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Original Article

The fisheries history of small pelagics in the Northern Mediterranean

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Since 2007, the biomass of sardine and anchovy in the NW Mediterranean has remained persistently low, whereas the biomass of the commercially low-valued sprat has exploded. Also, simultaneous decreases in condition, size, and/or age of these populations were observed. Altogether, this resulted in a drop in landings of small pelagics. To understand the amplitude of these events and to provide a baseline scenario against which current changes can be compared, we compiled exceptionally long landing series (1865–2013) of sardine, anchovy, and mackerel for different sub-regions of the southern French coast. We characterized the fluctuations of these landings and compared these with environmental drivers (sea surface temperature, Rhône river discharge, North Atlantic Oscillation, Western Mediterranean Oscillation—WeMO, and Atlantic Multidecadal Oscillation—AMO), using different time-series analyses. We also collated historical data to infer qualitative changes in fishing effort over time. A fishing effort related increase in landings was observed around 1962 for all three species, although current sardine landings have dropped below levels observed before this period. Sardine and anchovy landings were, respectively, positively and negatively related to the AMO index and anchovy landings were also positively related to the WeMO. We finished by discussing the potential role of the environmental variables and fishing on long-term fishery landings trends.

Keywords: anchovy, fish landings, Gulf of Lions, historical time series, mackerel, sardine.

Introduction

Small pelagic fish stocks are known to fluctuate substantially worldwide. These fluctuations are often attributed to climate variability, and sometimes to predator abundance (Checkley *et al.*, 2009). Additionally, these effects can be contingent on or amplified by fishing pressure (Deyle *et al.*, 2013). Here, we focus on the fluctuations of the small pelagic fish stocks of the Gulf of Lions, a bay spanning a substantial part of the French Mediterranean coast. In this area, a recent change in the pelagic ecosystem has been observed, as the biomass of sardine and anchovy has remained persistently low while the sprat biomass has increased considerably since 2007. Van Beveren *et al.* (2014) documented simultaneous changes in length and age structure of the populations as well as a decline in fish condition and postulated a bottom-up control as one of the possible main drivers of such changes. After this initial study, small pelagic fish condition in the NW Mediterranean was related to the environment (Brosset *et al.*, 2015) and the last GFCM report (General Fisheries Commission for the Mediterranean) indicated that those populations are not overfished (i.e. anchovy stock biomass and fishing mortality was considered low, whereas sardine was judged ecologically unbalanced; both based on harvest rates comparing landings with direct acoustic biomass estimates, as well as biological information, GFCM, 2014). However, the specific drivers of the population changes are still not completely unravelled, and it is unknown if a similar situation occurred in the past.

When looking at population dynamics, there is a need to consider the longest time span possible (Jackson *et al.*, 2001), such as was for example done by Ravier and Fromentin (2001), Grbec *et al.* (2002) and Thurstan *et al.* (2010). That is, relatively short time series might not be enough to depict substantial changes in the population's biomass, abundance or their landings. For example, major environmentally driven population fluctuations can occur with an extended periodicity (e.g. Ravier and Fromentin, 2001), processes can be slow and the effects of fisheries can be long-lasting (possibly creating a "shifting baseline syndrome", Pauly, 1995). Unfortunately, no sufficiently long time series of population biomass and/or abundance exist for the small pelagic stocks from the NW Mediterranean. However, an extraordinary long series of historical landings was compiled from French national statistics over the period 1865–2013.

Before 1940, the pelagic fisheries of the Gulf of Lions only used traditional techniques (e.g. the sardinal, a Catalan vessel targeting sardine), though with increasing motorization after World War I. After the beginning of the Second World War, several improvements allowed the fishery to develop, such as the expansion and innovation of the train network, the use of freezing and the modification of fishing techniques (Doumenge, 1952). Importantly, in 1941 "lamparo's", i.e. fishing vessels that use light to attract pelagic species, were introduced (Doumenge, 1952). However, they were quickly banned in some areas and were only legalized in 1960–1961 (Bailly and Le Grel, 1996). Almost simultaneously, the Algerian independence (1962) led to the repatriation of several fishing units. In addition, ultrasound sonars were implemented concurrently, larger nets were employed, fishing power increased significantly and gas was replaced by butane or propane for lamparo lamps. All of this coincided with a sudden increase in landings (Maurin, 1965; Bailly and Le Grel, 1996). Modern trawls were only employed from around 1975 onwards, as a reaction to a foregoing decrease in pelagic landings. Successively, trawling methods diversified and the number of lamparo's diminished. However, in 1977, regulations were already in place to limit the numbers of trawling vessels, their fishing zones, and their days at sea (Pichot and Dremière, 1978). Anchovy landings increased after 1986 to supply the surge in demand after Spain became a member of the European Union. Around 2007 however, the biomass of sardine and anchovy decreased, leading to the current low level of exploitation (GFCM, 2014; Van Beveren *et al.*, 2014). However, sardine landings had already shown a decline from 1980 onwards (Farrugio and Marin, 1999).

Although such basic prior knowledge was available, the causes for the fluctuations of landings were unknown. Specifically, these potential sources of variations were mostly qualitative and reported landings were annual or of very limited extent. Here, we compiled the longest possible landings series from the French Mediterranean fisheries for three species (sardine, anchovy, and mackerel). We first characterized the landings of these three species in terms of patterns, variability, cyclicity, and breakpoints. Then, we tested the relation between landings and SST (sea surface temperature), river run-off (Rhône), and climate indices such as the North Atlantic Oscillation (NAO), Western Mediterranean Oscillation (WeMO), and Atlantic Multidecadal Oscillation (AMO), as these parameters have previously been shown to have an influence on small pelagic biomasses and/or landings (Grbec *et al.*, 2002; Lloret *et al.*, 2004; Martín *et al.*, 2008, 2012; Checkley *et al.*, 2009; Alheit *et al.*, 2014). We compared the environmental patterns, cycles, and breakpoints with landings and assessed potential relationships using generalized additive models (GAMs). Although the use of landings instead of abundance or biomass can be misleading (Pauly *et al.*, 2013), it is the only long-term information available for these species and, with care, we can interpret results, given for example the available qualitative knowledge of effort. However, for these reasons we do not use these results to infer changes in stock size or status. To conclude, we discuss the results in view of the recently observed unbeneficial changes in the pelagic ecosystem.

