UNIVERSIDADE DE LISBOA
FACULDADE DE CIÊNCIAS

Effects of climate change on fisheries – from a global to a regional perspective

Doutoramento em Biologia
Biologia Marinha e Aquacultura

Rita Sofia Domingues Gamito Gomes Lopes

Tese orientada por:
Professor Doutor Henrique Nogueira Cabral
Professora Doutora Maria José Costa

Documento especialmente elaborado para a obtenção do grau de doutor

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FCT Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA EDUCAÇÃO E CIÊNCIA
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2015

“My big fish must be somewhere.”

Ernest Hemingway

***In* The Old Man and the Sea**

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AGRADECIMENTOS

Ao Professor Doutor Henrique Cabral, pela orientação desta tese, por ter proporcionado todas as condições necessárias ao desenvolvimento do meu trabalho, pela confiança depositada em mim, por todas as discussões científicas e, principalmente, pela amizade ao longo destes anos.

À Professora Doutora Maria José Costa por ter aceitado a orientação desta tese e por me ter dado a oportunidade de voltar à investigação no Centro de Oceanografia, FCUL.

À DGRM, particularmente à Dra. Paula Ramalho, pela disponibilização dos dados de desembarques da pesca.

Às DOCAPESCA de Setúbal e de Peniche, pela disponibilidade e simpatia.

À Doutora Cristina Pita, pela preciosa colaboração nos trabalhos sobre a vulnerabilidade e capacidade de adaptação das pescas, pela imensa disponibilidade e pela motivação.

Aos meus colegas de gabinete, Catarina, Célia, Filipa, Marina, Stéphanie e Valter, pelo ânimo e pelo excelente ambiente de trabalho. Ao Valter, particularmente, pela revisão exaustiva da tese.

À Catarina e à Célia, pelas discussões científicas, pelas gargalhadas que me permitiram manter a sanidade mental e, principalmente, pela confiança inabalável que sempre depositaram nas minhas capacidades.

À Célia, pela revisão, pela ajuda com os inquéritos, por toda a amizade ao longo destes anos, pela lealdade, pela generosidade.

A todos os colegas do MARE ULisboa, pelos anos de convívio e amizade.

A todos os pescadores que generosamente responderam às minhas perguntas com simpatia e paciência, apesar do frio, do vento e da chuva.

À Rita Barrocas, pela ajuda nas entrevistas aos pescadores, e pela amizade que nos une há já tantos anos.

Ao Sr. Domingos Chefe, primeiro pescador com que trabalhei, e que, além de me fazer amar o Tejo, me fez também continuar a querer trabalhar na área das pescas.

Aos meus amigos, mas especialmente à Ana Margarida, por estar sempre presente.

A toda a minha família, pelo apoio e amor, mas especialmente aos meus pais, pela presença constante e incondicional e pelo exemplo de vida, de valorização da responsabilidade e do trabalho.

Ao Mário e ao Tiago, os meus pilares, por todo o amor. Ao Tiago, pela curiosidade e procura constante de conhecimento. Ao Mário, por acreditar mais em mim do que eu mesma e por me encorajar sempre a continuar a procurar o meu "big fish".

Esta tese foi financiada pela Fundação para a Ciência e Tecnologia (FCT), por meio da bolsa de doutoramento SFRH/BD/78363/2011 atribuída à autora e do projeto estratégico UID/MAR/04292/2013 concedido à instituição de acolhimento (MARE).

This thesis was funded by Fundação para a Ciência e Tecnologia (FCT), through the PhD grant awarded to the author (SFRH/BD/78363/2011) and the strategic project UID/MAR/04292/2013 granted to the host institution (MARE).

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PORTUGAL 2007.2013

ABSTRACT

The present thesis focused on the effects of climate change on fisheries, both on a global and on a regional scale. Trends in annual catches of fish species in the large marine ecosystems of the world were analysed, taking into account changes in sea surface temperature (SST). The results obtained in this analysis agreed with a poleward shift in distribution of fish species as a response to ocean warming. The Portuguese coast is located in a biogeographic transition zone, where the effects of climate change are higher, which makes it particularly adequate for studies on the effect of climate change on fisheries. Landings of biogeographic groups of fish species were compared, for each Portuguese fleet component: trawl, purse-seine and multi-gear fisheries. Results pointed out to an easier adaptation of multi-gear fisheries to the effects of climate change. A long time series analysis was performed for Setúbal, an important fishing port in central Portugal. In 86 years, mean annual SST has increased 0.9 ºC in the area. The main target species in 2012 were the same as in 1927. However, their landings have changed and have responded to changes in environmental variables, particularly SST. The influence of river drainage on landings of coastal ports in the vicinity of four estuaries was investigated. No significant correlations between river drainage and landings were found, which could be due to a stronger dependence of the food web on the nutrients provided by coastal upwelling. Also, the possible interaction of several other smaller scale factors acting on recruitment of commercial species may mask the effects of river drainage on landings. Recruitment and landings of European sardine (*Sardina pilchardus*) and Atlantic horse mackerel (*Trachurus trachurus*), two highly consumed fish species in Portugal, were modelled. Models obtained emphasized the influence of SST and wind strength in landings of these pelagic species. Finally, trends in landings of the most important fishing *métiers*, as well as the vulnerability and adaptation capacity of Portuguese fisheries to climate change were analysed. A latitudinal pattern in the number of new species found in landings was observed, agreeing with a northward shift of subtropical species. The south coast showed a higher vulnerability to climate change, in terms of both exposure and sensitivity of target species and ecosystems to its effects. Trawl fisheries and multi-gear fisheries may be more adaptable and less vulnerable to climate change than purse-seine fisheries. In fact, the high sensitivity of sardine to the effects of climate change makes purse-seine fisheries particularly vulnerable to climate change. Overall, results responded to the main objective of this thesis of assessing trends and relationships between climate change and fisheries. Suggestions for future research in this subject are also proposed.

Keywords: fisheries; climate change; ocean warming; distribution shifts; adaptation capacity

RESUMO

A pesca é uma das atividades humanas mais ancestrais, devido à importância dos recursos marinhos como fonte proteica para a alimentação humana. As alterações climáticas são a ameaça antropogénica para os ecossistemas marinhos mais globalmente disseminada, originando aumento da temperatura da água do mar, alterações na salinidade, acidificação dos oceanos, mudanças nos padrões de circulação oceânica e subida do nível do mar. Por sua vez, estes efeitos nas condições dos oceanos têm impactos nos organismos marinhos, na composição das comunidades marinhas e no funcionamento dos ecossistemas, aumentando a complexidade dos desafios que o sector das pescas tem atualmente de enfrentar. Os efeitos das alterações climáticas têm assim importantes consequências para a sustentabilidade e gestão das pescas, cuja avaliação deve ser prioritária e é neste contexto que surge a presente tese.

Esta tese tem os seguintes objetivos: avaliar tendências e as relações entre os processos climáticos, os recursos marinhos e as pescas a diferentes escalas espaciais; desenvolver modelos que permitam investigar os efeitos das alterações climáticas nos recursos marinhos e analisar a capacidade de adaptação das pescarias face aos efeitos das alterações climáticas no sector. É composta por oito capítulos, dos quais seis correspondem a artigos científicos, publicados ou em revisão em revistas internacionais com arbitragem científica. Estes capítulos são precedidos de um capítulo de introdução geral e seguidos de um capítulo de conclusões e comentários finais, incluindo sugestões para estudos futuros.

Na Introdução geral (Capítulo 1), é apresentado um enquadramento do tema da tese. É salientada a importância das pescas marinhas e são referidos os possíveis efeitos das alterações climáticas nas mesmas. São também abordados os efeitos das alterações climáticas já observados nos ecossistemas e organismos marinhos, bem como os previstos mediante cenários futuros de emissões, a nível global. São ainda focados os efeitos das alterações climáticas na costa portuguesa, por esta se situar numa zona de transição biogeográfica, onde se espera que as alterações na temperatura e precipitação sejam particularmente acentuadas.

No Capítulo 2, foi realizada uma análise, à escala mundial, das tendências nas capturas da pesca. Para as oito espécies de peixes marinhos mundialmente mais importantes para as pescas, foram comparadas as capturas de anos de invernos frios e de anos de invernos quentes. Em geral, as capturas médias de espécies polares e de espécies temperadas foram maiores em anos de invernos quentes nas regiões mais a norte da sua distribuição geográfica e em anos de invernos frios nas zonas mais a sul da sua distribuição. Em relação às espécies subtropicais analisadas, as capturas médias foram maiores em anos frios nas latitudes mais baixas e em anos quentes nas latitudes mais altas. Estes resultados concordam com uma deslocação das distribuições geográficas das espécies de peixes em direção aos polos, como resposta ao aquecimento dos oceanos.

Os desembarques de grupos biogeográficos de espécies de peixes, em cada componente de frota das pescas portuguesas, foram comparados no Capítulo 3. No período de 1993 a 2009, os maiores desembarques de espécies temperadas foram observados nas pescas de arrasto, enquanto que as espécies subtropicais foram mais abundantes na frota polivalente, onde inclusivamente apresentaram uma tendência crescente. O aumento da importância relativa de espécies subtropicais nos desembarques portugueses, juntamente com o facto de estes desembarques serem mais elevados nas pescarias polivalentes, pode indicar uma mais fácil adaptação das pescarias polivalentes aos efeitos das alterações climáticas.

O Capítulo 4 apresenta uma análise de uma série de 86 anos (1927-2012) de estatísticas de pesca no porto de Setúbal, localizado no centro da costa portuguesa. Foram analisados desembarques das espécies mais importantes e investigadas as suas relações com a temperatura de superfície do mar, a precipitação e o índice NAO (*North Atlantic Oscillation*) de inverno. A temperatura média de superfície do mar aumentou 0,9 ºC de 1926 a 2012. As espécies que eram os principais alvos da pesca em Setúbal em 1927 continuaram a ser os alvos mais importantes em 2012. No entanto, os desembarques dessas espécies foram sofrendo alterações ao longo do tempo, correspondendo a alterações nos parâmetros ambientais, particularmente na temperatura de superfície do mar. Os desembarques de sardinha (*Sardina pilchardus*) apresentaram uma tendência decrescente no período estudado e estiveram negativamente correlacionados com a temperatura de superfície do mar e com o índice NAO, enquanto que os desembarques de cavala (*Scomber colias*) têm vindo a aumentar desde 2000. Os desembarques de choco (*Sepia officinalis*) têm-se mantido relativamente estáveis, mas correlacionados com a temperatura de superfície do mar. Os desembarques de linguados têm aumentado ao longo do tempo e também com o aumento da temperatura de superfície do mar. Os desembarques de polvo (*Octopus vulgaris*) estiveram correlacionados com a temperatura de superfície do mar e com o índice NAO. Maiores aumentos na temperatura do mar poderão constituir um desafio para a pescas em Setúbal no futuro. As pescas de cerco poderão tentar compensar as perdas previstas em desembarques de sardinha com um maior investimento na cavala como alvo das suas pescas. Embora os desembarques das pescarias polivalentes pareçam ter sido favorecidos pelo aumento da temperatura, são necessários mais estudos sobre a tolerância de cada espécie a futuros aumentos de temperatura.

Tendo em conta as previsões de diminuição da precipitação em Portugal, o Capítulo 5 foca-se na influência do escoamento dos rios nos desembarques de espécies que sejam dependentes de estuários, quer por os usarem como áreas de viveiro, quer por habitarem áreas próximas dos mesmos. Foram analisados desembarques e variáveis ambientais de zonas costeiras próximas dos estuários do Minho, Ria de Aveiro, Mondego e Tejo. Não foram encontradas correlações significativas entre o escoamento dos rios e os desembarques nas zonas costeiras adjacentes aos estuários, ao contrário do que tinha sido observado por outros autores no Mediterrâneo. As relações entre o escoamento dos rios e os desembarques podem ser inconsistentes de região para região, devido ao grau de dependência de cada teia trófica em relação a nutrientes e matéria orgânica de origem fluvial. Na costa portuguesa, o regime de afloramento costeiro é particularmente importante para a riqueza e diversidade do ecossistema costeiro e para as pescas. A complexidade deste fenómeno de afloramento, juntamente com uma possível interação de outros fatores que afetam o recrutamento de espécies comerciais, poderão camuflar os efeitos do escoamento dos rios nos desembarques.

As populações de peixes e ecossistemas localizados em áreas onde os efeitos das alterações climáticas são maiores, como é o caso da costa portuguesa, estão mais em risco. No Capítulo 6, são desenvolvidos modelos para o recrutamento e para os desembarques de sardinha e carapau (*Trachurus trachurus*), espécies pelágicas muito consumidas em Portugal e, como tal, muito importantes para as pescas portuguesas. O recrutamento da sardinha foi explicado pela intensidade do vento; esta variável também explicou os desembarques da mesma espécie, juntamente com a temperatura de superfície do mar e os desembarques de cavala. Embora não tenha sido possível obter um modelo para o seu recrutamento, o modelo para os desembarques de carapau teve a temperatura de superfície do mar como variável preditora. De acordo com os resultados deste Capítulo, os efeitos das alterações climáticas no ambiente marinho poderão estar a afetar o recrutamento e os desembarques de sardinha e carapau na costa portuguesa, com consequências consideráveis para as pescas portuguesas.

O Capítulo 7 analisa as tendências nos desembarques dos *métiers* mais importantes e a vulnerabilidade e capacidade de adaptação das pescas portuguesas às alterações climáticas. Foram analisados desembarques oficiais (1992-2012) e realizados inquéritos a pescadores, para avaliar a sua perceção relativamente às tendências nos desembarques e o seu potencial comportamento face aos efeitos das alterações climáticas nas pescas. Foram encontradas oito novas espécies nos desembarques dos últimos cinco anos analisados, das quais doze são subtropicais e cinco têm o seu limite de distribuição na costa portuguesa. Foi observado um padrão latitudinal no número de novas espécies nos desembarques, que está de acordo com uma deslocação das distribuições geográficas das espécies em direção aos polos. A costa sul demonstrou uma maior vulnerabilidade às alterações climáticas, em termos de exposição e sensibilidade das suas espécies-alvo e ecossistemas aos efeitos das mesmas. As pescarias com arrasto e polivalentes poderão ser mais adaptáveis e menos vulneráveis às alterações climáticas, devido à grande mobilidade da frota do arrasto e à maior flexibilidade da frota polivalente para mudar de espécie-alvo ou arte de pesca. Por outro lado, a grande sensibilidade da sardinha às alterações climáticas torna as pescarias de cerco particularmente vulneráveis às alterações climáticas.

Finalmente, no Capítulo 8, são apresentadas as principais conclusões dos Capítulos anteriores e perspetivas futuras de investigação complementar, no âmbito deste trabalho.

Palavras-chave: pescas; alterações climáticas; aquecimento dos oceanos; alterações na distribuição; capacidade de adaptação

LIST OF PAPERS

This thesis consists of the series of papers listed below, each one corresponding to a Chapter, from 2 to 7. The author wrote all papers and was responsible for the conception and design of the work, data collection, field surveys and data analysis. Remaining authors collaborated in some or several of these procedures. All papers published or in press were included with the publishers' agreement.

CHAPTER 2
Fisheries in a warming ocean: trends in fish catches in the large marine ecosystems of the world
Rita Gamito, Maria J. Costa, Henrique N. Cabral
Published in 2015 in Regional Environmental Change 15: 57-65

CHAPTER 3
Climate-induced changes in fish landings of different fleet components of Portuguese fisheries
Rita Gamito, Célia M. Teixeira, Maria J. Costa, Henrique N. Cabral
Published in 2013 in Regional Environmental Change 13: 413-421

CHAPTER 4
Are regional fisheries' catches changing with climate?
Rita Gamito, Célia M. Teixeira, Maria J. Costa, Henrique N. Cabral
Published in 2015 in Fisheries Research 161: 207-216

CHAPTER 5
Are Portuguese coastal fisheries affected by river drainage?
Rita Gamito, Catarina Vinagre, Célia M. Teixeira, Maria J. Costa, Henrique N. Cabral
Under review in Aquatic Living Resources

CHAPTER 6
Modelling recruitment and landings of pelagic fish under climate change
Rita Gamito, Célia M. Teixeira, Maria J. Costa, Henrique N. Cabral
Under review in Journal of Marine Systems

CHAPTER 7
Trends in landings, vulnerability and adaptation to climate change in different fleet components in the Portuguese coast
Rita Gamito, Cristina Pita, Célia M. Teixeira, Maria J. Costa, Henrique N. Cabral
Under review in Fisheries Research

CHAPTER 1

General introduction

General introduction

Seafood has long been an important source of food and protein and fishing is one of the most ancient human activities. The industrialization of fisheries started in the early 19th century with the use of steam trawlers in England, which were later replaced by diesel engines after the First World War. Freezer trawlers, radar and acoustic fish finders were then developed after World War II (Pauly *et al.*, 2002). The collection of global fisheries statistics started in 1950, with the newly founded Food and Agriculture Organization (FAO). Global fish production has continuously grown in the last five decades, with food fish supply increasing at an average annual rate of 3.2 % (FAO, 2014). In 2010, fish provided 16.7 % of the global population's intake of animal protein and 6.5 % of all protein consumed. World per capita apparent fish consumption increased from an average of 9.9 kg in the 1960s to 19.2 kg in 2012. Global fishery production in marine waters was 79.7 million tonnes in 2012, of which 24 % corresponded to the ten most productive species. Northwest Pacific had the highest production (26 %), followed by Southeast Pacific (15 %), Western Central Pacific (14 %) and Northeast Atlantic (9 %) (FAO, 2014). Employment in the fisheries sector has grown faster than the world's population. Of the 1,300 million people economically active in the broad agriculture sector worldwide in 2012, 4.4 % were employed in fisheries. In 2012, the total number of fishing vessels operating in marine waters was estimated at 3.2 million, of which 70 % were engine-powered (FAO, 2014). Nevertheless, when spatial and temporal patterns of global fishing effort and its relationship with catch are considered, our perception of the global status of fisheries may be different. Nowadays, fleets fish all of the world's oceans and their power has increased by an average of 10-fold (25-fold in Asia) since the 1950s (Watson *et al.*, 2013). In fact, for the equivalent fishing power expended, landings from global fisheries are now half what they were a half-century ago (Watson *et al.*, 2013).

Not only do global marine fisheries face overfishing, pollution and other anthropogenic impacts, but they also have to deal with climate change (Halpern *et al.*, 2008; Pauly *et al.*, 2002). Climate change is the most widespread anthropogenic threat for ocean ecosystems, leading to sea-level rise, sea temperature change, ocean acidification, changes in rainfall and changes in ocean circulation (Brander, 2007; Halpern *et al.*, 2008). These climate effects on ocean conditions will impact ocean organisms, the composition of marine communities and ecosystem function (Brown *et al.*, 2010), increasing the complexity of the challenges facing current fisheries (Sumaila *et al.*, 2011). Climate change impacts fish stocks either directly or indirectly. Direct impacts affect physiology and behaviour, altering growth, reproductive capacity, mortality and distribution. Indirect impacts are related with changes in productivity and in the structure and composition of the marine ecosystems on which fish depend (Brander, 2010; Hare *et al.*, 2010; Perry *et al.*, 2005). Changes in the geographic distribution of fish species in marine ecosystems have already been documented throughout the world and are more easily detected on its northern and southern distribution limits (Afonso *et al.*, 2013; Brander *et al.*, 2003; Engelhard *et al.*, 2013; Perry *et al.*, 2005). It has also been predicted that climate change may lead to local extinctions in the sub-polar and tropical regions as well as in semi-enclosed seas (Cheung *et al.*, 2009). These shifts in geographic range will most likely affect the abundance, distribution and composition of fisheries catches, and consequently fishing operations, catch shares and the effectiveness of fisheries management measures (Kim, 2010; Sumaila *et al.*, 2011). The potential consequences of climate change for marine fisheries include large-scale redistribution of fish stocks and productive habitats (Miller *et al.*, 2010) and redistribution of global catch potential, with an average of 30-70 % increase in high-latitude regions and a decrease of up to 40 % in the tropics (Cheung *et al.*, 2010). Therefore, climate change effects might not always be negative, as new fishing opportunities may also arise in some areas of the world.

The consequences of climate change on fishing communities will depend on their exposure to climate change, the sensitivity of target species and ecosystems to climate change, and fishermen's ability to adapt to climate change (Grafton, 2010). Fish populations and ecosystems located in areas most likely to suffer climate change impacts are more at risk (Brown *et al.*, 2010). Both the observation of the impact of recent climate change and the predictions of climate change in future scenarios show that the effects of climate change will not be homogeneous throughout the world (IPCC, 2007). For example, Southern Europe and the Mediterranean are more vulnerable to climate change than Central and Northern Europe (Santos, 2006). An increase in sea surface temperature from 1982 to 2006 has already been observed in large marine ecosystems (LME) (Belkin, 2009). A rapid warming (net sea surface temperature change higher than 0.6 ºC) was observed for three groups of LME: 1) Scotian Shelf, Newfoundland-Labrador Shelf, West Greenland Shelf, Iceland Shelf, Faroe Plateau and Norwegian Sea; 2) North Sea, Baltic Sea, Black Sea, Mediterranean Sea, Iberian Coastal and Celtic-Biscay Shelf; 3) Yellow Sea, East China Sea, Japan/East Sea and Kuroshio Current. A slow warming was observed in the Indian Ocean LME and most LME around Australia and between Australia and Indochina. The only cooling LME were the California Current and Humboldt Current, both located in the Eastern Pacific upwelling areas (Belkin, 2009).

The Portuguese coast is expected to suffer changes in temperature and precipitation more accelerated than the global mean alteration rate (IPCC, 2007) and the Iberian Coastal large marine ecosystem has already suffered a rapid warming, with an increase of 0.68 ºC in sea surface temperature from 1982 to 2006 (Belkin, 2009). In Portugal, there has also been a decrease in the intensity and frequency of rainfall and a decrease of more than 30 % in southern Portugal by 2100 has been predicted (IPCC, 2007; Miranda *et al.*, 2002). Regional circulation model HadRM3 predicts increases in SST in the Portuguese coast until 2100, for different future scenarios established by the Special Report on Emission Scenarios (Nakicenovic *et al.*, 2000; Reis *et al.*, 2006). This increase will be of 1 ºC under scenario B2 and 2 ºC under the scenario A2 (Reis *et al.*, 2006). The Portuguese coast is mainly north-south oriented and located in a biogeographic transition zone, between temperate and subtropical waters, where several temperate and subtropical fish species have their southern or northern distribution limit (Briggs, 1974). For that reason, this coast is particularly adequate for studies on the effects of climate change on marine organisms. Ecological responses to recent climate change have already been observed in Portuguese waters. An increase in the occurrence of species with tropical affinities and a decrease in temperate species have been reported (Cabral *et al.*, 2001; Henriques *et al.*, 2007). Vinagre *et al.* (2011) studied the impact of climate warming upon the fish assemblages of the Portuguese coast under future emission scenarios (Nakicenovic *et al.*, 2000) and predicted a general increase in species richness by 2100, with the appearance of new subtropical and tropical species and the elimination of only a few species. Recent studies have also focused on effects of ocean acidification on marine organisms (Rosa *et al.*, 2014a,b) and on the thermal tolerance of coastal organisms in the Portuguese coast (e.g. Madeira *et al.*, 2012, 2014; Vinagre *et al.*, 2014a,b). However, there is still a lack of knowledge on the effects of climate change on Portuguese fisheries.

Coastal and maritime activities have long been important in Portugal, not only to national economy, but also to its historical, social and cultural identity. Fisheries have been a major means of subsistence, especially for many Portuguese coastal communities that depend almost exclusively on this activity. The Portuguese Exclusive Economic Zone (EEZ) is eighteen times larger than its land territory. It is one of the largest EEZ of the European Union (EU) member states, with a total area of ca. 1.7 million km^2. Portugal is the third highest per capita consumer of fish in the world (Failler, 2007). Since joining the EU in 1986, fisheries have lost economic importance in Portugal. The size of the fleet, the number of fishermen, and catches have been decreasing since then. The number of fishing vessels in 2014 was the lowest since 2006, with 4,319 active vessels, of which 85 % were less than 12 m long (INE, 2015). The sector currently employs 16,779 fishermen, which is less than 0.3 % of the total active population in Portugal, contrasting with the 1.4 % back in 1950. Landings in 2014 were the lowest observed since 1969 (119,890 tonnes), which resulted on the highest medium price ever (2.02 €.kg^{-1}). As domestic output does not meet market demand, fish products must also be imported (INE, 2015). There are three main fleet components operating in Portuguese fisheries: trawl fisheries, purse-seine fisheries and multi-gear fisheries. The main targets of trawl fisheries are the Atlantic horse mackerel *Trachurus trachurus* (Linnaeus, 1758), the European hake *Merluccius merluccius* (Linnaeus, 1758) and cephalopods. Purse-seine fisheries target small pelagic fish, such as European sardine *Sardina pilchardus* (Walbaum, 1792), Atlantic chub mackerel *Scomber colias* Gmelin, 1789 and Atlantic horse mackerel. Sardine is particularly important, as it has traditionally been the most landed species in Portugal. Nowadays, it is the second most important species landed in Portuguese waters in quantity, just after chub mackerel (INE, 2015). Multi-gear fishery is the largest and most diversified fishing fleet component in Portugal, using a wide variety of fishing gears, such as gillnets, trammel nets, longlines and traps.

The present thesis aims to assess trends and relationships between climate processes, marine resources and fisheries, at different spatial scales; to model climate change effects on marine resources and to analyse the adaptation capacity of fisheries to climate change. The thesis consists of six scientific manuscripts published, or under review, in peer reviewed international scientific journals, each corresponding to a Chapter. In Chapter 2, trends in annual catches of fish species in the large marine ecosystems of the world are analysed and linked to changes in sea surface temperature. Comparisons between different biogeographic areas and latitudes are made. Chapter 3 studies the variation in the composition of Portuguese landings, in terms of biogeographic groups of fish species, over the period of 1993-2009. This is followed by an analysis of a long time series of landings in an important fishing port in central Portugal, in Chapter 4. Using eighty-six years of data, relationships between environmental variables and landings in a biogeographic transition zone are established. Given the prediction for decreased rainfall in Portugal (Miranda *et al.*, 2002), Chapter 5 focuses on the influence of river drainage on landings of species somewhat dependent on estuaries, either by using them as nurseries, or by living in their vicinity. In Chapter 6, models are fitted to recruitment and landings of sardine and horse mackerel in divisions VIIIc and IXa of the International Council for the Exploration of the Sea (ICES). These small pelagic fish species are highly consumed in Portugal and are main targets for the Portuguese fisheries (INE, 2015). For that reason, linking their recruitment and landings to climate change effects on ocean conditions is of the utmost importance. The consequences of climate change on fishing communities will not only depend on their exposure to climate change and the sensitivity of target species and ecosystems to climate change, but also to fishermen's ability to adapt to climate change (Grafton, 2010). Chapter 7 analyses trends in landings of the most important fishing *métiers* in the Portuguese coast and the vulnerability and adaptation capacity of Portuguese fisheries to climate change. In the present thesis, different fleet components of Portuguese fisheries were considered as *métiers*, depending on the fishing gear used: trawl, purse-seine, trammel nets, gillnets, bottom longline, dredge or traps. Finally, Chapter 8 draws the main conclusions of the thesis and outlines its contribution to knowledge on the effects of climate change on fisheries. Suggestions for further research needed on this subject are also given in this chapter.

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CHAPTER 2

Fisheries in a warming ocean: trends in fish catches in the large marine ecosystems of the world

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2015. Regional Environmental Change 15: 57-65

Fisheries in a warming ocean: trends in fish catches in the large marine ecosystems of the world

Abstract: Trends in annual catches of fish species in the large marine ecosystems (LMEs) of the world were analysed, relating them with changes in sea surface temperature. LMEs are large coastal areas with broad ecosystem similarities, and the vast majority of them have warmed in the period of 1982-2006. Changes in sea water temperature, induced by climate change, affect the geographic distribution of fish species in marine ecosystems. Shifts in distribution of fish will most likely affect the abundance, distribution and composition of fisheries catches. In the present paper, a decreasing trend in the catches of fish species in warming LMEs was observed. Catches in years of cold and warm winters were compared for each of the eight fish species most caught in the world. Generally, mean catches of polar and temperate species were higher in years of warm winters in the LMEs located in the northern part of the species range and in years of cold winters in LMEs of the southern regions of their ranges. Mean catches of subtropical species were higher in cold years in LMEs of lower latitudes and in warm years in LMEs of higher latitude regions. The results obtained for fish catches agree with a poleward shift of fish species as a response to ocean warming, posing challenges for future fisheries management.

Keywords: climate change; fish; fisheries; large marine ecosystems; sea surface temperature

Introduction

Global marine fisheries not only face overfishing, pollution and other anthropogenic impacts, but also climate change (Halpern *et al.*, 2008; Pauly *et al.*, 2002). Climate change is the most widespread anthropogenic threat for ocean ecosystems (Halpern *et al.*, 2008), causing sea-level rise, sea temperature change, ocean acidification, changes in precipitation and changes in ocean circulation (Brander, 2007). These climate effects on ocean conditions will impact ocean organisms, the composition of marine communities and ecosystem function (Brown *et al.*, 2010), increasing the complexity of the challenges facing current fisheries (Sumaila *et al.*, 2011). Climate change impacts fish stocks either directly or indirectly. Direct impacts affect the physiology and behaviour and alter growth, reproductive capacity, mortality and distribution. Indirect effects change the productivity, structure and composition of the marine ecosystems on which fish depend (Brander, 2010; Hare *et al.*, 2010; Perry *et al.*, 2005). Changes in the geographic distribution of fish species in marine ecosystems have already been documented throughout the world (Barange and Perry, 2009; Brander *et al.*, 2003; Perry *et al.*, 2005), and several studies have predicted that changes in water temperature, driven by climate change, may lead to local extinctions and also to colonization by species previously absent in those areas (Cheung *et al.*, 2009; Vinagre *et al.*, 2011). These shifts in geographic range will most likely affect the abundance, distribution and composition of fisheries catches, and consequently fishing operations, catch shares and the effectiveness of fisheries management measures (Gamito *et al.*, 2013; Kim, 2010; Sumaila *et al.*, 2011). However, these effects might not necessarily be negative, as new fishing opportunities may also arise in some areas of the world. The effects of climate change on fisheries may then be regarded to act on resource availability, fishing operations, fisheries management and conservation measures and profits from fisheries (Cheung *et al.*, 2012).

Both the observation of recent climate change and predictions of climate change in future scenarios show that the effects of climate change will not be homogeneous throughout the world (IPCC, 2007). Belkin (2009) has studied changes in sea surface temperature (SST) in large marine ecosystems (LMEs). LMEs are large coastal areas with broad ecosystem similarities, such as bathymetry, hydrography, productivity and trophically dependent populations (Sherman and Duda, 1999; Watson *et al.*, 2004). Belkin (2009) has found a coherent global pattern of rapid warming in LMEs, from 1982 to 2006. This rapid warming (net SST change higher than 0.6 ºC) was observed for three groups of LMEs: (1) Scotian Shelf, Newfoundland-Labrador Shelf, Canadian Eastern Arctic-West Greenland, Iceland Shelf and Sea, Faroe Plateau and Norwegian Sea; (2) North Sea, Baltic Sea, Black Sea, Mediterranean Sea, Iberian Coastal and Celtic-Biscay Shelf; (3) Yellow Sea, East China Sea, Japan/East Sea and Kuroshio Current. A slow warming was observed in the Indian Ocean LMEs and most LMEs around Australia and between Australia and Indochina. The only cooling LMEs were the California Current and the Humboldt Current, both located in the Eastern Pacific upwelling areas. As the LME spatial system groups together large coastal areas with similar ecosystem characteristics, this methodology has recently been used for several large-scale marine studies (Merino *et al.*, 2012; Pauly *et al.*, 2008; Pikitch *et al.*, 2014; Sherman and Duda, 1999; Watson *et al.*, 2004).

From a global perspective, analyses on the LME scale are extremely valuable for marine ecosystem-based management. And, as climate change increases the complexity of fisheries management, it is of the utmost importance that these analyses include the effects of climate change on fisheries. Therefore, the present paper aimed to (1) analyse the trends in annual catches of fish species in LMEs and relate them with changes in SST and (2) compare the mean catches of the most relevant fish species in cold and warm years.

Materials and methods

Large marine ecosystems were classified based on SST change from 1982 to 2006, as described in Belkin (2009). Three categories of LMEs based on SST change were used: rapid warming (0.67–1.35 ºC), slow warming (0.00–0.60 ºC) and cooling (-0.10 to 0.00 ºC) (Belkin, 2009) (Fig. 1).

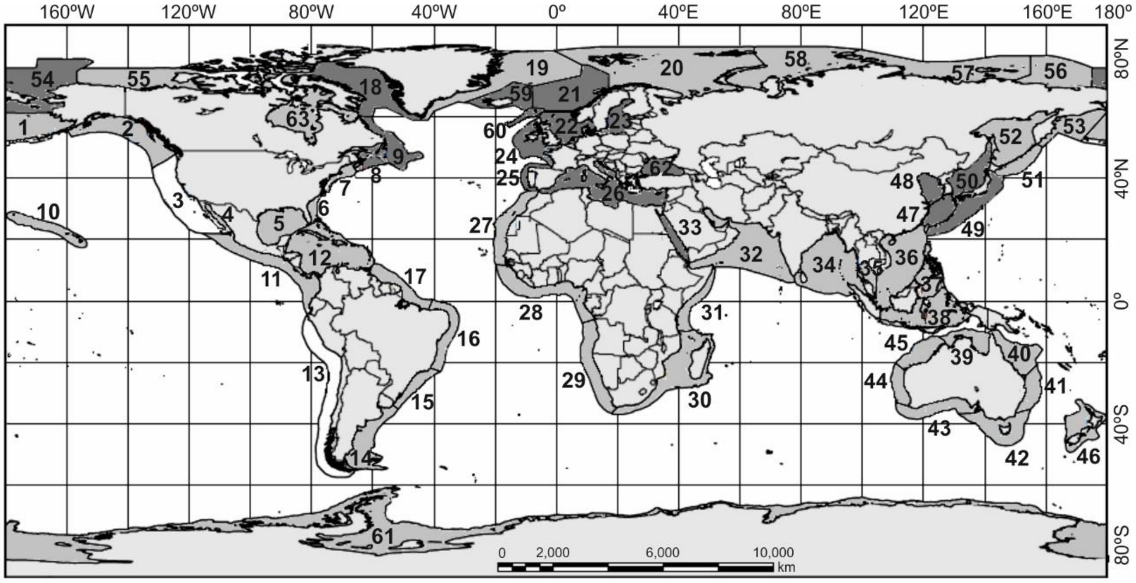

Fig. 1 Sea surface temperature change in large marine ecosystems (LME) from 1982 to 2006 (Belkin, 2009). Cooling (-0.10–0.00 ºC) LME are presented in white, slowly warming (0.00–0. 0.60 ºC) in light grey and rapidly warming (0.67–1.35 ºC) in dark grey. (1 – East Bering Sea; 2 – Gulf of Alaska; 3 – California Current; 4 – Gulf of California; 5 – Gulf of Meixco; 6 – Southeast U.S. Continental Shelf;7 – Northeast U.S. Continental Shelf; 8 – Scotian Shelf; 9 – Newfoundland-Labrador Shelf; 10 – Insular Pacific-Hawaiian; 11 – Pacific Central-American; 12 – Caribbean Sea; 13 – Humboldt Current; 14 – Patagonian shelf; 15 – South Brazil Shelf; 16 – East Brazil Shelf; 17 – North Brazil Shelf; 18 – Canadian Eastern Arctic - West Greenland Shelf; 19 –Greenland Sea; 20 – Barents Sea; 21 – Norwegian Sea; 22 – North Sea; 23 – Baltic Sea; 24 – Celtic-Biscay Shelf; 25 – Iberian Coastal; 26 – Mediterranean; 27 – Canary Current; 28 – Guinea Current; 29 – Benguela Current; 30 – Agulhas Current; 31 – Somali Coastal Current; 32 – Arabian Sea; 33 – Red Sea; 34 – Bay of Bengal; 35 – Gulf of Thailand; 36 – South China Sea; 37 – Sulu-Celebes Sea; 38 – Indonesian Sea; 39 – North Australian Shelf; 40 – Northeast Australian Shelf; 41 – East-Central Australian Shelf; 42 – Southeast Australian Shelf; 43 – Southwest Australian Shelf; 44 – West-Central Australian Shelf; 45 – Northwest Australian Shelf; 46 – New Zealand Shelf; 47 – East China Sea; 48 – Yellow Sea; 49 – Kuroshio Current; 50 – Sea of Japan / East Sea; 51 – Oyashio Current; 52 –Sea of Okhotsk; 53 – West Bering Sea; 54 – Northern Bering-Chukchi Seas; 55 – Beaufort Sea; 56 – East Siberian Sea; 57 – Laptev Sea; 58 – Kara Sea; 59 – Iceland Shelf and Sea; 60 – Faroe Plateau; 61 – Antarctic; 62 – Black Sea; 63 – Hudson Bay Complex) (Adapted from the NOAA LME Portal – http://www.lme.noaa.gov).

