UNIVERSITAT DE BARCELONA

Developing a management strategy for the red shrimp *Aristeus antennatus* fishery in the northwestern Mediterranean Sea

Desarrollo de una estrategia de gestión para la pesquería de la gamba roja *Aristeus antennatus* en el Mediterráneo Noroccidental

Giulia Gorelli

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Memoria presentada por

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Abstract

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The deep-sea red shrimp *Aristeus antennatus* is one of the main target species for bottom trawl fishery in the northwestern Mediterranean Sea. In the Catalan region, this species is fished along the continental margin of a system of submarine canyons and its landings present high inter-annual variability. Minimums in the historical series of yearly landings have been associated with the occurrence of strong bottom currents generated by an oceanographic phenomenon named Dense Shelf Water Cascading (DSWC). In fact, a drastic reduction of the red shrimp abundance in the fishing grounds of the Catalan area was observed during DSWC events. This thesis contains a thorough assessment of the red shrimp fishery in Catalonia, with the main objective to provide management advice for the sustainable exploitation of this resource.

Historical series of fishery data (including fishing effort directed to the red shrimp) were reconstructed from various data sources, and trends in the data series were analyzed. Stock status in the 1980s and in recent years (2005-2008) was assessed using pseudo-cohort and yield per recruit analysis and compared. Then, a stock assessment using a Statistical Catch at Age model (SCAA) was performed. This method allowed to include all the available data, covering a period of more than fifty years (1963-2015), as well as the effect of the DSWC. In particular, the SCAA was used to test alternate hypotheses on the mechanisms of interaction between the DSWC and the red shrimp population and to estimate reference points for management. In addition, the spatio-temporal variability of fishery discards in relationship to the submarine canyons' geomorphology was analyzed. Finally, the selectivity for red shrimp of three different codend mesh configurations was measured and compared: the 50 mm diamond mesh (50d), the 40 mm square mesh (40s) and the 50 mm square mesh (50s). A transition analysis to simulate the evolution of the yield per recruit and the biomass per recruit after a hypothetical implementation of the 50s in the fishery was performed.

The results presented in this thesis indicate that the fishing effort directed to the red shrimp in the Catalan area underwent a steep increase starting from the second half of the last century up to 2009, while CPUE decreased. Including the effect of DSWC significantly improved the stock assessment model for this species. In particular, it was demonstrated that the DSWC significantly increases the red shrimps natural mortality. Both the yield per recruit analysis and the Statistical Catch at Age model showed that this resource is in overexploitation. In particular, the yield per recruit decreased by 10% between the 1980s and the recent years (2005-2008). In addition, the predicted equilibrium maximum sustainable yield (MSY) was considerably reduced in years of DSWC, indicating that only little harvest may be sustainable in years of adverse environmental conditions. The average discard ratio found in this study (0.2) was low compared to other trawl fisheries, and showed a marked seasonal variability with a maximum in spring and a minimum in summer. Most of the discarded biomass (almost 96%) was constituted of species with no commercial interest. Furthermore, the mesh configurations currently used in the red shrimp fishery in Catalonia (50d y 40s) were found not suitable to reduce the amount of juvenile individuals in the catch, both displaying a 50% retention length well below the size at first maturity. On the other hand, the 50s would significantly improve the selectivity in this fishery, and its implementation would lead to an increase of the yield per recruit of about 9% after five years.

According to the results of this thesis, a fishery management aiming at the long term sustainable and profitable exploitation of the red shrimp should include measures to: reduce overfishing, increase yield per recruit and CPUE, lower the peak of discards in spring, and buffer the negative effect of DSWC. This could be achieved by decreasing fishing effort and fleet overcapacity, protecting the aggregations of juvenile individuals, and increasing the gear selectivity. In particular, the results of this thesis indicate that a

fishery closure in winter/spring, when shoals of juvenile individuals aggregate in the fishing grounds and the discard ratio reaches the yearly peak, would be particularly appropriate. In addition, fishing effort should be further reduced in years of intense DSWC events, to permit the recovery of the population. Finally, the mitigation of overfishing is also likely to increase the red shrimp population resilience to the effects of DSWC.

La gamba roja de profundidad *Aristeus antennatus* es una de las especies más importantes para la pesca de arrastre de fondo en el Mediterráneo nororiental. En la región catalana, esta especie se pesca en la plataforma profunda y en el margen continental de un sistema de cañones submarinos. Sus desembarques presentan una elevada variabilidad interanual. Los mínimos en la serie histórica de desembarques han sido asociados con la ocurrencia de fuertes corrientes de fondo generadas por un fenómeno oceanográfico conocido como *Dense Shelf Water Cascading* (DSWC). De hecho, se observa una disminución drástica en la abundancia de gamba roja en los caladeros del área catalana coincidiendo con los eventos de DSWC. Esta tesis contiene una evaluación exhaustiva de la pesquería de la gamba roja en Cataluña, con el objetivo principal de aportar recomendaciones de gestión para una pesca sostenible de este recurso.

Las series históricas de datos sobre la pesca (incluyendo el esfuerzo dirigido a la gamba roja) se reconstruyeron a partir de varias fuentes, y se analizaron los patrones en las series de datos. Se evaluó y comparó el estado del stock en los años 1980 y en años recientes (2005-2008). A continuación, se desarrolló una evaluación del stock utilizando un modelo de tipo *Statistical Catch at Age* (SCAA). Este modelo permitió utilizar todos los datos disponibles, incluido el efecto del DSWC, cubriendo un periodo de más de cincuenta años (1963-2015). En concreto, el modelo se utilizó para testar hipótesis alternativas sobre el mecanismo de interacción entre el DSWC y la población de gamba roja y para la estimación de puntos de referencia para la gestión. Además, se analizó la variabilidad espacio-temporal de los descartes en esta pesquería, en relación a la geomorfología de los cañones submarinos. Finalmente, se midió y comparó la selectividad de tres diferentes configuraciones de malla del copo de la red: malla romboidal de 50 mm (50d), malla cuadrada de 40 mm (40s), y malla cuadrada de 50 mm (50s). También, se llevó a cabo un análisis de transición para simular la evolución de la biomasa y rendimiento por recluta después de una hipotética implementación de la malla cuadrada de 50 mm en la pesquería.