Material and methods

Data

Landings

For sardine, anchovy, and mackerel, annual landings from the French Mediterranean fisheries in terms of total weight and market value (if available) were obtained from three principal sources: (i) the "Statistique des pêches maritimes" (SPM, http://archimer.ifremer.fr/statistique-peches-maritimes.htm), (ii) statam (Le Corre, 1971), and (iii) France Agrimer (www.franceagrimer.fr). We only considered the French part of the Mediterranean (almost equivalent to the Gulf of Lions) because this corresponds highly with the area used for stock assessments and this delineates a fishing fleet. However, this zone might perhaps not correspond to the biological limits of the stock, as these remain largely uncertain because research only started to approach the question recently (e.g. Fiorentino *et al.*, 2014). Data were aggregated into different areas (which will be referred to as subregions) in correspondence with current administrative units (such as Port-Vendres, Sète, and Marseille) or according to historical grouping of several administrative units (such as Martigues, Nice, and Toulon that were pooled together, see Figure 1). Landing series from the different chief data sources were verified against each other (as there were periods of overlap) and against literature and other data sources (correlation, plotting), such as Pêche sardinière en Mediterranée (Marine marchande, 1964), La pêcherie des petits pélagiques (Bailly and Le Grel, 1996), Monographie des pêches maritimes (Gouvernement français, 1975), Statistique des régions de pêches (l'Institut Scientifique et Technique des Pêches Maritimes, 1924), Système d'Informations Halieutiques (http://sih.ifremer.fr), and IFREMER files. For the overlapping periods, we selected only the most consistent data (showing maximal correlation with other information sources). Therefore, the final landing series were composed out of data from different origins: 1865–1970 (SPM), 1971–1993 (statam) and 1994–2013 (France Agrimer). Over the recent period (1950 until recent), the sum of the landings of all subregions is consistent with FAO data (Supplementary Figure S1).

From these series, small pelagic fish that were caught outside the Gulf of Lions were excluded. Also, we did not include catches taken inside the Gulf but landed by foreign vessels (Spanish or Italian) because of a lack of data. Given the local scale of these fisheries and the prevailing restrictions (both practical and lawful), this biomass is however limited (e.g. <5% of total landings for sardine during recent years, STECF, 2013).

Unfortunately, no information on fishing effort was available to confront landings with (e.g. such as in Thurstan *et al.*, 2010). Therefore, the following analyses were conducted on catch time series (see Ravier and Fromentin, 2001; Grbec *et al.*, 2002).

Environment

Environmental time series (see Supplementary Appendix S1 for details) were collected from online databases (SST, NAO, WeMO, AMO) or communicated by specialized companies (Rhône river flow). They all spanned the period of the landings (1865–2013), except for the Rhône river flow for which data were only available from 1920. We used three global indices (NAO, WeMO, and AMO). However, only two local climate variables (river discharge and SST) were used as on such a long-term basis local variables were only sporadically available. Also, these holistic indices might be more strongly related to biological effects than any single variable and can provide at least an initial robust and integrated idea of the ecological effect of climate variability (Stenseth *et al.*, 2003).

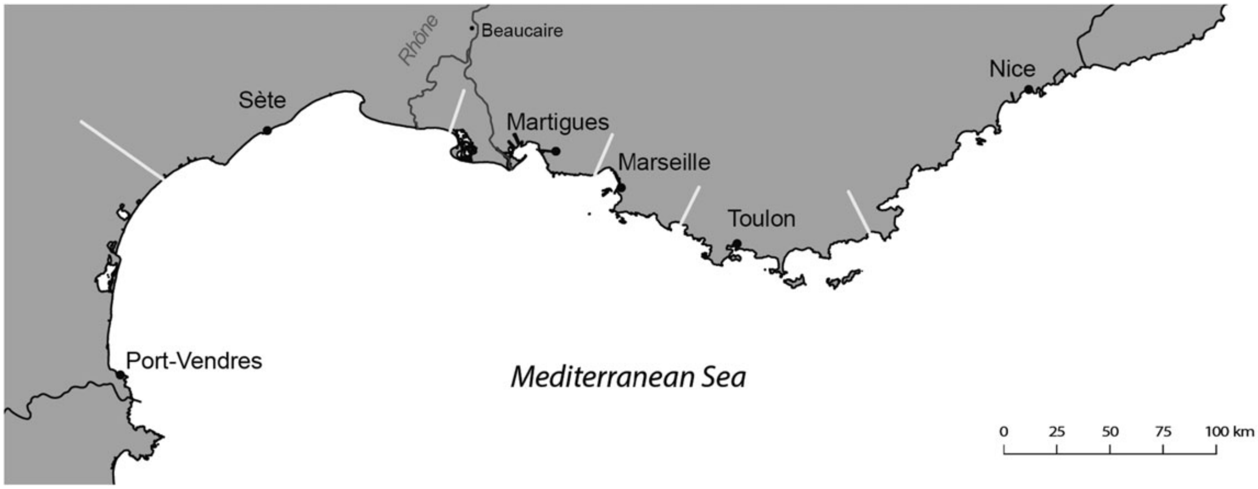

Figure 1. France's Southern coast, subdivided into the subregions applied in this study, named after their chief port. Borders are indicated by pale lines.