Fish catch data for each LME were collected from the Sea Around Us Project website (www.seaaroundus.org) (Pauly, 2007). These time series data were obtained using a method developed by Watson *et al.* (2004), which maps catches by species for more than 180,000 spatial cells of the world oceans, each covering 30 min of latitude and longitude. The catches in those spatial cells are then regrouped into the LMEs defined in the world’s oceans (Pauly *et al.*, 2008;

Watson *et al.*, 2004). All the analyses performed on fisheries catches covered the time series of 1982-2006. Trends in total fish catches for the three categories of LMEs were compared. Catches of the three categories of LMEs were comparatively analysed using a principal components analysis (PCA). The PCA aimed to highlight the similarities among years in terms of catches in these LMEs groups.

SST monthly data were collected from the United States of America National Oceanic and Atmospheric Administration (NOAA) database (http://nomad3.ncep.noaa.gov/ncep_data/), for the period of 1982-2006. As sensitivity to cold has been reported as a very important characteristic in shaping community composition (Henriques *et al.*, 2007; Pörtner and Peck, 2010), winter temperatures were used. In each LME, annual winter mean SST was calculated for each considered year and was then averaged for the period of 1982–2006. Winters of SST higher (0.1 ºC or more) or lower (0.1 ºC or less) than average were considered warm or cold winters, respectively. The catches of the eight most relevant fish species in terms of global catches, excluding the chub mackerel, were analysed. The chub mackerel was excluded, because the database does not provide separate data for the two recognized species (*Scomber colias* Gmelin, 1789, in the Atlantic, and *Scomber japonicus* Houttuyn, 1782, in the Pacific). Therefore, the studied species were: *Engraulis ringens* Jenyns, 1842, *Theragra chalcogramma* (Pallas, 1814), *Sardinops sagax* (Jenyns, 1842), *Clupea harengus* Linnaeus, 1758, *Gadus morhua* Linnaeus, 1758, *Mallotus villosus* (Müller, 1776), *Trichiurus lepturus* Linnaeus, 1758 and *Sardina pilchardus* (Walbaum, 1792). For each species, catches in years of cold and of warm winters were compared through *t*-tests or, whenever the assumptions of normality and homoscedasticity were not met, Mann-Whitney tests. A significance level of 0.05 was considered in all test procedures. All the analyses were performed on the environment R (R Core Team, 2012), and the R package "lattice" (Deepayan, 2008) was used.

Results

Total fish catches in rapidly warming LMEs (0.67–1.35 ºC) have decreased in more than 20 % from 1982 to 2006 (Fig. 2). Catches in slowly warming (0.00–0.60 ºC) LMEs have had a decrease in 12 % from 1982 (17,092,817 t) to 2006 (14,996,778 t). The total fish catches of the cooling (-0.10 to 0.00 ºC) LMEs group increased from 1982 (5,518,121 t) to 1994 (13,100,204 t); from 1995 to 2006, the catch trend oscillated, with a minimum record of 4,073,364 t in 1998.

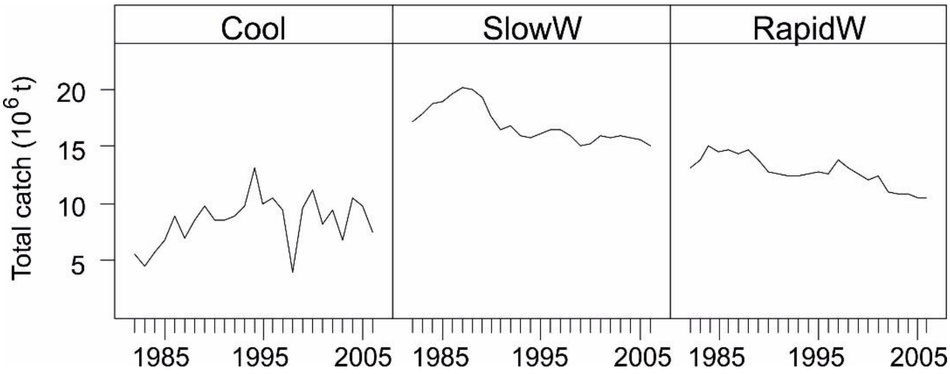

Fig. 2 Total annual fish catch in three different classes of large marine ecosystems, according to changes in sea surface temperature from 1982 to 2006 (Belkin, 2009) (Cool: -0.10–0.00 ºC; SlowW: 0.00–0. 0.60 ºC; RapidW: 0.67–1.35 ºC).

The first two ordination axes of the PCA had a cumulative variance of 95.5 %. The ordination diagram of the first two axes is presented in Fig. 3. The vectors of rapid warming (0.67–1.35 ºC) and slow warming (0.00–0.60 ºC) LMEs groups could both be found in the upper left quadrant of the diagram, whereas the cooling (-0.10 to 0.00 ºC) LMEs vector was drawn in the upper right section. Years 1984–1990 were strongly associated with warming LMEs, whereas the most recent years could be found in the opposing quadrant.

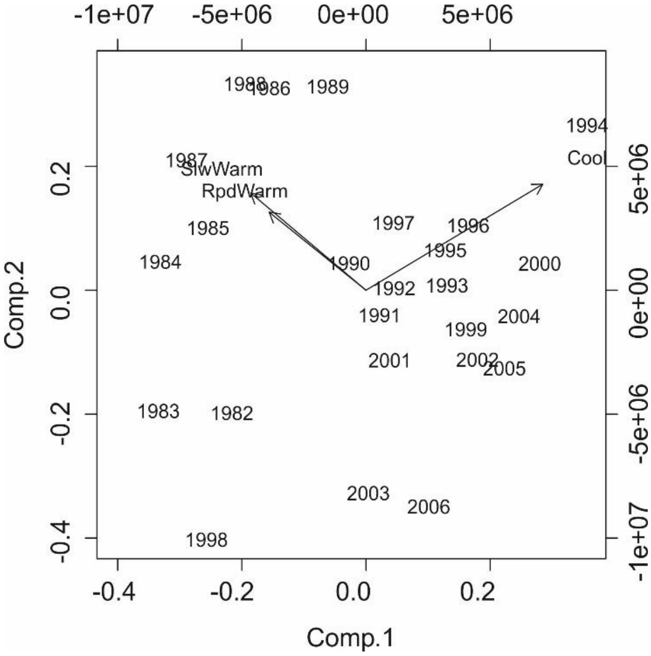

Fig. 3 Ordination plot of principal component analysis for fish catches in large marine ecosystems (LME). Years are indicated. Vectors for different groups of LME based on sea surface temperature change from 1982 to 2006 (Cool: -0.10–0.00 ºC; SlwWarm: 0.00–0.60 ºC; RpdWarm: 0.67–1.35 ºC) are represented.

Mann-Whitney tests and t-tests showed significant differences ($p < 0.05$) in the mean catches of *T. chalcogramma* in the East Bering Sea ($U = 30$; $p < 0.048$), Kuroshio Current ($t = 2.384$; $p < 0.029$) and Sea of Japan/ East Sea ($U = 22$; $p < 0.007$); *S. sagax* in the Agulhas Current ($U = 14$; $p < 0.027$), East China Sea ($U = 6$; $p < 0.002$), Yellow Sea ($U = 24$; $p < 0.009$), Kuroshio Current ($U = 24$; $p < 0.016$) and Sea of Japan/East Sea ($U = 27$; $p < 0.018$); *C. harengus* in the Norwegian Sea ($U = 23$; $p < 0.047$); *T. lepturus* in the East China Sea ($t = -4.8369$; $p < 0.001$) and Yellow Sea ($t = - 2.6535$; $p < 0.016$) and *G. morhua* in the North Sea ($t = 3.8587$; $p < 0.002$).

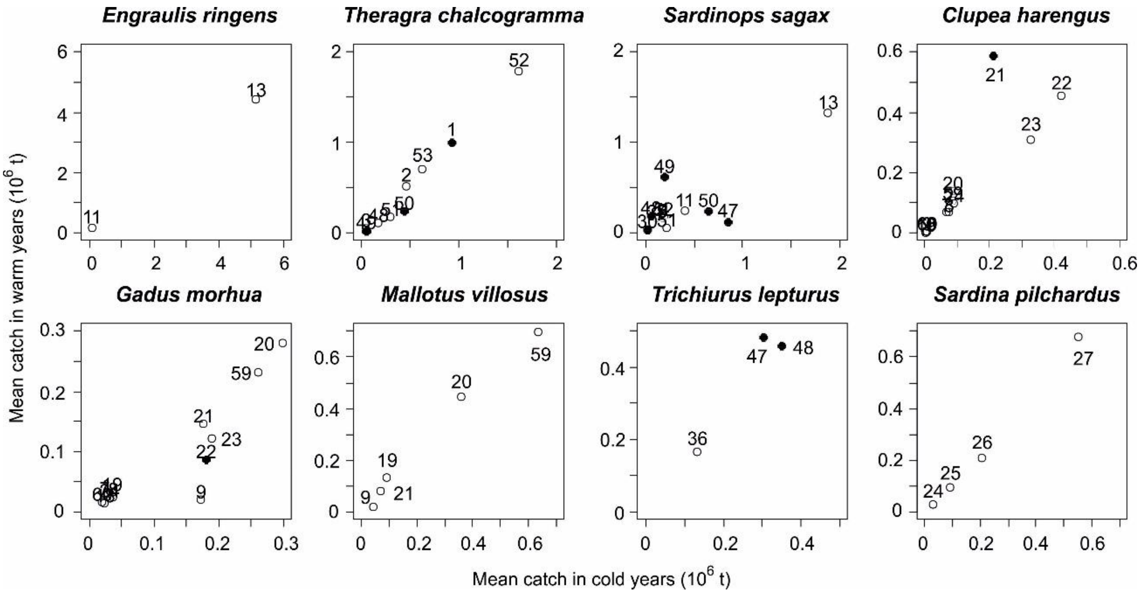

Fig. 4 Mean catches in cold and warm years, for the period of 1982-2006. Black dots represent significant results in t-tests and Mann-Whitney tests (1 – East Bering Sea; 2 – Gulf of Alaska; 3 – California Current; 4 – Gulf of California; 7 – Northeast U.S. Continental Shelf; 8 – Scotian Shelf; 9 – Newfoundland-Labrador Shelf; 11 – Pacific Central-American; 13 – Humboldt Current; 18 – Canadian Eastern Arctic - West Greenland Shelf; 19 – Greenland Sea; 20 – Barents Sea; 21 – Norwegian Sea; 22 – North Sea; 23 – Baltic Sea; 24 – Celtic-Biscay Shelf; 25 – Iberian Coastal; 26 – Mediterranean; 27 – Canary Current; 29 – Benguela Current; 30 – Agulhas Current; 36 – South China Sea; 47 – East China Sea; 48 – Yellow Sea; 49 – Kuroshio Current; 50 – Sea of Japan / East Sea; 51 – Oyashio Current; 52 – Sea of Okhotsk; 53 – West Bering Sea; 59 – Iceland Shelf and Sea; 60 – Faroe Plateau).

Table 1 Mean catches (t) of the 8 most relevant fish species in terms of global catches cold and warm years in each large marine ecosystem, for the period of 1982-2006. (Cold – cold years; Warm – warm years; E Bering Sea – East Bering Sea; Calif Cur – California Current; Gulf Calif – Gulf of California; NE US C S – Northeast U.S. Continental Shelf; Nflnd-Lab S – Newfoundland-Labrador Shelf; Pac C-Amer – Pacific Central-American; Humboldt C – Humboldt Current; W Grnlnd – Canadian Eastern Arctic - West Greenland Shelf; Grnlnd Sea – Greenland Sea; Norwegian – Norwegian Sea; C-Biscay S – Celtic-Biscay Shelf; Iberian C – Iberian Coastal; Mediterr – Mediterranean; Canary C – Canary Current; Benguela C – Benguela Current; Agulhas C – Agulhas Current; S China Sea – South China Sea; E China Sea – East China Sea; Kuroshio C – Kuroshio Current; S Japan/E S – Sea of Japan / East Sea; Oyashio C – Oyashio Current; W Bering S – West Bering Sea; Iceland S S – Iceland Shelf and Sea; Faroe P – Faroe Plateau).

LME	*Engraulis ringens*		*Theragra chalcogramma*		*Sardinops sagax*		*Clupea harengus*		*Gadus morhua*		*Mallotus villosus*		*Trichiurus lepturus*		*Sardina pilchardus*	
	Cold	Warm	Cold	Warm	Cold	Warm	Cold	Warm	Cold	Warm	Cold	Warm	Cold	Warm	Cold	Warm
1 E Bering Sea			928,428	1,003,091												
2 Gulf Alaska			458,087	519,580												
3 Calif Cur			46,948	51,843	181,141	163,565										
4 Gulf Calif					196,461	173,939										
7 NE US C S							68,354	67,036	23,523	26,938						
8 Scotian Shelf							72,628	67,244	36,490	25,028						
9 Nflnd-Lab S							6,509	4,830	171,205	19,661	42,006	19,598				
11 Pac C-Amer	66,144	141,067			400,419	247,988										
13 Humboldt C	5,116,646	4,420,968			1,872,036	13,232,549										
18 W Grnlnd							2,925	4,441	23,314	14,098						
19 Grnlnd Sea							2,144	1,544	33,607	33,498	89,393	133,202				
20 Barents Sea							86,484	139,253	298,896	280,200	358,009	445,534				
21 Norwegian							209,001	588,172	176,489	146,716	70,653	80,041				
22 North Sea							419,023	453,400	180,122	87,398						
23 Baltic Sea							325,859	308,145	188,832	122,596						
24 C-Biscay S							90,910	97,608	29,733	22,132					27,221	27,576
25 Iberian C															89,259	95,507
26 Mediterr															205,633	209,303
27Canary C															554,776	680,215
29 Benguela C					111,399	155,538										
30 Agulhas C					9,377	36,608										
36 S China Sea													131,409	166,983		
47 E China Sea					844,150	124,394							300,606	484,581		
48 Yellow Sea			172,304	110,507	58,516	190,365							347,892	459,375		
49 Kuroshio C			41,502	25,071	194,633	627,714										
50 S Japan/E S			431,584	241,827	640,373	244,132										
51 Oyashio C			298,670	174,965	210,876	59,094										
52 Sea Okhotsk			1,613,863	1,788,034	176,487	183,130										
53W Bering S			626,959	707,839												
59 Iceland S S							84,955	105,618	259,625	231,416	634,508	696,323				
60 Faroe P							4,791	5,907	19,369	16,258						

Mean catches in years of cold and warm years are plotted in Fig. 4 and presented in Table 1. Mean catches of *E. ringens* in years of warm winters were higher in the Pacific Central-American LME and lower in the Humboldt Current. *T. chalcogramma* had higher mean catches in years of cold winters in the Yellow Sea, Kuroshio Current, Sea of Japan/East Sea and Oyashio Current and higher mean catches in years of warm winters in the East Bering Sea, Gulf of Alaska, California Current, Sea of Okhotsk and West Bering Sea. Mean catches of *S. sagax* were higher in years of cold winters in most LMEs, except for the Benguela Current, the Agulhas Current, the Oyashio Current and the Sea of Okhotsk, where mean catches were higher in years of warm winters. Mean catches of *C. harengus* were higher in years of warm winters in the West Greenland, Barents Sea, Norwegian Sea, North Sea, Celtic-Biscay Shelf, Iceland Shelf and Sea and Faroe Plateau and lower in the Greenland Sea, Baltic Sea, Northeast US Continental Shelf, Scotian Shelf and Newfoundland-Labrador Shelf. Mean catches of *G. morhua* were always higher in years of cold winters, except for the Northeast US Continental Shelf. Except for the Newfoundland-Labrador Shelf, mean catches of *M. villosus* were higher in years of warm winters. Both *T. lepturus* and *S. pilchardus* had higher mean catches in years of warm winters.

Discussion

The present study has shown a decreasing trend in the catches of fish species in warming LMEs, from 1982 to 2006. Catches in years of cold and warm winters were compared for each of the eight most caught fish species. Generally, mean catches of polar and temperate species were higher in years of warm winters in the northern part of the species range and in years of cold winters in the southern part of their range; mean catches of subtropical species were higher in cold years in lower latitudes and in warm years in higher latitudes.

Several studies have focused on the prediction of shifts in species distributions in different future climate change scenarios (Cheung *et al.*, 2009; Vinagre *et al.*, 2011). The distribution of marine ectotherms tends to move poleward as the ocean warms up, which may result in an increase in species richness in high-latitude regions (Cheung *et al.*, 2009). Hiddink and Hofstede (2008) showed that the rise of species richness of fish in the North Sea, observed in a 22-year period, was related to higher water temperatures. Vinagre *et al.* (2011) predicted a general increase in species richness by 2100 in the Portuguese coast, with the appearance of new subtropical and tropical species and the elimination of only a few species, and Gamito *et al.* (2013) have reported a recent increase in the relative importance of subtropical fish species in Portuguese fisheries. Bioclimate envelope models have predicted a redistribution of the global catch potential, with an increase of 30-70 % in high-latitude regions and a decrease of up to 40 % in tropical regions (Cheung *et al.*, 2010). A different approach, using a physical-biogeochemical model coupled with a dynamic, size-based food web model, resulted in broadly similar predictions (Blanchard *et al.*, 2012). Fish catches in slowly warming LMEs have decreased from 1982 to 2006. As most of the area occupied by slowly warming LMEs is located in tropical regions, this result may be indicative of a decline in catches in tropical fisheries, as predicted by several studies (Blanchard *et al.*, 2012; Cheung *et al.*, 2010). Nevertheless, this result also includes catches in high latitudes, and a similar declining trend was observed for rapidly warming LMEs. Although high-latitude LMEs may be increasing their species richness due to the arrival of subtropical and tropical species, catches may not immediately reflect this change. Catches depend, among other factors, on the fishers decisions. The decision of fishers on whether to change target species and gear depends on several factors, such as resource abundance, commercial value, information from other fishers, weather conditions, distance to fishing grounds, cultural aspects and fisheries management measures (Christensen and Raakjær, 2006). Thus, the adaptation of fisheries to changes in the fish communities will not most likely be that fast. Also, the Sea Around Us Project database which was used in the present work includes only the species that were most caught in each LME. For that reason, an increase in other subtropical or tropical species not included in this database may have occurred, without having been detected in the present analyses.

Generally, mean catches of polar and temperate species were higher in years of warm winters in the northern part of the species range and in years of cold winters in the LMEs located in the southern part of their range. *T. chalcogramma* had higher catches in warm years in the Northwest Pacific and in cold years in the Southwest Pacific. *M. villosus* also had higher catches in warm years in the LMEs located in the northern part of its range and in cold years in the south. SST is higher in the southern LMEs (East Asian Seas) than in the northern LMEs (e.g. Bering Sea, Gulf of Alaska, Sea of Okhotsk). Warmer winters may result in a shift of polar species to higher latitudes, as the temperatures in the southern LMEs may reach values higher than those species can tolerate. Another important factor influencing the catches is the ice cover extent. The loss of ice cover in polar areas will strongly affect the ecology of those areas and will probably lead to positive effects in fisheries (MacNeil *et al.*, 2010). As ice cover is lost, new open-water areas will probably show a strong increase in primary productivity, which will increase zooplankton abundance and thus fish biomass (MacNeil *et al.*, 2010; Sherman *et al.*, 2009). In the Bering Sea, the winter fishing season for *T. chalcogramma* takes place during the period of maximum seasonal sea-ice extent. However, fishers avoid fishing in ice-covered waters, because vessels cannot physically enter those areas. In warm years, fishing vessels can reach areas which they would generally avoid due to ice cover, resulting in a change in effort. This distribution of winter fishing may shift as the ice cover declines with climate change (Pfeiffer and Haynie, 2012). *M. villosus* has previously been considered an early warning ‘‘canary’’ for climate change, as it appears to react quickly to environmental changes (Rose, 2005a). In fact, changes in *M. villosus* distribution have been reported as drifting at larval stage and as active feeding or spawning range changes of juveniles and adults. Changes in temperature as small as 1 ºC have been associated with changes in this species’ distribution over hundreds of kilometres, and larger changes in temperature may result in much larger shifts in distribution (Rose, 2005a, b). Drinkwater (2005) has studied the response of *G. morhua* to climate change and predicted that, by the year 2100, stocks in the Celtic and Irish Seas would disappear and those in the southern North Sea and Georges Bank would decline. The same author also predicted that *G. morhua* would likely spread northwards along the coasts of Greenland and Labrador, occupy larger areas of the Barents Sea, and even extend onto some of the continental shelves of the Arctic Ocean. In fact, even though distributional shifts have not been visible in the present study – higher catches of *G. morhua* were found in cold years for every LME studied – warming has already led to a northern range expansion of this species in Norway and Greenland (Drinkwater, 2006, 2009). Climate change is expected to lead to fish invasions into high-latitude regions and particularly into the Arctic (Cheung *et al.*, 2009). On the other hand, polar species generally have much narrower temperature limits than lower latitude species, making them highly sensitive to temperature change. Thus, despite the arrival of new species, polar regions may still be susceptible to climate change impact, in terms of biodiversity (Cheung *et al.*, 2009). *C. harengus* has also had higher catches in warm years in the northern LMEs and in cold years in southern LMEs. Like polar species *M. villosus*, this temperate species is considered to react strongly and quickly to climate change due its physiological limits and potential for fast population growth (Rose, 2005b). The same author observed that when Icelandic and Greenland waters warmed considerably in 1920-1940, *C. harengus*, *M. villosus* and *G. morhua* shifted north very quickly. Over the next 50 years, the value of fish production for the most important *C. harengus* stocks is expected to increase by 20 % in Iceland and 200 % in Greenland (Arnason, 2007). Temperate species are generally distributed close to the centre of their thermal tolerance range and thus show a greater capacity to shift ranges (MacNeil *et al.*, 2010). Changes in species composition in temperate regions will be caused by the departure of species moving to higher latitudes and the arrival of warm-water species from lower latitudes (Cabral *et al.*, 2001; Henriques *et al.*, 2007; MacNeil *et al.*, 2010; Vinagre *et al.*, 2011). Distributions of North Sea fishes have responded markedly to increases in sea temperature, with nearly two-thirds of species shifting in mean latitude or depth or both over 25 years (Perry *et al.*, 2005). In biogeographic transition zones, between temperate and subtropical areas, these changes can also be detected in fisheries catches (Gamito *et al.*, 2013). The East Asian Seas, the Subarctic Gyre and the European Seas have rapidly warmed from 1982 to 2006 (Belkin, 2009). The Bering Sea has slowly warmed in 1982–2006 (Belkin, 2009), and global climate models predict further warming and 40 % reduction in winter ice cover by 2050 (Overland and Wang, 2007; Pfeiffer and Haynie, 2012). The present results suggest a future poleward shift in the distribution of catches of polar and temperate species, due to their dislocation to higher latitudes. In polar regions, a reduction in ice cover will also favour an intensification of fishing effort in new open-water areas.

In general, the present study showed higher mean catches of subtropical species in cold years in low latitudes and in warm years in higher latitudes. Although *S. sagax* is known to be more productive during warm-water regimes in the California and the Humboldt Currents (MacCall *et al.*, 2005; Sumaila *et al.*, 2011), the catches analysed in the present study did not reflect that trend for warm-winter years. In fact, mean catch of *S. sagax* in those LMEs was lower in warm-winter years than in cold-winter years. Yet, this result when seen together with the other results obtained for this species agrees with a poleward movement of subtropical species in warm years. Both *T. lepturus* and *S. pilchardus* had higher catches in warm years. Although the analyses of the mean catches of *T. lepturus* included two temperate LMEs and a tropical LME, the results were not different for temperate and tropical LMEs. However, in the tropical LME – South China Sea – the difference between mean catches in cold and warm years was rather small. The analyses of *S. pilchardus* included catches from temperate/subtropical LMEs. In fact, these LMEs are located in a biogeographic transition zone, from temperate to subtropical areas. The northern and southern range limits of *S. pilchardus* are related with the average water temperature, which for this species should be between 10 and 20 ºC (Garza-Gil *et al.*, 2010). In the Portuguese coast, previous studies related decreasing trends in the recruitment of small pelagic populations in the 1980s and 1990s with the increase in upwelling events during winter (Santos *et al.*, 2001). The Celtic-Biscay Shelf, the Iberian Coastal and the Mediterranean LMEs have rapidly warmed in 1982-2006. Garza-Gil *et al.* (2010) have predicted that if the SST in the Iberian-Atlantic fishing grounds followed the current warming trend, lower biomass and catches of *S. pilchardus* would be obtained and therefore the economic yield would also decrease. In the Humboldt Current, warming effects on upwelling dynamics and productivity, related with the El Niño Southern Oscillation, are associated with declines of *E. ringens* (Lehodey *et al.*, 2006). Phases with mainly negative temperature anomalies parallel *E. ringens* regimes (Heileman *et al.*, 2009). The results obtained in the present paper agree with those findings. In the Humboldt Current, the mean catch of *E. ringens* in cold years was higher than in warm years. The Humboldt Current has cooled from 1982 to 2006 (Belkin, 2009). This LME is located in the East Pacific coastal upwelling zone, where the upwelling intensity is near its global maximum; the observed cooling in this LME suggests an increase in the upwelling intensity (Heileman *et al.*, 2009). Upwelling in the Humboldt Current varies with the El Niño, decreasing in warm years and reducing the planktonic food sources for juvenile and adult *E. ringens* (Heileman *et al.*, 2009). Since the frequency of regional climate anomalies, such as El Niño, is expected to increase (Timmermann *et al.*, 1999), devastating consequences could arise for the *E. ringens* fishery.

As temperature influences several life stages of fish species (Pörtner *et al.*, 2001; Pörtner and Peck, 2010), the effects of changes in SST may not always be immediately visible in fisheries catches. The present study analysed fish catches of a large number of species throughout LMEs. If only a few species, with similar life cycles, had been studied, this analysis could have considered a time lag between SST and catches. However, due to the large number of species considered, each with its particular life cycle, it was not possible to define a time lag adequate for every species. Also, the present study used catch data from the Sea Around Us Project database (Pauly, 2007), which is based on the official landings reported annually by the Food and Agriculture Organization of the United Nations (FAO). Therefore, as they exclude unreported landings and discards, landings are in fact underestimates of catches. Also, the lack of information on fishing effort in these databases may be a source of bias in our analysis. However, reported landings are the only data that are collected and made publicly available for fisheries in about 80 % of all maritime countries (Pauly *et al.*, 2013). Despite criticisms on the use of these data to detect and interpret trends in fisheries, several authors (e.g. Froese *et al.*, 2012; Pauly *et al.*, 2013) defend that when only catch data are available, fisheries researchers can and should use these data. In fact, several recent studies have used the Sea Around Us Project database (Cheung *et al.*, 2013; Christensen *et al.*, 2009; Merino *et al.*, 2012; Watson *et al.*, 2013).

The analyses of fish catches in the present study have agreed with a poleward shift of fish species in a warming ocean. A continued warming of the oceans will most likely result in further changes in catch composition throughout the world. The impact of these changes on fisheries may not always be negative, for new fishing opportunities may arise, particularly in temperate and polar regions. On the other hand, food security in tropical regions may be at risk.

Acknowledgements

This study had the support of the Fundação para a Ciência e Tecnologia (FCT) (Pest-OE/MAR/UI0199/2011). Rita Gamito was funded with a PhD Grant (SFRH/BD/78363/2011) by the FCT. We thank Catarina Vinagre for discussions and comments on the manuscript.

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CHAPTER 3

Climate-induced changes in fish landings of different fleet components of Portuguese fisheries

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2013. Regional Environmental Change 13: 413-421

Climate-induced changes in fish landings of different fleet components of Portuguese fisheries

Abstract: For each Portuguese fleet component, landings of biogeographic groups of fish species were compared for the period of 1993-2009. Wide-distribution species were the most abundant in landings, but have shown a decreasing trend. Temperate species had higher landings in trawl fisheries, whereas subtropical species were most abundant and exhibiting an increasing trend in landings of multi-gear fisheries. A latitudinal gradient was observed, with landings of temperate species being more important in the north-western coast than in the south-western and south coasts. Although trawl fisheries were relatively more important in the north-western coast, there has been a recent increase in the relative importance of multi-gear fisheries and of subtropical species in this area. The increasing relative importance of subtropical species in Portuguese fisheries along with the fact that landings of subtropical species were higher in multi-gear fisheries could indicate an easier adaptation of Portuguese multi-gear fisheries to the effects of climate change. However, as multi-gear fisheries include a wide range of gears, techniques and target-species, they may not all respond in the same manner to changes in fish species' distribution. Among multi-gear fisheries, trammel nets catch a wider variety of species and a wider size range than gillnets or longlines; thus, trammel net fishers can adapt to changes in abundance of the main target species more readily than those using more species- and size-specific gears. Therefore, trammel net fisheries could more easily adapt to the effects of climate change on fish distribution than gill net or longline fisheries.

Keywords: fisheries; climate change; fish distribution; fleet components; Portugal

Introduction

Climate change is the most widespread anthropogenic threat for ocean ecosystems (Halpern *et al.*, 2008). The effects of climate change include sea-level rise, sea temperature change, ocean acidification, changes in precipitation and changes in ocean circulation (Brander, 2007). Therefore, climate change impacts ocean organisms, the composition of marine communities and ecosystem function (Brown *et al.*, 2010). The effects of climate change on the marine environment affect fish stocks either directly or indirectly. The direct impacts are mainly physiological and behavioural effects, such as changes in growth, reproduction, mortality and distribution, whereas the indirect impacts are related with changes in productivity and in the structure and composition of marine ecosystems (Brander, 2010; Hare *et al.*, 2010; Perry *et al.*, 2005). Changes in geographical distribution of a species are more easily detected on its northern and southern distribution limits (Brander *et al.*, 2003; Perry *et al.*, 2005). Distribution changes in marine ecosystems can be found throughout the world (Brander *et al.*, 2003; Perry *et al.*, 2005), and modelling methods predict that climate change may lead to local extinctions in the sub-polar and tropical regions, as well as in semi-enclosed seas (Cheung *et al.*, 2009). As most marine commercial species are poikilothermal, their distribution will change depending on sea water temperature, and thus changing species composition in catches (Kim, 2010). The potential consequences of climate change for marine fisheries include large-scale redistribution of fish stocks and productive habitats (Miller *et al.*, 2010) and redistribution of global catch potential, with an average of 30-70 % increase in high-latitude regions and a decrease of up to 40 % in the tropics (Cheung *et al.*, 2010).

The observation of the impact of recent climate change and predictions of climate changes in future scenarios indicate that the effects of climate change will not be homogeneous throughout the world (IPCC, 2001; Santos, 2006). In fact, Southern Europe and Mediterranean regions are more vulnerable to climate change than Central and Northern Europe (Santos, 2006). The Iberian Peninsula is one of the areas where temperature has increased most, and the precipitation in Portugal has been decreasing in intensity and frequency (IPCC, 2001). The Portuguese coast is mainly north-south oriented and is located in a biogeographic transition zone, between temperate and subtropical waters. Therefore, several temperate and subtropical fish species have their southern or northern distribution limit along this coast (Briggs, 1974), making these species particularly vulnerable to climate change. In fact, ecological responses to recent climate change have already been observed in Portuguese waters (Vinagre *et al.*, 2009). Changes in the occurrence of species in these areas have been reported, with an increase in species with tropical affinities and a decrease in temperate species (Cabral *et al.*, 2001; Vinagre *et al.*, 2009). Vinagre *et al.* (2011) studied the impact of climate warming upon the fish assemblages of the Portuguese coast under the A2 and B2 scenarios of the Special Report on Emission Scenarios (Nakicenovic *et al.*, 2000). The B2 scenario envisions a future world with an emphasis on local rather than global solutions to economic, social and environmental problems, and a population that grows continuously, whereas the A2 scenario pictures a profoundly heterogeneous world with a socio-economical and technological fragmented development and a continuously increasing population at a higher rate than in the B2 scenario (Nakicenovic *et al.*, 2000). The regional circulation model HadRM3 predicts, for the scenarios B2 and A2, 1 ºC and 2 ºC of surface water warming, respectively, for the Portuguese coast until the year 2100 (Reis *et al.*, 2006). A general increase in species richness in the Portuguese coast was predicted, with the appearance of new subtropical and tropical species and the elimination of only a few species. The exception was the south coast, where species richness decreased when scenario A2 was considered, with more species being lost than gained (Vinagre *et al.*, 2011).

Portugal is the third highest per capita consumer of fish in the world (Failler, 2007) and thus fishing is an activity of great traditional and cultural importance in this country. There are three main fleet components in the Portuguese fisheries: trawl fisheries, seine fisheries and multi-gear fisheries. The fish species targeted by trawl fisheries are the Atlantic horse mackerel *Trachurus trachurus* (Linnaeus, 1758) and the European hake *Merluccius merluccius* (Linnaeus, 1758), whereas the purse seine fishery targets small pelagic species, particularly the European pilchard *Sardina pilchardus* (Walbaum, 1792), the most important species in terms of total Portuguese landings, and, to a lesser extent, the Atlantic chub mackerel *Scomber colias* Gmelin, 1789. Multi-gear fishery, which is the largest fleet component in Portugal, comprises a wide variety of fishing gears, such as gillnets, trammel nets or longlines. This fleet is mainly artisanal and coastal and targets a wide range of fish species. Also, the same multi-gear vessel can be licensed to operate with several different fishing gears.