Los resultados de esta tesis indican que el esfuerzo pesquero dirigido a la gamba roja en el área catalana sufrió un crecimiento abrupto en la segunda mitad del siglo pasado hasta 2009, mientras las capturas por unidad de esfuerzo disminuyeron. La inclusión del efecto del DSWC mejora significativamente el modelo de evaluación para la gamba roja. En concreto, se demostró que el DSWC aumenta significativamente la mortalidad natural de los individuos de gamba roja. El análisis de rendimiento por recluta y el SCAA detectaron una sobreexplotación del recurso. En particular, el rendimiento por recluta disminuyó de un 10% entre los años 1980 y años recientes (2005-2008). Además, se detectó una disminución significativa en la estimación de rendimiento máximo sostenible (MSY) en años de DSWC, indicando que en años coincidentes con condiciones ambientales desfavorables debería disminuirse aún más la explotación. La proporción promedia de descartes encontrada en esta pesquería (0.2) es menor comparada con otras pesquerías de arrastre, y presenta una marcada variabilidad estacional, con un máximo en primavera y un mínimo en verano. La mayoría de la biomasa de los descartes (casi el 96%) está constituida por especies sin ningún interés comercial. Además, se demostró que las mallas utilizadas actualmente en la pesquería de gamba roja en Cataluña (50d y 40s) no son adecuadas para disminuir la captura de juveniles, ambas caracterizadas por una talla de retención del 50% menor de la talla de primera madurez. Por otro lado, la malla de 50s mejoraría significativamente la selectividad en esta pesquería, y su implementación llevaría a un aumento del rendimiento por recluta de alrededor de 9% después de cinco años.

Según los resultados de esta tesis, una gestión cuyo objetivo sea establecer una pesquería de gamba roja sostenible en el largo plazo debería incluir medidas para: reducir la sobreexplotación, aumentar el rendimiento por recluta, disminuir el pico de descartes en primavera y limitar los efectos negativos del DSWC en la pesquería. Estos objetivos se obtendrían actuando sobre la sobrecapacidad de la flota y con una reducción del esfuerzo pesquero, protegiendo las agregaciones de individuos juveniles y aumentando la selectividad del arte de pesca. En concreto, los resultados de esta tesis indican que una veda en invierno/primavera, cuando las agregaciones de juveniles aparecen en los caladeros y la proporción de descartes llega a su máximo, sería una medida particularmente apropiada. También, el esfuerzo pesquero se debería disminuir ulteriormente en años de intensos eventos de DSWC, para permitir la recuperación de la población. Además, se prevé que una mitigación de la sobreexplotación incrementara la resiliencia da la población de gamba roja a los efectos negativos del DSWC.

La gamba vermella de profunditat *Aristeus antennatus* és una de les espècies més importants per a la pesca d'arrossegament de fons a la Mediterrània nord-occidental. A la regió catalana, aquesta espècie es pesca en els marges continentals d’un sistema de canyons submarins. Els seus desembarcaments presenten una elevada variabilitat interanual. Els mínims en la sèrie històrica de desembarcaments han estat associats amb l'ocurrència de forts corrents marins de fons generats per un fenomen oceanogràfic conegut com *Dense Shelf Water Cascading* (DSWC). De fet, s’observa una disminució dràstica en l'abundància de gamba vermella en els caladors de l'àrea catalana durant esdeveniments de DSWC. Aquesta tesi doctoral conté una avaluació exhaustiva de la pesqueria de la gamba vermella a Catalunya, amb l'objectiu principal de proveir recomanacions de gestió per una pesca sostenible d’aquest important recurs.

Les sèries de dades històriques sobre la pesca (incloent esforç dirigit a la gamba vermella), es van reconstruir a partir de diverses fonts, i es van analitzar els patrons de les sèries de dades. Es va avaluar i comparar l'estat de l'estoc en els anys 1980 i en anys més recents (2005-2008). A continuació, es va desenvolupar una avaluació utilitzant un modelo de tipus *Statistical Catch at Age* (SCAA). Aquest model va permetre utilitzar totes les dades disponibles, inclòs l'efecte de l'DSWC, cobrint un període de més de cinquanta anys (1963-2015). El model es va utilitzar per testar hipòtesis alternatives sobre el mecanisme d'interacció entre el DSWC i la població de gamba vermella, i per a l’estimació de punts de referència per a la gestió. A més, es va analitzar la variabilitat espai-temporal del rebuig de aquesta pesqueria, en relació a la geomorfologia dels canyons submarins. Finalment, es va a mesurar i comparar la selectivitat de tres configuracions diferents de malla del cop de l’art de pesca: malla romboïdal de 50 mm (50d), malla quadrada de 40 mm (40s), i malla quadrada de 50 mm (50s). També, es va fer una anàlisi de transició per simular l'evolució de la biomassa i rendiment per recluta després d'una hipotètica implementació de la malla quadrada de 50 mm en la pesqueria.

Els resultats de aquesta tesi doctoral indiquen que l'esforç pesquer dirigit a la gamba vermella a l'àrea catalana va patir un creixement abrupte a la segona meitat del segle passat fins 2009, mentre les captures per unitat d'esforç van disminuir. La inclusió dels efectes del DSWC millora significativament l'avaluació per la gamba vermella. En concret, es va demostrar que el DSWC augmenta significativament la mortalitat natural dels individuals de gamba vermella. L'anàlisi de rendiment per recluta i el model *Statistical Catch at Age* van detectar una sobreexplotació del recurs. En concret, el rendiment per recluta va disminuir d'un 10% entre els anys 1980 i els anys més recents (2005-2008). A més, es va detectar una disminució significativa en les estimacions de biomassa a l'equilibri i el redimint màxim sostenible (MSY) en anys de DSWC, indicant que en anys caracteritzats per les condicions ambientals desfavorables, només una explotació molt baixa podria mantenir la població. La proporció de rebutjos trobada en aquesta tesis (mitjana de 0.2) és menor comparada amb altres pesqueres d'arrossegament, i presenta una marcada variabilitat estacional, amb un màxim a la primavera i un mínim a l'estiu. La majoria de la biomassa dels rebutjos (gairebé el 96%) està constituïda per espècies sense interès comercial. A més, es va demostrar que les malles utilitzades actualment (50d i 40s) no són adients per disminuir la captura dels juvenils, ambdues caracteritzades per una mida de retenció del 50% menor de la mida de primera maduresa. Per altre banda, la malla de 50s milloraria significativament la selectivitat en aquesta pesqueria, i la seva implementació portaria un augment del rendiment per recluta de l'entorn de 9% després de cinc anys.