Statistical analyses

Landings

As some selected statistical analyses require contiguity and our series included some missing values, these were estimated using additional information present for those years or time-series modelling. Sardine landings between 1874 and 1890 were recorded in numbers, which were converted to biomass with the help of the earliest data available; the mean size of sardine caught in Marseille, Port-Vendres and Sète during 1972–1977 and the weight–length relationship calculated from Lee (1961). Since landings and total market value were always highly correlated for all three species between 1874–1890 and 1894–1914 ($p < 0.01$ and R^2 between 0.92 and 0.97), we estimated missing values for the periods 1865–1873 and 1891–1893 from market values using a linear regression. Only data up to 1914 were used for this, because thereafter the linear relation changes because of a war-associated price increase. Also, data were missing for 1894 and incomplete between 1994 and 1996 (and 1997 to a lesser extent) because of a change in the administrative data system. These years were filled per species and per subregion with an autoregressive integrated moving average (ARIMA) model based on the preceding series, i.e., respectively, 1865–1893 and 1970–1993 (so the 1960s increase was excluded). Furthermore, no data were available during the Second World War (WWII). This five-year gap was deleted or filled up depending on the analysis (see further). When filled, this was done by taking the mean of the two adjacent values. Also, from 1994 onwards, no data were available for Marseille. Although caused by administrative changes, landings are thought to have become extremely low due to closure of the fish auction and few active vessels remaining in that region (internal information from IFREMER, French Research Institute for the Exploitation of the Sea). Because this gap was fairly large and significant changes in exploitation took place between 1994 and 2013, we considered two types of total landing time series for the following analyses: (i) the sum of the landings of all the subregions from 1865 to 1993 and (ii) the sum of the landings from 1865 to 2013 of all the subregions except Marseille.

The population variability (*PV*; Heath, 2006) of all 12 time series (3 species × 4 subregions) was calculated to examine the difference between species and subregions in terms of temporal variations. The variable *PV* is a more recent metric than the more commonly used coefficient of variation (*CV*) and is less seriously influenced by rare events and zeros. Also, *PV* measures variability on a proportional scale, and should therefore be especially appropriate to compare populations experiencing different dynamics. Namely, it quantifies the average percentage of the absolute differences between all combinations of the time series:

$$D_{(z)} = \frac{|(z_i - z_j)|}{\mathrm{MAX}(z_i, z_j)} \quad \text{if } z_i \neq z_j \quad \text{and} \quad D(z) = 0 \text{ otherwise},$$

$$PV = \frac{\sum_{z=1}^{C} D(z)}{C} \quad \text{with} \quad C = \frac{n(n-1)}{2},$$

where C is the number of all possible combinations of landing values at two given time steps (z_i and z_j) of the time series of length n. The variable *PV* fluctuates between 0 and 1, with 0 being complete stability.

Patterns, periodicity, and breakpoints

The environmental and landing series were analysed together so that the main characteristics of the time series could be identified, as well as compared. Correspondence in terms of patterns, periodicity, or breakpoints could indicate if the environment might be influencing small pelagic landings. Excluding potential resonant effects for small pelagics (see Bjørnstad *et al.*, 2004), the forcing and the response variable might be quasi-linearly related, in which case the patterns of both tracks might be similar. However, while a small time-lag and/or a strongly non-linear relationship could conceal such an interaction, the patterns of cyclicity should remain analogous (on the condition that exploitation does not change the cyclic dynamics over time). Also, a discontinuity in the landings might be caused by an abrupt change (regime shift) in the environment and/or fishing effort. Hence, verifying the occurrence of such discontinuities is of interest and was done through a breakpoint analysis (see below). For all analyses (except the link with the environment and the breakpoint analysis), annual landings (without Marseille) were log transformed (natural logarithm) to stabilize the variance (Sen and Srivastava, 1990), whereby 1 was added due to the occurrence of zeros.

To estimate the general trend of each time series, data were analysed with Eigen vector filtering (EVF; Colebrook, 1978), as this technique has the advantage that the importance of the calculated trend is quantified (%) and the smoothed series is not shortened. For each time series, an autocovariance matrix is constructed by shifting the series between 1 and 5 years (this lag allows for retention only of medium- to long-term fluctuations, i.e. >15–20 years, Ravier and Fromentin, 2001). The series' trend is then given by the first axis of a principal component analysis (PCA) performed on this matrix. Because the percentage of variance explained can be calculated, this enables us to quantify the importance of the main trend (Ravier and Fromentin, 2001). EVF was done for all environmental series and the overall landings per species (without Marseille) and with the WWII period filled.

Given that non-stationarity was most often the rule in our series (e.g. because of the known drop in landings during the last years) and that the removal of the main pattern would discard part of the information, we used wavelet (Daubechies, 1992) rather than Fourier analyses to inspect the periodicity of the landings (without Marseille) and environmental series. This methodology has the intrinsic property to not only decompose the variance of a time series over frequencies, but also over time domains (hence tolerating non-stationary data). The wavelet transform (W) is done by decomposing a signal over functions called 'mother wavelets' $\Psi(t)$, which can be dilated (related to the frequency, a) and translated (related to the time position, τ):

$$W_x(a, \tau) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} x(t) \Psi\left(\frac{t-\tau}{a}\right) \mathrm{d}t,$$

where the asterisk indicates the complex conjugate form and $x(t)$ is the signal. In this study, we selected the Morlet mother wavelet, a continuous and complex wavelet with a simple link to frequencies and adapted to wave-like signals (Mallat *et al.*, 1998). Also, we used β-surrogates to test for significance, as they take both low and high frequencies into account and have been proved to be well suited to ecological time series (Rouyer *et al.*, 2008; Cazelles *et al.*, 2014). Beta was calculated as the slope of the spectrum in log-coordinates. The final wavelet power spectrum is presented as a time–frequency plot, with the intensity of the match between the time series and the wavelet represented on a colour scale range (blue = low variance and grey = high variance). Further details on the methodology can be found in Rouyer *et al.* (2008). When considering periodicity, continuous time series need to be used, so we filled the gap of the Second World War for this analysis.

For the environmental and all 12 landing series, a breakpoint analysis (R package strucchange, Zeileis *et al.*, 2013) was performed to compare the periods of major changes between time series. This method performs an ordinary least squares (OLS) for every segment of the time series, and puts the resulting residual sum of squares (RSS) in a matrix, with rows being the starting point of the OLS and columns being the endpoints. Then, the optimal combination of segments is found by minimizing the RSS. This method has the advantage that the number of breakpoints is automatically determined and a confidence interval can be given. The WWII period was deleted for this analysis.