Fish populations and ecosystems located in areas most likely to suffer climate change impacts are more at risk (Brown *et al.*, 2010). As the Portuguese coast is located in a biogeographic transition zone (Briggs, 1974) where changes in temperature and precipitation are expected to be more accelerated than the global mean alteration rate (IPCC, 2001), fisheries in the Portuguese coast may be particularly affected by climate change. Therefore, the present study aimed to analyse the trends in annual landings of different biogeographic groups of species in different fleet components of the most important Portuguese fishing ports.

Methodology

Study area

The Portuguese coast is located in south-western Europe. Its western coast is north-south oriented, whereas the southern coast is East-West oriented. In the present study, landings from the ten most important fishing ports in terms of total landings were considered: Matosinhos, Aveiro, Figueira da Foz, Nazaré, Peniche, Setúbal, Sesimbra and Sines in the West coast; Portimão and Olhão in the south coast (Fig. 1).

Data analysis

Fishing data for the period from 1993 to 2009 were obtained from official Portuguese landings. For each of the fishing ports considered, landing data included species caught, weight, year, number of fishing days and fleet component. Landings Per Unit of Effort (LPUE) were calculated as t.fishing day^{-1} and will be referred to as t.day^{-1} hereinafter. Fishing ports were compared in terms of percentages of LPUE for each fleet component. Species were classified based on biogeography (temperate, subtropical or tropical), according to Fishbase (Froese and Pauly, 2012). Data on species geographical distribution limits were collected from Fishbase (Froese and Pauly, 2012). Five groups of species were established, according to their biogeography and distribution limits: (1) temperate species which southern limit is in the Portuguese coast (TP); (2) temperate species with Western Sahara as southern limit (TWS); (3) subtropical species which northern limit is in the Portuguese coast (SP); (4) subtropical species with the Bay of Biscay as its northern limit (SBB); and (5) species having a wider distribution than the previous groups (WIDE). Trends in landings of these 5 groups of species were compared. Monthly data on the North Atlantic Oscillation (NAO) index, based on the pressure difference between Lisbon and Reykjavik, were taken from the United States of America NOAA National Weather Service database (http://www.cpc.noaa.gov). The average value of NAO index was calculated for each year studied. Sea surface temperature (SST) monthly data were collected from the ICOADS database, and monthly precipitation data were provided by the Portuguese Water Institute (INAG – http://snirh.inag.pt). Both precipitation and SST were averaged for each year considered.

Percentages of LPUE of the groups of species were comparatively analysed using principal components analyses (PCA) for each fleet component. The PCA aimed to highlight the similarities among years in terms of these groups. These analyses were carried out using the software Canoco 4.5 (ter Braak and Smilauer, 2002).

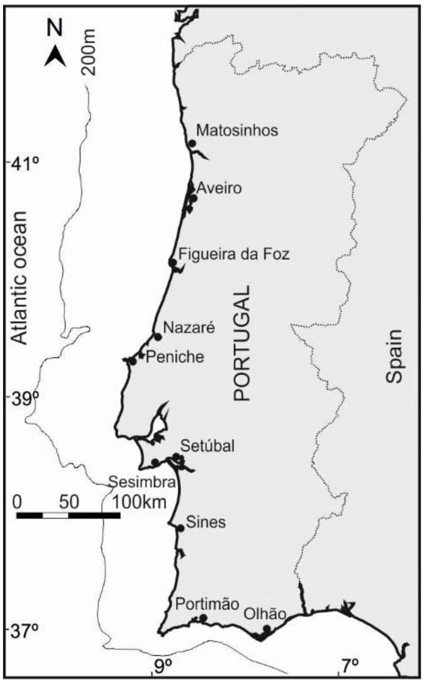

Fig. 1 Location of the ten ports studied along the Portuguese coast.

Results

Mean surface temperature (SST), precipitation and North Atlantic Oscillation (NAO) index in the Portuguese coast are presented in Fig. 2. Mean SST increased from 1993 (16.6 ºC) to 2000 (17.8 ºC), decreased until reaching the minimum value of 16.9 ºC in 2005 and increased again until reaching a maximum of 17.9 ºC in 2009 (Fig. 2a). The variability of SST has also generally been increasing along the years, whereas the variability of precipitation has been decreasing since 2002 (Fig. 2b). Mean precipitation varied between 3,692 and 4,912 mm in the period of 1993-1997 and dropped to 2,705 mm in 1998; in the following 3 years, it increased and reached 3,806 mm in 2001. In the period from 2002 to 2009, the mean precipitation has generally been between 1,000 and 2,000 mm, except for 2006, when it reached 3,165 mm. The mean North Atlantic Oscillation index varied along the years studied (Fig. 2c). In the years 1995-1998, 2001, 2005, 2006, 2008 and 2009, this index was negative, whereas in the remaining years was positive.

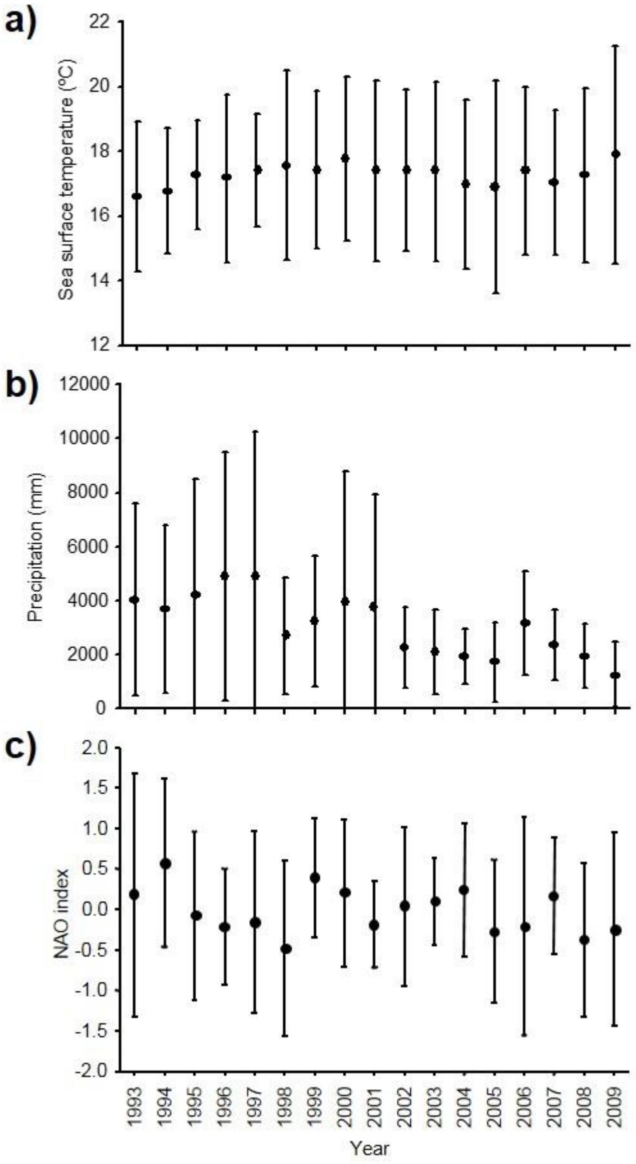

Fig. 2 Sea surface temperature (a), precipitation (b) and North Atlantic Oscillation index (c) for each year (mean ± SD), based on monthly data.

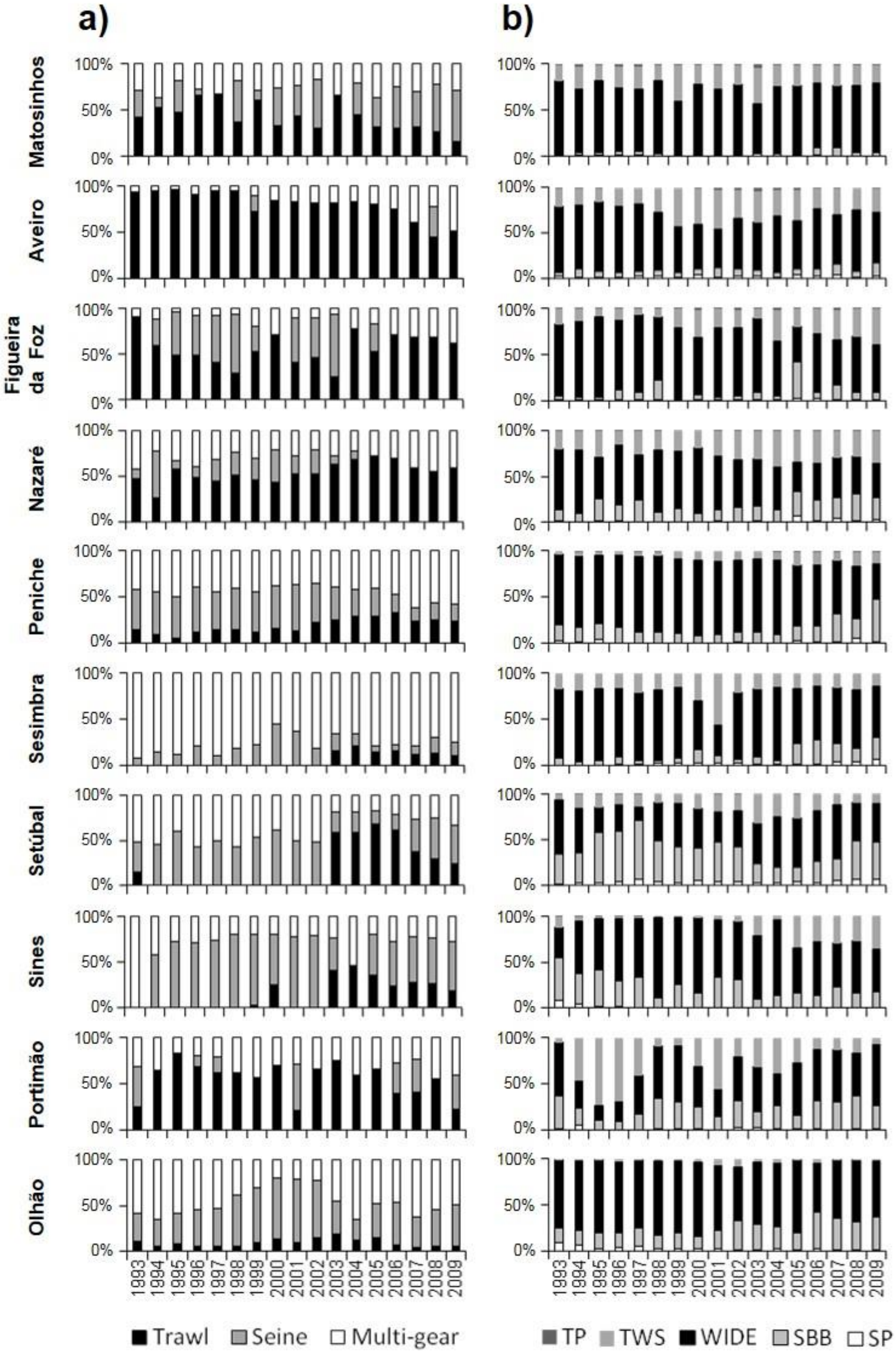

Fig. 3 Total annual percentage of LPUE of a) trawl, seine and multi-gear fisheries and b) biogeographical groups in the period of 1993-2009 for the fishing ports of Matosinhos, Aveiro, Figueira da Foz, Nazaré, Peniche, Setúbal, Sesimbra, Sines, Portimão and Olhão (TP – temperate species with their southern limit in the Portuguese coast; TWS – temperate species with their southern limit in Western Sahara; WIDE – wide-distribution species; SBB – subtropical species with their northern limit in the Bay of Biscay; SP – subtropical species with their northern limit in the Portuguese coast).

The composition of landings varied along the Portuguese coast, both in the proportion of fleet component responsible for the catches and the biogeographical groups landed (Fig. 3). As shown in Fig. 3a, in the north-western Portuguese coast, the highest percentages of LPUE were generally found in trawl fisheries. However, there has been a slight declining trend of the relative importance of this fleet component in recent years. In the south-western fishing ports, multi-gear fisheries have generally the highest percentage of LPUE. In Portimão, the highest percentages of LPUE belonged to trawl fisheries, whereas in Olhão seine, fisheries had the highest relative importance in terms of fleet components. Landings of wide-distribution species were generally the highest (Fig. 3b). As expected, the north-western coast had higher landings of temperate species than of subtropical species, whereas the opposite relation was observed in the south. Nevertheless, an increase in the relative importance of subtropical species in recent years could also be found, particularly in the north-western coast.

Regarding mean LPUE, wide-distribution species were the most abundant in landings, ranging from 28.6 t.day^{-1} in trawl fisheries to 38.9 t.day^{-1} in seine fisheries (Fig. 4). Generally, landings of temperate species were higher in trawl fisheries (15.2 t.day^{-1} for TWS and 0.3 t.day^{-1} for TP), whereas the highest values of LPUE of subtropical species were observed in multi-gear fisheries (1.7 t.day^{-1} for SP and 9.17 t.day^{-1} for SBB).

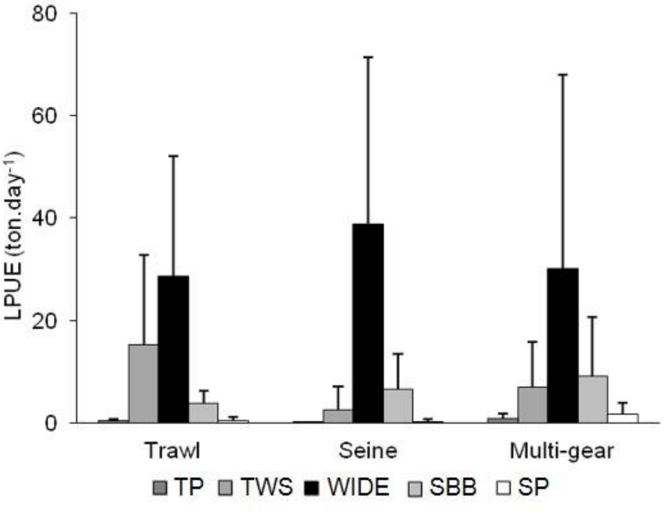

Fig. 4 Average LPUE of the groups of species in the trawl, seine and multi-gear fisheries (TP – temperate species with their southern limit in the Portuguese coast; TWS – temperate species with their southern limit in Western Sahara; WIDE – wide-distribution species; SBB – subtropical species with their northern limit in the Bay of Biscay; SP – subtropical species with their northern limit in the Portuguese coast).

Trends in annual LPUE of the five groups of species are presented in Fig. 5. For the three fleet components, landings of wide-distribution species showed a decline in the period from 1993 to

2009: from 401.3 to 135.1 t.day^{-1} in trawl fisheries; from 31.1 to 28.1 t.day^{-1} in seine fisheries and from 50.9 to 30.1 t.day^{-1} in multi-gear fisheries. Regarding temperate species, the values of LPUE have generally kept stable along the years, regardless of the fleet component. In trawl fisheries, LPUE of TWS was 101.0 t.day^{-1} in 1993, peaked in 1996 (240.0 t.day^{-1}) and decreased to 115.4 t.day^{-1} in 2009. In seine fisheries, TWS showed a LPUE of 13.2 t.day^{-1} in 1993 and of 13.0 t.day^{-1} in 2009, with a peak (85.5 t.day^{-1}) in 2001. In multi-gear fisheries, TWS remained almost constant from 1993 (80.8 t.day^{-1}) to 2009 (88.2 t.day^{-1}). The LPUE of subtropical species have generally been stable along the years, both in trawl and seine fisheries. However, in multi-gear fisheries, the landings of this biogeographic group have increased in recent years, particularly for SBB.

Concerning the principal components analyses performed to assess the similarities among years, the first two ordination axes had a cumulative variance of 99.7 % in trawl fisheries and 99.4 % both in seine and multi-gear fisheries. The ordination diagrams of the first two axes are presented in Fig. 6. In trawl fisheries (Fig. 6a), years 2007, 2008 and 2009 were strongly associated with SBB. Two main groups of sampled years can be observed in the seine fisheries diagram (Fig. 6b): one group associated with group 1 and a wider group of samples related with subtropical species, both of group 3 and group 4. In multi-gear fisheries (Fig. 6c), the vectors of subtropical species could both be found in the upper right quadrant of the diagram, whereas the temperate species vectors were drawn in the section below; the vector of wide-distribution species was observed in the lower left section of the diagram. There were two larger groups of sampled years, one associated with wide-distribution species and another with subtropical species, and a smaller and more scattered group around the temperate species vectors.

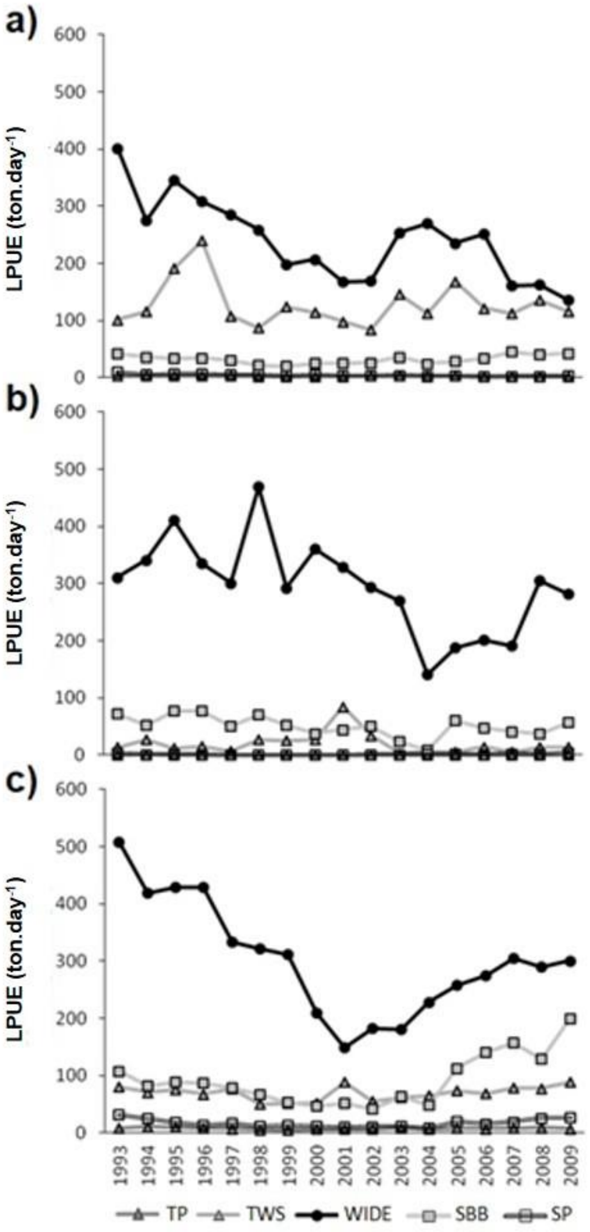

Fig. 5 Annual LPUE of the five groups of species in the a) trawl; b) seine and c) multi-gear fisheries, for the period of 1993-2009 (TP – temperate species with their southern limit in the Portuguese coast; TWS – temperate species with their southern limit in Western Sahara; WIDE – wide-distribution species; SBB – subtropical species with their northern limit in the Bay of Biscay; SP – subtropical species with their northern limit in the Portuguese coast).

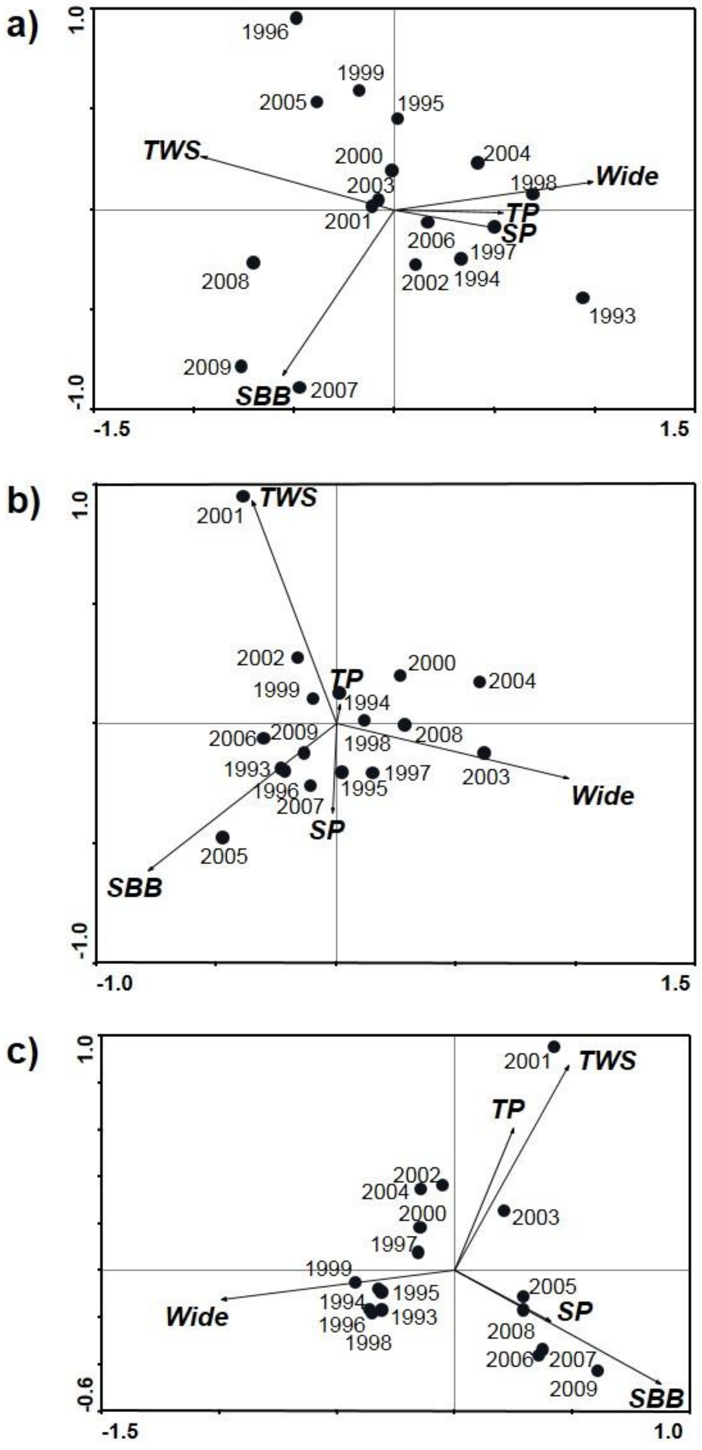

Fig. 6 Ordination plots of principal component analyses for A) trawl fisheries; B) seine fisheries; multi-gear fisheries. Years are indicated. Vectors for biogeographical groups of species (TP – temperate species with their southern limit in the Portuguese coast; TWS – temperate species with their southern limit in Western Sahara; WIDE – wide-distribution species; SBB – subtropical species with their northern limit in the Bay of Biscay; SP – subtropical species with their northern limit in the Portuguese coast) are represented.

Discussion

The present study was the first to analyse the effects of climate change on the Portuguese fishing fleet components. Despite being the most abundant group in landings, wide-distribution species decreased from 1993 to 2009. Temperate species had higher landings in trawl fisheries, whereas subtropical species were most abundant and exhibiting an increasing trend in landings of multi-gear fisheries. Along the Portuguese coast, a latitudinal gradient could be distinguished, with landings of temperate species being more important in the north-western coast than in the south-western and south coasts. Although trawl fisheries were relatively more important in the north-western coast, there has been a recent increase in the relative importance of multi-gear fisheries and of subtropical species in this area.

Generally, wide-distribution species were the most abundant in landings, particularly in seine and trawl fisheries, although exhibiting a declining trend from 1993 to 2009. This result could have been expected, as these two fisheries mainly target wide-distribution species, *S. pilchardus* and *T. trachurus*, which have shown a decline in the last decades (Borges *et al.*, 2003; Sousa *et al.*, 2007). Landings of temperate species were higher in trawl fisheries, whereas the highest values of landings of subtropical species were found in multi-gear fisheries and have been increasing in recent years. This increasing trend in the proportion of landings of subtropical species in multi-gear fisheries could also be observed in the principal component analysis. In fact, there were high landings of subtropical species in most recent years (from 2005 to 2009). Those years registered high sea surface temperature and climate change may have caused geographical distribution shifts which could have resulted in a recent adaptation of the fishing activity, with fishers focusing on subtropical species. Portuguese multi-gear fisheries use a wide variety of gears, exploiting resources in different habitat types, depths and substrata (Duarte *et al.*, 2009). The fishing practices of this fleet component vary both in space and time: a given fleet may change its target species, fishing gear or fishing location over a timescale of weeks or months (Duarte *et al.*, 2009; Teixeira *et al.*, 2011). Therefore, the composition of landings of this fleet component varies with the fishing gear used and the ecological community of the fishing grounds visited (Duarte *et al.*, 2009). The decision on whether to change target species and gear depends on several factors, such as resource abundance, commercial value, information from other fishers, weather conditions, distance to fishing grounds, cultural aspects and fisheries management measures (Christensen and Raakjær, 2006). In a case study of Danish demersal fisheries, Christensen and Raakjær (2006) found that the most important factors influencing the tactical behaviour of fishers were information from the last fishing trip and current fish prices, followed by their experience of what they had done at the same time the previous year, the winds and the currents. Thus, with the abundance of subtropical species increasing in recent years along the Portuguese coast, fishers naturally altered their behaviour and adapted their activity to these changes in fish species' distribution.

A latitudinal gradient could be observed along the Portuguese coast: landings of temperate species were relatively more important in the north-western coast than in the south-western and south coasts. However, an increase in the relative importance of multi-gear fisheries and of subtropical species could also be found in the north-western coast in recent years, which could also indicate an adaptation of the fishing activity to the effects of climate change. Furthermore, trawl fisheries, which are more important in the north-western coast, also presented an increase in the relative proportion of subtropical species in recent years.

Seine fisheries target *S. pilchardus*, which is the most important fishing resource in Portugal. Therefore, the results are difficult to interpret for this fishery, as they may mostly reflect the inter-annual variability of this species' landings. Nevertheless, the principal component analysis showed that, besides wide-distribution species (*S. pilchardus*), many sampled years were associated with the vectors of subtropical species. A study on the economic effects of climate change on the European sardine fishery has shown that as the sea surface temperature of the Iberian-Atlantic fishing grounds rises, lower biomass and catch levels are obtained, resulting in a decrease in the economic yield (Garza-Gil *et al.*, 2010). The economic losses will be higher for Portugal than for Spain, as the Portuguese catches represent more than 70 % of the total landings of this fishery (Garza-Gil *et al.*, 2010). The adaptation of fishers to the effects of climate change is therefore of the utmost importance for the survival of the fishing activity in Portugal.

There has been a decline in the LPUE of wide-distribution species, from 1993 to 2009. Subtropical species have generally been stable along the years in trawl and seine fisheries and have increased in multi-gear fisheries, in recent years. Therefore, the relative importance of subtropical species has been increasing in Portuguese fisheries. On the other hand, the present study has shown that the landings of subtropical species were higher in multi-gear fisheries. The combination of these two facts may indicate an easier adaptation of Portuguese multi-gear fisheries to the effects of climate change.

The consequences of climate change on fishing communities will be determined by their climate change exposure, the sensitivity to climate change in terms of targeted species and the ecosystem and the fishers' ability to adapt to change (Grafton, 2010). This author defends that artisanal fishers who harvest in a very limited geographical area are likely to be less able to adapt and more vulnerable to climate change than more mobile fishers with an ability to catch different species with different gears over a wide geographical area. As the Portuguese multi-gear fleets use a diversity of gears that allow exploitation of ecological communities in different habitat types, depths and substrata, the composition of the landings will strongly depend on the fishing gear used and on the ecological community of the fishing grounds visited (Duarte *et al.*, 2009). Thus, if the ecological community changes under the effects of climate change, the fishing activity of the Portuguese multi-gear fleet may also adapt to the change. Additionally, as the renewal of licenses of the Portuguese multi-gear fishery depends on proof of sale at auction of a minimum number of landings in the previous year, there is an annual adaptation of the fishing activity which could reflect the effects of climate change on fishing resources.

Nevertheless, as multi-gear fisheries include a wide range of gears, techniques and target species, they may not all respond in the same manner to changes in fish species' distribution. This small-scale fishing fleet is mainly artisanal and coastal and targets a wide range of fish species. Also, the same multi-gear vessel can be licensed to operate with several different fishing gears, alternating them according to the availability of resources. Small-scale fisheries are highly heterogeneous in terms of the fate of their landings, fishing gears used, fishing strategies and *métiers* (Stergiou *et al.*, 2006). Trammel nets are widely used throughout the world in small-scale fisheries, targeting several demersal and benthic species such as soles, sea breams, red mullets, skates, shrimps, lobsters and cuttlefish (Erzini *et al.*, 2006; Gonçalves *et al.*, 2008). Trammel nets catch a wider variety of species and a wider size range than gillnets or longlines, thus they are widely used in southern European waters (Erzini *et al.*, 2006, 2010; Stergiou *et al.*, 2006). For this reason, trammel net fishers can adapt to changes in abundance of the main target species more readily than those using more species- and size-specific gears (Gonçalves *et al.*, 2007). Moreover, trammel net fisheries of southern European waters show a multi-species character, with an important part of the catch being composed of a bycatch of both other demersal species and small- or medium-sized pelagic species (Stergiou *et al.*, 2006). Therefore, trammel net fisheries could more easily adapt to the effects of climate change on fish distribution than gill net or longline fisheries.

Although the long-term impact of climate change may be very large, it is also very uncertain (Brander, 2010). Therefore, besides not being homogeneous along the Portuguese coast, the adaptation of fishing communities to climate change can also be very uncertain in time.

Acknowledgements

This study had the support of the Portuguese Fundação para a Ciência e Tecnologia (FCT) through the grants awarded to R. Gamito (SFRH/BD/78363/2011) and C.M. Teixeira (SFRH/BPD/62986/2009).

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CHAPTER 4

Are regional fisheries' catches changing with climate?

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2015. Fisheries Research, 161: 207-216

Are regional fisheries' catches changing with climate?

Abstract: Climate change affects ocean conditions, which will in turn impact marine organisms and ecosystems, with consequences for fisheries. The Iberian Peninsula has faced an increase in both air and sea surface temperature, and rainfall has decreased in intensity and frequency in Portugal. As Portugal is the third highest per capita consumer of fish in the world and its coast is located in a biogeographic transition zone, between temperate and subtropical waters, the study of the effects of climate change on Portuguese fisheries is of the utmost importance. The present work focused on Setúbal, an important fishing port in central Portugal. Landings Per Unit of Effort (LPUE) time series (1927-2012) of the most important species were analysed and their relationships with sea surface temperature (SST), rainfall and the winter North Atlantic Oscillation (NAO) index were investigated. Mean annual SST has increased 0.9 ºC from 1926 to 2012. The main target species in 2012 were the same as in 1927. However, their landings have changed and have responded to changes in environmental variables, particularly SST. LPUE of the European sardine has shown a decreasing trend and was negatively correlated with SST and NAO, whereas the LPUE of the Atlantic chub mackerel has been increasing since 2000. The LPUE of the common cuttlefish has kept more or less stable through the studied time series, but it was correlated with SST. The LPUE of soles has increased with time and SST. The LPUE of the common octopus was correlated with SST and NAO and has presented higher values since 1975. Further increases in sea temperature in the future will pose challenges for fisheries in Setúbal. Purse-seine fisheries may try to compensate the expected losses in sardine landings by targeting the chub mackerel. Although landings of the most important species in multi-gear fisheries seem to have been favoured by increases in temperature, further studies on the tolerance of each particular species to increases in temperature are needed. As a recent increase in the relative importance of subtropical species in Portuguese fisheries has already been previously detected, climate change may also bring new fishing opportunities for this region.

Keywords: climate change; sea surface temperature; fisheries; NAO; Portugal

Introduction

Climate change is the most widespread anthropogenic threat for ocean ecosystems (Halpern *et al.*, 2008), affecting sea temperature, sea-level, ocean pH, rainfall and ocean circulation (Brander, 2007). These effects of climate change on ocean conditions will have an impact on ocean organisms, the composition of marine communities and ecosystem function (Brown *et al.*, 2010), increasing the complexity of the challenges facing fisheries (Sumaila *et al.*, 2011). Climate change impacts fish stocks either directly or indirectly. The direct impacts are mainly physiological and behavioural effects, such as changes in growth, reproduction, mortality and distribution; the indirect impacts are related with changes in productivity and in the structure and composition of marine ecosystems on which fish depend (Brander, 2010; Hare *et al.*, 2010; Perry *et al.*, 2005). Changes in the geographic distribution of fish species have already been documented throughout the world and are more easily detected on its northern and southern distribution limits (Brander *et al.*, 2003; Perry *et al.*, 2005). Several studies have predicted that changes in water temperature, driven by climate change, may lead to local extinctions and also to colonization by species previously absent in those areas (Cheung *et al.*, 2009; Vinagre *et al.*, 2011), which will most likely affect the abundance, distribution and composition of fisheries catches (Gamito *et al.*, 2013; Sumaila *et al.*, 2011).

The observation of the impact of recent climate change and predictions of climate changes in future scenarios indicate that the effects of climate change will not be homogeneous throughout the world (IPCC, 2007; Santos, 2006). Southern Europe and the Mediterranean are more vulnerable to climate change than Central and Northern Europe (Santos, 2006). The Iberian Peninsula is one of the areas where air temperature has increased most (IPCC, 2007) and the Iberian Coastal large marine ecosystem has suffered a rapid warming, with an increase of 0.68 ºC in sea surface temperature from 1982 to 2006 (Belkin, 2009). In Portugal, there has also been a decrease in the intensity and frequency of rainfall (IPCC, 2007). The Portuguese coast, mainly north-south oriented, is located in a biogeographic transition zone, between temperate and subtropical waters, where several temperate and subtropical fish species have their southern or northern distribution limit (Briggs, 1974). Ecological responses to recent climate change have already been observed in Portuguese waters (e.g. Vinagre *et al.*, 2009). An increase in the occurrence of species with tropical affinities and a decrease in temperate species have been reported (Cabral *et al.*, 2001; Vinagre *et al.*, 2009). Vinagre *et al.* (2011) studied the impact of climate warming upon the fish assemblages of the Portuguese coast under future emission scenarios (Nakicenovic *et al.*, 2000) and predicted a general increase in species richness, with the appearance of new subtropical and tropical species and the elimination of only a few species.

Fishing is an activity of great traditional and cultural importance in Portugal, the third highest per capita consumer of fish in the world (Failler, 2007). There are three main fleet components in Portuguese fisheries: trawl fisheries, purse-seine fisheries and multi-gear fisheries. The main targets of trawl fisheries are the Atlantic horse mackerel *Trachurus trachurus* (Linnaeus, 1758), the European hake *Merluccius merluccius* (Linnaeus, 1758) and cephalopods, whereas the purse-seine fishery targets small pelagic species, particularly the European sardine *Sardina pilchardus* (Walbaum, 1792), the most important species in terms of total Portuguese landings, the Atlantic chub mackerel *Scomber colias* Gmelin, 1789 and the Atlantic horse mackerel. Multi-gear fishery is the largest fleet component in Portugal, using a wide variety of fishing gears, such as gillnets, trammel nets, longlines and traps. In the central coast of Portugal, the main targets of multi-gear fisheries are soles, the common cuttlefish *Sepia officinalis* Linnaeus, 1758 and the common octopus *Octopus vulgaris* Cuvier, 1797.

