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Commercial catch rates of the clam *Spisula solida* reflect local environmental coastal conditions

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A B S T R A C T

The effect of environmental variables and fishing pressure (explanatory variables were lagged 1 year) on commercial catch rates of the clam *Spisula solida* was studied on an annual basis over a 21 year period in three areas off the Portuguese coast (the Northwest, the Southwest and the South) between 1989 and 2009. Each area showed distinct environmental (oceanographic and hydrological) characteristics. Different sensitivities of *S. solida* fishing grounds to environmental variables were found among the study areas. On the Northwest coast, the combined effect of NAO indices and sea surface temperature had a positive effect on *S. solida* fisheries, particularly during the spawning season. On the Southwest coast, the variation of *S. solida* catches was negatively associated with wind magnitude and positively related with South–Southeast winds. Winter river discharges and summer sea surface temperature negatively affected *S. solida* catches on the South coast. Fishing effort also affected *S. solida* catch rates in the South. However, "extreme" changes in environmental conditions were the main drivers of short-term variations in catch rates. These results indicate that variations of *S. solida* catches strongly reflect a regional signature of local climatic features off the coast. Information on local environmental conditions should therefore be used for the purpose of identifying management actions to ensure long-term sustainability of *S. solida* fisheries.

1. Introduction

It is now widely recognized that climate change has a considerable impact on the dynamics of marine ecosystems around the world (Bertram et al., 2001), namely on the survival, growth, reproduction, distribution (Brander, 2007), morphology, physiology and behavior (Harley et al., 2006) of marine species. It also impacts on population structures at community and ecosystem levels (Brander, 2007, 2010; Lehodey et al., 2006; O'Reilly et al., 2003; Perry et al., 2010; Pörtner and Knust, 2007). The consequences of climate change on marine food webs and commercial fisheries are of particular concern (Brander, 2007, 2010; Coyle et al., 2011). Temperature, salinity, wind, tidal currents and oceanic circulation, rainfall, river run-off and nutrients all affect productivity, abundance and distribution of fishing stocks (Barange, 2002; Brander, 2007, 2010; Drinkwater and Frank, 1994; Dulvy et al., 2008; Lehodey et al., 2006; Perry et al., 2005). Most of the evidence of climate change impacts on commercial fisheries derives from fishery catch data (for example, Allison et al., 2009; Brander, 2007, 2010; Erzini, 2005; Erzini et al., 2005; Klyashotorin, 1998; Lehodey et al., 2006; Lloret et al., 2001; Planque and Frédou, 1999). However, there is very little evidence on the extent to which these changes affect marine invertebrates, particularly bivalve molluscs (Baptista et al., in press; Fernández-Reiriz et al., 2011, 2012).

Bivalves inhabit littoral and sublittoral areas and are therefore very sensitive to alterations in climate (Helmuth et al., 2006; Somero, 2002). Bivalves are easy to sample and monitor because they constitute a large fraction of benthic communities in these littoral areas (Rufino et al., 2010). Consequently, bivalves are extensively used as bioindicators of marine ecosystem changes (Carroll et al., 2009; Grémare et al., 1998; Simboura and Zenetos, 2002). Many bivalve species in shallow temperate coastal waters have short life cycles and this permits studying short-term variations in the environment where they grow and reproduce (Zeichen et al., 2002).

The harvesting of bivalves for human consumption is socially and economically important to many local communities (Gaspar et al., 2005a; Leitão, 2003; Leitão and Gaspar, 2007; Rufino et al., 2010). In Portugal, commercial harvesting of bivalves is a century-old activity, comprises an important element of the contemporary artisanal fishery sector (Gaspar et al., 1999, 2001, 2005b) dating from 1969 (Chícharo et al., 2002; Gaspar et al., 1999). Harvestable stocks have always been subject to large and often unpredictable natural fluctuations (Gaspar, 1996; Joaquim et al., 2008a). In 2009, landings peaked to 2600 tons with an average commercial value of 2 euros kg^{-1}. In bivalve fisheries only mechanical dredges are allowed (Gaspar et al., 2003b). The dredges consist of a rigid iron frame ("dredge mouth") with a toothed bar that digs clams out of the sediment attached to a mesh bag or metallic grid