Relationship with the environment

We modelled the effect of multiple environmental factors (SST, NAO, WeMO, AMO, and river outflow) on the landings of each species separately, using generalized additive models (GAMs). This technique extends the linear models by handling multiple error types (i.e. not only Gaussian) and by allowing the effect of the predictor(s) to be non-linear, as it can be estimated as a smooth function (Hastie and Tibshirani, 1990). Here, a smoother (cubic spline) was only applied on the year effect (except for mackerel) to capture the non-linear trend in landings that is likely mostly due to changes in fishing effort (see below). As this approach did not remove all autocorrelation, landings at $t-1$ were also added as explanatory variable (note that different intervals were tried, but a 1 year delay proved to be optimal). This removed residual autocorrelation successfully from each model. Environmental explanatory variables were included as linear effects. Model selection was based on AIC (Aikake Information Criterion). When models were within two AIC units of the lowest AIC value, the most parsimonious one was selected (Arnold, 2010). We repeated each model for two types of time series, i.e. including (1865–1993) or excluding (1865–2013) Marseille. Similarly, data for the Rhône was only available from 1920 onwards. Hence, the models were run first including this factor, but for a shorter period. Only when river flow was shown insignificant were the models run for the complete period. The WWII period was deleted from all the time series. The correlation between all environmental variables (Supplementary Table S1) was, although sometimes significant ($p < 0.05$), never strong ($r < 0.45$). For most variables, this linear relationship has already been discussed, though for a shorter time series (Martín *et al.*, 2012). The mgcv R package (Wood, 2014) was used, and a gamma distribution with log link was selected, as the estimates of this model performed best.

Results

Landings description

Over the investigated period, sardine was the most important of the three small pelagic species in terms of landings, followed in order by anchovy and mackerel (Figure 2). Maximal reported landings in the total region were 22 090 t for sardine (1970), 9593 t for anchovy (1988), and 1693 t for mackerel (2007). Over the studied period (1865–2013), sardine was the most landed species in every subregion. The relative importance of anchovy and mackerel depended on the subregion and the period, except from the late 1980s onwards, when anchovy landings usually exceeded those of mackerel in every subregion.

Generally, sardine and anchovy landings increased sharply in the early 1960s, but strongly declined during the most recent years, eventually reaching a level similar as 60 years earlier. This pattern however differed for the grouped subregion (Nice, Toulon and Martigues, NI/TL/MT), for which a sharp rise only took place around 1986, following a more gradual intensification. Also, the timing of the last main decrease in landings was irregular as this already occurred earlier for eastern subregions (Marseille and NI/TL/MT). For anchovy, the 1960s increase in landings was not as abrupt as for sardine. The most prominent rise in the anchovy time series actually took place around 1987. Furthermore, when compared with the earliest years (1865–1914), total anchovy landings were relatively low between the First World War and the 1960s rise.

We also noticed that anchovy landings fluctuated on average more heavily than sardine and mackerel landings (PV_{anchovy} between 0.67–0.75, PV_{sardine} between 0.52–0.68, and PV_{mackerel} between 0.51–0.64 depending on the subregions). Species landings in NI/TL/MT were usually the most stable (except for anchovy, $PV_{\mathrm{NI/TL/MT}}$ for sardine, anchovy and mackerel, respectively, 0.52, 0.67 and 0.51), followed by the subregion of Marseille (also except for anchovy, $PV_{\mathrm{Marseille}}$, respectively, 0.55, 0.74 and 0.54) then by