Fish populations and ecosystems located in areas most likely to suffer climate change impacts are more at risk (Brown *et al.*, 2010). Not only is the Portuguese coast expected to suffer changes in temperature and precipitation more accelerated than the global mean alteration rate (IPCC, 2007), but it is also located in a biogeographic transition zone (Briggs, 1974). Therefore, this coast is particularly adequate for studies on the effect of climate change on fisheries. In fact, an increase in the relative importance of landings of subtropical fish species (Gamito *et al.*, 2013) and higher landings of subtropical species and lower landings of temperate species in warm years (Teixeira *et al.*, 2014) have already been reported for the Portuguese coast. Gamito *et al.* (2013) have also detected higher landings of subtropical species in multi-gear fisheries, which could indicate an easier adaptation of Portuguese multi-gear fisheries to the effects of climate change. However, it is yet to determine how these changes in the composition of landings will affect the landings of the most traditionally important species in local fisheries. Thus, the aim of the present study was to analyse trends in landings of the most important commercial species of different fleet components, using long time-series (1927-2012), and to relate them with trends in environmental variables. The study focused on Setúbal, an important fishing port in the central coast of Portugal, where landings cover a wide variety of commercial species and multi-gear fisheries are particularly relevant.

Methodology

Study area

The Portuguese coast is located in south-western Europe, with a north-south oriented western coast and an east-west oriented southern coast. The port of Setúbal was chosen for this study due to its location in the centre of the western Portuguese coast (Fig. 1), in a biogeographic transition zone.

Data source

Fishing data for the period of 1927 to 2012 were obtained from official Portuguese landings. Landing data included species caught, year and number of active fishing vessels. Fleet component and fishing gear were also available for the period of 1992-2012. Monthly data on the North Atlantic Oscillation (NAO) index, based on the pressure difference between Lisbon and Reykjavik, were taken from the United States of America NOAA National Weather Service database (http://www.cpc.noaa.gov). Sea surface temperature (SST) monthly data for a 2º x 2º grid centred in Setúbal were collected from the International Comprehensive Ocean- Atmosphere Data Set (ICOADS) database (http://icoads.noaa.gov). Annual rainfall data taken at the Moinhola station were provided by the Portuguese Water Resources Information System (http://snirh.pt).

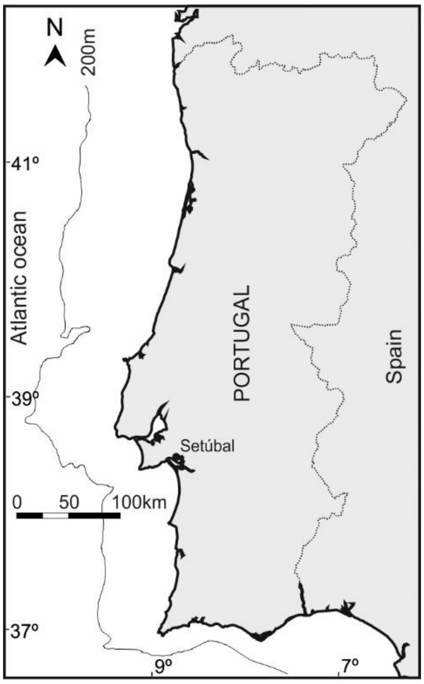

Fig. 1 Location of the port studied – Setúbal – on the Portuguese coast.

Data analysis

Annual mean SST was obtained by averaging monthly values for each year. Annual winter NAO indices were calculated by averaging the indices obtained for winter months (December-February). When analysing fisheries data, fishing effort should be taken into account. Several effort estimators have been used in previous studies, such as number of fishing days, number of fishing hours, number of vessels, vessel size or vessel power (e.g. Engelhard *et al.*, 2013; Ligas *et al.*, 2010; Tzanatos *et al.*, 2013). In the present study, the most reliable effort estimator available for the entire time series was the number of active fishing vessels in the studied area. Although this proxy to the real effort may be biased, it is expected that this bias is stable over a large number of years, not compromising the analysis of LPUE in the present work. Therefore, landings per unit of effort (LPUE) were calculated as t.vessel^{-1}. LPUE of the six most important species, both in terms of biomass and value, were analysed. Those species were: European sardine (*S. pilchardus*); Atlantic chub mackerel (*S. colias*); Atlantic horse mackerel (*T. trachurus*); common cuttlefish (*S. officinalis*) and common octopus (*O. vulgaris*). Senegalese sole *Solea senegalensis* Kaup, 1858, common sole *Solea solea* (Linnaeus, 1758) and bastard sole *Microchirus azevia* (de Brito Capello, 1867) were grouped together as soles, as the 1927-1991 dataset did not discriminate each of these species. For the period of 1992-2012, LPUE was also analysed in terms of fishing gear used. As trawl vessels operate along the entire Portuguese coast and land their catches in several fishing ports, regardless of where species were actually caught, this analysis excluded trawl fishery landings. Four groups of fishing gear were thus considered: purse-seine, nets (comprising both gill and trammel nets), bottom longline and traps. Most vessels that use traps for catching common cuttlefish also use trammel nets. For that reason, it was impossible to discriminate landings of cuttlefish caught in traps from the ones caught in trammel nets and therefore the category “nets” also includes some cuttlefish caught using traps.

A correlation of a variable with itself at different points in time is known as autocorrelation or serial correlation (Cowpertwait and Metcalfe, 2009). The autocorrelation function consists of the Pearson correlation of a time series with itself with a lag of *k* years, thus representing the overall association between points that are *k* years separated (Zuur *et al.*, 2007). The autocorrelation function can indicate a pattern in a time series. For example, an auto-correlation that shows a slow decrease with increasing time lags may indicate a trend in the time series (Zuur *et al.*, 2007). A variable can also be correlated with another variable at different time lags (Cowpertwait and Metcalfe, 2009). The cross-correlation function is also based on the Pearson correlation function and quantifies the association between two variables with a time lag of *k* years (Zuur *et al.*, 2007). Auto-correlations and cross-correlations between time series of environmental variables (SST, rainfall and NAO) and of LPUE were investigated with the “acf” R function, able to deal with missing values.

Relationships between LPUE of each of the considered species and each of the environmental variables (SST, rainfall and NAO) were tested with Spearman rank correlation coefficient. As the effects of environmental variables are stronger on early life stages, they will influence recruitment success and subsequently LPUE of later years. In this analysis, time-lags based on the available knowledge on age at first maturity were considered: 2 years for European sardine, Atlantic chub mackerel and Atlantic horse mackerel (Abaunza *et al.*, 2003; Martins, 2007; Silva *et al.*, 2006); 3 years for soles (Teixeira and Cabral, 2010; Teixeira *et al.*, 2009, 2010); and 1 year for the common octopus and the common cuttlefish (Katsanevakis and Verriopoulos, 2006a; Neves *et al.*, 2009).

When first exploring the data, a higher LPUE of chub mackerel in years of lower LPUE of sardine was observed. Thus, the relationship between the LPUE of these two species was tested with Spearman rank correlation coefficient.

All the analyses were performed on the environment R (R Core Team, 2012).

Results

Mean annual SST has increased 0.9 ºC in 86 years (Fig. 2a). The lowest temperature was recorded in 1934 (15.4 ºC), and 2006 was the warmest year, with mean SST reaching as high as 18 ºC. Despite showing high inter-annual variability, annual rainfall has been lower in the 2000s (Fig. 2b). Winter NAO index has decreased from 1950 to 1970 and increased from 1980 to 2012 (Fig. 2c). Nevertheless, this index has presented a high inter-annual variability; the minimum value (−2.12) has been recorded in 2010 and 1995 had the highest value (1.07).

Landings have shown marked inter-annual variability (Fig. 3). European sardine had high LPUE in the 1930s and early 1940s, reaching a maximum of 95.8 t.vessel^{-1} in 1936. In 1945, landings of this species suffered a huge decline and have kept under 20 t.vessel^{-1} from 1948 to 2012. Atlantic chub mackerel had higher LPUE, reaching more than 12 t.vessel^{-1}, in the 1960s and 1970s, followed by lower landings in the following years and a slight increase since 2000. Landings of Atlantic horse mackerel were usually below 6 t.vessel^{-1}, except for two peaks in 1941-1944 and 1961-1965, when LPUE reached more than 10 t.vessel^{-1}. Although high inter-annual variability could be observed, the LPUE of the common cuttlefish has kept fairly stable along the time series, around 0.7 t.vessel^{-1}. The maximum value was observed in 1935 (1.3 t.vessel^{-1}) and the lowest landings were registered in 1981 (0.1 t.vessel^{-1}). Landings of soles have shown an increasing trend through the time series, from 0.07 t.vessel^{-1} in 1927 to 0.2 t.vessel^{-1} in 2012. Despite having shown high inter-annual variability, landings of the common octopus were higher in the period of 1975-2012 than in 1927-1970. In fact, the lowest LPUE was recorded in 1969 (0.02 t.vessel^{-1}) and the highest in 1987 (0.6 t.vessel^{-1}).

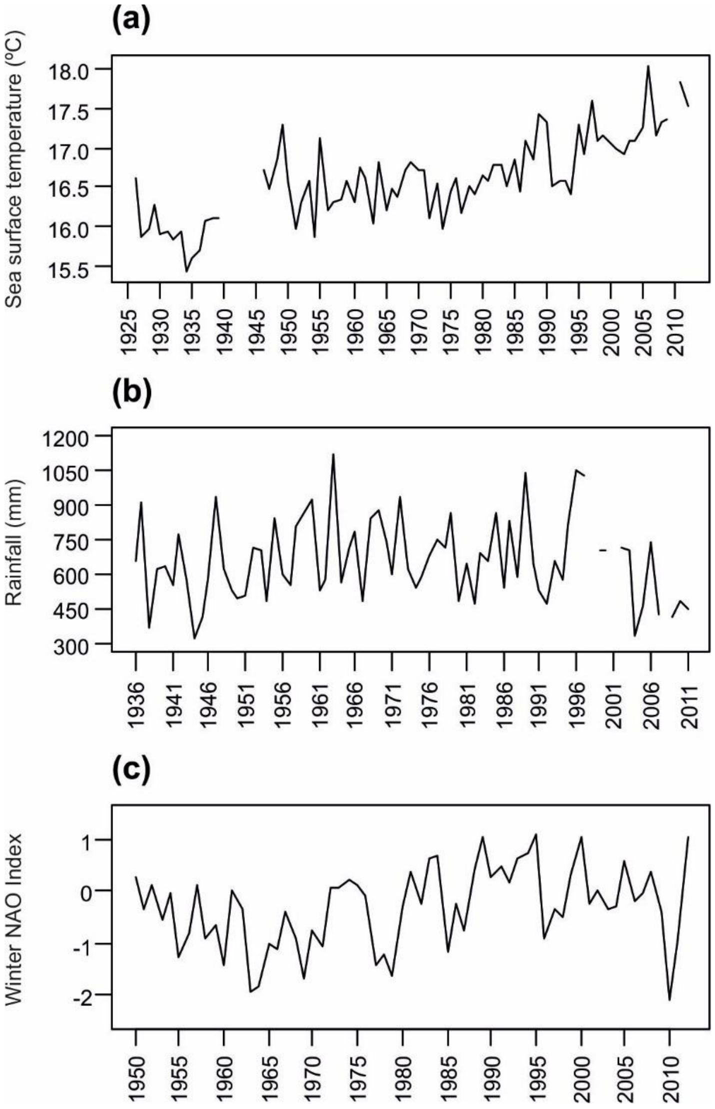

Fig. 2 Annual mean sea surface temperature (a), annual rainfall (b) and winter mean NAO index (c), based on monthly data.

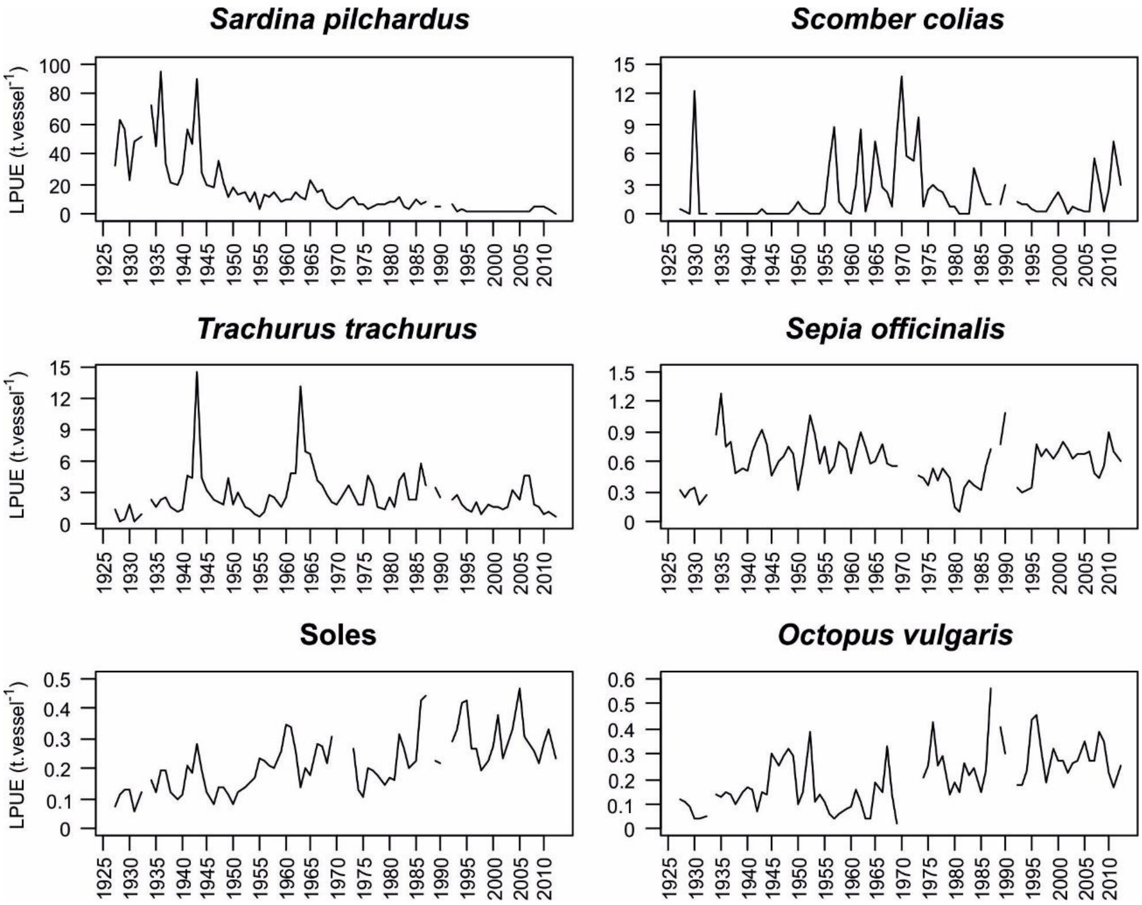

Fig. 3 Annual LPUE of the six studied species landed in Setúbal.

Fig. 4 depicts landings of each of the considered species/group of species per fishing gear, for the period of 1992-2012. Sardine, chub mackerel and horse mackerel were mostly caught by purse-seine fisheries, through the whole time series. A small fraction of LPUE of these pelagic species was caught with nets; for sardine, this fraction has increased in recent years. Although bottom longline fisheries presented landings of common cuttlefish through the entire time series, this species was mainly landed by vessels using nets. Soles were almost entirely landed by vessels operating with nets; the amount of LPUE caught by bottom longline fisheries was negligible and for that reason, not visible in the figure. Nets, bottom longline and traps were responsible for landings of common octopus. However, their relative importance has changed with time: in the beginning of the time series, nets had the highest LPUE; LPUE of traps increased with time and from 2003 on became the highest.

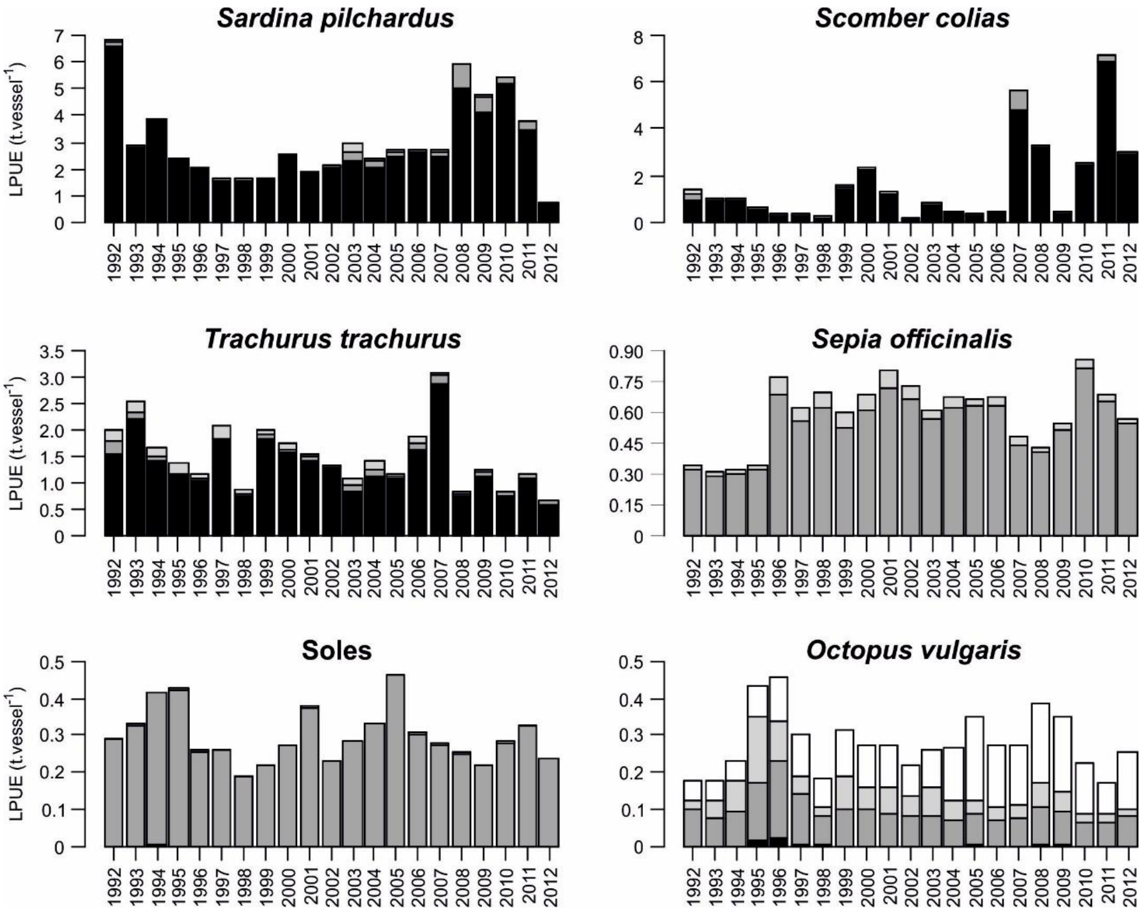

Fig. 4 Annual LPUE of the six studied species, caught using purse-seine, nets, bottom longline and traps, and landed in Setúbal (black bars – purse-seine; dark gray bars – nets; light gray bars – bottom longline; white bars – traps).

Autocorrelation for the SST time series was particularly high for lags of 1-5 years (Fig. 5). The autocorrelation of rainfall was very low for every lag considered and NAO index had an autocorrelation of 0.371 for a lag of 1 year. In general, autocorrelations in the LPUE of the species studied were particularly high for lags of 1-2 years, except for the chub mackerel, which only showed a strong autocorrelation for a lag of 1 year.

Cross-correlations between the time series of rainfall and LPUE were generally low (Fig. 6). The sardine LPUE time series was negatively correlated with SST and NAO; cross-correlations with SST were particularly high for time lags of 0-5 years. Cross-correlations of the LPUE of chub mackerel and horse mackerel with SST and NAO were weak. The common cuttlefish was positively correlated with SST and negatively correlated with NAO. Soles landings showed strong positive correlation with SST, particularly for time lags of 0-5 years; these landings were also positively correlated with the NAO index time series. The LPUE of common octopus were also positively correlated with SST and NAO.

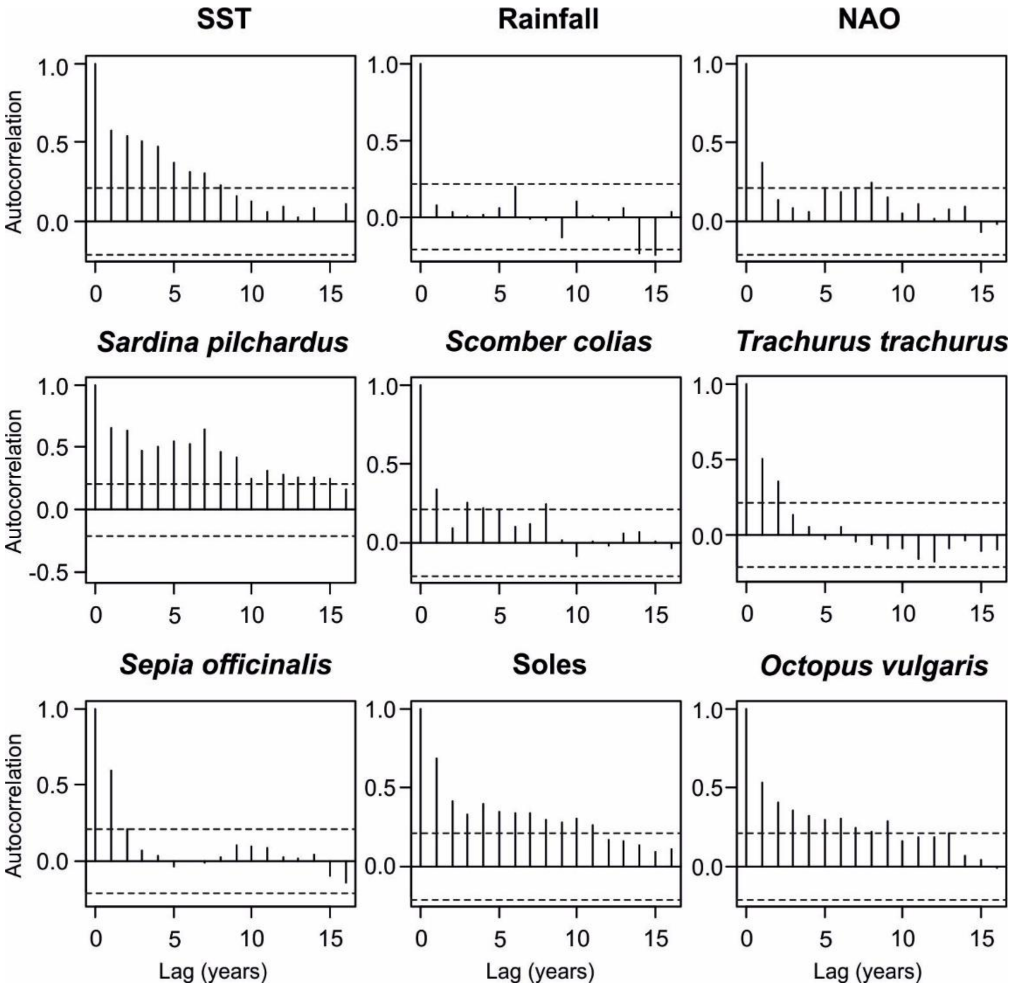

Fig. 5 Correlograms of SST, rainfall, winter NAO index and LPUE of the six studied species (dashed lines represent significance limits at the 5 % level).

LPUE of European sardine, soles, common cuttlefish and common octopus were significantly correlated with SST and/or NAO index ($p < 0.05$). SST was negatively correlated with the LPUE of European sardine ($\rho = -0.60$) and positively correlated with the LPUE of soles ($\rho = 0.37$), cuttlefish ($\rho = 0.32$) and common octopus ($\rho = 0.45$). The NAO index was negatively correlated with the LPUE of sardine ($\rho = -0.36$) and positively correlated with the LPUE of octopus ($\rho = 0.35$).

A significant ($p < 0.05$) negative correlation of the LPUE of sardine and chub mackerel was also found ($\rho = -0.41$).

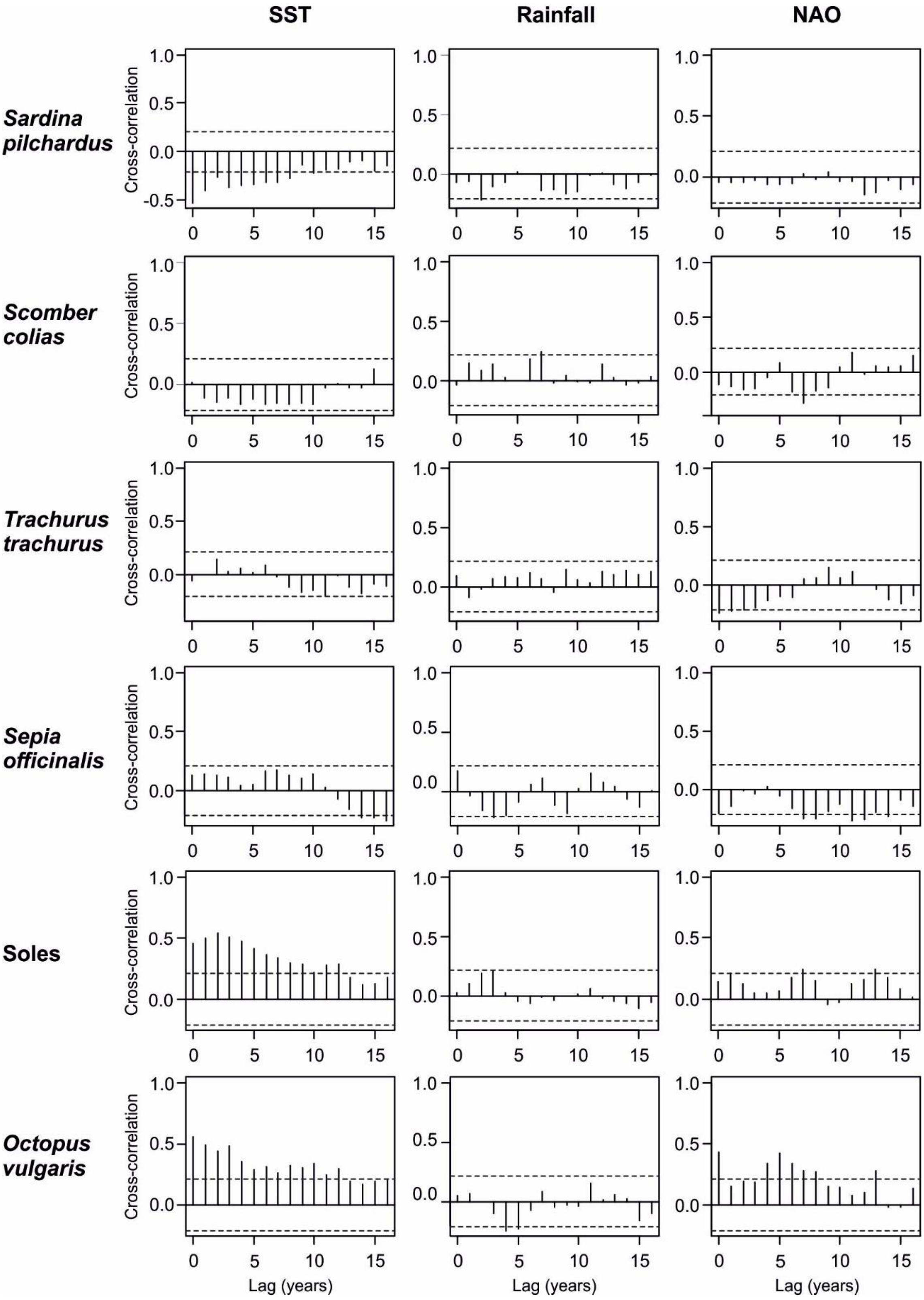

Fig. 6 Cross-correlograms for the environmental variables (SST, rainfall and winter NAO index) and the LPUE of the six species studied (dashed lines represent significance limits at the 5 % level).

Discussion

The present paper found relationships between environmental variables and landings of fisheries in a biogeographic transition zone, using 86 years of data. Sea surface temperature (SST) has increased in the studied area, with mean annual values rising from 16.6 ºC in 1926 to 17.5 ºC in 2012. LPUE of the European sardine have shown a decreasing trend, and significant negative effects of SST and NAO on landings of this species were found. Landings of the Atlantic chub mackerel have been increasing since 2000. Although showing a somewhat stable trend, LPUE of the common cuttlefish were positively correlated with SST. Landings of soles have shown a clearly increasing trend and a positive relationship with SST. The common octopus had higher LPUE from 1975 to 2012 than in the previous studied period and its landings have shown a significant positive effect of SST and NAO, for the whole time series.

The increasing trend found in SST agreed with previous studies that have pointed to a significant increase of SST in this region (Belkin, 2009; Lemos and Pires, 2004; Lemos and Sansó, 2006). In the Portuguese coast, a weakening of the upwelling regime in the Portuguese coast and a steady increase in SST of coastal waters from 1941 onwards have been recorded (Lemos and Pires, 2004; Lemos and Sansó, 2006).

Small pelagic fish species, such as the European sardine and the Atlantic horse mackerel, are highly consumed in Portugal and therefore are main targets for the Portuguese fisheries (INE, 2013). Most of the horse mackerel landed in Portugal is fished by bottom trawlers, followed by purse-seine and multi-gear fisheries (INE, 2013). Two long term periods have previously been detected in the time series of sardine catches in Portugal: high catches before the late 1960s and lower catches from then onwards (Borges *et al.*, 2003). Due to the lack of strong recruitments since 2004, the spawning stock biomass (SSB) of the Iberian sardine stock is currently far below the long-term average (ICES, 2013). In the present work, a similar trend was found in the LPUE of sardine in Setúbal. However, a peak was also observed in the early 1940s, which may be explained by the intense activity of the sardine canning industry in Setúbal during World War II, that may have led to higher fishing effort in the region. The reproductive strategy of pelagic fish species, such as sardine and horse mackerel, is adapted to the coastal upwelling ecosystems. Spawning occurs in winter, when the northerly winds are weaker, thus minimizing Ekman transport offshore and ensuring inshore transport and larval retention (Borges and Gordo, 1991; Nunes *et al.*, 2011; Stratoudakis *et al.*, 2007). Also, the feeding of the larvae will later benefit from the increase of productivity due to the summer upwelling (Santos *et al.*, 2001). Previous studies have tried to link sardine recruitment and several environmental variables, such as sunspots, NAO, wind strength, upwelling and SST (Borges *et al.*, 2003; Guisande *et al.*, 2001, 2004; Santos *et al.*, 2001). Borges *et al.* (2003) found that favourable upwelling winter wind conditions (high intensity and frequency of northerlies) were associated with positive NAO index and absent or weaker northerlies with negative NAO index. In the present study, landings of sardine in Setúbal showed a significant negative correlation with winter NAO. A negative effect of winter upwelling on recruitment of sardine and horse mackerel has previously been recorded (Santos *et al.*, 2001). This negative effect could be due to increased upwelling in winter, during the spawning season of these species, thus favouring offshore larval transport and subsequent larval mortality (Santos *et al.*, 2001). Although no significant correlations between the studied environmental variables and the LPUE of horse mackerel were found, a negative relationship between winter NAO and the LPUE was observed in the cross-correlograms, which might indicate a negative effect of winter upwelling on recruitment of horse mackerel, as well (Santos *et al.*, 2001). On the other hand, Santos *et al.* (2012) have considered SST to be the best candidate to explain the recruitment success of sardine, when compared to other environmental variables. In fact, Garza-Gil *et al.* (2010) have observed decreases in SSB of the Iberian sardine following periods of higher water temperature and Santos *et al.* (2012) found a significant negative effect of winter SST on recruitment. Temperature has a direct effect on many physiological processes that may affect adult reproduction or larval survival and, subsequently, recruitment success (Santos *et al.*, 2012). In the present work, a significant negative effect of SST on the LPUE of sardine was observed. The optimum temperature for spawning activity in sardine is 14-15 ºC, with avoidance occurring with temperatures below 12 ºC or above 16 ºC (Coombs *et al.*, 2006; Stratoudakis *et al.*, 2007). Therefore, if temperatures in winter continue to rise, the egg production of sardine may decrease (Santos *et al.*, 2012). Garza-Gil *et al.* (2010) have predicted lower biomass and catch levels of sardine with rising sea surface temperature, resulting in a decrease of the economic yield for the Iberian-Atlantic fishing grounds. If SST would rise at a faster rate than the current one, biomass and profits would further decrease with greater intensity, whereas in a palliation of global warming scenario, both variables would decrease to a lesser degree (Garza-Gil *et al.*, 2010). Although sardine is by far the most important species caught in purse-seine fisheries in Portugal, the Atlantic chub mackerel is second in total annual landings biomass of this fishery, despite its low commercial value (INE, 2013). The chub mackerel is usually a by-catch of the sardine fishery, but it may be an alternative income in seasons when it is abundant and sardine is not (Martins *et al.*, 2013). In fact, the chub mackerel has been increasing in importance in recent years, as its landings have increased and sardine landings have decreased (Martins *et al.*, 2013). Landings of chub mackerel in Portugal were high from the mid-1960s to the mid-1970s, low from then on until the early 2000s and have been increasing recently

(Martins *et al.*, 2013). This pattern could also be observed in the LPUE of the same species in Setúbal. When looking at the entire time series (1927-2012), the LPUE has shown a high inter-annual variability, which was confirmed by its low auto-correlation. This variability may not only be explained by changes in abundance of chub mackerel, but also by the decision of fishers on whether to land or discard the chub mackerel. In years of high sardine abundance, it is possible that fishers choose to discard the chub mackerel. Also, the LPUE of chub mackerel was usually higher in years of lower LPUE of sardine and lower in years of higher landings of sardine and a significant negative correlation between the LPUE of the two species was found, agreeing with the negative correlation between landings of sardine and chub mackerel in the southwestern Portuguese coast observed by Martins *et al.* (2013). These authors have also found an inverse correlation between the recruitment indices of the two species (Martins *et al.*, 2013). This inverse correlation between the recruitment indices may be due to an adverse effect of one species on the recruitment of the other, through competition for food or predation, or to a different response of each species to the same environmental conditions (Martins *et al.*, 2013). Species-specific differences in the tolerance to abiotic factors (e.g. temperature, salinity or other environmental conditions) and prey requirements will cause species-specific responses of fish to climate-driven changes in aquatic habitats (Peck *et al.*, 2013). In fact, although the LPUE of the chub mackerel showed negative cross-correlations with SST and NAO for the lower time lags, Spearman correlations were not significant, unlike sardine. Temperature, which had a significant negative effect on sardine, appears not to have such a negative effect on chub mackerel. This may be explained by differences in tolerance to increases in temperature between the two species. The Atlantic chub mackerel is a subtropical small pelagic fish, ranging, in the eastern Atlantic, from the Bay of Biscay to South Africa (Castro-Hernández and Santana-Ortega, 2000). Spawning occurs in winter-spring with temperatures from 15 ºC to 20 ºC (Castro-Hernández and Santana-Ortega, 2000). Thus, the chub mackerel spawns later and at higher temperatures than the sardine, which, together with its affinity to subtropical waters, may indicate a higher tolerance of the chub mackerel to increases in SST. However, the inverse relationship between landings of these two species may not necessarily be due to the inverse relationship in recruitment, but to an adaptation of the fishery; in years of low abundance in sardine, the chub mackerel may provide an alternative income (Martins *et al.*, 2013), resulting in higher landings of this species.