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where the catch is retained (Gaspar et al., 2003b). Although several bivalve species are commercially harvested along the Portuguese coast, such as wedge clam *Donax trunculus*, stripped venus clam *Chamelea gallina*, smooth clam *Callista chione* and razor clam *Ensis siliqua* (Leitão et al., 2009), only the solid surf clam *Spisula solida* is harvested from fishing grounds along the whole of the Portuguese continental shelf (Gaspar et al., 2003b). Historically, assessments of fishery data and biological information relating to *S. solida* compiled by the Instituto de Investigação das Pescas e do Mar — IPIMAR (National Fisheries Institute) have considered different *S. solida* fishing grounds as distinct management units. Measures to manage these stocks currently include fishing licenses, closed seasons to protect spawning individuals, daily quotas, minimum landing size (25 mm) and minimum mesh size (Chícharo et al., 2002; Gaspar et al., 1999, 2002; Joaquim et al., 2008a; Leitão et al., 2009). The dredges used to harvest *S. solida* are highly selective and have high capture efficiency (Gaspar, 1996; Gaspar et al., 1999). Stock assessment surveys have shown that inter-annual population sizes are variable, irrespective of the region (Gaspar, 1996; Joaquim et al., 2008a). Such variations are related to both external (*e.g.* environmental influences on larval life history) and internal (*e.g.* density-dependent) controls of exploited populations that act during recruitment (Planque et al., 2010).

Ideally, fisheries management measures should be based on findings from long-term biological data from several stocks within a given geographical area. Many exploited bivalve populations display different responses to environmental change because abiotic factors exert different biological and ecological impacts on species and ecosystems in different regions (Planque and Frédou, 1999). This is the case of the Portuguese coast which is influenced by climatic phenomena from both the North Atlantic Ocean and the Mediterranean Sea (Cunha, 2001). This study evaluates the effect of environmental variability and fisheries on commercial catch rates on each management unit of *S. solida* from three distinct areas along the Portuguese coast.

2. Methods

2.1. Study sites

Three areas of the Portuguese coast representing the range of biogeographical and climatic influences were selected for this study: the Northwest and the Southwest coasts, which represent subtropical eastern boundaries of the North Atlantic Ocean (Santos et al., 2001) and the Southern region which has transitional characteristics of the Atlantic Ocean and the more saline and warm waters of the Mediterranean Sea (Cunha, 2001; Rufino et al., 2010) and typical Mediterranean climate. Fig. 1 shows the location of the three fishing grounds of the surf clam *S. solida* within these three biogeographical areas (Gaspar et al., 2003b), different oceanographic conditions (Bettencourt et al., 2004; Cunha, 2001) and different ecological communities and species assemblages (Sousa et al., 2005). The fleet that targets this species are based at the following ports (Fig. 1): (i) the Northwest, includes Matosinhos and Aveiro fishing ports; (ii) the Southwest comprises Cascais, Trafaria, Setúbal and Sines fishing ports; and (iii) the South, comprises ports across the Algarve region, namely Quarteira, Faro, Olhão, Tavira and Vila Real de Santo António. In the Algarve, *S. solida* inhabits extensive areas of clean sandy bottoms (Gaspar, 1996; Gaspar et al., 2002; Leitão et al., 2009) and displays distinct distribution patterns with depth. In the Northwest region, clams are caught between 5 and 34 m depth (Gaspar et al., 2005b); in the Southwest, the densest areas are distributed between 3 and 25 m depth (Gaspar et al., 2003a) and in the Southern region this species inhabits sandy bottoms between 3 and 14 m depth (Dolbeth et al., 2006; Gaspar et al., 1995, 1999, 2003a, 2005b). Using the information on the distribution of clam beds and fishing ports, coastal bathymetry and environmental conditions, the IPIMAR (Gaspar et al., 2003b) establishes management measures for the three management units: the Northwest, the Southwest and the South.

