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Temperature and food-mediated variability of European Atlantic sardine recruitment

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ABSTRACT

The influence of the environmental conditions during larval development on the resulting recruitment strength was investigated for European sardine (*Sardina pilchardus*) at Atlanto-Iberian waters. Satellite-derived Sea Surface Temperature (SST) and Chlorophyll-*a* concentration (Chla) data from the previous spawning seasons (January to March/April and October to December of the previous year) were related to recruitment success data in the main recruitment hotspots. Recruitment data was taken from yearly acoustic scientific cruises and from the ICES recruitment index estimated by an age-structured model for the entire stock. A linear discriminant analysis model using SST, Chla, and the abundance of spawners during the spawning season identified years of high and low recruitment for all the recruitment hotspots with an accuracy of ≥79%. In general, high recruitment years were associated with high Chla and low SST, although the most important variables to discriminate between the groups were area-specific. High recruitment years were mostly related to high food availability (Chla), particularly during the last quarter of the previous year. In Western Iberia and in the Gulf of Cadiz, high recruitment years were also associated to lower SST, whereas in the Bay of Biscay, where SST during the winter was generally below the optimal range ≈11–12 °C for sardine larval development, higher recruitment was associated with high SST. For ICES data of the southern European sardine stock, lower SST and higher Chla during the last quarter of the previous year were associated with high recruitment years and SST alone was able to discriminate between the two recruitment groups with 73% accuracy. Although the time-series of available data are still small, these significant relationships are consistent with field and laboratory studies relating larval growth and mortality with main environmental drivers. These relationships should be further investigated in the following years to evaluate if they can be used to construct reliable indicators to predict the level of recruitment and abundance with sufficient advance to help in the management of this important fishing resource.

1. Introduction

Small pelagic fish are key species in the most productive regions of the world's oceans, particularly in upwelling regions, where they occupy a fundamental intermediate trophic level (Bakun, 2006). The dominant pelagic fish in the Western Iberian Upwelling Ecosystem is the European sardine (*Sardina pilchardus*; hereafter called sardine). This species is distributed from the North Sea to Mauritania (Culley, 1971), off the Madeira, Azores and Canary Archipelagos and in the Mediterranean and adjacent waters (Andreu, 1969; Suau, 1959). Sardine fishery in the northern areas to the Iberian stock (from the Bay of Biscay up to the North Sea), are currently unregulated (regulation is currently limited to Portugal and Spain). However, there is an increasing fishery being developed in the northern areas (> 35% increase in the last decade compared to the 90′s, ICES, 2015) where sardine population dynamics is still poorly studied. Off the Iberian Peninsula, sardines are the most landed fish, representing approximately 40% of the total capture (DGRM, 2016). The Atlanto-Iberian sardine stock has been declining since 2006, and sardine abundance is now at an historical minimum, with severe socio-economic consequences for Portuguese and Spanish fishing communities. Although fishing mortality estimates were particularly high in some of the recent years, environmental

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parameters are hypothesized as the main causes for the decline of sardine abundance (ICES, 2015).

Fish recruitment strength is considered to be strongly related to environment conditions (Houde, 2008). The impact of environmental conditions is particularly important for short lived small pelagics, whose stocks can potentially recover with one year of good recruitment or collapse with a short series of low recruitment years (Katara, 2014). In these situations, the recovery of the stock is highly dependent on a high pulse of recruitment. Since the work by Hjort (1914) it is recognized that the mortality occurring during the early life stages is particularly relevant in shaping the strength of the recruitment. Larval survival is affected by both abiotic and biotic factors; temperature and hydrography, predation and food availability, respectively, being considered the most relevant ones (Houde, 2008). Temperature and food availability are known to affect both year-to-year fluctuations and long-term trends in fish populations (e.g. Loeng, 1989). Water temperature affects the rate of metabolic processes and therefore shapes the distribution and abundance of poikilothermic organisms such as sardines (e.g. Blaxter, 1991). The recent expansion of sardine distribution further north, to the North and Baltic Seas, after 40 years of absence in those areas (Alheit et al., 2012), can be associated with increased water temperature registered for the north Atlantic (e.g. Levitus et al., 2005). At the Iberian Peninsula, higher temperatures have been associated to lower landings (Solari et al., 2010; Santos et al., 2012; Leitão et al., 2014; Gamito et al., 2015; Teixeira et al., 2016; Malta et al., 2016), although no clear mechanism by which temperature negatively affects recruitment has been identified yet.

Temperature influences the seasonality of sardine reproduction (Stratoudakis et al., 2007) and the subsequent survival of the developing larvae (Garrido et al., 2016). These two biological processes can significantly affect the inter-annual strength of sardine recruitment, as shown for other fish species, including clupeoids (Ottersen et al., 2013). Increased temperature is likely to have an impact on the timing and density of plankton blooms, and by that indirectly affect the recruitment. Interannual and geographic variations of plankton productivity can affect the reproductive potential of the indeterminate serial spawning sardines (Zwolinski et al., 2001; Garrido et al., 2007) but food concentration can also have a massive impact in larvae survival (Caldeira et al., 2014). Massive stocks of pelagic fishes are only possible in the most productive regions of the world oceans, such as the Eastern Boundary Upwelling Ecosystems (Fréon et al., 2009), supporting the notion that food availability plays a critical role in their dynamics.