The common cuttlefish landed in Setúbal is caught by artisanal multi-gear fisheries, both inside the Sado estuary in spring and in the adjacent coastal areas in autumn/winter (Batista *et al.*, 2009; Serrano, 1992). Spawning, which only occurs once in the life span of cuttlefish, takes place inside the Sado estuary, from February to June (Neves *et al.*, 2009), where cuttlefish spawners are the most important target of the artisanal fishery (Serrano, 1992). Juveniles remain in the estuary throughout the summer until late autumn, when temperature starts to decrease and they leave the estuary (Neves *et al.*, 2009). SST was positively correlated with the LPUE of cuttlefish in Setúbal. Temperature is an important regulating factor in the life cycle of *S. officinalis*, influencing survival, reproduction, feeding and growth (Bloor *et al.*, 2013; Wang *et al.*, 2003).

The increase in landings of soles from 1927 to 2012 in Setúbal agrees with the increasing trend of flatfish landings in Portugal (Teixeira and Cabral, 2009). Flatfish fisheries have a high socio-economic importance along the Portuguese coast and sole landings are of particular relevance in the central coast, since about 60 % of total sole landings occur in this area, almost exclusively from trammel nets (Batista *et al.*, 2009; Teixeira and Cabral, 2009; Teixeira *et al.*, 2011). In fact, in the present study, soles were landed almost exclusively by multi-gear fisheries using nets, from 1992 to 2012. Temperature influences several life stages of fish species (Pörtner *et al.*, 2001) and, in the case of flatfish, temperature has been shown to affect growth, maturity, spawning or development (Fincham *et al.*, 2013; Mollet *et al.*, 2013; Petitgas *et al.*, 2012; Vinagre *et al.*, 2013). Fincham *et al.* (2013) have found an inverse correlation between the timing of spawning of sole and winter temperature in the North Sea, Irish Sea and English Channel, which has led these authors to believe that sole populations will spawn earlier in the future, as water temperature increases. A latitudinal trend has also been observed for the spawning of sole, starting earlier at lower latitudes (Vinagre *et al.*, 2008). In the present study, SST and the LPUE of soles were significantly correlated. The distribution range of *S. solea* extends from Norway to Portugal, with juveniles occurring in most of the Portuguese estuaries; on the other hand, *S. senegalensis* distributes from the Bay of Biscay to Senegal and in the Portuguese coast juveniles occur mainly in central and southern estuaries, such as the Sado (Vasconcelos *et al.*, 2010). Although increasing SST may be a disadvantage to the temperate *S. solea*, it can also be beneficial to the subtropical *S. senegalensis*, as this species has a higher thermal tolerance (Vinagre *et al.*, 2007). As the nurseries of the Sado estuary have a large contribution to the adult populations of *S. senegalensis* in the central and southwestern coast of Portugal (Tanner *et al.*, 2013), the LPUE of soles in Setúbal may be favoured by increasing SST.

The common octopus is currently the second most important target in Portuguese fisheries in terms of value (Pilar-Fonseca *et al.*, 2014). Landings of octopus in Setúbal have increased along the time series, with two marked periods (1927-1970 and 1975-2012), agreeing with the trend observed for landings of this species in Portugal (Moreno *et al.*, 2014; Pilar-Fonseca *et al.*, 2014). More than 90 % of the octopus landings in Portugal are caught by the multi-gear fishery, using traps (Pilar-

Fonseca *et al.*, 2014). In Setúbal, the common octopus was mostly caught with nets and traps, but traps have lately been increasing in importance. *O. vulgaris* has a short life cycle of 12-18 months and reaches minimum landing weight at 9-10 months-old (Katsanevakis and Verriopoulos, 2006b). In the southwestern coast of Portugal, octopus pre-recruits aggregate in recruitment grounds close to the Tejo and Sado estuaries (Moreno *et al.*, 2014). Despite being stenohaline in all life stages and not residing in estuaries, the octopus may take advantage of the high productivity of estuarine systems by living close to them (Moreno *et al.*, 2014). The LPUE of the octopus showed a significant positive correlation with SST. Previous studies have shown the importance of temperature for octopus (Garofalo *et al.*, 2010; Katsanevakis and Verriopoulos, 2006b; Vargas-Yáñez *et al.*, 2009). A significant positive effect of SST on pre-recruit distribution in the west Portuguese coast has been found, with pre-recruits preferring habitats where SST was between 15.3 ºC and 16.0 ºC (Moreno *et al.*, 2014). Nevertheless, a significant negative effect of SST on the pre-recruit distribution in the south Portuguese coast, where SST is higher, has been found (Moreno *et al.*, 2014). A detrimental effect of warm anomalies in the landings of octopus has also been found in the Western Mediterranean (Vargas-Yáñez *et al.*, 2009). Therefore, although increasing SST may have positively influenced the octopus landings in Setúbal, if temperature increases beyond the thermal optimum of the species, it may have an adverse effect on landings. A significant correlation of octopus landings with winter NAO index has also been found. Positive NAO phases have been associated with winter wind conditions favourable to upwelling (Borges *et al.*, 2003). Upwelling does not necessarily lead to offshore transport of octopus larvae; in fact, octopus larvae may take advantage of the landward flow of the deeper layer during upwelling events (Otero *et al.*, 2009).

Conclusions

Sea surface temperature has suffered a marked increase from 1927 to 2012 and although the main target species in the studied area have remained the same, their landings have responded to changes in temperature. Further increases in sea temperature will pose challenges for the future of fisheries in the studied area. Purse-seine fisheries may compensate the predicted losses in sardine landings by targeting the chub mackerel. Landings of the most important targets of multi-gear fisheries seem to have been favoured by the increase in temperature. However, further studies on the tolerance of each species to increasing temperature are needed. A future increase in commercial species in this area of the Portuguese coast has previously been predicted (Vinagre *et al.*, 2011) and a recent increase in the relative importance of subtropical fish species in Portuguese fisheries has already been observed (Gamito *et al.*, 2013). Therefore, climate change may not only bring new challenges for the current fisheries, but also new fishing opportunities for this region.

Acknowledgements

This study had the support of Fundação para a Ciência e Tecnologia (FCT), through the strategic project Pest-OE/MAR/UI0199/2011 granted to Centro de Oceanografia and the grants awarded to. R. Gamito (SFRH/BD/78363/2011) and C.M. Teixeira (SFRH/BPD/62986/2009).

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CHAPTER 5

Are Portuguese coastal fisheries affected by river drainage?

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Under review in Aquatic Living Resources

Are Portuguese coastal fisheries affected by river drainage?

Abstract: The Portuguese coast is particularly adequate for studies on the impact of climate change on fisheries, as it has faced an increase in both air and sea surface temperature and a decrease in intensity and frequency of rainfall. Ecological responses to climate change have already been observed in Portuguese waters, with consequences in fisheries. Regional climate models have predicted a further decrease in rainfall in Portugal by the end of the century, which will have a strong impact on the runoff into coastal areas. River drainage affects the physical, chemical and biological properties of coastal ecosystems, regulating habitat availability and favouring their productivity. The present study analysed the influence of river drainage on landings of coastal ports in the vicinity of four hydrologically distinct estuaries. Unlike previous results obtained for the Mediterranean, no significant correlations between river drainage and landings were found. Relationships between drainage and landings can be inconsistent among regions and dependent on how strongly a food web relies on nutrients and organic matter of river origin. In the Portuguese coast, an upwelling regime is of particular importance for the richness and diversity of the coastal ecosystem and for fisheries. The complexity of the coastal upwelling phenomenon together with a possible interaction of several other smaller scale factors acting on recruitment of commercial species may mask the effects of river drainage on landings. Nevertheless, as accentuated decreases in rainfall have been predicted for Portugal, the resulting reduction in river drainage may still strongly impact fisheries in the future.

Keywords: river drainage; coastal ecosystems; fisheries landings; climate change

Introduction

Climate change has been considered the most widespread anthropogenic threat for ocean ecosystems (Halpern *et al.*, 2008), affecting sea temperature, sea-level, ocean pH, rainfall and ocean circulation (Brander, 2007). These effects of climate change on ocean conditions will have an impact on marine organisms, the composition of marine communities and ecosystem function, therefore affecting fisheries (Brown *et al.*, 2010; Sumaila *et al.*, 2011). Both predictions of climate change in future scenarios and recently observed impact of climate change indicate that its effects will not be homogeneous throughout the world (IPCC, 2007; Santos, 2006). Southern Europe and the Mediterranean are more vulnerable to climate change than Central and Northern Europe (Santos, 2006). The Iberian Peninsula is one of the areas where air temperature has increased most (IPCC, 2007). Also, the Iberian Coastal large marine ecosystem has recently suffered a rapid warming, with an increase of 0.68 ºC in sea surface temperature from 1982 to 2006 (Belkin, 2009). The Portuguese coast is mainly north-south oriented and located in a biogeographic transition zone, between temperate and subtropical waters, where several fish species have their southern or northern distribution limit (Briggs, 1974). Ecological responses to recent climate change have been observed in Portuguese waters (Cabral *et al.*, 2001; Vinagre *et al.*, 2009) and the rising sea surface temperature in the region has been linked to fisheries landings (Gamito *et al.*, 2013, 2015; Teixeira *et al.*, 2014). A decrease in the intensity and frequency of rainfall has also been observed in Portugal (IPCC, 2007). Regional climate models predict a decrease of more than 30 % in southern Portugal by the end of the century (Miranda *et al.*, 2002). This decrease in rainfall will have an impact on the runoff of Portuguese rivers into coastal areas.

River runoff affects the physical, chemical and biological properties of coastal ecosystems (Gillson, 2011). Changes in salinity, turbidity, temperature and sediment delivery caused by variations in river flow regulate habitat availability for fish and invertebrates in coastal areas (Gillson, 2011). Furthermore, the productivity of coastal ecosystems may be favoured by terrestrial inputs from the runoff of adjacent rivers (Simenstad and Wissmar, 1985). River water carries nutrients and organic matter of terrestrial origin into coastal ecosystems, which will enhance plankton production and deposit in benthos (Cloern, 2001; Moutin *et al.*, 1998). Also, terrestrial particulate organic matter (POM) is extremely important for the dynamics of coastal macrobenthic communities (Hermand *et al.*, 2008; Salen-Picard and Arlhac, 2002; Salen-Picard *et al.*, 2002). As various marine commercial fish species have nursery grounds mainly located in estuarine and coastal areas (Cabral *et al.*, 2007), they are affected by river water inputs. Terrestrial POM has been shown to be incorporated into higher levels of the food web, such as commercial fish species, in coastal areas adjacent to the Tejo estuary (Vinagre *et al.*, 2011). Therefore, variations in river flow can have an indirect impact on coastal fisheries, through a trophic cascade (Darnaude, 2005; Darnaude *et al.*, 2004).

As the third highest per capita consumer of fish in the world, fisheries hold a great traditional and cultural importance in Portugal (Failler, 2007). Three main fleet components operate in Portuguese fisheries: trawl fisheries, purse-seine fisheries and multi-gear fisheries. The largest fleet component in Portugal belongs to multi-gear fisheries, which comprise a wide variety of fishing gears, such as gillnets, trammel nets, longlines and traps. This mainly artisanal fleet targets a wide range of species along the coastal area of Portugal and the same multi-gear vessel can be licensed to operate with several different fishing gears. However, the main targets of this fishery are *Solea* spp., the common cuttlefish *Sepia officinalis* Linnaeus, 1758 and the common octopus *Octopus vulgaris* Cuvier, 1797.

As higher river drainage has previously been considered to increase fishery production (e.g. Darnaude *et al.*, 2004; Le Pape *et al.*, 2003; Salen-Picard *et al.*, 2002), the aim of the present study was to analyse the influence of river drainage on landings of Portuguese fisheries, as well as the relative importance of other environmental variables. This study is of particular importance in the context of climate change, given the predicted decrease in rainfall in Portugal (Miranda *et al.*, 2002). As the variability observed in relationships between freshwater flow and landings of fish and invertebrates has previously been related with factors such as geographic location (Gillanders and Kingsford, 2002) or estuarine geomorphology (Saintilan, 2004), the present study focused on landings of coastal ports in the vicinity of four hydrologically distinct estuaries.

Methodology

Study area

Landings of ports in the vicinity of Minho, Ria de Aveiro, Mondego and Tejo estuaries were studied (Fig. 1). The hydrological characteristics of each estuary are presented in Table 1. The ports analysed were located in the coastal area adjacent to each estuary, within a radius of 20 km.

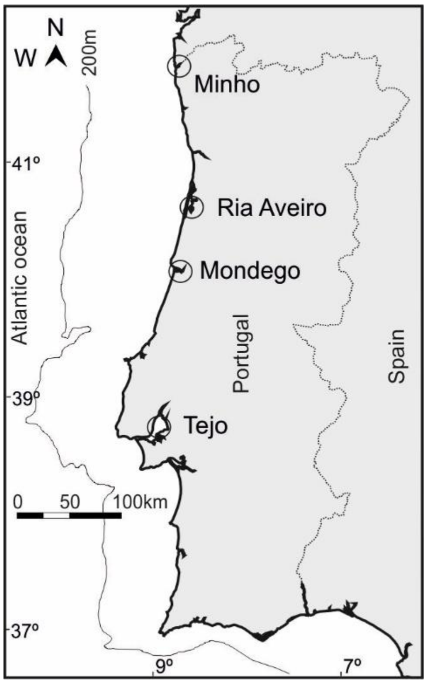

Fig. 1 Location of the studied areas on the Portuguese coast.

Data source

Fishing data of local multi-gear fisheries were obtained from official Portuguese landings, covering the period of 1992 to 2012. Landing data included fishing port, species caught, year and number of fishing days. Sea surface temperature (SST) monthly data were collected from the International

Comprehensive Ocean-Atmosphere Data Set (ICOADS) database (http://icoads.noaa.gov). Rainfall and river drainage monthly data were provided by the Portuguese Water Resources Information System (http://snirh.pt).

Table 1. Hydrologic and geomorphologic characteristics of Minho, Ria de Aveiro, Mondego and Tejo estuaries.

Estuary	Total area (km^2)	Mean river flow (m^3s^{-1})	Mean depth (m)	Mean residence time (days)	Entrance width (m)	Intertidal area (% of total area)
Minho	24.5	300	3	2	1246	9
Ria de Aveiro	120.8	40	2	17	437	64
Mondego	8.6	79	2	3	264	64
Tejo	367.5	300	5	25	4909	40

Data analysis

For each environmental variable, the values obtained for the rainiest months (November-March) were averaged. Landings Per Unit of Effort (LPUE) were calculated as $t.day^{-1}$. LPUE of 6 commercial species / group of species with life cycles which are somewhat dependent on estuaries, either by using them as nurseries, either by living in their vicinity, were analysed: European seabass (*Dicentrarchus labrax* (Linnaeus, 1758)) seabreams (*Diplodus* spp.); European flounder (*Platichthys flesus* (Linnaeus, 1758)); soles (*Solea* spp.); common cuttlefish (*Sepia officinalis* Linnaeus, 1758) and common octopus (*Octopus vulgaris* Cuvier, 1797).

For each estuary, relationships between LPUE of each of the considered species and river drainage were tested with Spearman rank correlation coefficient. The effects of environmental variables are stronger on early life stages, influencing recruitment success and subsequently LPUE of later years. For that reason, time-lags based on the available knowledge on age at first maturity were considered: 2 years for seabreams (Benchalel and Kara, 2013; Gonçalves *et al.*, 2003; Gordoa and Moli, 1997); 3 years for seabass, flounder and soles (Pawson *et al.*, 2007; Teixeira and Cabral, 2010; Teixeira *et al.*, 2009, 2010); and 1 year for octopus and cuttlefish (Katsanevakis and Verriopoulos, 2006a; Neves *et al.*, 2009).

The LPUE of each species / group of species were modelled with generalized linear models (GLMs), using the previously mentioned time lags. GLMs are an extension of linear models that allow the incorporation of non-normal distributions of the response variable and its transformation to linearity (McCullagh and Nelder, 1983). As LPUE data consist of positive values, log-normal or gamma distributions may be appropriate to the response variable (Stefánsson, 1996). However, gamma distribution has been considered more suitable for fisheries data (Maynou *et al.*, 2003; Myers and Pepin, 1990).

LPUE were modelled as a function of estuary, year, month, river drainage, rainfall and SST. The general model used was:

$$\log(\mu) = \beta_0 + \beta_1 X_1 + \ldots + \beta_p X_p$$

where β_p is the parameter set relating the descriptors X_p to the response, using a log link function and a gamma distribution for the response variable. Time lags previously mentioned were also considered in the models. The goodness-of-fit of the models was assessed by comparing their relative contribution to total deviance explained. The statistical significance of each descriptor was tested at a level of 0.05. All analyses were performed on the environment R (R Core Team, 2012).

Results

Mean winter SST showed a latitudinal trend, increasing from north to south (Fig. 2a). Nevertheless, the four areas presented very similar patterns along the time series. The highest values were recorded in 1998 (15.8 ºC in Minho; 16.2 ºC in Ria de Aveiro and Mondego and 16.9 ºC in Tejo) and the lowest in 2009 (13.8 ºC in Minho; 14.0 ºC in Ria de Aveiro and Mondego and 15.1 ºC in Tejo). Mean winter rainfall has shown high inter-annual variability (Fig. 2b). Although Minho and Ria de Aveiro had values of rainfall much higher than Mondego and Tejo, the rainiest years were the same in all studied areas: 1996 and 2001. The year of 2001 was also the peak for river drainage (Fig. 2c). The highest river drainage was observed in Tejo, reaching 4310×10^6 m^3 in 2001, whereas Ria de Aveiro presented the lowest values (< 200×10^6 m^3).

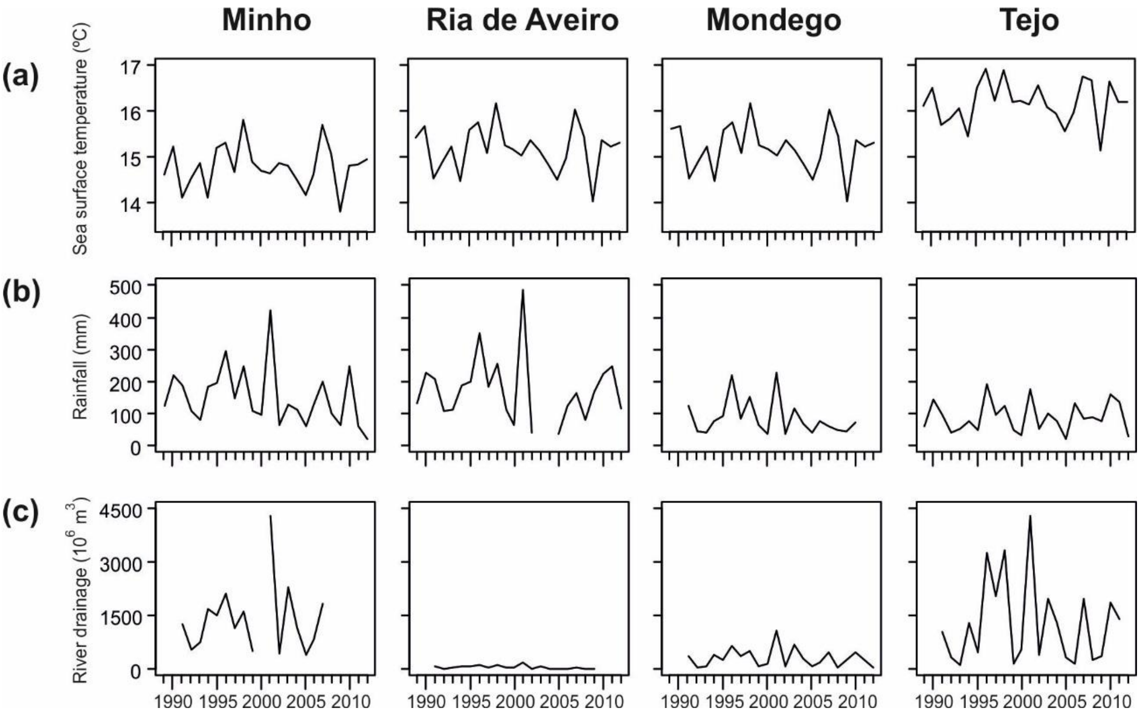

Fig. 2 Mean winter (November – March) sea surface temperature (a), rainfall (b) and river drainage (c), based on monthly data.

Landings of *Diplodus* spp., *Solea* spp. and *O. vulgaris* were higher in the Tejo study area, whereas *S. officinalis* was mainly landed in the area of Ria de Aveiro (Fig. 3). LPUE of both *Diplodus* spp. and *D. labrax* in Tejo have increased throughout the time series. On the other hand, landings of *P. flesus* in the same region have declined and become almost negligible since 2000.

The relationship between river drainage and time lagged LPUE can be observed in Fig. 4. No significant ($p < 0.05$) correlations between the LPUE of each considered species and river drainage could be found.

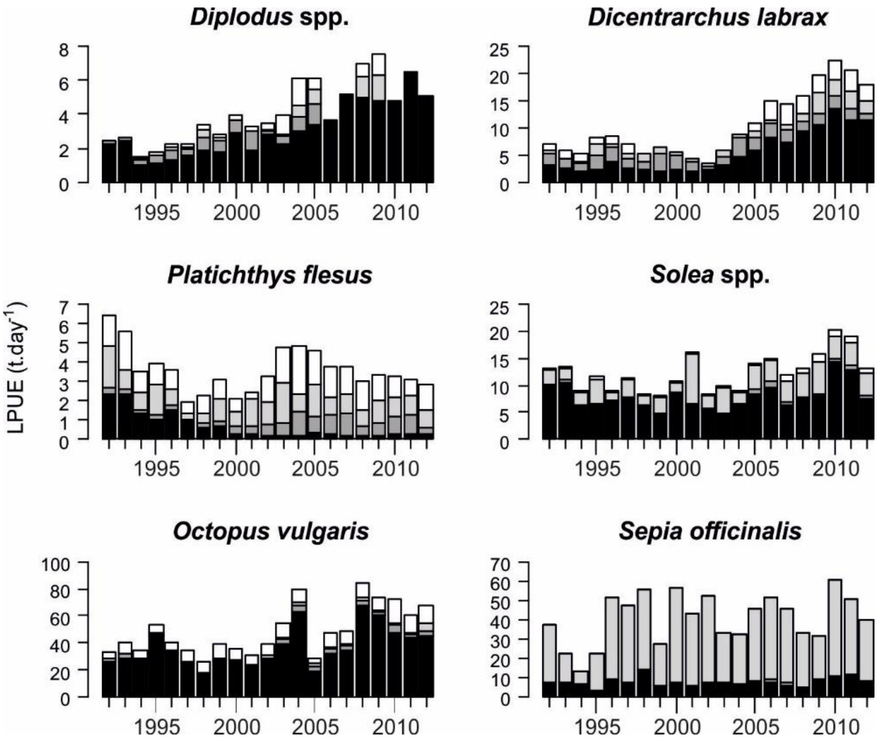

Fig. 3 Annual LPUE of the six studied species landed in the four studied areas (black bars – Tejo; dark gray bars – Mondego; light gray bars – Ria de Aveiro; white bars – Minho).

Goodness-of-fit statistics for the GLMs fitted to time lagged LPUE are presented in Table 2. Generally, estuary, year and month were the most important explanatory variables. The model for *Diplodus* spp. explained 74.10 % of the total deviance, with estuary and year being the variables that most contributed to the total explained deviance (33.14 % and 15.39 %, respectively). The interaction of drainage with rainfall was also included in this model, being responsible for 1.67 % of the deviance explained. Estuary (21.23 %) and year (15.85 %) contributed most to the 61.12 % of total explained deviance of the model fitted to landings of *D. labrax*. Although the interactions of estuary with year (20.82 %) and estuary with month (15.95 %) were the main contributors to the total explained deviance of the *P. flesus* model (62.39 %), rainfall and SST were also included, explaining 0.37 % and 0.95 %, respectively. The variable estuary explained 62.11 % of the total explained deviance (84.61 %) of the model fitted to the LPUE of *Solea* spp. and 59.52 % of the total explained deviance (79.49 %) of the *O. vulgaris* model. *S. officinalis* model had a total explained deviance of 82.52 %, with a contribution of 53.18 % and 18.60 % of the variables estuary and month, respectively.

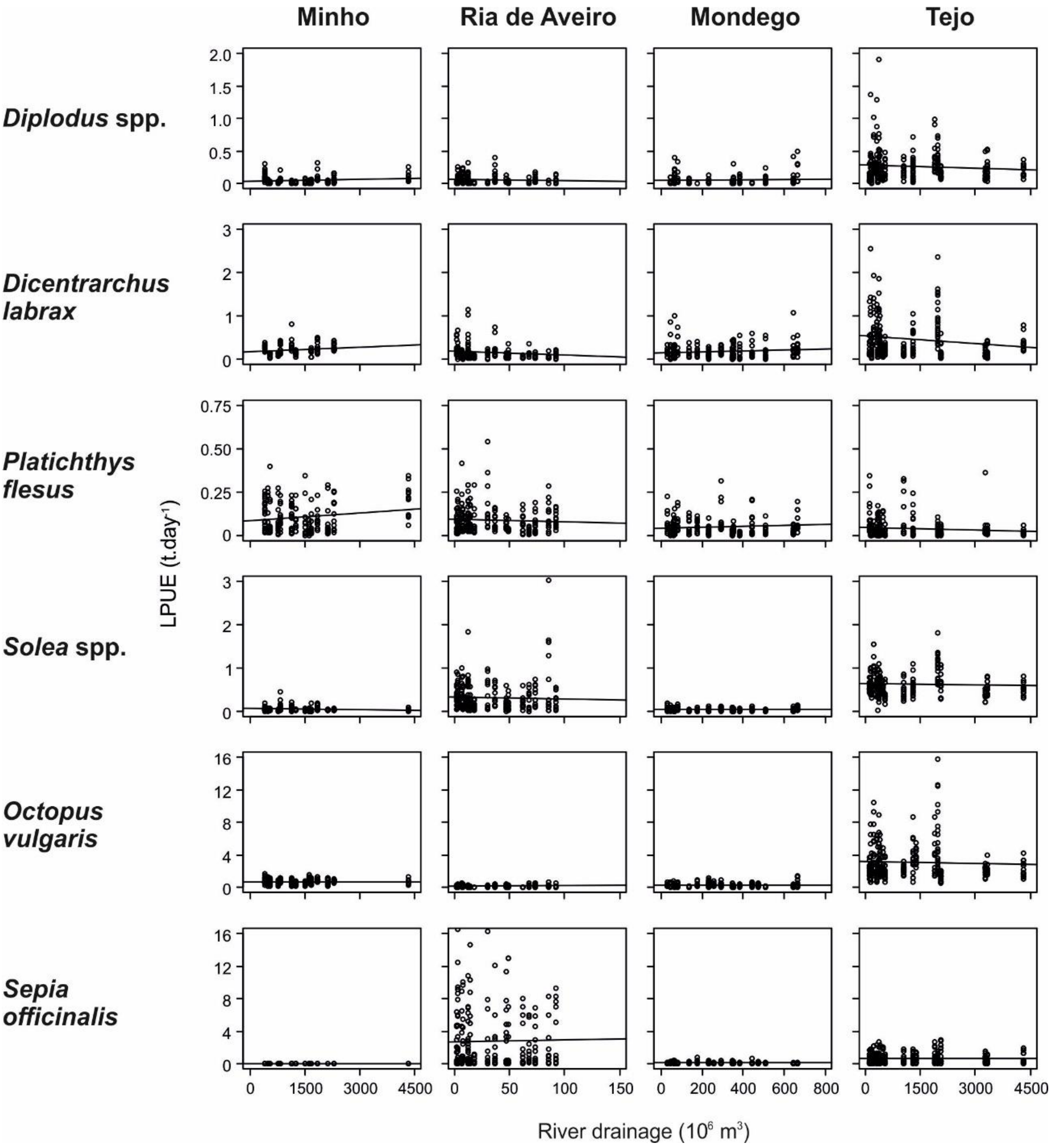

Fig. 4 Relationship between river drainage and monthly LPUE of the six studied species landed in the four studied areas.

Table 2. Goodness-of-fit statistics for the GLMs fitted to LPUE of each species / group of species considered (% explained – percentage of the total deviance explained).

Model	**Deviance**	**Residual deviance**	**% explained**	***p*-value**
***Diplodus* spp.**				
NULL		1301.16		
factor (estuary)	431.20	869.96	33.14	< 0.001
factor (year)	200.23	669.73	15.39	< 0.001
factor (month)	98.27	571.47	7.55	< 0.001
drainage	1.59	569.88	0.12	< 0.01
rainfall	4.54	565.34	0.35	< 0.05
drainage: rainfall	21.69	543.65	1.67	< 0.01
factor(estuary): factor(year)	122.93	420.72	9.45	< 0.001
factor(estuary): factor(month)	83.72	337	6.43	< 0.001
Total explained			74.10	
Dicentrarchus labrax				
NULL		899.19		
factor (estuary)	190.86	708.33	21.23	< 0.001
factor (year)	142.49	565.84	15.85	< 0.001
factor (month)	43.30	522.54	4.82	< 0.001
factor(estuary): factor(year)	130.66	391.88	14.53	< 0.001
factor(estuary): factor(month)	42.30	349.58	4.70	< 0.001
Total explained			61.12	
Platichthys flesus				
NULL		1204.56		
factor (estuary)	112.06	1092.50	9.30	< 0.001
factor (year)	93.04	999.45	7.72	< 0.001
factor (month)	87.65	911.80	7.28	< 0.001
rainfall	4.44	907.37	0.37	< 0.01
SST	11.43	895.94	0.95	< 0.001
factor(estuary): factor(year)	250.76	645.17	20.82	< 0.001
factor(estuary): factor(month)	192.09	453.08	15.95	< 0.001
Total explained			62.39	< 0.001
***Solea* spp.**				
NULL		1985.78		
factor (estuary)	1233.31	752.47	62.11	< 0.001
factor (year)	113.1	639.38	5.69	< 0.001
factor (month)	135.73	503.65	6.84	< 0.001
factor(estuary): factor(year)	98.15	405.5	4.94	< 0.001
factor(estuary): factor(month)	99.97	305.52	5.03	< 0.001
Total explained			84.61	< 0.001
Sepia officinalis				
NULL		3190.2		
factor (estuary)	1696.56	1493.6	53.18	< 0.001
factor (month)	593.33	900.3	18.60	< 0.001
factor(estuary): factor(month)	342.73	557.5	10.75	< 0.001
Total explained			82.52	
Octopus vulgaris				
NULL		2011.36		
factor (estuary)	1197.14	814.22	59.52	< 0.001
factor (year)	117.18	697.04	5.83	< 0.001
factor (month)	19.47	677.57	0.97	< 0.01
factor(estuary): factor(year)	151.73	525.84	7.54	< 0.001
factor(estuary): factor(month)	113.24	412.6	5.63	< 0.001
Total explained			79.49	

Discussion

The present work analysed coastal fisheries data in four areas near estuaries and could not find an effect of river drainage on landings of the species studied. Not only correlations between river drainage and LPUE were not significant, but also river drainage was only included as an explanatory variable in the model for landings of *Diplodus* spp. The variable estuary was always the best explanatory variable in the models, regardless of the species considered.

Inter-annual and seasonal variations in freshwater flow affect growth, survival and recruitment of fish and invertebrates (Gillson, 2011). The resulting changes in distribution and abundance of these species are therefore likely to affect fisheries in coastal areas. In fact, previous works have pointed to an increase in fishery production following higher river runoff (e.g. Darnaude *et al.*, 2004; Le Pape *et al.*, 2003; Salen-Picard *et al.*, 2002). Various mechanisms underlying the relationship between river runoff and fisheries have been proposed, but food availability has most often been considered the main factor, both through increased planktonic production following nutrient loads (Cloern, 2001; Moutin *et al.*, 1998) and enrichment in POM in macrobenthic communities (Salen-Picard *et al.*, 2002). A study in the north-western Mediterranean searched for relationships between the river drainage of the Rhone, the benthic communities of its delta and landings of *S. solea* in the Gulf of Lions (Salen-Picard *et al.*, 2002). A positive correlation between the Rhone river drainage and landings of *S. solea* in two nearby fishing ports, with a time lag of 5 years, was found (Salen-Picard *et al.*, 2002). As the authors observed that floods caused pulses of organic matter and peaks of polychaetes, with different time lags, they have linked the increase in landings to an increase in food resources following higher river drainage (Salen-Picard *et al.*, 2002). For the same region, it has been stated that a significant proportion of flesh carbon in *S. solea* came from terrestrial origin (Darnaude *et al.*, 2004). According to these studies, higher landings would be expected in years following higher river drainage, with each species' response depending on a time lag reflecting age at recruitment (Darnaude, 2005). In the Bay of Biscay, the availability of estuarine nursery grounds, and consequently the production of juvenile *S. solea*, has been shown to be influenced by the extent of the riverine plume front (Le Pape *et al.*, 2003).

The variability of the relationships between river flow and landings of fish and invertebrates may be related to factors such as geographic location (Gillanders and Kingsford, 2002) or estuarine geomorphology (Saintilan, 2004). For the same species, relationships between freshwater flow and landings can be positive, negative, or inconsistent among regions (Gillson, 2011). In fact, the present work has used time lags based on age at first maturity and has not found a significant relationship of landings with river drainage. The influence of the river Tejo extends up to 30 km from the river mouth in low flow conditions, where terrestrial POM accounts for 24 % of the total POM (Vinagre *et al.*, 2011). Therefore, the extent of the influence of terrestrial carbon from the Tejo under low flow conditions is much larger than that found for the river Rhone, where at approximately 30 km from the river mouth the percentage of terrestrial carbon was null (Hermand *et al.*, 2008). As the influence of Tejo in coastal areas remains particularly high even in low flow conditions, it is possible that the difference in flow in wetter years is not sufficiently large to induce ecological responses which would lead to higher landings of the studied species. On the other hand, relationships between river drainage and fisheries production will depend on how strongly a food web relies on nutrients and organic matter of river origin (Gillson, 2011). Semi-enclosed coastal regions, such as the Mediterranean Sea, receive limited nutrient supplies from oceanic currents or upwelling events and therefore fisheries production may be more dependent on river nutrients (Gillson, 2011), as was found in previously mentioned works (Darnaude *et al.*, 2004; Salen-Picard *et al.*, 2002). In the Western Portuguese coast, however, an upwelling regime is of particular importance for the richness and diversity of the coastal ecosystem and for fisheries (Lemos and Sansó, 2006) and thus variations in river flow observed in the present work did not result in higher landings of the studied species.