Segons els resultats d'aquesta tesi, una gestió amb el objectiu d'establir una pesqueria sostenible a llarg termini hauria d'incloure mesures per: reduir la sobreexplotació, augmentar el rendiment per recluta, disminuir el pic de rebuig a la primavera i limitar, en la mesura del possible, els efectes negatius del DSWC a la pesqueria. Aquests objectius s’obtindrien amb una disminució de l'esforç pesquer i de la sobre-capacitat de la flota, protegint les agregacions de juvenils i augmentant la selectivitat de l'art de pesca. En concret, els resultats d’aquesta tesi doctoral indiquen que una veda a l'hivern/primavera, quan les agregacions de juvenils apareixen en els caladors, i la proporció del rebuig arriba al seu màxim, seria una mesura particularment apropiada. També, l'esforç pesquer s'hauria de disminuir ulteriorment en anys d’intensos esdeveniments de DSWC, per permetre la recuperació de la població. A més, es preveu que una mitigació de la sobreexplotació incrementés la resiliència de la població de gamba vermella en front dels fenòmens de DSWC.

1. Introduction

Overfishing is widely recognized as a threat to the sustainable exploitation of marine resources, biodiversity, ecosystem integrity and food security (Jennings and Kaiser 1998, Myers and Worm 2003, Garcia and Rosenberg 2010, Hutchings et al. 2010). The Food and Agriculture Organization of the United Nations (FAO, UN) estimates that, in 2013, 31.4% of fish stocks assessed worldwide was overfished, 58.1% was fully fished and 10.5% was underfished. Although good management has improved the status of several stocks in some of the best assessed areas of the world (Hilborn 2007, Worm et al. 2009), there is no doubt that rebuilding the depleted stocks around the world must be considered a priority to avoid stocks collapse (Worm and Branch 2012, Pauly and Zeller 2016). For the Mediterranean Sea, overfishing remains a particularly serious, unresolved issue, with the majority of the stocks being overfished (Tsikliras et al. 2015, GFCM 2016, Quetglas et al. 2016). Several studies have demonstrated that the impact of fisheries is not isolated to the target species (lowering their abundance and average size), but includes a wide range of ecosystem effects, such as reduction of biodiversity, changes in the food web structure, and profound changes in the seafloor morphology (Jennings and Kaiser 1998, Tudela 2004, Guidetti and Sala 2007, Puig et al. 2012, Coll et al. 2014).

The deep-sea red shrimp *Aristeus antennatus* (Risso, 1816) is a crustacean species belonging to the Class Malacostraca, Order Decapoda, Family Aristeidae (Fransen et al., 2011). It is distributed in the whole Mediterranean Sea and in the Eastern Atlantic Ocean from southern Portugal and the Azores to Cabo Verde. It is one of the most important target species for trawl fisheries in the western and central Mediterranean Sea. It is a very appreciated sea food and a high value species in the market, reaching peaks of more than 200 €/kg. *A. antennatus* is characterized by a long, needle-like rostrum which is bent upwards. The rostrum presents three dorsal teeth at the base and is smooth otherwise. In adult males, the rostrum is shorter (Sardà and Demestre 1989) than in females. This species owes its name to the body color, which is red or dark pink and orangey, with purple reflections on the dorsal part of the carapace (Fig. 1) that are particularly intense in mature females.

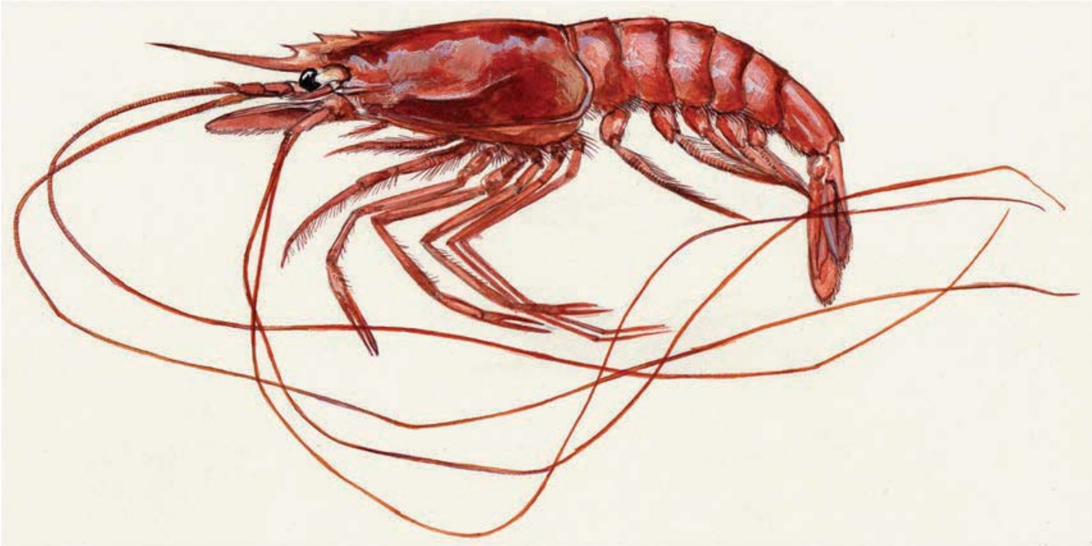

Figure 1. Female specimen of *Aristeus antennatus.* Source: Food and Agriculture Organization of the United Nations. Original Scientific Illustrations Archive. Reproduced with permission.

The red shrimp is a demersal nectobenthic species, typically found on muddy bottoms. It is a eurybathic species, with individuals found from 100 to 3000 m depth (Relini Orsi and Relini 1979, Sardà and Cartes 1993, Bianchini and Ragonese 1994, Sardà et al. 2003b, Carbonell 2005). It is a species displaying marked sexual dimorphism: females have a longer life span compared to males (5-6 years versus 3-4 years) and can reach up to 76 mm of cephalothoraxes length, while males only reach up to 54 mm (Sardà and Demestre 1987, Demestre 1990). By virtue of their highest size, females are also more valuable in the market. The size at first maturity was estimated at 27 mm CL for females and 24 for males (Sardà and Demestre 1987, Demestre and Fortuño 1992). The sex ratio shows variations with depth, with adult females dominating the population at fishing depths (shallower than 1000 m) and constituting 70% of catches (Sardà et al. 1994b, Sardà et al. 2003a). Males dominate the population below 1000 m depth, with a sex ratio of almost 2:1 (Sardà 2003b). Early juveniles (< 20 mm cephalotorax length) are mainly found below 1000 m (Sardà and Cartes 1997, Sardà and Company 2012), indicating that the pelagic larvaes first settle to the deep-basin. Then, during their first year of age, red shrimp individuals undergo an ontogenetic migration towards the shallower waters (Sardà and Company 2012). The biological stock boundaries of *A. antennatus* are not known. Genetic studies have indicated that there are no barriers to the gene flow within the Mediterranean Sea (Roldán et al. 2009, Marra et al. 2015). However, larval stages and the dynamics of their dispersal have not been studied in depth (Carbonell et al. 2010). In addition, there is a large portion of the stock dwelling in the deep-basin, and the exchanges between the exploited and non-exploited portion of the stock(s) have not been quantified (Sardà et al. 2004, Marra et al. 2015).