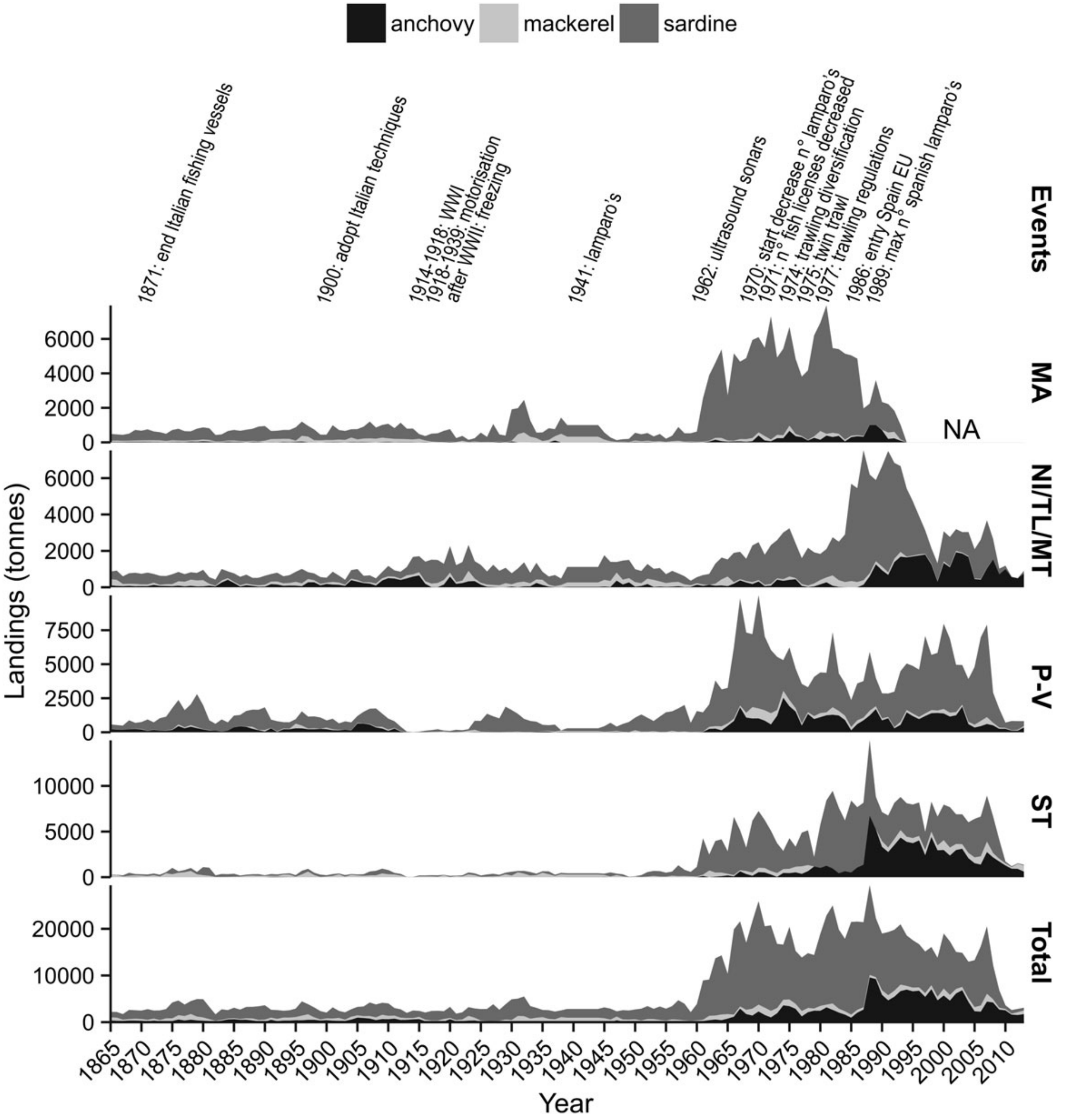

Figure 2. Landings of anchovy, mackerel, and sardine per subregion. No data were available for the Second World War (1939 – 1944) and from 1994 onwards for Marseille. The total series (including Marseille) thus underestimates landings slightly during this period (see text). The upper facet indicates several events that impact fisheries effort. The dotted vertical line indicates 1960, the moment around which an effort increase occurred.

Port-Vendres and Sète ($PV_{\text{Port-Vendres}}$, respectively, 0.60, 0.75 and 0.65; $PV_{\text{Sète}}$, respectively, 0.69, 0.72 and 0.61). For these two last subregions, landings in Port-Vendres were always fluctuating most, except for sardine, for which landings were more variable in Sète.

Patterns, periodicity, and breakpoints

Environmental factors and landings fluctuated differently in terms of pattern and periodicity (Figure 3). Log-transformed total landings (without Marseille) showed a clear long-term pattern. Sardine was characterized by the 1960s increase and smaller heights around the beginning of the time series and between the two World Wars. This trend explained 90% of the variance of the series. Anchovy landings were intermediate before 1914, low between the wars and elevated after them (explained variance by the trend: 87%, Figure 3). Mackerel showed an uneven gradual increase, but this trend is not as important as for sardine and anchovy (explained variance: 61%). The landings also showed a generally red-shifted spectrum (i.e. a spectrum dominated by periods

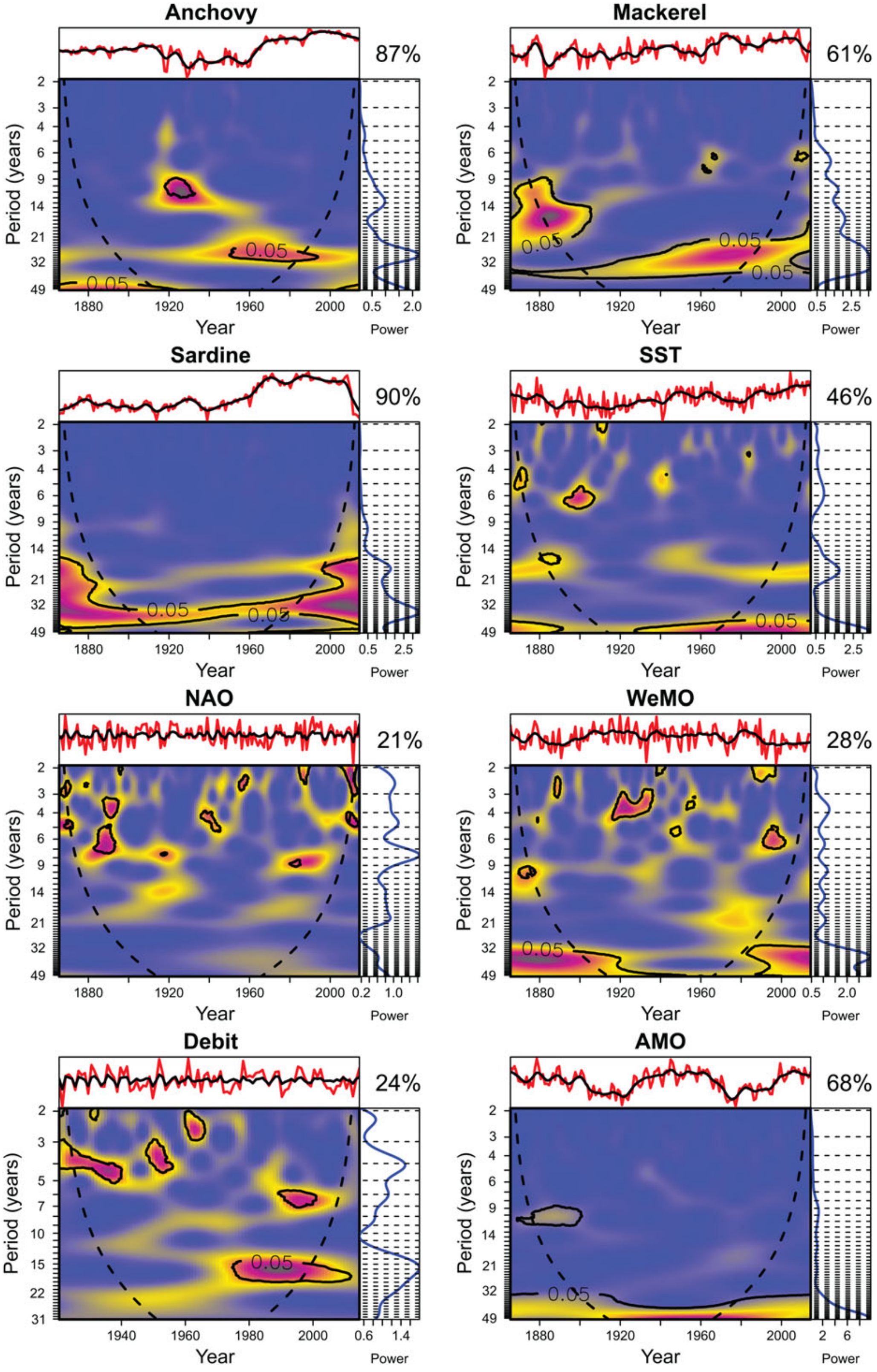

Figure 3. Wavelet and EVF analyses for each of the normalized landings and environmental time series. The main panels are the wavelet power spectrum. Power values range from blue (low) to grey (high). The black striped line forming a cone delimits the region not influenced by edge effects. Continuous black lines show 5% significant areas. The top panel represents the standardized data time series (in red) as well as the EVF analysis of this series (in black). The right panel is the global spectrum. The percentage on the top right represents the percentage of deviance explained by the EVF. All series begin in 1865, except for the Rhône river runoff, that starts in 1920.