Recent laboratory experiments have shown that the optimal temperature for larval sardine development varies between 13 and 17 °C and that survival outside these boundaries is reduced, particularly during the first weeks of life (Garrido et al., 2016). These results were in accordance with a previous analysis of field samples, showing that sardine spawning activity is linked to SST, with an optimum at 14–15 °C and avoidance below 12 °C and above 16 °C (Stratoudakis et al., 2007). During the protracted spawning season off Iberian waters, sardines might experience temperatures that are higher than tolerable during the first months of reproduction (autumn), and experience temperatures lower than optimal during the last months of the spawning season (winter and spring), which can have important consequences for larval survival. On the other hand, recent laboratory experiments have also shown that sardine larvae depend of large food concentrations to be able to survive (Caldeira et al., 2014) and only from ≈ 20 days-post-hatching are able to swim effectively and maximize foraging efficiency (Silva et al., 2014). Therefore low larval survival linked with sub-optimal temperature and low food availability may result in low recruitment strength.

Previous works have studied the relationships between environmental factors and sardine abundance/recruitment/catches in the Atlanto-Iberian ecosystem (e.g. Borges et al., 2003; Solari et al., 2010; Santos et al., 2012; Leitão et al., 2014; Gamito et al., 2015; Teixeira et al., 2016). Most of these studies focus on the effect of environmental factors causing the transport of eggs and larvae offshore (e.g. upwelling index) on the survival of early life stages of sardine, while other direct effects, such as the effect of food availability and water temperature on larval growth and condition received less attention (Solari et al., 2010). The great majority of these studies used data of landings to compare with environmental data and analyse pooled data of the entire Atlanto-Iberian region, finding significant relationships of total sardine landings with several environmental factors, mainly SST followed by wind strength and NAO. Few studies have addressed the regional variability of environmental factors. Leitão et al. (2014) analysed the relationship between landings and environmental variables separately according to different sub-stocks, corresponding to ICES sub-divisions, identifying different environmental drivers of sardine landings according to the regions, and showing that the study of the effect of environmental drivers on sardine populations should be area-specific. In fact, *Sardina pilchardus* like other small pelagic fish species, has a large distribution, inhabiting permanent and seasonal upwelling regions, gulfs, bays and coastal waters surrounding islands. The predominant environmental factors of larval survival (e.g. prey availability and water temperature) differ significantly throughout the vast latitudinal range of the distribution of the species. Therefore, relationships between the inter-annual variability of environmental drivers and recruitment strength is likely to be area-specific. Within each area, sardines have recruitment hotspots which are defined as the main spawning grounds where environmental conditions are important for the survival of larvae, and thus contributing to the success of recruitment (Checkley et al., 2009; ICES, 2015). The aim of this study is to evaluate if temperature and food availability at the time of sardine larvae development can be used as proxies to estimate the subsequent recruitment strength at the main recruitment hotspots off Atlanto-Iberian waters (Northwestern Iberian coast, Gulf of Cadiz, and Bay of Biscay, Silva et al., 2009). Ultimately, the goal is to predict sardine recruitment with sufficient advance to help in the management of the Atlanto-Iberian stocks, using satellite-derived SST and Chla.

2. Materials and methods

2.1. Study area

The relation between environmental data and sardine recruitment was investigated for the areas that are considered to be recruitment "hotspots" for sardine in the Iberian-Biscay region, particularly the northwestern Iberia, the Gulf of Cadiz and the Bay of Biscay (Checkley et al., 2009; ICES, 2015, Fig. 1). The western Iberia area is influenced by freshwater outflow (e.g. Douro and Minho rivers) and has a summer seasonal upwelling regime while the Bay of Biscay and Gulf of Cadiz are sheltered areas which also have an important input of freshwater from rivers (e.g., Adour and Girond, and Guadalquivir respectively) and are not propitious for upwelling (Aristegui et al., 2009).

2.2. Recruitment index and abundance of sardine

Sardine recruitment data were derived from spring acoustic cruises carried out annually by IPMA (Portuguese Institute for the Ocean and the Atmosphere) off the Western Portuguese coast from 1986 to 2014 with gaps in 1987, between 1989 and 1994, 1996, 2004 and 2012 (ICES, 2015). As of 1996 the area covered was extended southward to the Gulf of Cadiz and from 2000 in the Bay of Biscay (by IFREMER, L'Institut Français de Recherche pour l' Exploitation de la Mer, cruises). The acoustic surveys are carried out along predefined parallel transects, perpendicular to bathymetry from 20 to 200 m depth with 8 nautical miles (nm) inter-transect distance. Surveying was limited to daylight and echo-integration was performed from 20 cm above the seabed (prior, echogram bottom was manually corrected) to 3 m below the transducer, along 1 nm elementary distance sampling units (ESDU). Fish samples were collected with pelagic and bottom trawls. Trawl