In northeastern Spain, the red shrimp has been traditionally exploited (Bas et al. 1955, Demestre 1990, Carbonell et al. 1999) and is a resource with a huge economic importance. Here, the annual landings of this species constitute around 3% of total landings while making more than 20% of the incomes for the local Fishermen's Associations on a yearly average. In some harbours, the contribution of this resource to the annual incomes reaches 50%. The whole fishery is worth around 16 million euros per year (Official fishery statistics from Autonomous Government of Catalonia). Periodical stock assessments are carried out by the General Fishery Commission for the Mediterranean (GFCM) which classifies this species “in overexploitation” in the whole Spanish Mediterranean (GFCM 2014, GFCM 2015). Despite its economic importance, there is no specific management for this fishery neither at European nor at national level (not even a minimum landing size).

In the Catalan region (northeastern Spain), there are 13 fishing harbors with a fishing fleet dedicated to the fishery of the red shrimp. The species is fished exclusively by bottom trawling at depths between 400 m and 1000 m depth, where it is the only target of the fishery. In particular, the fishing grounds are located along the continental margin of a system of submarine canyons carved in the continental shelf, which create considerable depth at locations relatively close to the coast (Fig. 2).

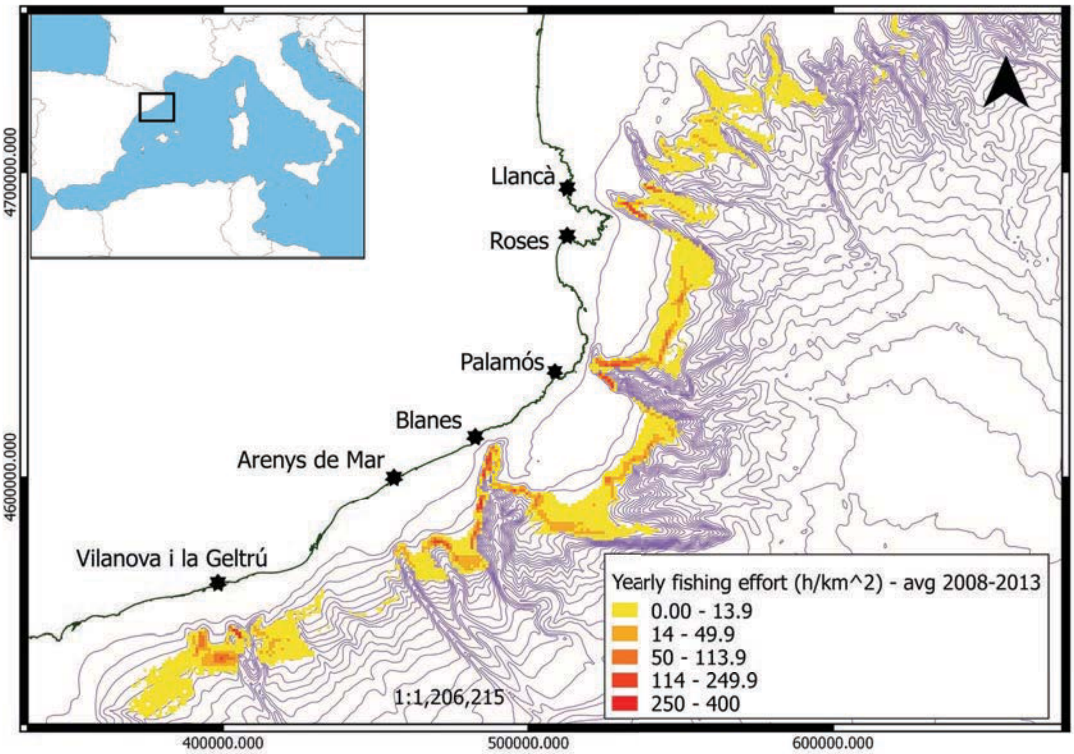

Figure 2. Spatial distribution of fishing effort (average for the years 2008-2013) directed to the deep-sea red shrimp for the harbors of Llancà, Roses, Palamós, Blanes, Arenys de Mar, and Vilanova i la Geltrú in Catalonia. Bathymetry is displayed every 100 m.

Before reaching the market, the shrimps are sorted into commercial size classes (from 2 to 4 according to the harbor). The smallest size class ("small") is made of shrimps with a cephalotorax length < 30 mm, including individuals of 1-2 years of age, mostly immature. The price per kg increases with the shrimp size, with the small individuals being sold at about 15 euros/kg and the big ones (≥ 30 mm cephalotorax lenght) at 40 euros/kg (average values for years 2010-2015; data from selling bills of the Fishermen's Association of Palamós, Catalonia). The total landings of red shrimp and their size composition display marked seasonal fluctuations (Fig. 3), which are related to the ecology of the species and the seasonal migrations along the canyons conformations (Tobar and Sardà 1987, Sardà and Demestre 1987, Tudela et al. 2003). In summer, when reproduction occurs, aggregations of big, mature females appear on the middle slope at depths between 600 m and 800 m. This period corresponds to the yearly peak of catches. In autumn and winter, density of individuals on the mid-slope decreases and aggregations of juvenile individuals appear at shallower depths in the submarine canyon heads (i.e. the most embedded part of the canyons) between 500 m and 600 m depth (Sardà et al. 1994b, Sardà et al. 1997, Tudela et al. 2003). These aggregations are actively targeted by the fishermen and contribute to keeping their income stable throughout the year (Sardà et al. 1994b, Sardà et al. 1997).