> 10 years). Periodicities were however still moderately different for the three species. Sardine only had low-frequency oscillations (~35 years) during the whole period. Mackerel had before 1910 intermediate frequency oscillations (~16 years) and during the complete period also low-frequency oscillations (~32 years). Anchovy had significant patterns around 11 years (during the 1920s) and 30 years (±1945–2000). This corresponds to the *PV* values per species, as one could expect a higher *PV* when high frequencies are relatively more important.

SST and AMO showed a clear pseudo-cyclic long-term trend together with year-to-year fluctuations (Figure 3). SST displayed three periods of higher values (around 1860s, 1950s, and 2000s) and two periods of lower values (around the 1910–1920s and the 1970s). The AMO had maximal values around 1884, 1948, and 2008 and minimal ones around 1915 and 1980 (i.e. quite similar to those of the SST). Both series had significant low-frequency patterns (period > 40 years) and the trends explained 46 and 68% of the variance of the SST and AMO time series, respectively. Additionally, SST had also had some high power values at higher frequencies (Figure 3). Consequently, no common pattern emerged with the landing time series.

The Rhône debit and the NAO and WeMO indices mostly displayed year-to-year fluctuations without any clear trend, although the WeMO index decreased slightly during the most recent years (Figure 3). Therefore, the percentage of variance explained by the EVF-trend was rather low for each of these three time series (respectively, 24, 21, and 28%). All three series were characterized by mainly high-to-intermediate frequencies (periods up to 10 years for NAO and up to ~20 for the Rhône debit). Only the WeMO had also high power values for low frequencies during certain periods, which mainly fell out of the cone marking the influence of the edge effect. A 40 years oscillation pattern around 1910 and 1980 was also observed in sardine, but despite this small similarity, these three series also differ from the landings' ones in both the frequency (wavelet) and the time (EVF) domain (Figure 3).

For each of the 12 landings series, the breakpoint analyses detected several discontinuities (Figure 4, top). A breakpoint was identified for most of the series (8 of 12) around 1962 because of the steep increase in the landings (except for all species in the subregion of NI/TL/MT and in Marseille for mackerel). Two periods around which breakpoints were also common (although to a lesser extent) were near the beginning of the First World War (5/12) and 1985–1992 (5/12), caused by upsurges in Sète and NI/TL/MT. Also, breakpoints appeared to be more similar between subregions than between species. Breakpoints were not always detected for each environmental time series (Figure 4, bottom). The NAO index and the Rhône debit did not display any discontinuity, while the WeMO index showed only one breakpoint (1988). Although the AMO index and SST displayed several breakpoints, it is interesting that most breakpoints from environmental series had a large uncertainty and did not clearly co-occur with most breakpoints of landings series. In general, the breakpoint analysis was quite consistent with the EVF: time series displaying significant long-term fluctuations also displayed several breakpoints, while time series without long-term fluctuations had no or little breakpoints.

Relationship with the environment

As EVF and wavelet analyses showed that long-term trends as well as periodicity were different between landings and environmental series, we included a smoother on the year effect in the GAM models (except for mackerel) to account for the long-term trend that should be related to another external factor (probably to fishing effort, as indicated by the co-occurrence of the breakpoints in the early 1960s in the landings series and expert knowledge, see also Discussion). The outputs of the GAM analyses with (1865–1993) or without (1865–2013) Marseille were always highly similar and led to the same conclusion (Table 1; Supplementary Table S2). Finally, the Rhône river run-off (1920–2013) was never significant (Supplementary Table S2), so the model could be run on the complete datasets. Residuals were always normally distributed and no outliers were present when plotting the predicted vs. the residuals or fitted values (Supplementary Figure S2). The deviance explained (respectively, for models with and without Marseille) was highest for sardine (93.3 and 88.8%), followed by anchovy (79.6 and 79.0%) and mackerel (43.1 and 46.2%). This was mainly due to the high deviance explained by the smoothed predictor (year), which was, in general, very similar as the trends extracted by the EVF analyses (Supplementary Figure S3). Therefore, the actual environmental factors (i.e. leaving out this year effect and the landings at $t-1$) explained, respectively, only 5.80 and 1.60% of the deviance for sardine, and 12.2 and 2.4% for anchovy. For sardine, the AMO was the only significant (positively related) environmental variable ($p < 0.05$). Anchovy landings were significantly and positively influenced by the WeMO index and the AMO exerted a negative effect. Mackerel on the other hand did not show any significant relationship with an environmental factor.

Because of the important changes around 1960, the GAMs were also run for the previously identified periods of low and high landings (1865–1960 and 1963–2013). For sardine, no environmental variables were significant for either of the periods, whereas for anchovy only the AMO or WeMO was significant, in respectively, the pre- and post-60s. As the use of these shorter time series thus resulted mainly in a loss of information, results are not presented here in more detail (Supplementary Table S3).