Flatfish landings have been increasing in Portugal, where their fisheries have a high socio-economic importance (Teixeira and Cabral, 2009). Sole landings are particularly relevant in the central coast, as 60 % of total sole landings occur there (Batista *et al.*, 2009; Teixeira and Cabral, 2009; Teixeira *et al.*, 2011). In fact, in the present work, landings of this group of species were higher in the Tejo study area. Food, predators and temperature are considered the most important factors contributing to habitat quality for the growth and survival of flatfish juveniles (Gibson, 1994; Vinagre *et al.*, 2006). Temperature affects growth, maturity, spawning and development of flatfish species (Fincham *et al.*, 2013; Mollet *et al.*, 2013; Petitgas *et al.*, 2012; Vinagre *et al.*, 2013). SST was included in the model of *P. flesus* landings. Teixeira and Cabral (2009) analysed flatfish landings in the Portuguese coast and found that SST was the variable explaining most of the deviance of *P. flesus* landings' model. Although once abundant in the Tejo, *P. flesus* is now restricted to the northern estuaries, due to increasing SST in the Portuguese coast, where this species has its southern distribution limit (Cabral *et al.*, 2001, 2007; Vinagre *et al.*, 2009). The increasing SST has also been indicated as the reason for the increasing abundance of *D. bellottii* in the Tejo estuary, as this southern species finds its northern limit in the Portuguese coast (Cabral *et al.*, 2001; Vinagre *et al.*, 2009). The increasing abundance of this species may be responsible for the higher and increasing landings of *Diplodus* spp. in the Tejo area found in the present work.

The highest landings of *D. labrax* were observed in the Tejo area and have been increasing since the 2000s. Although a positive correlation of abundance of *D. labrax* juveniles with river drainage in the Tejo estuary has previously been reported (Vinagre *et al.*, 2009), landings have not shown such a relationship with river drainage. The fact that the same authors have not found a trend in *D. labrax* abundance in the Tejo estuary over time (Vinagre *et al.*, 2009) may indicate that the increasing trend observed in landings is probably due to the growing interest of consumers in this species.

O. vulgaris is currently the second most important target in Portuguese fisheries in terms of value (Pilar-Fonseca *et al.*, 2014). In the present work, landings of this species were highest in the Tejo area. *O. vulgaris* has a short life cycle of 12-18 months and reaches minimum landing weight at 9-10 months-old (Katsanevakis and Verriopoulos, 2006b). Moreno *et al.* (2014) found that in the southwestern coast of Portugal octopus pre-recruits aggregated in recruitment grounds close to the Tejo and Sado estuaries. *O. vulgaris* is stenohaline in all life stages and does not reside in estuaries, but the authors hypothesised that it may take advantage of the high productivity of estuarine systems by living in their vicinity (Moreno *et al.*, 2014). Bottom salinity and river runoff have been considered the environmental variables with most impact on pre-recruit distribution and abundance on the Portuguese western coast (Moreno *et al.*, 2014). Gamito *et al.* (2015) analysed 86 years of fisheries data in an area south of the Tejo and did not find a relationship between rainfall and *O. vulgaris* landings. However, a significant effect of SST was observed (Gamito *et al.*, 2015). The present work did not find significant relationships between river runoff and landings of this species in any of the coastal areas studied.

S. officinalis was mainly landed in the Ria de Aveiro area. Spawning, which only occurs once in the life span of cuttlefish, usually takes place in shallow waters inshore, such as estuarine systems, from February to June. In late autumn, when temperature starts to decrease, they migrate to nearby coastal waters (Neves *et al.*, 2009; Wang *et al.*, 2003). Ria de Aveiro is a shallow coastal lagoon system with large intertidal areas, where *S. officinalis* finds adequate conditions for spawning (Pereira *et al.*, 2009). The variable month was also included in the model, which would likely be explained by the seasonality of cuttlefish fisheries, which target *S. officinalis* spawners inside estuarine systems (Batista *et al.*, 2009; Gamito *et al.*, 2015). No relationship between river drainage and landings of *S. officinalis* was found. As this species was mainly landed in the area with the lowest river drainage in the present study, it is possible that the impact of river drainage on cuttlefish in that area is not a determinant factor on landings.

Most fisheries production worldwide is associated with three nutrient-enrichment processes: coastal upwelling, tidal mixing, and land-based runoff, including major river outflow (Caddy and Bakun, 1994). Coastal upwelling is a well-studied phenomenon in the Portuguese coast, where it has a strong effect on fisheries (Lemos and Sansó, 2006). The effect of upwelling on pelagic fish fisheries has received particular attention (Borges *et al.*, 2003; Santos *et al.*, 2001, 2004). Several pelagic fish species have their reproductive strategy adapted to coastal upwelling systems. They spawn in winter, when the northerly winds that cause upwelling are weaker, thus reducing the risk of Ekman transport offshore and ensuring inshore transport and larval retention (Nunes *et al.*, 2011; Stratoudakis *et al.*, 2007). The increase in productivity from summer upwelling will later benefit the feeding of the larvae (Santos *et al.*, 2001). Although the traditional upwelling season is between April and September, northerly winds that favour this phenomenon are recurrent in the Portuguese coast throughout the year (Huthnance *et al.*, 2002). When winter upwelling occurs, it will likely transport eggs and larvae offshore, resulting in high mortality rates. These events have already been reported for sardine (Borges *et al.*, 2003; Santos *et al.*, 2001) and may also occur with other species. The recruitment of coastal species is also dependent on other factors, such as temperature (Rijnsdorp *et al.*, 1995), predation (Bailey and Houde, 1989) or food availability (Cushing, 1972), and the interaction of different factors (Santos *et al.*, 2004). The complexity of the coastal upwelling on the Portuguese coast, and its possible interaction with all other factors affecting recruitment, makes the task of detecting the effects of river drainage on landings particularly difficult.

Climate-induced changes in Portuguese fisheries have already been reported (Gamito *et al.*, 2013, 2015; Teixeira *et al.*, 2014). There has been a reduction in the intensity and frequency of rainfall in Portugal (IPCC, 2007), which will also decrease the drainage of Portuguese rivers into coastal areas. Although the present work has not found a relationship between river drainage and landings of the studied species, future decreases in river drainage may have strong impacts on fisheries. River flow influences a myriad of environmental factors that are determinant for the habitat characteristics of estuarine and coastal systems, such as rates of sediment delivery, salinity, turbidity and temperature (Gillson, 2011). In fact, temperature in the Portuguese coast has been increasing (Belkin, 2009; IPCC, 2007), with observed effects on fisheries (Gamito *et al.*, 2013, 2015; Teixeira *et al.*, 2014). However, the combined effect of changes in temperature and river flow in the future remains unknown. River plumes may also have a crucial role as cues of the proximity of nursery areas for fish larvae (Vinagre *et al.*, 2009). *S. solea*, *S. senegalensis* and *D. labrax* larval immigration into the Tejo estuary has been found to be positively influenced by river drainage

(Vinagre *et al.*, 2007, 2009). Although the present work has not found a relationship between river drainage and landings of these species, the predicted decrease in rainfall (Miranda *et al.*, 2002) could potentially lead to a decrease in larval immigration into estuaries in the future, with consequences for fisheries.

The present study used time-lags based on the available knowledge on age at first maturity, assuming that the effects of environmental variables are stronger on early life stages. However, it is possible that events in later life stages of this species could affect fisheries landings without being detected in the present study. Longer time series and data on juvenile abundance in estuaries could possibly bring new insight to the subject of influence of river drainage on fisheries. However, as it is often the case when dealing with long-term studies, those data were not available for the present study.

Acknowledgements

This study had the support of Fundação para a Ciência e Tecnologia (FCT), through the strategic project UID/MAR/04292/2013 granted to MARE, the grants awarded to R. Gamito (SFRH/BD/78363/2011) and C.M. Teixeira (SFRH/BPD/62986/2009) and the project PTDC/AAG-REC/2139/2012.

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CHAPTER 6

Modelling recruitment and landings of pelagic fish under climate change

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Under review in Journal of Marine Systems

Modelling recruitment and landings of pelagic fish under climate change

Abstract: Climate change is the most widespread anthropogenic threat for ocean ecosystems, affecting water temperature, sea-level, ocean pH, rainfall and ocean circulation. Fish populations and ecosystems located in areas most likely to suffer climate change impacts are more at risk. The Iberian Coastal large marine ecosystem has suffered a rapid warming from 1982 to 2006 and the Portuguese coast is expected to suffer changes in temperature and rainfall more accelerated than the global mean alteration rate. Also, the Portuguese coast is north-south oriented and located in a biogeographic transition zone. Therefore, this coast is particularly adequate for studies on the effect of climate change on fisheries. Fisheries hold a great traditional and cultural importance in Portugal, as the country is the third highest per capita consumer of fish in the world. European sardine (*Sardina pilchardus*) and Atlantic horse mackerel (*Trachurus trachurus*) are highly consumed in Portugal, where they are main targets for fisheries. The present study modelled recruitment and landings of these two commercially important species in the Portuguese coast. The goodness-of-fit of the models was high. Sardine recruitment was explained by wind strength. Wind strength was also important explaining sardine landings, right after sea surface temperature. Chub mackerel landings were also an important predictor of sardine landings. No model could be fitted to horse mackerel recruitment. However, a model was fitted to landings of horse mackerel in the Portuguese coast, with sea surface temperature as the predictor. The effects of climate change on the marine environment seem to be affecting recruitment and subsequent landings of sardine and horse mackerel in the Portuguese coast, with consequences for Portuguese fisheries.

Keywords: Fisheries; recruitment; climate change; *Sardina pilchardus*; *Trachurus trachurus*; GLM

Introduction

Fishing is an activity of great traditional and cultural importance in Portugal, as the country is the third highest per capita consumer of fish in the world (Failler, 2007). There are three main fleet components in Portuguese fisheries: trawl fisheries, purse-seine fisheries and multi-gear fisheries. The main targets of trawl fisheries are the Atlantic horse mackerel *Trachurus trachurus* (Linnaeus, 1758), the European hake *Merluccius merluccius* (Linnaeus, 1758) and cephalopods. Purse-seine fisheries target small pelagic fish, such as European sardine *Sardina pilchardus* (Walbaum, 1792), Atlantic chub mackerel *Scomber colias* Gmelin, 1789 and Atlantic horse mackerel. Sardine is particularly important, as it has traditionally been the most landed species in Portugal. Nowadays, it is the second most important species landed in Portuguese waters in quantity, just after chub mackerel (INE, 2015). The multi-gear fishery is the largest and most diversified fishing fleet component in Portugal, using a wide variety of fishing gears, such as gillnets, trammel nets, longlines and traps.

Climate change affects water temperature, sea-level, ocean pH, rainfall and ocean circulation (Brander, 2007) and it is therefore the most widespread anthropogenic threat for ocean ecosystems (Halpern *et al.*, 2008). These effects will have an impact on ocean organisms, the composition of marine communities and ecosystem function (Brown *et al.*, 2010), increasing the complexity of challenges facing fisheries (Sumaila *et al.*, 2011). Climate change impacts fish stocks either directly or indirectly. The direct impacts are mainly physiological and behavioural effects, such as changes in growth, reproduction, mortality and distribution; the indirect impacts are related with changes in productivity and in the structure and composition of marine ecosystems on which fish depend (Brander, 2010; Hare *et al.*, 2010; Perry *et al.*, 2005). Changes in geographic distribution of fish species have already been documented throughout the world and are more easily detected on northern and southern distribution limits (Brander *et al.*, 2003; Perry *et al.*, 2005). It has been predicted that changes in water temperature, driven by climate change, may lead to local extinctions and also to colonization by species previously absent in those areas (Cheung *et al.*, 2009) and this will most likely affect the abundance, distribution and composition of fisheries catches (Gamito *et al.*, 2013; Sumaila *et al.*, 2011). Fish populations and ecosystems located in areas most likely to suffer climate change impacts are more at risk (Brown *et al.*, 2010). Both the observation of the impact of recent climate change and predictions of climate change in future scenarios indicate that its effects will not be homogeneous throughout the world (IPCC, 2007; Santos, 2006). Southern Europe and the Mediterranean are more vulnerable to climate change than Central and Northern Europe (Santos, 2006). The Iberian Coastal large marine ecosystem has suffered a rapid warming, with an increase of 0.68 ºC in sea surface temperature from 1982 to 2006 (Belkin, 2009) and the Portuguese coast is expected to suffer changes in temperature and rainfall more accelerated than the global mean alteration rate (IPCC, 2007). Regional circulation model HadRM3 predicts increases in sea surface temperature (SST) in the Portuguese coast until 2100, for different future scenarios established by the Special Report on Emission Scenarios. This increase will be of 1 ºC under scenario B2 and 2 ºC under the scenario A2 (Nakicenovic *et al.*, 2000; Reis *et al.*, 2006). Also, the Portuguese coast is north-south oriented and located in a biogeographic transition zone, between temperate and subtropical waters, where several fish species have their southern or northern distribution limit (Briggs, 1974). For these numerous reasons, this coast is particularly adequate for studies on the effect of climate change on fisheries and indeed several recent studies have focused on that subject (e.g. Gamito *et al.*, 2013, 2015; Teixeira *et al.*, 2014).

Two long term periods have previously been detected in the time series of sardine catches in Portugal: high catches before the late 1960s and lower catches from then onwards (Borges *et al.*, 2003). There has been a lack of strong recruitments in Iberian sardine since 2004 and the spawning stock biomass (SSB) is currently far below the long-term average (ICES, 2015). Recruitment and landings of both sardine and horse mackerel have been linked to several environmental variables, such as sunspots, North Atlantic Oscillation (NAO) index, wind strength, upwelling and SST (Borges *et al.*, 2003; Gamito *et al.*, 2015; Guisande *et al.*, 2001, 2004; Santos *et al.*, 2001). SST has been considered the best candidate to explain the recruitment success of sardine, when compared to other environmental variables (Santos *et al.*, 2012) and decreases in SSB of the Iberian sardine following periods of higher water temperature have also been observed (Garza-Gil *et al.*, 2010). However, it is yet to investigate whether the number of recruits is the main factor influencing future landings of these species or if other environmental and biotic agents could play a major role in this process. This knowledge is of the utmost importance in the context of climate change. Thus, the main objectives of the present study are (1) to model sardine and horse mackerel recruitment in the Portuguese coast, and (2) to model sardine and horse mackerel landings, taking into account environmental and biotic variables.

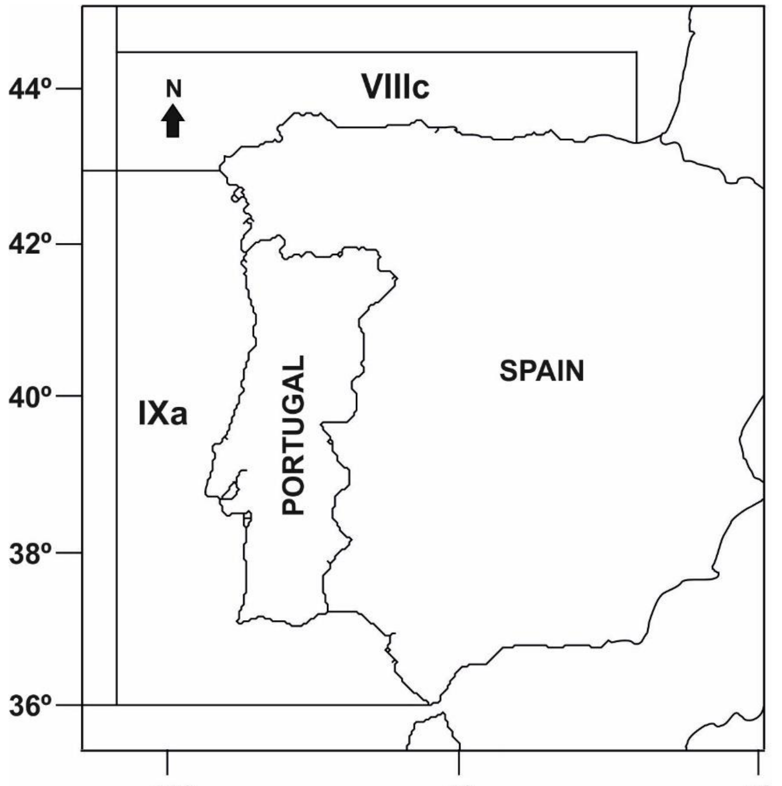

Fig. 1 Location of the study area, showing ICES divisions VIIIc and IXa.

Methodology

Study area

The Portuguese coast is located in south-western Europe, in the International Council for the Exploration of the Sea (ICES) division IXa (Fig. 1). The coast is 942 km long and consists of a north-south oriented western section and a shorter southern section, east-west oriented.

Data source

Recruitment, spawning stock biomass (SSB) and landings data of sardine *Sardina pilchardus* and horse mackerel *Trachurus trachurus* in ICES divisions VIIIc and IXa were collected from ICES (2015). Fishing data for the period of 1965 to 2015 were also obtained from official Portuguese landings. Monthly data on sea surface temperature (SST), wind strength, north-south wind component and east-west wind component were collected from the International Comprehensive Ocean-Atmosphere Data Set (ICOADS) database (http://icoads.noaa.gov). Monthly data on the North Atlantic Oscillation (NAO) index, based on the pressure difference between Lisbon and Reykjavik, were taken from the United States of America NOAA National Weather Service database (http://www.cpc.noaa.gov).

Data analysis

Generalized linear models (GLMs) were fitted to recruitment and landings data of sardine and horse mackerel. GLMs are an extension of linear models that allow the incorporation of non-normal distributions of the response variable and its transformation to linearity (McCullagh and Nelder, 1983). As data consisted of positive values, log-normal or gamma distributions may be appropriate to the response variable (Stefánsson, 1996). However, gamma distribution has been considered more suitable for fisheries data (Maynou *et al.*, 2003; Myers and Pepin, 1990). For each model, the response variable was modelled as a function of the variables presented in Table 1. The general model used was:

$$\log(\mu) = \beta_0 + \beta_1 X_1 + \dots + \beta_p X_p$$

where β_p is the parameter set relating the descriptors X_p to the response, using a log link function and a gamma distribution for the response variable. The goodness-of-fit of the models was assessed by comparing their relative contribution to the total deviance explained. The statistical significance of each descriptor was tested at a level of 0.05. All analyses were performed on the environment R (R Core Team, 2014).

Table 1. Variables used in the construction of models for recruitment (R), ICES landings (LndIc) and Portuguese landings (LndPt) of sardine *Sardina pilchardus* (SP) and horse mackerel *Trachurus trachurus* (TT). Models for recruitment and ICES landings were based on data for divisions VIIIc + IXa for sardine (1978-2014) and divison IXa for horse mackerel (1992-2014). Models for Portuguese landings were based on official landings data (1965-2014) of purse-seine fisheries for sardine and trawl fisheries for horse mackerel.

Variable	**Observations**	**Model**			
		R	**LndIc**	**LndPt**	
				SP	TT
Sea surface temperature					
Annual	Averaged (January-December)	X	X	X	X
Winter	Averaged (December-February)	X	X	X	X
North Atlantic Oscillation Index					
Annual	Averaged (January-December)	X	X	X	X
Winter	Averaged (December-February)	X	X	X	X
Wind strength					
Annual	Averaged (January-December)	X	X	X	X
Winter	Averaged (December-February)	X	X	X	X
Summer	Averaged (June-August)	X	X	X	X
North-south wind component					
Annual	Averaged (January-December)	X	X	X	X
Winter	Averaged (December-February)	X	X	X	X
Summer	Averaged (June-August)	X	X	X	X
East-West wind component					
Annual	Averaged (January-December)	X	X	X	X
Winter	Averaged (December-February)	X	X	X	X
Summer	Averaged (June-August)	X	X	X	X
Spawning stock biomass	Annual	X			
Recruits	Annual		X		
Predators					
Merluccius merluccius	Annual landings			X	X
	Annual landings – 1-year lagged			X	X
	Annual landings – 2-year lagged			X	X
Competitors					
Scomber colias	Annual landings			X	
	Annual landings – 1-year lagged			X	
	Annual landings – 2-year lagged			X	
Trachurus picturatus	Annual landings				X
	Annual landings – 1-year lagged				X
	Annual landings – 2-year lagged				X

Recruitment models had the number of recruits (age 0) of sardine (1978-2014) and horse-mackerel (1992-2014) (ICES, 2015) in divisions VIIIc + IXa and IXa, respectively, as response variables. Models were also fitted to landings of sardine and horse mackerel of the same origin (ICES, 2015). As the effects of environmental variables are stronger on early life stages, the environmental variables used in landings' models had a 2-year time lag, based on the available knowledge on age at first maturity (Abaunza *et al.*, 2003; Silva *et al.*, 2006). The models obtained for landings in ICES divisions did not include the number of recruits as an explaining variable (Table 2). For that reason, new models were developed using landings of Portuguese official fisheries data, in order to allow for a larger time series and the inclusion of other biotic variables. Those models were fitted to Portuguese landings of sardine in purse-seine fisheries and of horse mackerel in trawl fisheries, for the period of 1965-2014. As previously, the environmental variables were lagged 2 years. Landings of European hake *Merluccius merluccius* (Linnaeus, 1758) were used as a proxy of predators in both models. Landings of chub mackerel *Scomber colias* Gmelin, 1789 and blue jack mackerel *Trachurus picturatus* (Bowdich, 1825) were used as proxies of competitors of sardine and horse mackerel, respectively. Each of these biotic variables was considered in the models with no time lag, a 1-year time lag and 2-year time lag. For each model obtained, a linear regression between observed and predicted values was performed, in order to evaluate model performance.

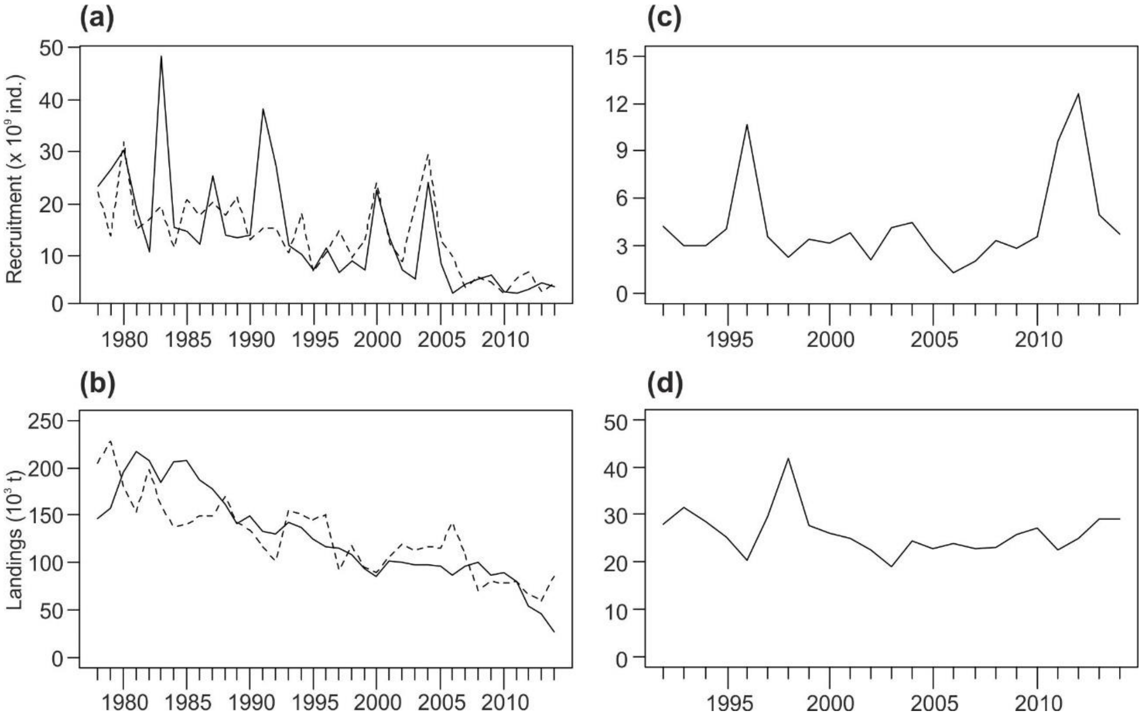

Fig. 2 Sardine and horse mackerel recruitment and landings in ICES divisions VIIIc + IXa and IXa, respectively. (a) sardine recruitment from 1978 to 2014; (b) sardine landings from 1978 to 2014; (c) horse mackerel recruitment from 1992 to 2014; (d) horse mackerel landings from 1992 to 2014 (dashed line – values predicted by the fitted models).

Results

Sardine recruitment in the ICES divisions VIIIc and IXa has suffered a marked decrease from 1978 to 2014 (Fig. 2a). The highest number of sardine recruits (48.4×10^9 ind.) was recorded in 1983 and the lowest value in 2006 (2.8×10^9 ind.). In terms of sardine landings in the same area and period, a decreasing trend could be observed, with the maximum value being registered in 1981 (217,000 t) and the minimum in 2014 (28,000 t) (Fig. 2b). Goodness-of-fit statistics for the GLMs fitted to the number of recruits and landings of sardine in the ICES divisions VIIIc + IXa are presented in Table 2. The model for sardine recruitment explained 56.84 % of total deviance, with wind strength as the only explanatory variable. Sea surface temperature (SST) (46.12 %) and wind strength (10.77 %) contributed most to the 56.89 % of total explained deviance of the model fitted to sardine landings. Linear regressions between observed and predicted values were significant ($p < 0.001$) both for sardine recruitment ($R^2 = 0.39$) and ICES landings ($R^2 = 0.53$) (Fig. 3).

Table 2. Goodness-of-fit statistics for the GLMs fitted to number of recruits and landings of sardine (*Sardina pilchardus*) in 1978-2014 in ICES divisions VIIIc + IXa (% explained – percentage of the total deviance explained).

Model	Deviance	Residual deviance	% explained	*p*-value
Recruitment				
NULL		19.68		
wind strength	11.19	8.50	56.84	< 0.001
Total explained			56.84	
Landings				
NULL		6.02		
sea surface temperature	2.78	3.24	46.12	< 0.001
wind strength	0.65	2.60	10.77	< 0.001
Total explained			56.89	

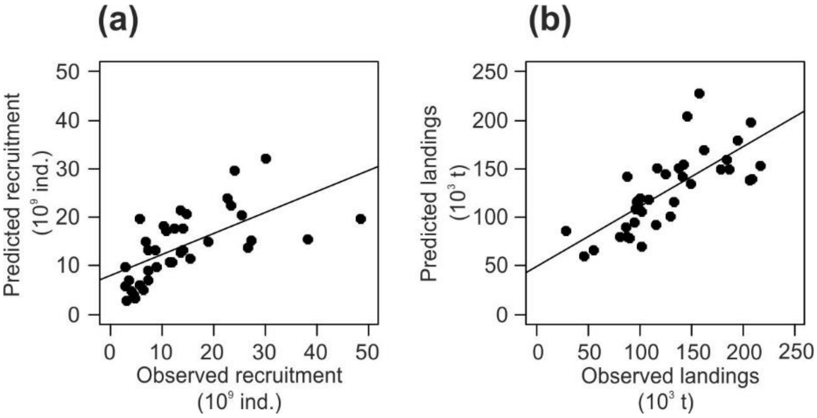

Fig. 3 Regression lines between observed and predicted values by the models fitted to (a) recruitment and (b) landings of sardine in ICES divisions VIIc and IXa, from 1978 to 2014.

Horse mackerel recruitment and landings in ICES division IXa have not shown a trend from 1992 to 2014. Two peaks could be observed in recruitment, one in 1996 (10.7×10^9 ind.) and the other in

2012 (12.6x10^9 ind.) (Fig. 2c). The highest value in landings (41,661 t) was recorded in 1998 and the lowest (18,887 t) in 2003 (Fig. 2d). However, no models could be fitted for the number of recruits and landings of horse mackerel in ICES division IXa.

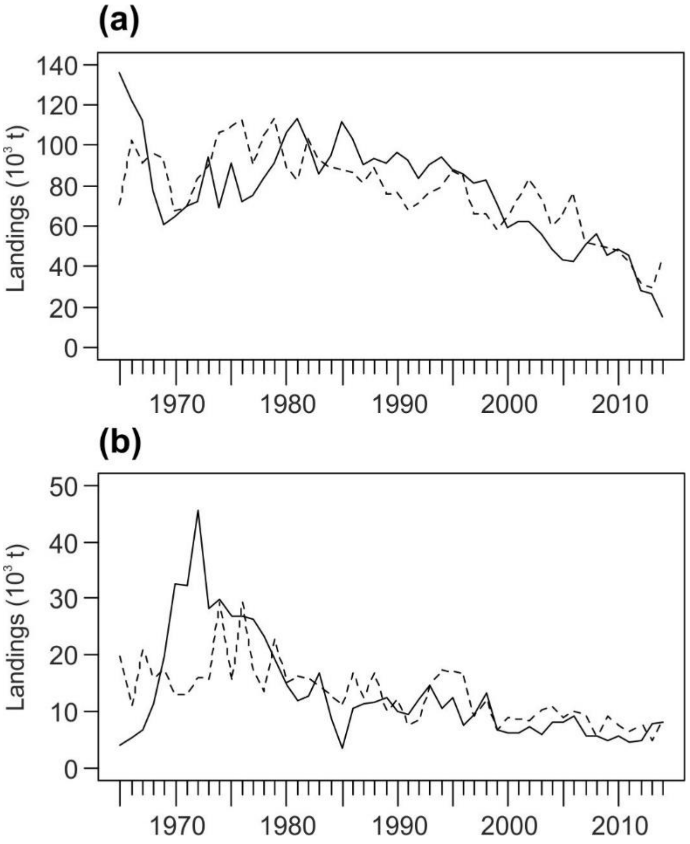

Fig. 4 Sardine and horse mackerel landings in the Portuguese coast, from 1965 to 2014. (a) sardine landings from purse-seine fisheries; (b) horse mackerel landings from trawl fisheries (dashed line – values predicted by the fitted models).

Table 3. Goodness-of-fit statistics for the GLMs fitted to Portuguese landings of sardine *Sardina pilchardus* and horse mackerel *Trachurus trachurus* in 1965-2014. Models were based on official landings data of purse-seine fisheries for sardine and trawl fisheries for horse mackerel. (% explained – percentage of the total deviance explained).

Model	Deviance	Residual deviance	% explained	*p*-value
Sardina pilchardus				
NULL		7.05		
sea surface temperature	1.91	5.15	27.04	< 0.001
wind strength	1.08	4.06	15.34	< 0.001
competitors	0.56	3.50	7.97	< 0.001
Total explained			50.35	
Trachurus trachurus				
NULL		19.67		
sea surface temperature	7.11	12.56	36.16	< 0.001
Total explained			36.16	

Sardine landings in Portuguese purse-seine fisheries decreased from 136,154 t in 1965 to 15,532 t in 2014 (Fig. 4a). The GLM fitted to landings of sardine in Portuguese purse-seine fisheries explained 50.35 % of total deviance (Table 3). SST explained 27.04 % of the model, followed by wind strength (15.34 %) and competitors (7.97 %). The linear regression between landings observed and predicted was significant ($R^2 = 0.40$; $p < 0.001$) (Fig. 5a).

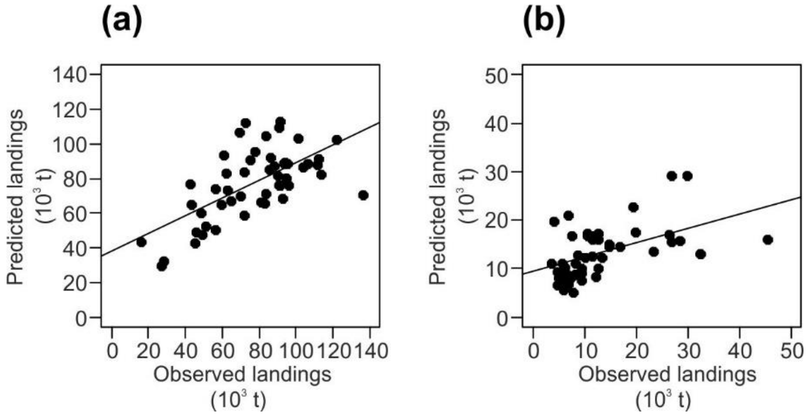

Fig. 5 Regression lines between observed and predicted values by the models fitted to landings of (a) sardine from purse-seine fisheries and (b) horse mackerel from trawl fisheries in the Portuguese coast, from 1965 to 2014.

Landings of horse mackerel in Portuguese trawl fisheries were higher in the 1970s, with a peak of 45,452 t in 1972, followed by a decreasing trend to a minimum of 3,579 t in 1985 (Fig. 4b). Since 1999, annual landings have been of less than 10,000 t. SST was the sole predictor of horse mackerel landings in Portuguese trawl fisheries, explaining 36.16 % of the total deviance (Table 3). The linear regression between landings observed and predicted was significant ($R^2 = 0.25$; $p < 0.001$) (Fig. 5b).

The relationship between predictors and landings is depicted in Fig. 6.

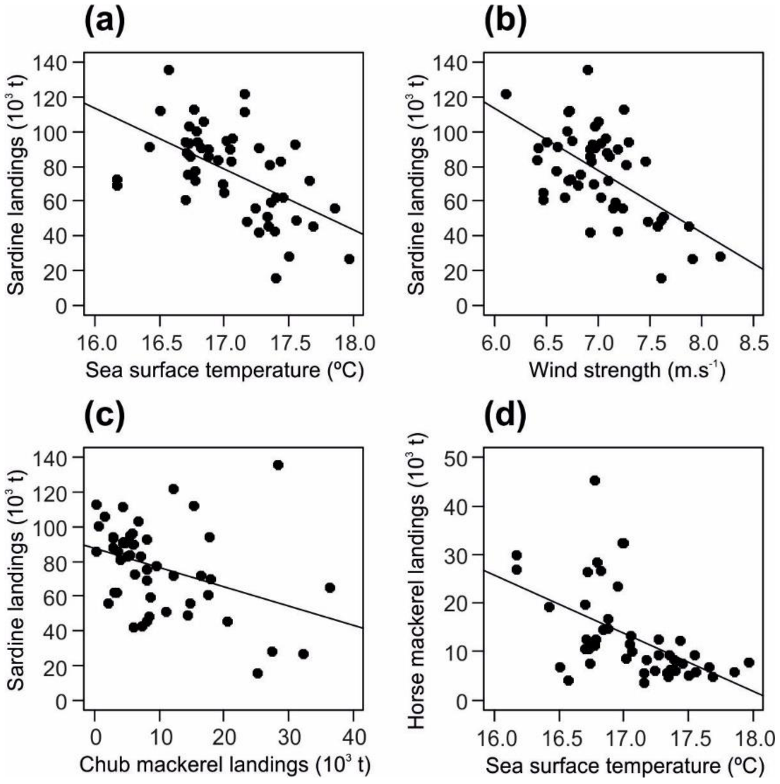

Fig. 6 Regression lines between (a) sea surface temperature and landings of sardine from purse-seine fisheries; (b) wind strength and landings of sardine from purse-seine fisheries; (c) landings of chub mackerel and landings of sardine from purse-seine fisheries; (d) sea surface temperature and landings of horse mackerel from trawl fisheries, from 1965 to 2014, in the Portuguese coast.