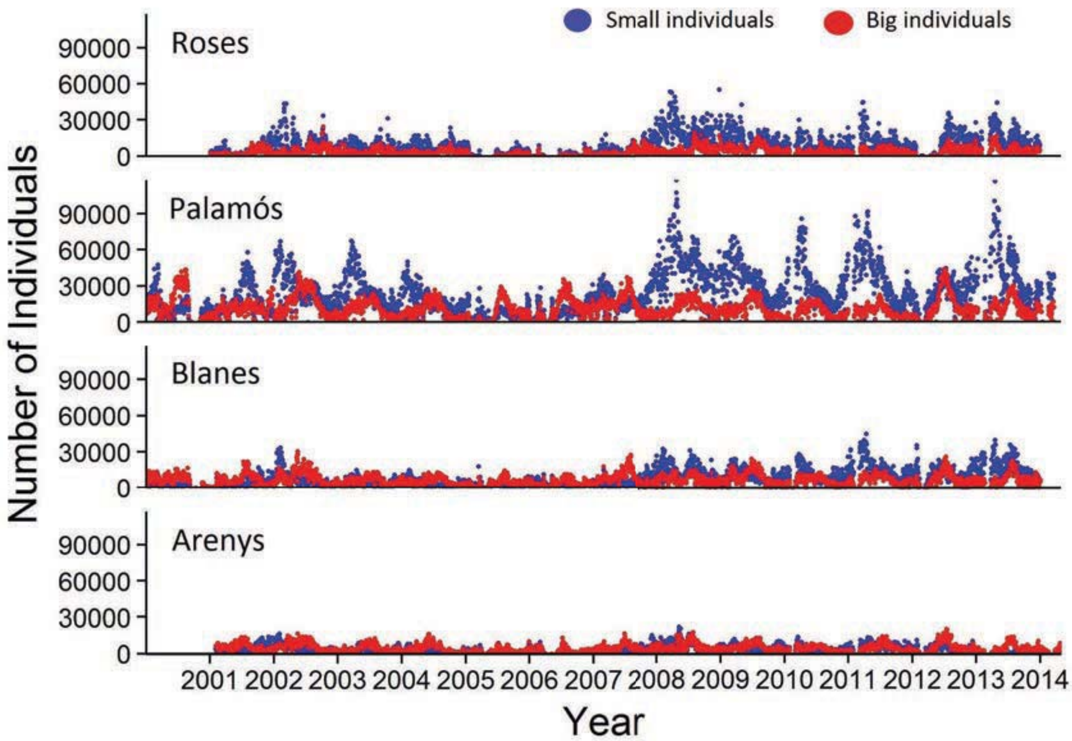

Figure 3. Number of individuals of red shrimp landed in four of the most important Catalan harbors. Blue dots correspond to the landings of small individuals (< 30 mm cephalotorax length), while red dots correspond to the landings of medium/big individuals (≥ 30 mm cephalotorax length). Major DSWC events occurred in 1999-2000, 2005-2006 and 2012-2013.

The red shrimp landings in Catalonia also show considerable interannual fluctuations (Fig. 4). Minimums in the time series of landings have been associated to the occurrence of strong bottom currents in the area, generated by an oceanographic process called Dense Shelf Water Cascading (DSWC) (Company et al. 2008). DSWC is a specific type of current triggered by particular climate conditions, occurring at a few locations in the world and contributing, together with Open Ocean Convection, to the formation of deep-waters (MEDOC group 1970, Font et al. 1988, Fohrmann et al. 1998, Puig et al. 2013). In the northwestern Mediterranean, during winter, the surface waters of the Gulf of Lion become saltier and colder than the surrounding waters and sink to the shelf bottom. Then, they continue to cascade down the continental slope, channelled through the submarine canyons of the Catalan shelf, until they reach their equilibrium depth, usually between 170 m and 800 m (Millot 1990, Durrieu de Madron et al. 2005, Canals et al. 2006). Particularly strong DSWC events have been observed at a decadal scale, during exceptionally dry and cold winters. In these conditions, the cascading waters

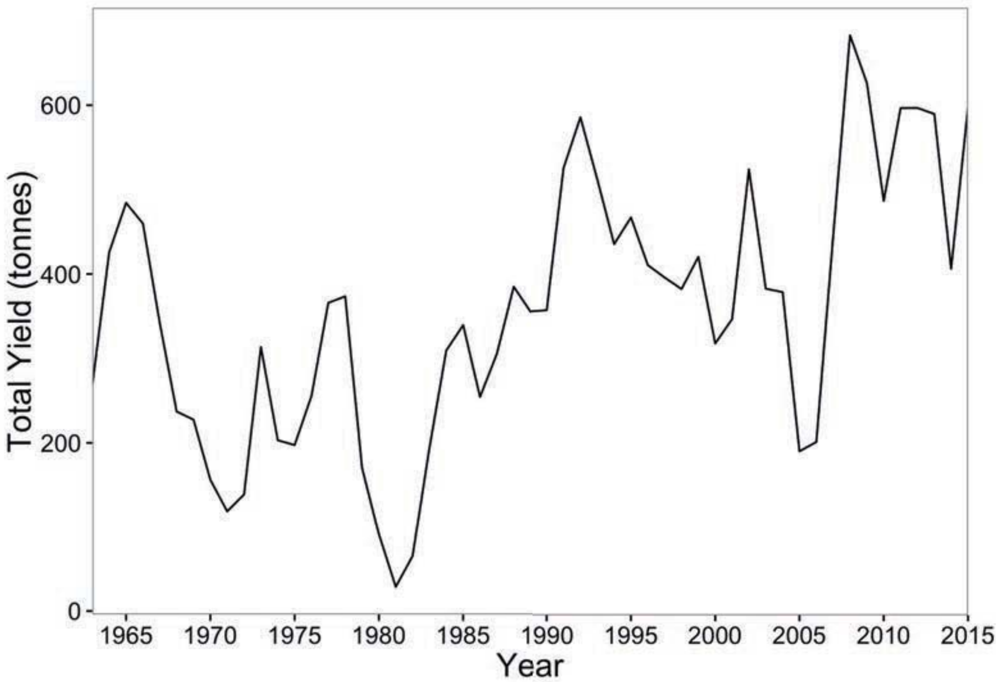

Figure 4. Yearly landings of deep-sea red shrimp in Catalonia from 1963 to 2015.

generate extremely strong bottom currents (up to 85m/s), transporting large quantities of organic matter and reaching depths of more than 1000 m (Bethoux et al. 2002, Puig et al. 2013). Company et al. (2008) analyzed the particularly intense and well documented DSWC of 2005. They found that the energetic cascades of water in the submarine canyons of the Catalan continental margin coincided in time and space with the disappearance of the red shrimp from the fishing grounds (Fig. 5).