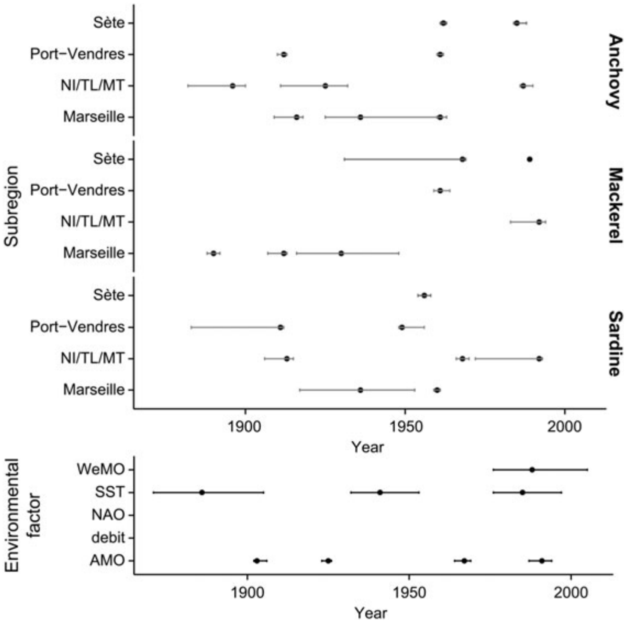

Figure 4. Breakpoint analyses of the 12 landings series (per subregion and per species, top) and the 5 environmental factors (bottom). Horizontal lines indicate the confidence interval around the detected breakpoint.

Table 1. Results of the GAM models, per species, and for two series (with and without Marseille).

	With Marseille				**Without Marseille**			
	Estimate	**s.e.**	***t***	***p***	**Estimate**	**s.e.**	***t*-value**	***p***
Sardine								
Intercept	7.98	7.09×10^{-2}	112.45	***	7.56	7.31×10^{-2}	103.44	***
AMO	0.13	5.28×10^{-2}	2.46	*	0.14	6.35×10^{-2}	2.19	*
$\text{Sard}_{(t-1)}$	4.74×10^{-5}	1.19×10^{-5}	3.98	***	1.02×10^{-4}	1.45×10^{-5}	7.05	***
	edf	λ	*F*	*P*	edf	λ	*F*	*p*
s (year)	8.23	8.84	8.84	***	8.23	8.84	8.84	***
Anchovy								
Intercept	5.79	1.05×10^{-1}	56.02	***	5.97	1.14×10^{-1}	56.017	***
WeMO	7.77×10^{-2}	3.06×10^{-2}	2.54	*	6.21×10^{-2}	3.04×10^{-2}	2.54	*
AMO	-4.24×10^{-1}	1.24×10^{-1}	-3.41	***	-3.60×10^{-1}	1.22×10^{-1}	-3.41	***
$\text{Anch}_{(t-1)}$	2.25×10^{-4}	7.23×10^{-5}	3.11	**	2.35×10^{-4}	6.37×10^{-5}	3.11	**
	edf	λ	*F*	*p*	edf	λ	*F*	*p*
s (year)	6.09	7.28	13.49	***	6.35	7.52	14.57	***
Mackerel								
Intercept	5.55	2.09	0.27	***	-0.77	1.89×10^{-2}	-0.41	***
$\text{Mack}_{(t-1)}$	8.69×10^{-4}	1.21×10^{-4}	7.19	***	9.44×10^{-4}	1.30×10^{-4}	7.28	***
Year	2.75×10^{-3}	1.10×10^{-3}	2.50	*	3.35×10^{-3}	9.96×10^{-4}	3.37	***

For every retained linear term, the estimate (mean) is given with its standard error (s.e.) and the corresponding *t*- and *p*-value. For the smoothed (s) year effect, the effective degrees of freedom (edf), the estimated smoothing parameter (λ), the *F*-statistic, and the *p*-value are shown. *p*-values were categorized into high ($p < 0.001$,***), intermediate ($0.01 < p < 0.001$,**) or low significance ($0.05 < p < 0.01$,*).

Discussion

In this study, we investigated the characteristics and potential causes of fluctuations in the landings of sardine, anchovy, and mackerel from the French part of the Mediterranean Sea. Therefore, we compiled several exceptionally long time series. Such series are hard to obtain, as long-term data are often inexistent or (partially) lost, fragmented, hardly accessible, geographically scattered, not digitized, etc. Here, we managed to obtain 12 extended time series, allowing us not only to consider a multispecies fishery but also to account in part for its geographical aspect. Such data are extremely rare for most species in the Mediterranean (except for bluefin tuna, Ravier and Fromentin, 2001), and especially pelagics, as for example a single long-term series for sardine was only known from the Adriatic (Grbec *et al.*, 2002). Even globally, long-term information on small pelagic landings is uncommon for the fisheries that have a long history, the longest being from Japan, California, and the Canary Current, starting between around 1890 and 1915 (Lluch-Belda *et al.*, 1989; Schwartzlose *et al.*, 1999).

However, when considering the results, one should keep in mind the usual issues of under- and misreporting, black landings, discards, etc., which might be associated with any landing data. Unfortunately, when reading through the historical literature, no information on these was found. However, concerning the issue of discards, we might think that they remained at all times reasonably limited for sardine, as this species was always of commercial. Also, management is and was relatively weak, so that species were not discarded because of quota or a minimum landing size (which exists, but is small). However, we know that during the last years when a mixture of anchovy and sprat was caught, fishers often threw back their catch instead of separating it. This might perhaps also have happened in the past (especially before the entry of Spain to the European Union), when anchovy was less targeted. Finally, the absence of quota and the small minimum landing size might have also limited the under- and misreportings.

In this study, the two most striking events were the rapid and considerable (i.e. at least five-fold) increase in the landings of sardine and anchovy around 1962 and their recently observed decrease. During 2010–2013, sardine landings became historically low, i.e. recent landings became even lower than during the investigated period before the 1960s. Even during the 1800s, at least twice as much sardine was fished. This stresses the exceptionality of the current situation. Present anchovy landings still remain at rather high levels, but landings were extremely low before the 1960s, in contrast to sardine. Mackerel landings did not show as prominent fluctuations as sardine and anchovy (beside a relatively small increase around the 1960s). This might be because mackerel is less targeted.