Discussion

The present study modelled recruitment and landings of two commercially important species in a coastal area affected by climate change. The goodness-of-fit of the models obtained was high, as confirmed by the percentage of total deviance explained and the linear regressions between values observed and predicted by the models. Sardine recruitment was explained by wind strength. Wind strength was also important explaining sardine landings, right after SST. In terms of Portuguese sardine landings, chub mackerel landings were also an important predictor. No model could be fitted to horse mackerel recruitment or landings in ICES division IXa. However, a model was fitted to a longer time series of horse mackerel landings in the Portuguese coast, with SST as the predictor.

Iberian sardine recruitment has been weak since 2004 (ICES, 2015). Several previous studies have tried to link sardine recruitment and abiotic variables, such as sunspots, NAO, wind strength, upwelling and SST (Borges *et al.*, 2003; Guisande *et al.*, 2001, 2004; Santos *et al.*, 2001). Santos *et al.* (2012) have considered SST to be the best candidate to explain recruitment in sardine, when compared to other environmental variables. However, the sardine recruitment model obtained in the present study had wind strength as the explanatory variable. The reproductive strategy of pelagic fish species, such as sardine and horse mackerel, is well adapted to coastal upwelling ecosystems. Spawning occurs in winter, when northerly winds are weaker, thus minimizing Ekman transport offshore and ensuring inshore transport and larval retention (Borges and Gordo, 1991; Nunes *et al.*, 2011; Stratoudakis *et al.*, 2007). The feeding of the larvae will later benefit from the increase of productivity due to summer upwelling (Santos *et al.*, 2001). A negative effect of winter upwelling on recruitment of sardine has previously been recorded (Santos *et al.*, 2001). This effect could be due to increased offshore transport and subsequent larval mortality in winter (Santos *et al.*, 2001). Thus, the negative effect of wind strength on sardine recruitment found in the present work may be due to increased offshore larval transport.

The model fitted to sardine landings during the same period (1978-2014) and the same area (ICES divisions VIIIc + IXa) also had wind strength as a predictor. Favourable upwelling winter wind conditions (high intensity and frequency of northerlies) have been associated with positive NAO index (Borges *et al.*, 2003) and landings of sardine in central Portugal have previously shown a significant negative correlation with winter NAO (Gamito *et al.*, 2015). In the present study, landings of sardine were also negatively influenced by wind strength. So, not only is wind strength negative for recruitment, through larval transport offshore, but it also seems to have an important role in the processes occurring between recruitment (age 0) and fisheries catches (2 years later). Rates of natural mortality of pelagic fish are strongly size-dependent: mortality rates are highest early in life, decreasing at later stages of development (Houde, 2002). There are several causes of mortality in early life, such as starvation and nutritional deficiency, predation, physical oceanographic processes and disease (Houde, 2002). Besides wind strength, SST explained most of the deviance in the model, agreeing with what was observed by Gamito *et al.* (2015), who found a negative correlation between sardine landings and SST in central Portugal. Garza-Gil *et al.* (2010) have predicted lower biomass and catch levels of sardine with rising sea surface temperature, resulting in a decrease of the economic yield for the Iberian-Atlantic fishing grounds. If SST would rise at a faster rate than the current one, biomass and profits would further decrease with greater intensity, whereas in a palliation of global warming scenario, both variables would decrease to a lesser degree (Garza-Gil *et al.*, 2010). Temperature directly impacts many physiological processes that may affect adult reproduction or larval survival and, subsequently, recruitment success (Santos *et al.*, 2012). The optimum temperature for spawning activity in sardine is 14-15 ºC, with avoidance occurring with temperatures below 12 ºC or above 16 ºC (Coombs *et al.*, 2006; Stratoudakis *et al.*, 2007). Therefore, although SST was not a predictor for sardine recruitment in the present study, if temperatures in winter continue to rise, the egg production of sardine may decrease (Santos *et al.*, 2012).

As the number of recruits was not an explanatory variable in models of landings in ICES divisions VIIIc and IXa, the modelling was extended to Portuguese landings. This methodology allowed for a longer time series and for the inclusion of biotic variables. Again, SST and wind strength were the most important predictors. However, this time they were followed by a biotic variable: the proxy of competitors, landings of chub mackerel *Scomber colias*, without time lags. The Atlantic chub mackerel is a subtropical small pelagic fish, ranging, in the eastern Atlantic, from the Bay of Biscay to South Africa (Castro Hernández and Santana Ortega, 2000), and it is traditionally a by-catch of the sardine fishery. However, chub mackerel has been increasing in importance in recent years and nowadays it is the most landed species in Portuguese fisheries (INE, 2015). Martins *et al.* (2013) observed an inverse correlation between the recruitment indices of sardine and chub mackerel, which was also found between landings of the same species (Gamito *et al.*, 2015). This may be due to an adverse effect of one species on the recruitment of the other, through competition for food or predation, or to a different response of each species to the same environmental conditions (Martins *et al.*, 2013). Species-specific differences in the tolerance to abiotic factors and prey requirements will cause species-specific responses of fish to climate-driven changes in aquatic habitats (Peck *et al.*, 2013). In a previous work focusing on landings in a port in central Portugal, temperature seemed not to have such a negative effect on chub mackerel landings as it had on sardine (Gamito *et al.*, 2015). This could be explained by differences in tolerance to increases in temperature between the two species. The chub mackerel spawns later and at higher temperatures than the sardine (Castro Hernández and Santana Ortega, 2000; Coombs *et al.*, 2006; Stratoudakis *et al.*, 2007). This fact, together with its affinity to subtropical waters, may indicate a higher tolerance of the chub mackerel to increases in SST. Nevertheless, the inverse relationship between landings of these two species may not necessarily be due to the inverse relationship in recruitment, but to an adaptation of the fishery; in years of low abundance in sardine, the chub mackerel may provide an alternative income (Martins *et al.*, 2013), resulting in higher landings of this species. In years of high sardine abundance, it is possible that fishers choose to discard the chub mackerel.

No model could be fitted to either recruitment or landings of horse mackerel in ICES division IXa. However, this could be due to the shortness of the time series, as data were only available since 1992. It has been previously shown that the detection of relationships between environment and recruitment strongly depends on the length of the time series (Francis, 2006). In fact, using the longer time series of Portuguese landings, a model could be fitted, with SST as the predictor. Lower SST in spring and summer seem to favour horse mackerel recruitment (Abaunza *et al.*, 2007). Cooler temperatures are also beneficial for the survival and development of the pelagic eggs of this species (Abaunza *et al.*, 2007).

Along with the warming that it has already suffered (Belkin, 2009), the Portuguese coast is expected to suffer changes in temperature and rainfall more accelerated than the global mean alteration rate (IPCC, 2007). In fact, a regional circulation model (HadRM3) predicts increases in SST in the Portuguese coast of 1 ºC and 2 ºC until 2100, under emissions scenarios B2 and A2, respectively (Reis *et al.*, 2006). Given the results obtained in the present study, this rising SST could strongly decrease landings of sardine and horse mackerel in the Portuguese coast. Shifts in species distributions in future climate change scenarios have already been predicted (Cheung *et al.*, 2009; Vinagre *et al.*, 2011). The distribution of marine ectotherms tends to move poleward as the ocean warms up, which may result in an increase in species richness in high latitude regions (Cheung *et al.*, 2009). Bioclimate envelope models have predicted a redistribution of the global catch potential, with an increase of 30-70 % in high-latitude regions and a decrease of up to 40 % in tropical regions (Cheung *et al.*, 2010). A different approach, using a physical-biogeochemical model coupled with a dynamic, size-based food web model, resulted in broadly similar predictions (Blanchard *et al.*, 2012). In fact, changes in the geographic distribution of fish species in marine ecosystems have already been documented throughout the world (Brander *et al.*, 2003; Perry *et al.*, 2005). An increase in the relative importance of landings of subtropical fish species (Gamito *et al.*, 2013) and lower landings of temperate species in warm years (Teixeira *et al.*, 2014) have already been reported for the Portuguese coast. A strong subtropicalization of the North Sea and Baltic Sea assemblages has been observed (Montero-Serra *et al.*, 2014). These areas have shifted away from typical cold-water assemblages (with Atlantic herring and European sprat) in the 1980s to warmer-water assemblages, including sardine and horse mackerel, from the 1990s onwards. The models built by the same authors have indicated SST as the primary driver of these change in the assemblage (Montero-Serra *et al.*, 2014). Thus, sardine and horse mackerel appear to be shifting north. Therefore, the effects of climate change on the marine environment may be affecting recruitment and subsequent catches of sardine and horse mackerel in the Portuguese coast, but also, as SST continues to rise, the geographic distribution of both species may continue to shift north, with consequences for Portuguese fisheries.

Acknowledgements

This study had the support of Fundação para a Ciência e Tecnologia (FCT), through the strategic project UID/MAR/04292/2013 granted to MARE and the grants awarded to R. Gamito (SFRH/BD/78363/2011) and C.M. Teixeira (SFRH/BPD/62986/2009).

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CHAPTER 7

Trends in landings, vulnerability and adaptation to climate change in different fleet components in the Portuguese coast

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Under review in Fisheries Research

Trends in landings, vulnerability and adaptation to climate change in different fleet components in the Portuguese coast

Abstract: Portugal is the third highest per capita consumer of fish in the world, with a fishing fleet consisting of trawlers, purse-seiners and multi-gear vessels, which use a wide variety of fishing gears, such as gillnets, trammel nets, longlines or traps. Climate change affects ocean conditions, impacting marine organisms and ecosystems, with consequences for marine fisheries. The consequences of climate change on fishing communities will depend on their exposure to climate change, the sensitivity of target species and ecosystems to climate change and fishermen's ability to adapt to climate change. The Portuguese coast is mainly north-south oriented and located in a biogeographic transition zone, between temperate and subtropical waters, where the northern or southern distribution limits of several species can be found. Also, the Portuguese coast is expected to suffer changes in temperature and precipitation more accelerated than the global mean alteration rate, which makes it particularly adequate for studies of the effect of climate change on coastal communities and fisheries. The present study analysed trends in landings of the most important fishing *métiers* in the Portuguese coast and the vulnerability and adaptation capacity of Portuguese fisheries to climate change. Official Portuguese landings (1992-2012) were analysed and a survey was conducted to assess fishermen's perception of landings and potential behaviour to the effects of climate change on fisheries. Eighteen new species were landed in Portuguese fisheries over the past 5 years, of which 12 were tropical or subtropical and 5 had their distribution limit along the Portuguese coast. A latitudinal pattern in the number of new species in landings was found, agreeing with a northward shift of subtropical species. The south coast has shown a higher vulnerability to climate change, in terms of both exposure and sensitivity of target species and ecosystems to its effects. Trawlermen may be more adaptable and less vulnerable to climate change, given the high mobility of their fleet. Multi-gear fisheries may be more flexible in changing target species or fishing gear, which makes it potentially less vulnerable to climate change. On the other hand, the high sensitivity of sardine to the effects of climate change makes the purse-seine fisheries particularly vulnerable to climate change.

Keywords: Climate change; fisheries; trawl; purse-seine; multi-gear

Introduction

Fisheries are traditionally, economically, socially and culturally important in Portugal, as the country is the third highest per capita consumer of fish in the world (Failler, 2007). The fishing fleet in Portugal consists of three main fleet components: trawl fisheries, purse-seine fisheries and multi-gear fisheries. Traditionally, trawl fishery targets Atlantic horse mackerel *Trachurus trachurus* (Linnaeus, 1758), European hake *Merluccius merluccius* (Linnaeus, 1758) and cephalopods. Purse-seine fisheries target small pelagic fish species, such as European sardine *Sardina pilchardus* (Walbaum, 1792), Atlantic chub mackerel *Scomber colias* Gmelin, 1789 and

Atlantic horse mackerel. Sardine is particularly important, as traditionally it has been the most landed species in Portugal. Nowadays, it is the second most important species landed in Portuguese waters in quantity, just after chub mackerel (INE, 2015). The multi-gear fishery is the largest and most diversified fishing fleet component in Portugal; it uses a wide variety of fishing gears, such as gillnets, trammel nets, longlines or traps. Therefore, target species in multi-gear fisheries vary according not only to the fishing gear used, but also to the geographic area along the Portuguese coast where the fishery takes place.

Climate change, the most widespread anthropogenic threat for ocean ecosystems (Halpern *et al.*, 2008), affects sea temperature, sea-level, ocean pH, rainfall and ocean circulation (Brander, 2007). These effects will have an impact on ocean organisms, the composition of marine communities and ecosystem function (Brown *et al.*, 2010), increasing the complexity of challenges facing fisheries (Sumaila *et al.*, 2011). Climate change impacts fish stocks either directly or indirectly: directly through physiological and behavioural effects, such as changes in growth, reproduction, mortality and distribution; indirectly by changing productivity and the structure and composition of marine ecosystems on which fish depend (Brander, 2010; Hare *et al.*, 2010; Perry *et al.*, 2005). Changes in geographic distribution of fish species have already been observed throughout the world and are more easily detected on northern and southern distribution limits (Brander *et al.*, 2003; Perry *et al.*, 2005). It has been predicted that changes in water temperature, driven by climate change, may lead to local extinctions and also to colonization by species previously absent in those areas (Cheung *et al.*, 2009; Vinagre *et al.*, 2011) and this will most likely affect the abundance, distribution and composition of fisheries catches (Gamito *et al.*, 2013; Sumaila *et al.*, 2011).

The consequences of climate change on fishing communities will depend on their exposure to climate change, the sensitivity of target species and ecosystems to climate change and fishermen's ability to adapt to climate change (Grafton, 2010). Both the observation of the impact of recent climate change and the predictions of climate change in future scenarios show that the effects of climate change will not be homogeneous throughout the world (IPCC, 2007; Santos, 2006). Southern Europe and the Mediterranean are more vulnerable to climate change than Central and Northern Europe (Santos, 2006). The Portuguese coast is expected to suffer changes in temperature and precipitation more accelerated than the global mean alteration rate (IPCC, 2007) and in fact the Iberian Coastal large marine ecosystem has already suffered a rapid increase in temperature, with an increase of 0.68 ºC in sea surface temperature between 1982 and 2006 (Belkin, 2009). Also, the Portuguese coast is mainly north-south oriented and located in a biogeographic transition zone, between temperate and subtropical waters, where the northern or southern distribution limits of several species can be found (Briggs, 1974). Hence, this coast is particularly adequate for studies of the effect of climate change on coastal communities and fisheries and several recent studies have focused on the influence of climate change on Portuguese fisheries (e.g. Gamito *et al.*, 2013, 2015a; Teixeira *et al.*, 2014, 2015). An increase in the occurrence of species with tropical affinities and a decrease in temperate species have been reported for the Portuguese coast (Cabral *et al.*, 2001; Vinagre *et al.*, 2009). To add to this, an increase in species richness, led by the arrival of new subtropical and tropical species and the loss of a few species, has been predicted for 2100 (Vinagre *et al.*, 2011). In terms of fisheries, an increase in the relative importance of landings of subtropical fish species (Gamito *et al.*, 2013) and lower landings of temperate species in warm years (Teixeira *et al.*, 2014) have already been reported for the Portuguese coast. Gamito *et al.* (2013) have also detected higher landings of subtropical species in multi-gear fisheries, which could indicate a capacity for adaptation amongst Portuguese multi-gear fisheries to the effects of climate change. Although climate change may bring challenges for fisheries, it may also result in new fishing opportunities in some geographical areas or *métiers* (Gamito *et al.*, 2015a; Sumaila *et al.*, 2011). However, it has not been investigated how different *métiers* along the Portuguese coast have been adapting to climate change. Therefore, the main objectives of the present study were (1) to detect effects of climate change in landings of the most important *métiers* in the Portuguese coast; (2) to analyse the vulnerability and adaptation capacity of Portuguese fisheries to climate change.

Methodology

Study area

The Portuguese coast is located in south-western Europe, with a north-south oriented western coast and an East-West oriented southern coast (Fig.1). Three biogeographic areas along the Portuguese coast were considered for this study, based on oceanographic conditions and ecological communities (Sousa *et al.*, 2005): northwest, southwest and south coasts.

Data source

Fishing data for the period of 1992 to 2012 were obtained from official Portuguese landings. Landing data included fleet component (trawl, purse-seine or multi-gear), fishing port, year, species landed and number of fishing days. For the multi-gear fleet, information on the fishing gear used was also available, allowing for the analysis of trammel nets, gillnets, bottom longline, dredge and traps. Multi-gear fisheries which had short time series (e.g. beach seine) were not considered in the present study.

A survey was conducted to assess fishermen's perception of landings and potential behaviour to the effects of climate change on fisheries. The survey consisted of a structured questionnaire carried out face-to-face with professional fishermen in fishing ports of high importance and tradition: Aveiro and Nazaré (northwest coast), Peniche and Setúbal (southwest coast) and Portimão and Olhão (south coast), from January to May 2015. The questionnaire collected information on target species, fishing gears used, fishermen's perception on recent trends in the catches of target species, attitudes towards a downfall in catches of target species in the future, willingness to fish a newly arrived commercial species and willingness to change fishing gear to catch that same species, as well as personal characteristics, such as age or educational level.

The response rates were high for the three fleet components (trawl, purse-seine and multi-gear) and the interviews ranged from 5 to 10 min. Altogether 80 fishermen were interviewed, 33 from trawl fisheries, 7 from purse-seine fisheries and 40 from multi-gear fisheries. This number was considered representative as, according to Morgan *et al.* (2002), when conducting in-depth interviews, the number of new concepts associated with each additional interview generally tends to diminish between 20 and 30 interviews.

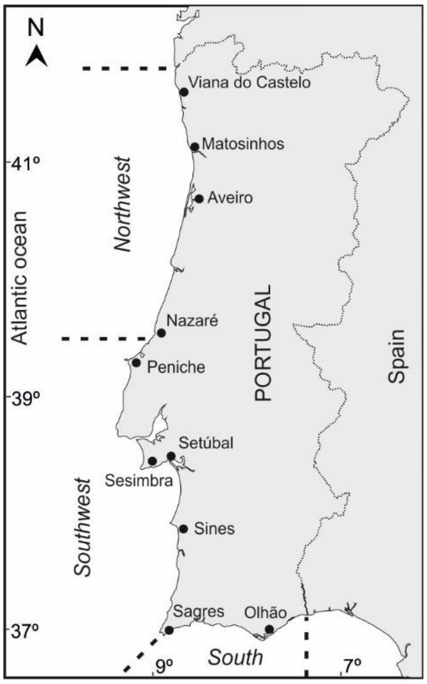

Fig. 1 Location of the three biogeographic areas of the Portuguese coast considered (northwest, southwest and south) and the ports considered for the analysis of landings per unit effort (LPUE) in multi-gear fisheries.

Data analysis

For each fishery (trawl, purse-seine, trammel nets, gillnets, bottom longline, dredge and traps) and each species, annual landings per unit effort (LPUE) were calculated as $t.day^{-1}$, for the Portuguese coast as a whole, and the biogeographic areas considered (northwest, southwest and south coasts), whenever possible. The amount of data was extremely high in multi-gear fisheries and sometimes patchy, with incomplete time series. Therefore, 10 ports were selected (Fig.1) for the analysis of LPUE, based on their importance for multi-gear fisheries and their geographic representativity. As trawl vessels operate along the entire Portuguese coast and land their catches in several ports, regardless of where they were actually caught, the analysis of LPUE in trawl fisheries was carried out for the total of the Portuguese coast.

Temporal trends in the LPUE of the most important species, both in biomass and value, in each *métier* and biogeographic area, were investigated through linear regressions.

For each *métier* and biogeographic area, new species and lost species in landings were identified. New species consisted of species only landed in the last five (consecutive) years of the time series. If a species was present in landings in the first five years of the time series and then absent, it was considered a lost species. New species and lost species were classified based on biogeography (temperate, subtropical, tropical or deep-water) and habitat, according to Fishbase (Froese and Pauly, 2015) and SeaLifeBase (Palomares and Pauly, 2015). Data on geographical distribution limits of these species were also collected from those databases.

Results

Trends in landings

Relative proportion of the most landed species in the total landings of the trawl fishery has not shown particular trends along the time series considered (Fig. 2). Horse mackerel *T. trachurus* and blue whiting *Micromesistius poutassou* (Risso, 1827) have been the most landed species over the 20 years in analysis. Sardine *S. pilchardus* has been the most landed species in the purse-seine fishery, particularly in the northwest coast, where it was responsible for more than 50 % of the total LPUE. In the southwest and south coasts, Atlantic chub mackerel *S. colias* has been increasing in relative importance, especially in the south coast, where it has become the main species caught in the purse-seine fishery since 2004. The percentage of LPUE of European anchovy

Engraulis encrasicolus (Linnaeus, 1758) has decreased through the time series, in every biogeographic area of the Portuguese coast.

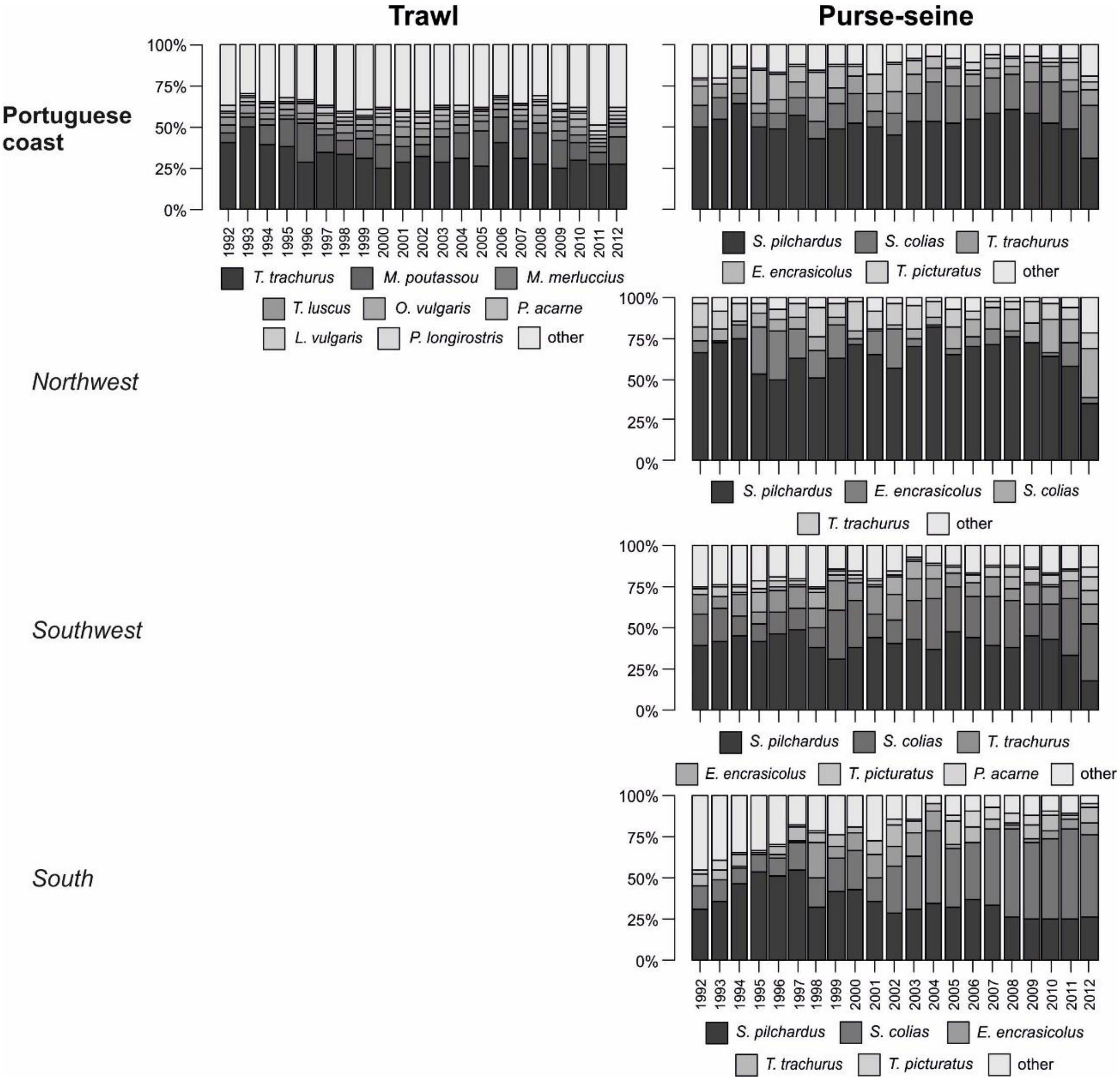

Fig. 2 Annual percentage of landings per unit effort (LPUE) for the most landed species in trawl and purse-seine fisheries in the Portuguese coast (whole Portuguese coast, northwest, southwest and south coasts), from 1992 to 2012.

Skates (*Raja* spp.) have shown the highest percentage of LPUE in the trammel nets fishery along the Portuguese coast (Fig. 3), particularly in the southwest and south areas. In the northwest area, pouting *Trisopterus luscus* (Linnaeus, 1758) was the most landed species, followed by soles (*Solea* spp.), common cuttlefish *Sepia officinalis* Linnaeus, 1758, European seabass *Dicentrarchus labrax* (Linnaeus, 1758) and European hake *M. merluccius* (Linnaeus, 1758). Nevertheless, given the high diversity of species caught by trammel nets and gillnets, when the most landed species are summed they still do not reach 50 % of the total annual LPUE for these fisheries.

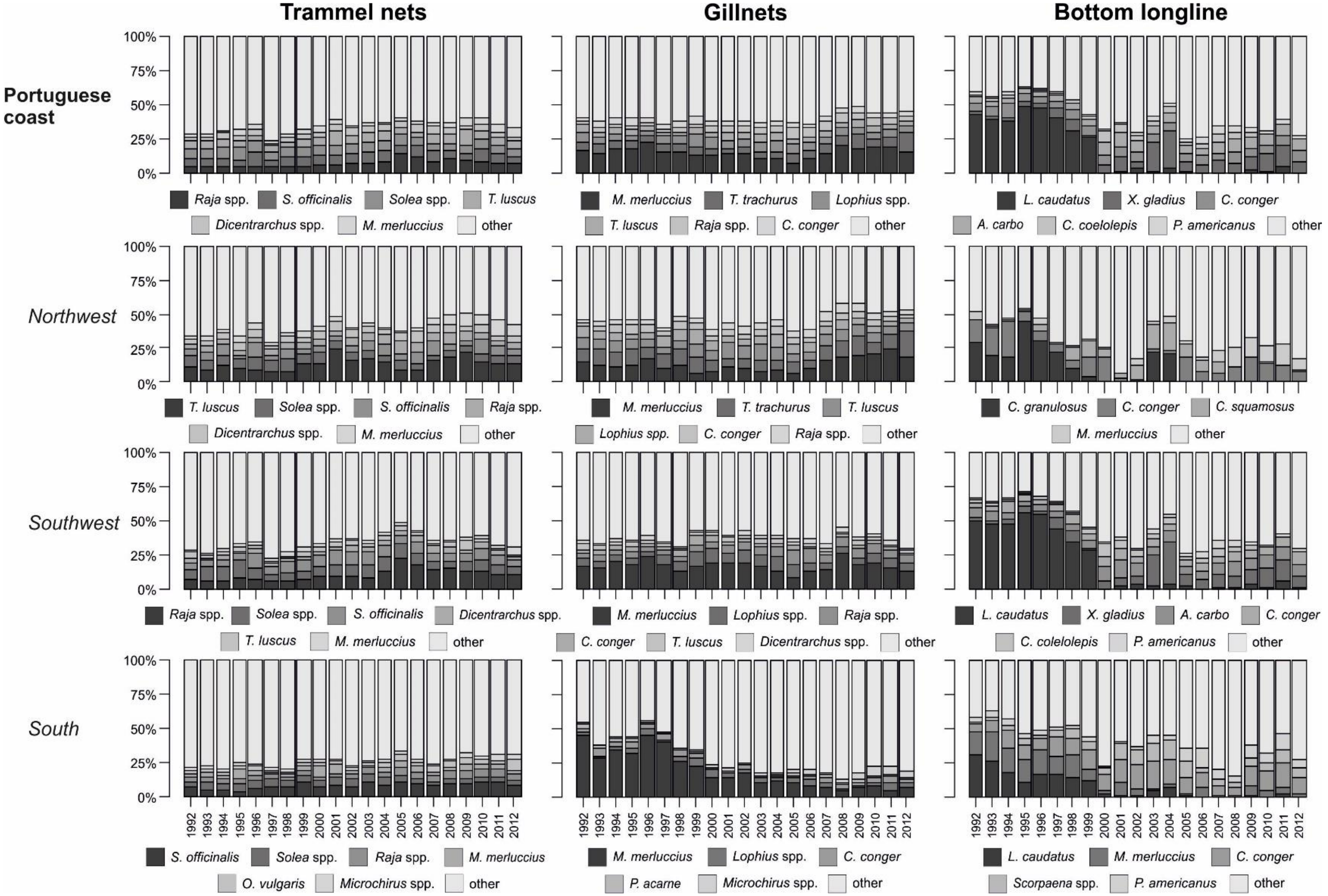

Fig. 3 Annual percentage of landings per unit effort (LPUE) for the most landed species in trammel nets, gillnets and longline fisheries in the Portuguese coast (whole Portuguese coast, northwest, southwest and south coasts), from 1992 to 2012.

The most landed species in gillnets' fishery was *M. merluccius*, followed by *T. trachurus* and anglers (*Lophius* spp.). Although the silver scabbardfish *Lepidopus caudatus* (Euphrasen, 1788) was the most landed species in the bottom longline fishery, it showed a marked decrease since 2000. On the other hand, the black scabbardfish *Aphanopus carbo* Lowe, 1839 has been increasing in relative importance, especially in the southwest coast. The solid surf clam *Spisula solida* (Linnaeus, 1758) was the most landed species in the dredge fishery (Fig. 4). Traps mainly landed the common octopus *Octopus vulgaris* Cuvier, 1797.

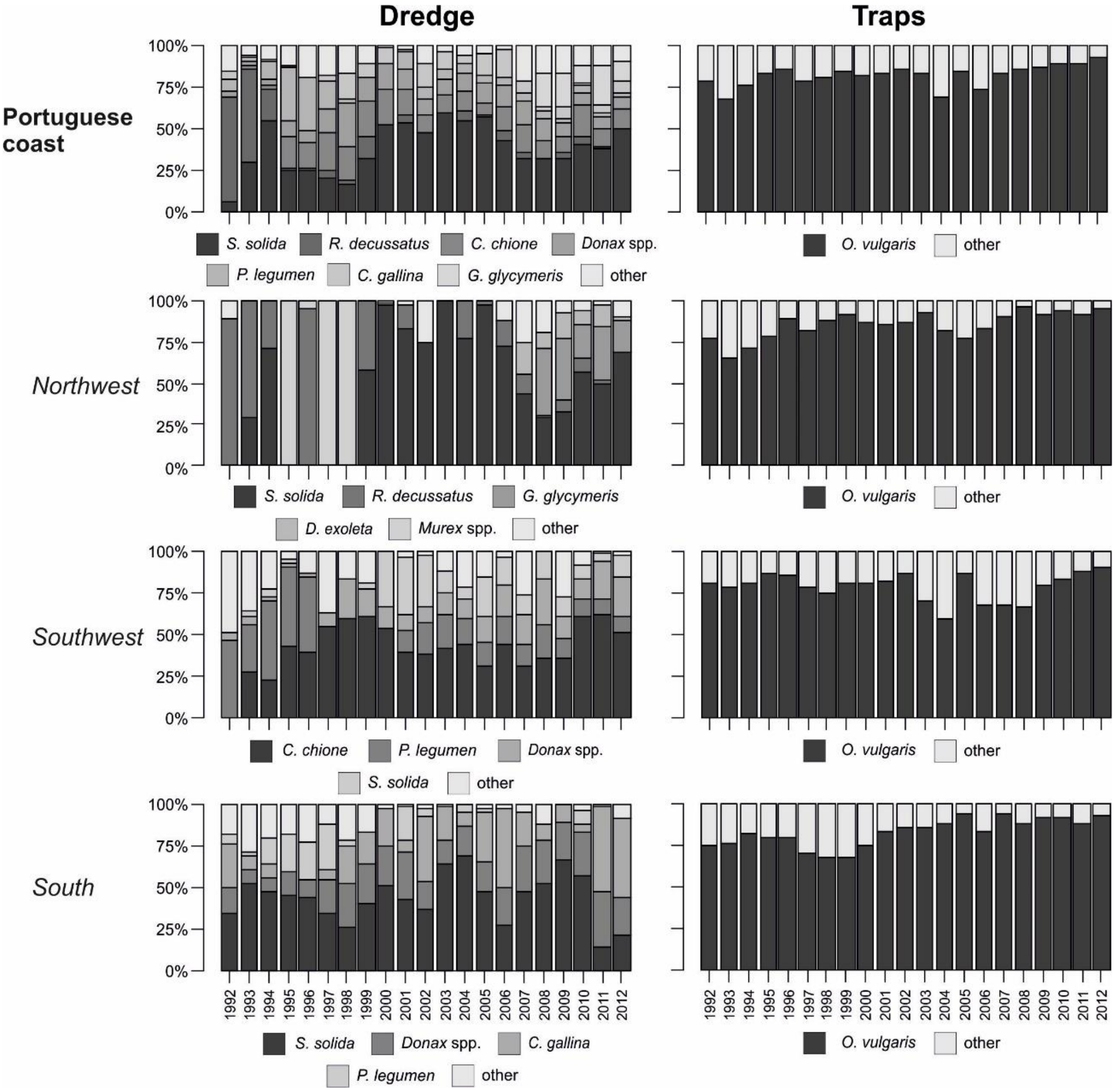

Fig. 4 Annual percentage of landings per unit effort (LPUE) for the most landed species in dredge and traps in the Portuguese coast (whole Portuguese coast, northwest, southwest and south coasts), from 1992 to 2012.

Table 1. Significant ($p < 0.05$) trends in LPUE (1992-2012) of the main species in trawl, purse-seine, trammel nets, gillnets, bottom longline, dredge and traps fisheries in the Portuguese coast (whole coast, northwest, southwest and south coasts). (- decreasing trend; + increasing trend).