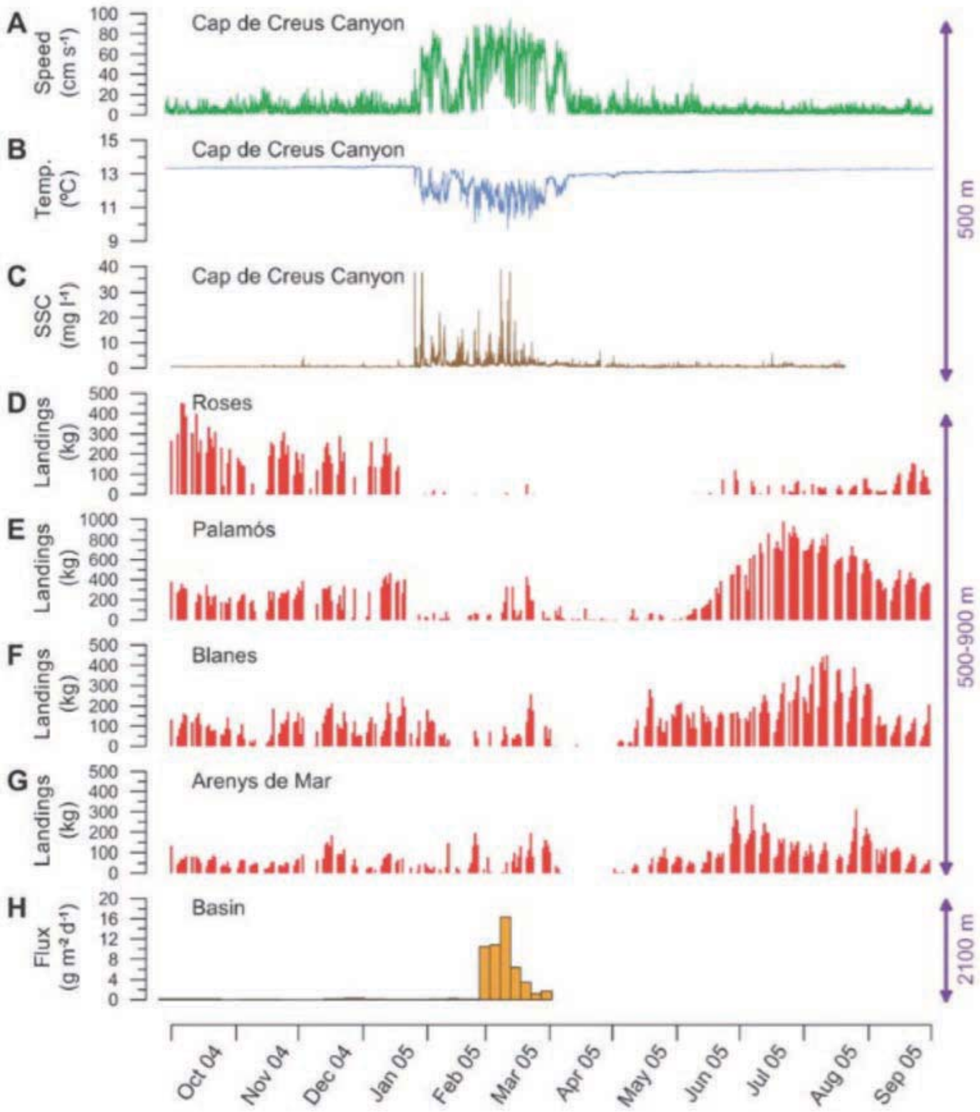

Figure 5. A-C: Current speed (A), temperature (B) and suspended sediment concentration (SSC) (C) recorded in the Cap de Creus Canyon on the Catalan continental margin at 500 m depth (sensor placed at 5 m above bottom), before, during and after the cascading event of winter 2005. D-G: Daily landings of *Aristeus antennatus* at the studied harbors are plotted as red bar charts, ordered from northeast (Roses) to southwest (Arenys de Mar). (H) Downward mass fluxes recorded at 2100 m depth by the sediment trap moored in the basin at 2350 m depth (i.e. 250 m above bottom) are illustrated by the orange bar chart. Modified from Company et al. (2008).

These authors also found that most of the minimums in the historical series of red shrimp landings coincided with years in which intense DSWC had occurred. Furthermore, they reported a peak in landings of small individuals (< 30 mm cephalotorax length) after 3-5 years from the occurrence of a cascading event (Fig. 3). This observation led to the formulation of the hypothesis that cascading might enhance the recruitment of red shrimp in the following years, by increasing the survival of post-larval individuals, thanks to the high quantity of organic matter transported to the deep-basin (Fohrmann et al. 1998, Canals et al. 2006, Palanques et al. 2006, Puig et al. 2008). The DSWC has a huge impact on the red shrimp fishery in Catalonia: in 2005 the landings of this species were reduced by more than 50% compared to the average of the previous 5 years, with the involved fishing harbors suffering a severe economic damage. However, the mechanism of interaction between the DSWC and the red shrimp remains yet to be clarified.

Palamós is the most important harbor in Catalonia for the fishery of the deep-sea red shrimp, landing around 30% of all red shrimp in the area. Here, after the 2005 DSWC, the local Fishermen's Association initiated a collaboration with scientists and local administration (in a co-management mode) in order to draft a long-term management plan for this fishery. The stakeholders involved in this process shared a strong interest to manage the fishery in a way that would be sustainable and profitable in the long term. The objective of the management was to mitigate overfishing, increase the catch per unit of effort (CPUE) and the average individual size in the catch. Bearing these objectives in mind, it was decided to adopt a management strategy to decrease the fishing effort and the fleet overcapacity, and to protect small, immature individuals of red shrimp. In particular, the following management measures were included in the management plan: i) 20% reduction in the number of vessels operating in the red shrimp fishing grounds of Palamós, ii) a two-month fishery closure in winter/spring (when shoals of small individuals form in the fishing grounds), and iii) the use of a more selective mesh size (40 mm square mesh instead of 50 mm diamond mesh). These management measures were established on the basis of ecological and biological knowledge of the species, without any previous evaluation of the fishery. The management was finally approved by the Spanish Government and came into force in May 2013 (BOE 2013).