Generally, landings of sardine and anchovy elsewhere in the Mediterranean have not shown similar fluctuations since 1950 (Supplementary Figure S4). However, in most locations landings of small pelagics generally increase in the 1960s or 1970s. For example, in the Eastern Adriatic landings started rising around 1960 too, also claimed to be caused by the installation of echosounders (Grbec *et al.*, 2002). However, these increases appear usually to be more gradual (Supplementary Figure S4). Particularly, the concurrent addition of multiple Algerian vessels triggered by the Algerian independence is likely to have caused a steeper increase in the French landings.

Often, catch or landings per unit of effort are used as a proxy for abundance. In this study, no proper long-term information was available on the effort directed to each of the considered species, as the best information available was the total number and capacity of boats per subregion (which included for example boats directed to the collection of mussels and oysters, as well as those used to fish benthic and demersal species). Furthermore, quantifying fishing effort with the number or capacity of fishing boats can be misleading, especially over long periods of time, as there is little in common between a small wooden boat using nets or lines from the beginning of the 20th century and modern pelagic trawlers or lamparos from the 1980s. Also, information on market demand should be available to better assess changes in the targets of the fisheries. Because of the clear impossibility to consider stock status over time, we aimed instead at characterizing the landing fluctuations of sardine, anchovy, and mackerel. Analyses were carefully selected so that they were complementary and underpinned the use of a GAM to relate landings directly to the environment. Specifically, we used a smoother on the year effect because the breakpoint and the wavelet analyses, as well as the general qualitatively known trends in effort in the area (see upper panel Figure 2 and introduction) clearly indicated that the major change in the time series during the 1960s (which explains the bulk of the long-term trend) was probably due to major changes in fishing effort. Doing so, we indirectly took into consideration major changes in fishing effort in the GAM analysis.

Although it is very likely that the major changes in the landings time series (which translate mostly into long-term trends) were due to major shifts in fishing effort, changes in fishing effort do not always result in a visible change in catch. This was the case for, e.g. the adoption of more developed Italian fishing techniques, motorization and freezing, that did not translate in higher landings even some years after they were implemented. Further, not all major variations in landings could be explained by changes in effort or market demand. Hence, these fluctuations might be related to a changed availability of the species (resulting from a higher biomass, potentially partially produced by immigration, or capturability caused by, e.g. more nearshore located or denser schools). In particular, variations in landings can also be environmentally driven (Cushing, 1995). From all the environmental factors considered, the AMO appeared to be the most important, for both anchovy and sardine (but with opposite effects). In some cases, its positive phase is known to be associated with a population increase (reviewed by Nye *et al.*, 2014), through intensified recruitment and growth resulting from an increased temperature. This hypothesis would fit the positive effect of the AMO on sardine landings that we found in this study. However, other mechanisms might be important for anchovy landings in the NW Mediterranean, that are negatively related to the AMO (as was already noted by Alheit *et al.*, 2014 and by Friedland *et al.*, 2014 for other species elsewhere). For our study, one possible explanation could be based on different trophic niches. Anchovy generally feed on larger zooplankton than do sardine. The AMO, having the capacity to indirectly affect plankton communities (Edwards *et al.*, 2013; Harris *et al.*, 2014) can thereby alternatively favour sardine or anchovy. A positive AMO phase can have a negative effect on large copepods (Harris *et al.*, 2014), resulting in an equally negative effect on anchovy. Also, anchovy was positively related to the WeMO index, which supports Martín (2012) who postulated that the regional WeMO index can provide a more accurate representation of the environmental conditions affecting anchovy biomass in the NW Mediterranean than the NAO.

Additionally, the effects of river discharge, the NAO and SST on sardine and anchovy landings might have been too small to be detected or work at different time scales. For example, a relationship between small pelagic population size (LPUE or cpue) and the Rhône outflow was already established twice for the NW Mediterranean (Lloret *et al.*, 2001; Martín *et al.*, 2008). However, these studies used relatively shorter time series and more important, monthly data. When for example both landings and an environmental factor have a strong seasonal cycle, a relationship between them could be unambiguous, but might be undetectable yearly. Furthermore, the functional response of the populations to the environment might change over time (Schmidt *et al.*, 2014), so that looking at small and long time series might produce different results.

Overfishing was so far not considered to be the chief driver of the recent changes (GFCM, 2014). This idea was mainly based on the magnitude and timing of maximal exploitation levels, as well as the nature of the observed changes (Van Beveren *et al.*, 2014). However, these two components were only considered for the last two decades. Our analyses clearly show that the bulk of the variance in landings time series is due to long-term trends that are very likely related to abrupt changes in fishing effort in the early 1960s. Therefore, fishing-induced mortality on small pelagic fish in the Gulf of Lions had to increase greatly since the 1960s, its effect perhaps echoing in what we observe today. But although the presence of it is undeniable, the resulting effect should be put into perspective. Specifically, the biomass peaks of sardine and anchovy in the ecosystem during some of the most recent years, estimated from scientific acoustic surveys (sardine 2004 and 2005: respectively, 216×10^3 and 264×10^3 t; anchovy 2001: 112×10^3 t; GFCM, 2014), attained levels around 10 times higher than the earlier historical peak of landings (sardine: 22×10^3 t, anchovy: 10×10^3 t). When considering the period 1993–2014 (PELMED), on average annual July biomass of both species was still four times higher than their respective historical landing peaks. Even if some uncertainty is present on the landings and estimated biomass values (both potentially rather underestimated, see, e.g. Brehmer *et al.*, 2006), this shows that both populations can still attain considerable biomasses in regard to the preceding fishing pressure. Therefore, this study does not contradict the previously stated idea that overfishing alone is an improbable cause of the recent changes (GFCM, 2014; Van Beveren *et al.*, 2014).

To conclude, the compilation and investigation of historical landings of sardine, anchovy, and mackerel in the French part of the Mediterranean Sea (1) shed light on environmental landing drivers, although not being conclusive about the causes of the recent changes and (2) also place into perspective the history of the fisheries. This could both benefit to the understanding of the pelagic ecosystem and the management of the stocks. Specifically, the new extended time series will be included in future stock assessments as to (i) get a historical perspective of the catches and (ii) use it through the development of catch only methods. Significant environmental parameters might also be incorporated in a stock recruitment function.

Supplementary data

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

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