	Portuguese coast		***Northwest***		***Southwest***		***South***	
	Trend	*p*	Trend	*p*	Trend	*p*	Trend	*p*
TRAWL								
Trachurus trachurus	-	< 0.001						
Merluccius merluccius	-	< 0.05						
Trisopterus luscus	-	< 0.01						
Loligo vulgaris	-	< 0.01						
Octopus vulgaris	-	< 0.001						
Aristeus antennatus	-	< 0.05						
Parapenaeus longirostris	+	< 0.05						
PURSE-SEINE								
Sardina pilchardus	-	< 0.05			-	< 0.001	-	< 0.01
Scomber colias	+	< 0.01	+	< 0.05			+	< 0.01
Trachurus trachurus					-	< 0.05		
TRAMMEL NETS								
Raja spp.	+	< 0.01	+	< 0.01	+	< 0.01	+	< 0.001
Sepia officinalis							+	< 0.001
Trisopterus luscus	+	< 0.05	+	< 0.05				
Dicentrarchus spp.	+	< 0.05			+	< 0.01		
Merluccius merluccius	+	< 0.01	+	< 0.01				
Octopus vulgaris							+	< 0.001
Microchirus spp.							+	< 0.01
GILLNETS								
Merluccius merluccius	-	< 0.01			-	< 0.05	-	< 0.001
Lophius spp.	-	< 0.001	-	< 0.01			-	< 0.05
Trisopterus luscus	-	< 0.01	-	< 0.05	-	< 0.001		
Conger conger					-	< 0.001	-	< 0.001
Microchirus spp.							+	< 0.05
BOTTOM LONGLINE								
Lepidopus caudatus	-	< 0.001			-	< 0.001	-	< 0.001
Conger conger	-	< 0.001	-	< 0.01	-	< 0.05	-	< 0.001
Centroscymnus coelolepis			-	< 0.001				
Centrophorus granulosus			-	< 0.001				
Merluccius merluccius							-	< 0.001
Scorpaena spp.							-	< 0.01
DREDGE								
Spisula solida							-	< 0.01
Ruditapes decussatus	-	< 0.05	-	< 0.05				
Donax spp.					+	< 0.01	-	< 0.01
Pharus legumen	-	< 0.01			-	< 0.01	-	< 0.01
Glycymeris glycymeris			+	< 0.001				
Dosinia exoleta			+	< 0.001				
TRAPS								
Octopus vulgaris	+	< 0.001	+	< 0.001			+	< 0.001

Significant trends ($p < 0.05$), both decreasing and increasing, were found in the LPUE of several species and can be observed in Table 1. Most of the significant trends found in trawl, gillnets and bottom longline fisheries were decreasing trends. On the other hand, significant trends found in trammel nets fisheries were increasing trends. In terms of purse-seine fisheries, sardine has shown a decreasing trend, whereas chub mackerel has increased.

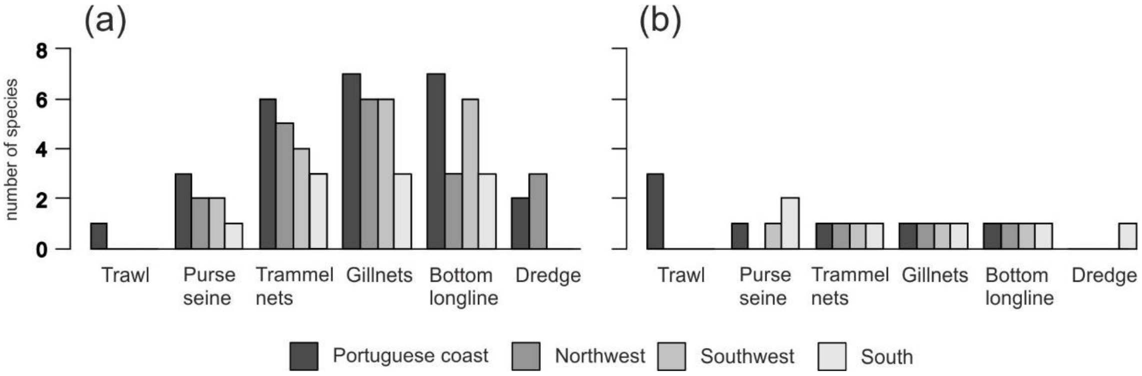

Fig. 5 Number of (a) newly arrived species and (b) lost species in landings of trawl, purse-seine, trammel nets, gillnets, bottom longline and dredge fisheries in the Portuguese coast (whole Portuguese coast, northwest, southwest and south coasts).

Except for the trawl fishery, for all other *métiers* the number of new species was higher than the number of species lost (Fig. 5). Gillnets and bottom longline fisheries had the highest number of new landed species (7), whereas trawl fisheries had only 1 new species landed in recent years (Fig. 5a). Generally, 1 species was lost in each *métier*, except for trawl fisheries, which have lost 3 species (Fig. 5b). The new species landed consisted of 4 tropical species, 8 subtropical species, 2 temperate species and 4 deep-water species (Table 2). Of these new 18 species, 5 had their northern limit along the Portuguese coast. The grey triggerfish *Balistes capriscus* Gmelin, 1789 was a new species in landings in purse-seine, trammel nets, gillnets and bottom longline fisheries in every area of the Portuguese coast considered. As to the lost species in landings, 2 were subtropical and 4 were temperate (Table 3). Three of the temperate species lost (common shrimp *Crangon crangon* (Linnaeus, 1758), European flounder *Platichthys flesus* (Linnaeus, 1758) and pouting *T. luscus*) had their southern distribution limit along the Portuguese coast. *P. flesus* and *T. luscus* have been lost in landings in the south coast. The subtropical ocean sunfish *Mola mola* (Linnaeus, 1758) has been lost in landings in every area considered.

Table 2. New species landed in the Portuguese coast in trawl, purse-seine, trammel nets, gillnets, bottom longline and dredge fisheries (PT – whole Portuguese coast; NW – northwest coast; SW – southwest coast; S – south coast; * northern distribution limit along the Portuguese coast).

	Biogeographic type	Habitat occupation	Fleet component	Fishing area			
				PT	NW	SW	S
Auxis rochei	Tropical	Pelagic	Purse-seine	X	X		X
Balistes capriscus	Subtropical	Reef-associated	Purse-seine	X	X	X	
			Trammel nets	X	X	X	X
			Gillnets	X	X	X	X
			Longline	X	X	X	X
Deania calcea	Deep-water	Bathydemersal	Gillnets	X	X	X	
Dentex angolensis	Tropical	Demersal	Longline	X		X	X
Dosinia exoleta	Subtropical	Benthic	Dredge	X	X		
Gaidropsarus guttatus	Tropical	Demersal	Trammel nets	X	X		
			Gillnets	X	X		X
			Longline	X	X		
Glycymeris glycymeris	Subtropical	Benthic	Dredge	X	X		
Gymnura altavela	Subtropical *	Demersal	Trammel nets			X	
			Gillnets			X	
Helicolenus dactylopterus	Deep-water	Bathydemersal	Trammel nets			X	
			Gillnets		X	X	
			Longline		X	X	
Labrus bergylta	Temperate	Reef-associated	Trammel nets	X	X		
			Gillnets	X	X		
Pagrus caeruleostictus	Subtropical *	Benthopelagic	Trammel nets	X			X
			Gillnets	X			X
			Longline	X			X
Parapristipoma octolineatum	Subtropical *	Demersal	Trawl	X			
			Trammel nets	X	X		
			Gillnets		X		
Pomadasys jubelini	Tropical	Demersal	Trammel nets				X
Pontinus kuhlii	Deep-water *	Bathydemersal	Trammel nets	X	X	X	
			Gillnets	X		X	
			Longline	X		X	
Scymnodon ringens	Deep-water	Bathypelagic	Longline	X		X	
Seriola dumerili	Subtropical *	Reef-associated	Gillnets	X		X	
			Longline	X		X	
Trachurus mediterraneus	Subtropical	Pelagic	Purse-seine	X		X	
Venerupis pullastra	Temperate	Benthic	Dredge		X		

Table 3. Species lost in recent landings in the Portuguese coast in trawl, purse-seine, trammel nets, gillnets, bottom longline and dredge fisheries (PT – whole Portuguese coast; NW – northwest coast; SW – southwest coast; S – south coast; * southern distribution limit along the Portuguese coast).

	Biogeographic type	Habitat occupation	Fleet component	Fishing area			
				PT	NW	SW	S
Crangon crangon	Temperate *	Benthic	Trawl	X			
Mola mola	Subtropical	Pelagic	Trawl	X			
			Purse-seine	X		X	
			Trammel nets	X	X	X	X
			Gillnets	X	X	X	X
			Longline	X	X	X	X
Platichthys flesus	Temperate *	Demersal	Purse-seine				X
Sphyraena sphyraena	Subtropical	Pelagic	Trawl	X			
Trisopterus luscus	Temperate *	Benthopelagic	Purse-seine				X
Venerupis pullastra	Temperate	Benthic	Dredge				X

Characteristics of fishermen and fishing operation

Demographic and fishing characteristics of the interviewed fishermen are shown in table 4. Mean age ranged from 47.7 years-old in trawl fisheries to 54.6 years old in purse-seine fisheries and experience in the fishing activity varied from 31.1 years in trawl fishery to 39.6 years in purse-seine fishery. The percentage of fishermen interviewed who owned the vessels they worked on was highest in purse-seine fishery (85.7 %), followed by multi-gear (72.5 %) and trawl fisheries (33.3 %). The main target species were *T. trachurus* (51.5 %) and crustaceans (30.3 %) in trawl fishery, *S. pilchardus*, *T. trachurus* and *S. colias* in purse-seine fishery, and *S. officinalis* and *Solea* spp. in multi-gear fisheries.

Fishermen's perceptions about trends in catches of target species

Most fishermen in trawl and multi-gear fisheries perceived no trend in recent catches of their target species (75.8 % and 47.5 %, respectively), whereas most purse-seine fishermen reported a decreasing trend in catches (71.4 %) (Table 5).

Table 4. Demographic and fishing characteristics (mean (standard deviation) for continuous variables and percentage for categorical variables).

	Trawl operators (n=33)	Purse-seine operators (n=7)	Multi-gear operators (n=40)
Demographic			
Mean age (years)	47.7 (11)	54.6 (14.5)	49.7 (13.9)
Educational level (%)			
No formal education			5 %
Basic 1st stage education (4 years of schooling)	9.1 %	28.5 %	32.5 %
Basic 2nd stage education (6 years of schooling)	42.4 %	42.9 %	27.5 %
Basic 3rd stage education (9 years of schooling)	27.3 %	14.3 %	22.5 %
Secondary education (12 years of schooling)	6.1 %	14.3 %	12.5 %
University degree	15.2 %		
Fishing activity			
Experience fishing (years)	31.1 (13)	39.6 (13.8)	34.9 (15)
Vessel ownership (%)	33.3 %	85.7 %	72.5 %
Number of crew on board	8.1 (4.9)	11 (5)	2.4 (0.9)
Fishing gear used (%)	Otter trawl (100 %)	Purse-seine (100 %)	Gillnets (47.5 %) Trammel nets (67.5 %) Dredge (2.5 %) Hand jigs (5 %)
Target species (%)	*T. trachurus* (51.5 %) Crustaceans (30.3 %) *M. merluccius* (9.1 %) *M. poutassou* (6.1 %) *Solea* spp. (3 %) Clams (3 %) *H. hipoglossus* (3 %)	*S. pilchardus* (100 %) *T. trachurus* (100 %) *S. colias* (100 %)	*S. officinalis* (70 %) *Solea* spp. (62.5 %) *O. vulgaris* (32.5 %)

Although most trawlermen have reported the absence of a trend in target species catches, the present work detected negative trends in LPUE of the most important target species of this fishery (Table 6). For the vast majority of purse-seine fishermen (71.4 %), there has been a decreasing trend in catches and that perception agrees with the decreasing trend observed in sardine *S. pilchardus* LPUE. However, there has also been an increasing trend in chub mackerel *S. colias* in this fishery. Generally, the perception of multi-gear fishermen was that there was no trend in their catches (47.5 %) or that a decreasing trend could be observed (45 %). The analysis on the LPUE of the main target species for trammel nets detected no trend, whereas in traps an increasing trend was observed for octopus *O. vulgaris*.

Table 5. Fishermen's perceptions and potential adaptation strategies (percentage).

	Trawl operators (n=33)	Purse-seine operators (n=7)	Multi-gear operators (n=40)
Perceptions about trends in catches of target species (%)			
Increasing trend	3 %		7.5 %
No trend	75.8 %	28.6 %	47.5 %
Decreasing trend	18.2 %	71.4 %	45 %
Potential adaptation strategies			
Adaptation strategies in case of downfall in catches (%)			
Stop fishing	26 %	71.4 %	35 %
Move to another fishing area	51.9 %	14.3 %	22.5 %
Change the fishing gear	11.1 %	28.6 %	27.5 %
Change the target species	18.6 %		
Change in fishing routine	18.6 %		7.5 %
Does not know			2.5 %
Willingness to target a new species (%)			
Yes	100 %	85.7 %	85 %
No		14.3 %	15 %
Willingness to change fishing gear to fish new species (%)			
Yes	9.1 %	14.3 %	72.5 %
No	84.8 %	85.7 %	27.5 %
Maybe	6.1 %		

When asked about what they would do in the case of a severe downfall in catches of their target species, most fishermen operating purse-seiners and multi-gear vessels answered that they would stop fishing (Table 5). This choice was particularly high in purse-seine fishermen (71.4 %). On the other hand, most trawlermen reported that they would move to another fishing area (51.9 %). The vast majority of fishermen were willing to fish a newly arrived species (100 % of trawlermen, 85.7 % of purse-seine fishermen and 85 % of fishermen from the multi-gear fishery). However, 72.5 % of multi-gear fishermen were willing to change fishing gear in order to target new species, whereas trawl and purse-seine fishermen were not (84.8 % and 85.7 %, respectively).

Table 6. Trends in landings per unit effort (LPUE) (1992-2012) and fishermen's perceptions of landings of the main species in trawl, purse-seine and multi-gear fisheries in the Portuguese coast. (- decreasing trend; + increasing trend).

	Trend	*p*	Fishermen's perception of landings		
			Increasing	*No trend*	*Decreasing*
TRAWL			3 %	75.8 %	18.2 %
Trachurus trachurus	-	< 0.001			
Micromesistius poutassou					
Merluccius merluccius	-	< 0.05			
Trisopterus luscus	-	< 0.01			
Pagellus acarne					
Loligo vulgaris	-	< 0.01			
Octopus vulgaris	-	< 0.001			
Aristeus antennatus	-	< 0.05			
Parapenaeus longirostris	+	< 0.05			
Nephrops norvegicus					
PURSE-SEINE			0 %	28.6 %	71.4 %
Sardina pilchardus	-	< 0.05			
Scomber colias	+	< 0.01			
Trachurus trachurus					
Engraulis encrasicolus					
Trachurus picturatus					
MULTI-GEAR			7.5 %	47.5 %	45 %
TRAMMEL NETS					
Sepia officinalis					
Solea spp.					
TRAPS					
Octopus vulgaris	+	< 0.001			

Discussion

The Portuguese coast is located in a biogeographic transition zone, between temperate and subtropical waters, where the northern or southern distribution limits of several species can be found (Briggs, 1974). It is precisely in areas with these characteristics that changes in the geographic distribution of fish species may be more easily detected (Brander *et al.*, 2003; Perry *et al.*, 2005) and the present work found 18 new species landed in Portuguese fisheries over the past 5 years, of which 12 were tropical or subtropical and 5 had their distribution limit along the Portuguese coast.

Changes in water temperature, driven by climate change, may lead to local extinctions and also to colonization by species previously absent in certain areas (Cheung *et al.*, 2009). As temperature increases, the distribution of marine ectotherms tends to move poleward, which may result in an increase in species richness in higher latitudes and a decrease in tropical regions (Cheung *et al.*, 2009, 2010; Gamito *et al.*, 2015b). A general increase in species richness in the Portuguese coast by 2100 has been predicted, with the appearance of new subtropical and tropical species and the elimination of only a few species (Vinagre *et al.*, 2011) and a recent increase in the relative importance of subtropical fish species in Portuguese fisheries has been reported (Gamito *et al.*, 2013). However, the south coast of Portugal may be particularly vulnerable to climate change, as many of temperate and subtropical species in the area have their upper thermal limit at 19 ºC and may disappear if temperature reaches 20 ºC, which is the temperature predicted by the regional circulation model HadRM3 for the A2 scenario envisioned by the Special Report on Emission Scenarios (Nakicenovic *et al*,. 2000; Reis *et al.*, 2006; Vinagre *et al.*, 2011). The present study detected less new species in landings in the south coast than in the other biogeographic areas considered. In fact, a latitudinal pattern could be observed in the number of new species in landings, with more new species appearing in the north. Also, most of the new species in landings in the northwest coast were subtropical and tropical, and some had their northern limit along the Portuguese coast. This supports the idea of a northward shift of subtropical species that were not previously present in landings in the northwest coast.

Sardine *S. pilchardus* was the most landed species in the purse-seine fishery over the years, especially in the northwest coast, where it is usually responsible for more than 50 % of the total landings of this fishery. Small pelagic fishes are highly consumed in Portugal and are thus main targets for Portuguese fisheries (INE, 2015). The reproductive strategy of sardine, such as other pelagic fish species, is adapted to coastal upwelling ecosystems. Spawning occurs in winter, when northerly winds are weaker, minimizing Ekman transport offshore and ensuring inshore transport and larval retention (Nunes *et al.*, 2011; Stratoudakis *et al.*, 2007). Larvae will then benefit from the increase in productivity due to the summer upwelling (Santos *et al.*, 2001). Sardine recruitment and landings have previously been linked to sea surface temperature (SST) (Gamito *et al.*, 2015a; Santos *et al.*, 2001). The optimum temperature for spawning in sardine is 14-15 ºC, with avoidance occurring with temperatures below 12 ºC or above 16 ºC (Coombs *et al.*, 2006; Stratoudakis *et al.*, 2007). Thus, if temperatures in winter continue to rise, the egg production of sardine may decrease (Santos *et al.*, 2001). If SST in the Iberian-Atlantic fishing grounds would rise at a faster rate than the current one, biomass and profits in sardine fisheries would further decrease with greater intensity, whereas in a palliation of global warming scenario, both variables would decrease to a lesser degree (Garza-Gil *et al.*, 2010). In fact, a declining trend was observed in sardine LPUE for the Portuguese coast as a whole and for the southwest and south coast, which coincides with the increasing SST in the Portuguese coast (Belkin, 2009; Gamito *et al.*, 2013), and particularly in the southern areas (Gamito *et al.*, 2015a). Chub mackerel *S. colias* is usually a by-catch of sardine fishery, but it may be an alternative income in seasons when it is abundant and sardine is not (Martins *et al.*, 2013). In fact, the chub mackerel has been increasing in importance in recent years, as its landings have increased and sardine landings have decreased (Gamito *et al.*, 2015a; INE, 2015; Martins *et al.*, 2013). This pattern could also be observed in LPUE in the present work, with the relative importance of *S. colias* increasing in the southwest and south coast; in the south coast it has even become the most important species since 2004. *S. colias* is a subtropical small pelagic fish that in the eastern Atlantic ranges from the Bay of Biscay to South Africa (Castro Hernández and Santana Ortega, 2000). Spawning occurs in winter-spring with temperatures from 15 ºC to 20 ºC (Castro Hernández and Santana Ortega, 2000). As this species spawns later and at higher temperatures than *S. pilchardus*, it may have a higher tolerance to increases in SST.

Although no particular trends in the relative importance of the main species landed in trawl fisheries were visible, declining trends in the LPUE of several species were found, including for the most landed species, horse mackerel *T. trachurus*. This species is a small pelagic whose reproductive strategy, like *S. pilchardus*, is well adapted to coastal upwelling ecosystems (Borges and Gordo, 1991; Santos *et al.*, 2001). Therefore, winter upwelling may have negative effects on recruitment of horse mackerel, as larvae may be transported offshore (Santos *et al.*, 2001).

Elasmobranchs are an important by-catch component in Portuguese artisanal fisheries (Erzini *et al.*, 2002) and most skates *Raja* spp. caught in trammel nets fishery in the southwest coast are landed (Baeta *et al.*, 2010; Batista *et al.*, 2009). In fact, the present study showed that landings of *Raja* spp. have been increasing and that this group of species was the most landed in trammel nets in the Portuguese coast, particularly in the southwest and south areas. In the northwest area, pouting *T. luscus* was the most landed species in trammel net fisheries. This temperate species has its southern distribution limit in the Portuguese coast and its total landings in Portugal have been decreasing (Teixeira *et al.*, 2014). The same authors have also detected lower landings of *T. luscus* in warm years (Teixeira *et al.*, 2014). This may indicate a distribution shift of this species to the north, led by ocean warming. Soles *Solea* spp. and cuttlefish *S. officinalis* were also quite abundant in trammel nets fishery landings. Flatfish fisheries have a high economic importance along the Portuguese coast and sole landings are of particular relevance in the southwest coast, since about 60 % of total sole landings occur in this area, almost exclusively from trammel nets (Batista *et al.*, 2009; Teixeira and Cabral, 2009; Teixeira *et al.*, 2011). Landings of both *Solea* spp. and *S. officinalis* have been previously correlated with SST in the southwest coast, which may indicate a positive effect of rising temperature in landings of these species (Gamito *et al.*, 2015a). However, trammel nets fisheries are still quite diverse along the Portuguese coast and land a huge variety of species. Most fishermen interviewed operating multi-gear vessels perceived no trend in recent catches of their target species. Given the fact that most of these fishermen operated with trammel nets and had *Solea* spp. and *S. officinalis* as main target species, this perception agreed with what was found for LPUE of these species. However, it is important to note that these fishermen have stated that they would stop fishing in case of a severe downfall in catches hence a decrease in landings of these species could have serious social impacts. The most landed species in gillnets fishery were hake *M. merluccius*, horse mackerel *T. trachurus* and anglers *Lophius* spp. Both *M. merluccius* and *Lophius* spp. showed declining trends in landings. In fact, the southern stock of *M. merluccius* has been under a recovery plan since 2006, which aims to rebuild the stock to safe biological limits by decreasing fishing mortality (ICES, 2013). The recruitment of *Lophius* spp. in the Portuguese coast has been relatively low in recent years and shows little evidence of strong year classes since 2001 (ICES, 2013). Nevertheless, gillnets also land a high diversity of other species, which summed together account for more than 50 % of the total LPUE for this fishery. Although silver scabbardfish *L. caudatus* has been the most landed species in the bottom longline fishery, it showed a marked decrease since 2000. On the other hand, black scabbardfish *A. carbo* has been increasing in relative importance, especially in the southwest coast. Although solid surf clam *S. solida* was the most landed species in the dredge fishery, this temperate species has been declining in landings in the south coast. The pullet carpet shell *Venerupis pullastra* (Montagu, 1803), also a temperate species, has disappeared from landings in the south coast and become a new species in the northwest coast, which may indicate a northward shift of this species. Two other new species were found in landings in the north coast: the mature dosinia *Dosinia exoleta* (Linnaeus, 1758) and the common European bittersweet *Glycymeris glycymeris* (Linnaus, 1758), both subtropical, which have had an increasing trend in landings in the north coast. The main species in traps fisheries landings is the octopus *O. vulgaris*. This species is currently the most important species in Portuguese landings in terms of value (INE, 2015). Landings of octopus in Portugal have increased since the 1970s and more than 90 % of its landings in Portugal are caught with traps (Moreno *et al.*, 2014; Pilar-Fonseca *et al.*, 2014). In fact, the present study found a significant increasing trend in landings of *O. vulgaris* in traps fishery. A significant positive effect of SST on *O. vulgaris* pre-recruit distribution in the west Portuguese coast has been found, with pre-recruits preferring habitats where SST was between 15.3 ºC and 16.0 ºC (Moreno *et al.*, 2014), and landings of this species in an area of the southwest coast have been positively correlated with SST (Gamito *et al.*, 2015a). However, Moreno *et al.* (2014) also found a significant negative effect of SST on the pre-recruit distribution in the south coast, where SST is higher. A detrimental effect of warm anomalies in the landings of octopus has also been found in the Western Mediterranean (Vargas-Yáñez *et al.*, 2009). Therefore, although increasing SST may seem to favour octopus landings, if temperature increases beyond the thermal optimum of the species, its effect on landings may be adverse. This is especially a problem in the south, where most small-scale fisheries and coastal communities dependent on fisheries are heavily economically dependent on octopus landings (Pita *et al.*, 2015).

The consequences of climate change on fishing communities will depend on their exposure to climate change, the sensitivity of target species and ecosystems to climate change and fishermen's ability to adapt to climate change (Grafton, 2010). The Portuguese coast is highly exposed to climate change. The Iberian Coastal large marine ecosystem has already suffered a rapid warming (Belkin, 2009) and Portugal is expected to suffer changes in temperature and precipitation more accelerated than the global mean alteration rate (IPCC, 2007). The Portuguese coast is located in a biogeographic transition zone, between temperate and subtropical waters, where northern or southern distribution limits of several species can be found (Briggs, 1974). As the Portuguese coast is north-south oriented, there are differences in oceanographic conditions and ecological communities along the coast (Sousa *et al.*, 2005). As temperature increases, species richness in the south coast may also increase, by the arrival of new subtropical and tropical species. However, if the increase is too high, this area may also lose several temperate species, decreasing its species richness (Vinagre *et al.*, 2014) and losing species which fisheries depend on. For that reason, the south coast might be considered more vulnerable to climate change than the northwest and southwest coasts, in terms of both exposure and sensitivity of target species and ecosystems to its effects. However, the present study has found changes in the relative importance of the main species landed in the south coast, particularly in purse-seine fisheries, where chub mackerel *S. colias* has recently become the most important species, instead of sardine *S. pilchardus*. This could mean that south coast fishermen are adapting to change, by compensating declines in their usual target species (*S. pilchardus*) with a more abundant fishing resource (*S. colias*), thus reducing their vulnerability. Nevertheless, the increasing amount of static gear vessels, specializing in targeting octopus with traps, makes fishermen in the south coast vulnerable to changes (Pita *et al.*, 2015).

Most trawlermen perceived no changing trend in recent catches of their target species and, when asked about what they would do in case of a severe decrease in catches, they said they would move to another fishing area. This is not surprising, as the trawler fleet is quite mobile. It is generally accepted that more technologically advanced fleets are usually more likely to be better prepared to adapt to climate change by moving to other fishing grounds (MacNeil *et al.*, 2010). For that reason, trawlermen may be more adaptable and therefore less vulnerable to climate change. In fact, every trawlerman interviewed was willing to fish new species. However, most of them were not willing to change fishing gear in order to catch it. This might easily be explained by the fact that to change from otter trawl to other fishing gear would require huge physical alterations on vessels, at huge costs.

The high exposure of the Portuguese coast and the high sensitivity of sardine *S. pilchardus* to the effects of climate change make the purse-seine fisheries particularly vulnerable to climate change. The vast majority of purse-seine fishermen interviewed reported a decreasing trend in catches, which can be confirmed by the decreasing trend observed in *S. pilchardus* LPUE. However, as it was said previously, there was also an increasing trend in chub mackerel *S. colias*, which was not mentioned by fishermen. Most interviewed purse-seine fishermen said that they would stop fishing, in case of a severe downfall in catches. However, fishermen were also willing to fish a new species, as long as they would not have to change fishing gear. Vulnerability of purse-seine fisheries in the Portuguese coast depends on fishermen´s ability to adapt. In order to improve this ability, assistance to fishermen in their planning processes should be a priority, by transferring knowledge about the possible long-term effects of climate change (Grafton, 2010).

An increase in the relative importance of landings of subtropical fish species (Gamito *et al.*, 2013) and lower landings of temperate species in warm years (Teixeira *et al.*, 2014) have already been reported for the Portuguese coast. Higher landings of subtropical species in multi-gear fisheries have also been detected, which could indicate an easier adaptation of Portuguese multi-gear fisheries to the effects of climate change (Gamito *et al.*, 2013). The present study has now revealed several new species in landings of multi-gear fisheries, especially in trammel nets, gillnets and bottom longline fisheries. Most new species were subtropical or tropical, many of them with their northern distribution limit in the Portuguese coast. Most multi-gear fishermen interviewed declared that they were willing to fish a new species, even if it was necessary to change fishing gear in order to do it. This may be due to a higher flexibility of multi-gear fisheries, as this fleet component is used to change target species, fishing gear or fishing location over a time scale of weeks or months (Duarte *et al.*, 2009; Teixeira *et al.*, 2011). Thus, despite the high exposure to climate change, the high adaptation ability of these fishermen makes them potentially less vulnerable to climate change.

The present study has found a northward shift of species in landings of Portuguese fisheries and a higher vulnerability of fisheries in the south coast to the effects of climate change. In terms of fleet components, purse-seine fisheries are particularly vulnerable to climate change, whereas trawl and multi-gear fisheries may be more adaptable to changes.

Acknowledgements

This study had the support of Fundação para a Ciência e Tecnologia (FCT), through the strategic project UID/MAR/04292/2013 granted to MARE and the grants awarded to R. Gamito (SFRH/BD/78363/2011), and C.M. Teixeira (SFRH/BPD/62986/2009). C. Pita was supported by the "Cátedra do Mar" UA-CGD grant. Furthermore, the authors would like to thank Ana Rita Barrocas for the help with the questionnaires and all the anonymous fishermen who kindly answered them.

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CHAPTER 8

Main conclusions and final remarks

Main conclusions and final remarks

The present work has shown that the effects of climate change on ocean conditions affect fisheries and, to our knowledge, is the first approach to the effects of climate change on Portuguese fisheries, in particular.

A poleward shift of fish species as a response to ocean warming has previously been suggested (Cheung *et al.*, 2009). Results in the present work agree with this statement, both on a global scale (Chapter 2) and on a regional scale (Chapters 3 and 7). In Chapter 2, catches in years of cold and warm winters were compared for each of the eight most caught fish species, in each of the world's large marine ecosystems (LME). Mean catches of polar and temperate species were higher in years of warm winters in the LME located in the northern part of the species range and in years of cold winters in LME of the southern regions of their ranges. On the other hand, mean catches of subtropical species were higher in cold years in LME of lower latitudes and in warm years in LME of higher latitude regions. A continued warming of the oceans will most likely result in further changes in catch composition throughout the world, due to this poleward shift in geographic distributions. The impact of these changes on fisheries may not always be negative, for new fishing opportunities may arise, particularly in temperate and polar regions. However, fishermen's decisions on whether to change target species depend on other factors besides resource abundance, namely commercial value, information from other fishermen, weather conditions, distance to fishing grounds, cultural aspects and fisheries management measures (Christensen and Raakjær, 2006). Therefore, the adaptation of fisheries to changes in fish communities will most likely not be that fast. On the other hand, this poleward shift in distribution may jeopardize food security in tropical regions. Landings of biogeographic groups of fish species in Portuguese fisheries are compared in Chapter 3. Subtropical species have been increasing in their relative importance in Portuguese landings, which agrees with a distribution shift with rising ocean temperature in the Portuguese coast. In Chapter 7, trends in landings of the most important fishing *métiers* in the Portuguese coast are analysed. Eighteen new species were detected in landings, of which twelve were tropical or subtropical and five had their distribution limit along the Portuguese coast. A latitudinal pattern in the number of new species in landings was found, with more new species appearing in the north. In fact, most of the new species in landings in the northwest coast were subtropical and tropical, and some had their northern limit along the Portuguese coast. This supports the idea of a northward shift of subtropical species that were not previously present in landings in the northwest coast.

In fact, sea surface temperature was the main environmental variable linked to fisheries landings, throughout the present thesis. In Chapter 4, a marked increase in sea surface temperature from 1927 to 2012 was observed in central Portugal. Although the main target species in that area have remained the same through that time period, their landings have responded to temperature change. Landings of the most important targets of multi-gear fisheries seem to have been favoured by the increase in temperature, whereas sardine landings were inversely correlated with sea surface temperature. Recruitment and landings of sardine and horse mackerel in the Portuguese coast were modelled in Chapter 6. Landings of both species were mainly explained by sea surface temperature; landings of sardine were also explained by wind strength and landings of chub mackerel. Given the results obtained in that chapter, increasing sea surface temperature could strongly decrease landings of sardine and horse mackerel in the Portuguese coast. Unlike previous studies performed in the Mediterranean (e.g. Salen-Picard *et al.*, 2002), no significant correlations between river drainage and fisheries landings were found in Chapter 5. An upwelling regime is of particular importance for the richness and diversity of the coastal ecosystem and for fisheries in the Portuguese coast. The complexity of the coastal upwelling phenomenon together with a possible interaction of several other smaller scale factors acting on recruitment of commercial species may have masked the effects of river drainage on landings.

The vulnerability and adaptation capacity of Portuguese fisheries to climate change varied along fleet components and coastal areas. An increasing relative importance of subtropical species in Portuguese fisheries was found in Chapter 3. In this same chapter, landings of subtropical species were higher in multi-gear fisheries, and Chapter 7 revealed several new species in landings of multi-gear fisheries, especially in trammel nets, gillnets and bottom longline fisheries. Most new species were subtropical or tropical, many of them with their northern distribution limit in the Portuguese coast. These findings could indicate an easier adaptation of multi-gear fisheries to the effects of climate change. This fleet component may be more flexible in changing target species or fishing gear, making it potentially less vulnerable to climate change. Regarding different *métiers* in multi-gear fisheries, trammel nets catch a wider variety of species and a wider size range than gillnets or longlines and, for that reason, trammel net fishermen can adapt to changes in abundance of main target species more readily than those using more species- and size-specific gears. Therefore, trammel net fisheries could more easily adapt to the effects of climate change on fish distribution than gillnet or longline fisheries (Chapter 3). Trawl fishery may also be more adaptable and less vulnerable to climate change, due to the high mobility of its fleet (Chapter 7). On the other hand, the high exposure of the Portuguese coast and the high sensitivity of sardine to the effects of climate change make purse-seine fisheries particularly vulnerable to climate change (Chapters 4, 6 and 7). However, purse-seine fisheries may compensate the predicted losses in sardine landings by targeting the chub mackerel, which appears to be less sensitive to climate change (Chapters 4 and 7). The south coast of Portugal has shown a higher vulnerability to climate change than the west coast, in terms of both exposure and sensitivity of target species and ecosystems to its effects (Chapter 7).

The present thesis emphasised the relationship between ocean warming and fisheries. The effects of rising temperature are already visible in landings and further increases in temperature have been predicted. However, there is still a lack of knowledge on the thermal tolerance of most commercial species. Future research should focus on that subject, in order to allow for more accurate predictions for future fisheries and subsequent better fisheries management. Also, other effects of climate change on ocean conditions, such as ocean acidification, changes in ocean currents or changes in upwelling regimes will most likely affect fisheries and, therefore, future research should also focus on the influence of these effects.

The present thesis has found several new species landings of Portuguese fisheries in most recent years. The abundance of these species should be monitored in future years, as well as their importance in future landings along the Portuguese coast. The same monitoring should be performed to detect species lost in landings and whether those losses are related to climate change.

This thesis has shown that purse-seine fisheries are particularly vulnerable to climate change and that one possible future solution would be for these fisheries to target chub mackerel. However, despite seeming to be less sensitive to rising temperature than sardine, the chub mackerel has not yet been thoroughly studied. Future research on the thermal tolerance of this species to further increases in temperature is of the utmost importance. Also, given its growing importance in Portuguese fisheries, the stock of chub mackerel should also be regularly assessed.

This thesis considered *métiers* as different fleet components operating with a certain fishing gear. However, along the Portuguese coast, there are also differences in *métiers* regarding target species. Therefore, it would be interesting to refine this analysis, taking into account target species and fishing area. This analysis could also allow for the assessment of impacts of climate change on fishing communities highly dependent on a particular target species.

Besides the present thesis, several recent studies on the effects of climate change on fisheries have been based on official landings data (Cheung *et al.*, 2013; Christensen *et al.*, 2009; Merino *et* *al.*, 2012; Watson *et al.*, 2013). Although landings are underestimates of catches – as they exclude unreported landings and discards – , reported landings are the only data that are collected and made publicly available for fisheries in about 80 % of all maritime countries (Pauly *et al.*, 2013). Despite criticisms on the use of these data to detect and interpret trends in fisheries, several authors (e.g. Froese *et al.*, 2012; Pauly *et al.*, 2013) defend that when only catch data are available, fisheries researchers can and should use these data. Nevertheless, it would be extremely valuable to deal with total catch data in future studies on the effects of climate change on fisheries.

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