013. China's distant water fishing industry: evolving policies and implications. Marine Policy 38, 99–108. https://doi.org/10.1016/j.marpol.2012.05.024.

Maritorena, S., d'Andon, O.H.F., Mangin, A., Siegel, D.A., 2010. Merged satellite ocean color data products using a bio-optical model: Characteristics, benefits and issues. Remote Sens. Environ. 114 (8), 1791–1804. https://doi.org/10.1016/j.rse.2010.04.002.

McCauley, D.J., Jablonicky, C., Allison, E.H., Golden, C.D., Joyce, F.H., Mayorga, J., Kroodsma, D., 2018. Wealthy countries dominate industrial fishing. Sci. Adv. 4 (8), eaau2161. https://doi.org/10.1126/sciadv.aau2161.

Modica, L., Velasco, F., Preciado, I., Soto, M., Greenstreet, S.P.R., 2014. Development of the large fish indicator and associated target for a Northeast Atlantic fish community. ICES J. Mar. Sci. 71, 2403–2415. https://doi.org/10.1093/icesjms/fsu101.

Möllmann, C., Diekmann, R., Muller-Karulis, B., Kornilovs, G., Plikshs, M., Axe, P., 2009. Reorganization of a large marine ecosystem due to atmospheric and anthropogenic pressure: A discontinuous regime shift in the Central Baltic Sea. Glob. Change Biol. 15, 1377–2139. https://doi.org/10.1111/j.1365-2486.2008.01814.x.

Möllmann, C., Lindegren, M., Blenckner, T., Bergstrom, L., Casini, M., Diekmann, R., Flinkman, J., Muller-Karulis, B., Neuenfeldt, S., Schmidt, J.O., Tomczak, M., Voss, R., Gårdmark, A., 2013. Implementing ecosystem-based fisheries management:

from single-species to integrated ecosystem assessment and advice for Baltic Sea fish stocks. ICES J. Mar. Sci. 71, 1187–1197. https://doi.org/10.1093/icesjms/fst123.

Oksanen, J., Blanchet, F.G., Friendly, M., Kindt, R., Legendre, P., McGlinn, D., Minchin P. R. O'Hara, R.B., Simpson, G.L., Solymos, P., Stevens, M.H.H., Szoecs, E., Wagner, H. 2019. vegan. Community Ecology Package. R package version 2.5-5, https://cran.r-project.org/web/packages/vegan/vegan.pdf.

Patrick, W.S., Link, J.S., 2015. Myths that continue to impede progress in ecosystem-based fisheries management. Fisheries 40 (4), 155–160. https://doi.org/10.1080/03632415.2015.1024308.

Pauly, D., Zeller, D., 2016. Catch reconstructions reveal that global marine fisheries catches are higher than reported and declining. Nat. Commun. 7, 10244. https://doi.org/10.1038/ncomms10244.

Planque, P., Arneberg, P. 2018. Principal component analyses for integrated ecosystem assessments may primarily reflect methodological artefacts. ICES Journal of Marine Science, 75(3), 1021–1028. https://doi.org/10.1093/icesjms/fsx223.

R Development Core Team. R: a language and environment for statistical computing. 2018. R Foundation for Statistical Computing, Vienna.

Ramos, F. 2015. On the population structure of the European anchovy (Engraulis encrasicolus) in ICES Division IXa: a short review of the state of art. Working document presented in the ICES Stock Identification Methods Working Group (SIMWG).

Reynolds, R.W., Smith, T.M., Liu, C., Chelton, D.B., Casey, K.S., Schlax, M.G., 2007. Daily high-resolution-blended analyses for sea surface temperature. J. Clim. 20, 5473–5496. https://doi.org/10.1175/2007JCLI1824.1.

Rodionov, S.N., 2004. A sequential algorithm for testing climate regime shifts. Geophys. Res. Lett. 31 (9), n/a–n/a. https://doi.org/10.1029/2004GL019448.

Rodionov, S.N., 2006. The use of prewhitening in climate regime shift detection. Geophys. Res. Lett. 31, L12707. https://doi.org/10.1029/2006GL025904.

Rogers-Bennett, L., Haaker, P.A., Huff, T.O., Dayton, P.K., 2002. Estimating baseline abundances of abalone in California for restoration. CalCOFI Rep. 43, 97–111.

Rogers-Bennett, L., Hubbard, K.E., Juhasz, C.I., 2013. Dramatic declines in red abalone populations after opening a "de facto" marine reserve to fishing: Testing temporal reserves. Biol. Conserv. 157, 423–431. https://doi.org/10.1016/j.biocon.2012.06.023.

Scheffer, M., Carpenter, S., Young, B., 2005. Cascading effects of overfishing marine systems. Trends Ecol. Evol. 20 (11), 579–581. https://doi.org/10.1016/j.tree.2005.08.018.

SEDAR 52. 2018. Stock assessment report of SEDAR 52 Gulf of Mexico red snapper. Southeast Data, Assessment, and Review. North Charleston, South Carolina. 434.

Shapiro, D. E., Switzer, P. 1989. Extracting time trends from multiple monitoring sites. Technical report No. 132. Department of Statistics, Standford University, California.

Silva, L., Vila, Y., Ángeles Torres, M., Sobrino, I., Acosta, J.J., 2011. Cephalopod assemblages, abundance and species distribution in the Gulf of Cadiz (SW Spain). Aquat. Living Resour. 24 (1), 13–26. https://doi.org/10.1051/alr/2011101.

Sobrino, I., Silva, L., Bellido, J.M., Ramos, F., 2002. Rainfall, river discharges and sea temperature as factos affecting abundance of two coastal benthic cephalopod species in the Gulf of Cádiz (SW Spain). Bull. Mar. Sci 71, 851–865.

Sumaila, U.R., Lam, V.W.Y., Miller, D.D., Teh, L., Watson, R.A., Zeller, D., Cheung, W.W. L., Côté, I.M., Rogers, A.D., Roberts, C., Sala, E., Pauly, D., 2015. Winners and losers in a world where the high seas is closed to fishing. Sci. Rep. 5 (1) https://doi.org/10.1038/srep08481.

Taylor, A., 1995. North–south shifts of the Gulf Stream and their climatic connection with the abundance of zooplankton in the UK and its surrounding seas. ICES J. Mar. Sci. 52 (3-4), 711–721. https://doi.org/10.1016/1054-3139(95)80084-0.

Taylor, A.H., 1996. North–south shifts of the Gulf Stream: ocean– atmosphere interactions in the North Atlantic. Int. J. Climatol. 16, 559–583. https://doi.org/10.1002/(SICI)1097-0088.

Torres, M.A., Coll, M., Heymans, J.J., Christensen, V., Sobrino, I., 2013. Food-web structure of and fishing impacts on the Gulf of Cadiz ecosystem (South-western Spain). Ecol. Model. 265, 26–44. https://doi.org/10.1016/j.ecolmodel.2013.05.019.

United Nations. 1982. United Nations Convention on the Law of the Sea of 10 December 1982. United Nations, New York. 208. http://www.un.org/Depts/los/index.htm.

Using the Grammar of Graphics. R package version 3.2.0, https://cran.r-project.org/web/packages/ggplot2/ggplot2.pdf.

Woillez, M., Rivoirard, J., Petitgas, P., 2009. Using min/max autocorrelation factors of survey-based indicators to follow the evolution of fish stocks in time. Aquat. Living Resour. 22 (2), 193–200. https://doi.org/10.1051/alr/200902010.1051/alr/2009020.olm01.