In this thesis, the fishery of the red shrimp in Catalonia is analyzed in several aspects that are crucial for its sustainability, and management advice is drawn from the results obtained. Thanks to the flexible and participatory management regime in Palamós, the results of this thesis might directly contribute to adjust the management measures included in the current management plan. Eventually, the successful management model developed in Palamós could be extended to the other harbors of Catalonia, given the similarities in the fishing operations, trawling fleets, and socio-economic conditions among all the Catalan harbors.

1.1 Thesis Objectives and Structure

The main objective of this thesis was to assess the status of the deep-sea red shrimp fishery in Catalonia taking into account the environmental effect of DSWC, and to provide management advice to ensure the sustainability of the fishery and to reduce its overall impact on the ecosystem. To achieve this main objective, several smaller sub-objectives were identified and addressed. In particular, these were:

1) Reconstruct and analyze historical trends of fishery data (1950-2013), and estimate the stock status evolution over a period of almost twenty-five years using a simple stock assessment method.

2) Test different ecological hypotheses on the mechanism of interaction between the DSWC and the red shrimp population.

3) Perform a stock assessment of the red shrimp using a method able to take into account all the available data, including the effect of the DSWC, and provide reference points for the red shrimp management.

4) Determine spatio-temporal patterns of discards in the red shrimp fishery in relationship with the vulnerable environment of the submarine canyons.

5) Measure and compare the selectivity of three different codend mesh configurations (two already used in the fishery, and one not yet used) and their ability to reduce the catch of small, immature red shrimp individuals.

6) Provide management advice according to the results obtained for each of the previous objectives.

The results of this thesis are included in **Chapter 2** and are structured as a collection of scientific articles published (**Chapters 2.1 and 2.3**), accepted (**Chapter 2.4**) or in preparation (**Chapter 2.2**) for peer-reviewed specialized journals. In particular:

- **Chapter 2.1** presents a compilation and reconstruction of historical series of data for the fishery of the red shrimp in Catalonia (1950-2013). An analysis of historical trends in fishery data (landings, fishing effort, CPUE and length frequencies) is presented, as well as a comparison of stock status in the 1980s (1984-1989) and in recent years (2005-2008), performed with a simple stock assessment method.

- **Chapter 2.2** presents the construction and implementation of an *ad hoc* stock assessment model for the red shrimp in the Catalan area, designed to include all the available information as well as the effect of DSWC. In particular, the model is used to test different ecological hypotheses on the mechanism of interaction between cascading and the red shrimp population. Finally, the model including the most likely hypothesis according to the data is used to provide population estimates, fishing mortalities and reference points for management.

- **Chapter 2.3** includes a detailed analysis of the spatio-temporal variability of discards in the fishery of the deep-sea red shrimp in relationship to the submarine canyons geo-morphology

- **Chapter 2.4** analyses the differences in selectivity between three different codend mesh configurations: the 40 mm diamond mesh, used prior the implementation of the fishery management plan in Palamós, the 40 mm square mesh, used after the implementation of the plan, and the 50 mm square, not yet used in the fishery. In addition, this chapter includes a simulation of the yield per recruit (Y/R) and biomass per recruit (B/R) evolution after the hypothetical adoption of the 50 mm square mesh codend in the red shrimp fishery.

Chapter 2.5 summarizes the main results obtained in the previous chapters, while **Chapter 3** contains a general discussion. **Chapter 4** enumerates the main conclusions of the thesis and **Chapter 5** provides the list of the bibliographic references.

Finally, **Chapter 6** (Annexes) compiles a series of publications that resulted from the research presented in this thesis. In particular, **Annexes 1-2** contain the original peer reviewed articles underlying Chapters 2.1 and 2.3, while **Annex 3** contains a paper published in the *Marine Stewardship Council Science Series*. **Annex 4** presents a poster that was displayed at the *Fishery Dependent Information Symposium* (Rome, 2014), and **Annex 5** lists peer-reviewed publications to which I contributed as a co-author.

2. Results

2.1 Reconstruction of historical series of fishery data (1950-2015) and stock status evolution

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Fishing effort increase and resource status of the deep-sea red shrimp *Aristeus antennatus* (Risso, 1816) in the Northwest Mediterranean Sea since the 1950s

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Abstract

The deep-sea red shrimp *Aristeus antennatus* is one of the most valuable demersal resources for bottom trawl fishery in the Mediterranean Sea. Nevertheless, this fishery lacks specific management at Mediterranean level, data availability is sparse and official records are often unreliable. In particular, misreporting of trawlers engine power is a widespread issue, complicating the process of fish stock assessments. In Catalonia (Northeast Spain) the red shrimp is particularly important and the stock has been traditionally exploited. The aim of this study was to investigate the long-term effects of intense fishing activities on this resource. For this purpose, we built a reliable series of fishing effort and CPUE, integrating official data with information obtained by interviews to fishermen. Stock assessment at two different time periods, 1984-1989 and 2008-2010, was performed. In this study, we provide the first evidence of the remarkable increase of fishing effort in the Northwest Mediterranean in the last decades. Overfishing of the red shrimp was detected at all years studied. A decrease in the yield per recruit and mean individual length over the two time periods considered was also detected. In addition, the CPUE presented a marked decreasing trend, indicating a possible reduction in the resource abundance. Our results show that an appropriate fishery management for this

resource is needed, and should aim at reducing fishing mortality and increasing yield per recruit. These objectives could be achieved by reducing fishing effort and increasing size at first capture.

See original publication in Annex I

Introduction

The deep-sea red shrimp *Aristeus antennatus* is among the most important target species for demersal trawl fishery in the Mediterranean Sea. The bathymetrical distribution of this species ranges between100 and 3000 m depth (Sardà et al. 2004), with a large portion of the stock dwelling at depths beyond the fishing grounds limits (1000 m depth). Biology and ecology of this species have been widely studied, except for the larval phase which is still largely unknown (Carbonell et al. 2010). It displays marked sexual dimorphism for secondary sexual characters and growth characteristics. Females have a longer life span compared to males (5-6 years versus 3-4 years) and can reach a maximum cephalotorax length of 76 mm, while males reach a maximum of 54 mm (Sardà and Demestre 1987, Demestre 1990). It is a highly appreciated sea food and a very high value species at market, reaching peaks of more than 200 € /kg during holidays. It is actively targeted by bottom trawlers mainly at depths between 350 and 900 meters depth in various areas of the western and central Mediterranean Sea (Carbonell et al. 1999, D'Onghia et al. 2005, Fiorentino et al. 1998). Catches are mainly made up of females, which dominate the population at the depth range of the fishing grounds, where they constitute 70% of the population (Sardà et al. 1994a, Sardà et al. 2003a). There are no discards for this species, and all the catches are landed.