2.2. Data acquisition

Annual landings per unit effort (LPUE) were used as a proxy for bivalve biomass production (abundance index proxy). LPUE (response variable) were estimated by dividing the total annual landings by the total annual number of fishing days (LPUE units: kg per fishing day/event). Landing data for the period 1989–2009 were obtained from Direcção-Geral das Pescas e Aquacultura (DGPA). The database includes information on fishery practices such as species monthly effort (number of fishing days and/or fishing events) and monthly landings per boat per month. For the purposes of this study, fishing data were amalgamated into annual periods.

The NAO and NAO winter (December–March) indices were used as climatic explanatory variables (http://www.cgd.ucar.edu/jhurrell/nao.html, last accessed 2010; Hurrell, 1995). The NAO indices are the differences between sea level atmospheric pressure at the Azores and Iceland. These phenomena largely regulate rainfall, temperature and wind regimes over most of the Northwestern Europe (Witbaard et al., 2005).

The annual and seasonal mean sea surface temperature (SST), annual and seasonal upwelling index (UPW), and yearly and seasonal u- and v-wind components were used as oceanographic explanatory variables. The geostrophic winds from satellite data are broken into two horizontal components. The "u" component, which represents the east–west component of the wind and the "v" component, which represents the north–south component. SST data were obtained from imagery data obtained from Modis–Aqua 4km satellite available on the NASA Ocean Color Giovanni website, (http://gdata1.sci.gsfc.nasa.gov). The upwelling index was obtained from Pacific Fisheries and Environmental Laboratory website (www.pfeg.noaa.gov). Wind components (u- and v-) were obtained from PO.DAAC (http://podaac.jpl.nasa.gov/dataset/CCMP_MEASURES_ATLAS_L4_OW_L3_5A_MONTHLY_WIND_VECTORS_FLK?ids=&values=) (Atlas et al., 2011). Wind magnitude [WMag: SQRT($u^2 + v^2$)] and wind direction [WDir: degree Arc tangent^2 (u, v)] were modeled using u- and v-wind components. Due to the lack of satellite data (cloud effect) in some nearshore areas, the coastal oceanographic data considered the range of depths from Mean High Water Line to 200 m (Fig. 1). Therefore, SST, UPW, WMag and WDir data are averaged means of the geographical area.

The Northwest coast is characterized by highly energetic hydrodynamics (Abrantes et al., 2005) strongly influenced by freshwater plumes from the Douro River and the Vouga River. The Southwest region is influenced by the Tagus River and the Sado River. The Southern region is mainly influenced by freshwater discharge from the river Guadiana and minor inputs from three smaller river systems (Seco, Alportel and Almargem) discharging into the Ria Formosa lagoon. River discharge (RD) data were obtained from the Instituto dos Recursos Hidricos de Portugal webpage (http://snirh.pt/;accessed October 2011).

2.3. Data analysis

To investigate the relationship between environmental (explanatory) variables and LPUE, explanatory data were firstly amalgamated by year and season as follows: (1) winter (January to March); (2) spring (April to June); (3) summer (July to September); and (4) autumn (October to December).

Quantile–quantile plots (QQ-plots) were used to test the normality of datasets. The square root transformation was applied to LPUE southern region data to ensure more symmetrical distribution of the data. Pair plots were used to investigate collinearity between explanatory data.

Trend analyses of the effect of environmental and fishing variables on catch rates of *S. solida* were studied independently for each region by means of Dynamic Factor Analysis (DFA). This is a multivariate time-series analysis technique commonly used for non-stationary time series analysis to estimate underlying common patterns, evaluate interactions between response variables (LPUE) and determine the effects of explanatory variables (environmental and fishery variables)