Many authors agree on the overexploitation status of the red shrimp in the Mediterranean Sea (Ragonese and Bianchini 1996, García-Rodríguez and Esteban 1999, Carbonell 2005). However, the assessment process is often complicated by the general scarcity and unreliability of official fishery data (Lleonart and Maynou 2003). One example is constituted by the engine power of the Spanish Mediterranean trawling fleets. Here, a national regulation establishes since 1988 a maximum engine power of 500 horsepower for trawlers (BOE 1988). Unfortunately, compliance to this regulation has always been extremely low and misreporting in the official records extremely common. Although it is recognized that fishing effort in the area has increased significantly in the last decades mainly due to the modernization of fleets (Alegret and Garrido 2004, Coll et al. 2014), no attempt to rectify the official records quantifying such increase was performed so far. In addition, despite the economic importance of the red shrimp and the risks related to intense and unregulated fishing activities, no specific national or international fishery management for this resource has been established, not even a minimum landing size.

In Catalonia (Northeast Spain), the red shrimp is an extremely important resource for the local fishermen associations (Fig. 1), which rely to a large degree on the incomes from this fishery (Maynou et al. 2006). Here, this species constitutes 3% of total landings

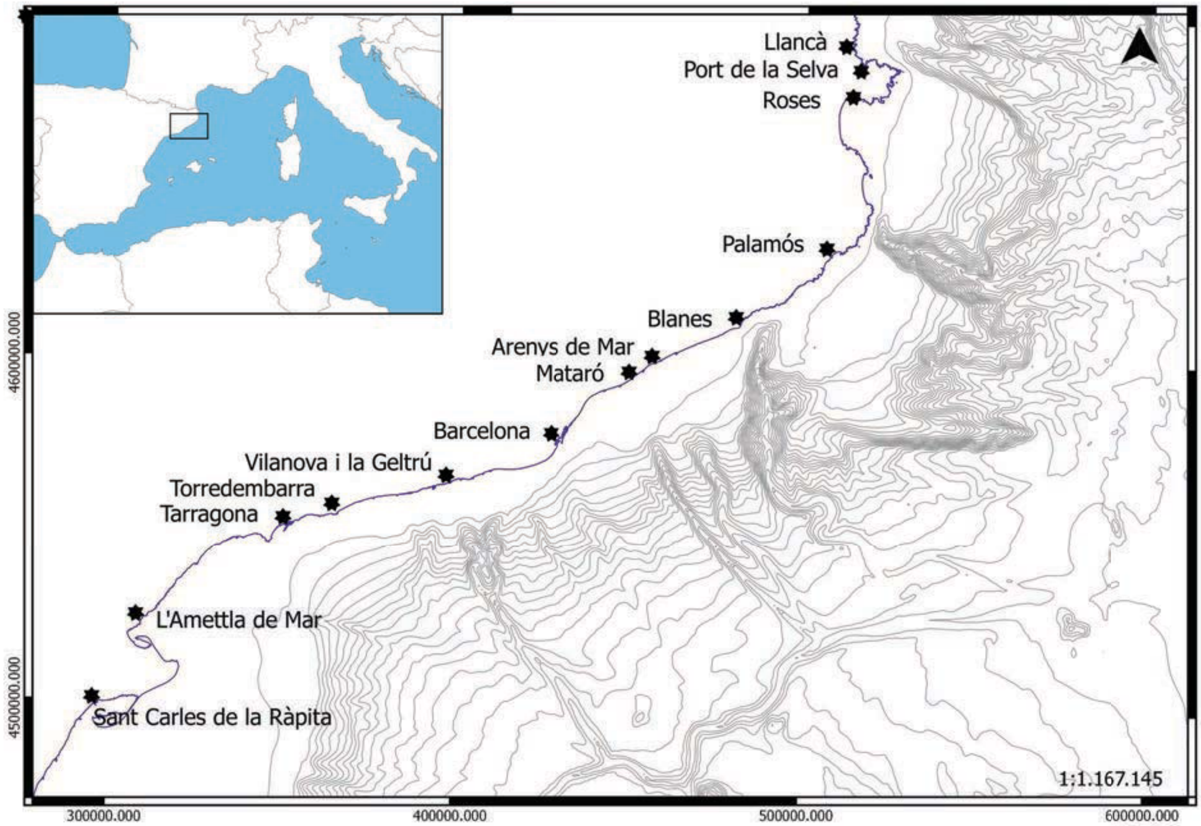

Figure 1. Map of the Catalan coast (NE Spain). The fishing harbors with a trawling fleet targeting red shrimp are shown.

while making 21% of economic incomes on a yearly average (Official fishery statistics from Autonomous Government of Catalonia). Landings of this species in the area are characterized by marked inter annual fluctuations, with minimums associated to the occurrence of an oceanographic process known as dense shelf water cascading (DSWC) (Company et al. 2008). DSWC in the area occurs when coastal surface waters on the wide shelf of the Gulf of Lions become denser than surrounding waters and cascade downslope, until reaching their equilibrium depth (Canals et al. 2006, Puig et al. 2013). In particularly dry, windy and cold winters the cascading is exceptionally intense and generates currents reaching depths > 500 m, creating a thermo-haline and turbidity anomaly in the deep waters. This anomaly is believed to increase the shrimps mortality and/or decrease their availability in the fishing grounds leading to a drastic reduction in their abundance and a temporary fishery collapse (Company et al. 2008).

The last stock assessment available in literature for the red shrimp in the Catalan area dates back to the period 1984-1989, when size structured data were sampled and analyzed in Demestre and Lleonart (1993). These authors defined the red shrimp at an optimum level of exploitation. Starting in 2013, Palamós, the most important harbor for this fishery in Catalonia, implemented a local management plan for the red shrimp fishery (BOE 2013). The measures included in the management plan aim at reducing the fishing effort and preserving red shrimp juveniles by i) reducing the number of vessels allowed in the fishing grounds, ii) performing a fishery closure in winter (when shoals of small individuals form in the fishing grounds), and iii) establishing the use of a more selective mesh size (40 mm square mesh instead of 50 mm diamond mesh). However, a more recent stock assessment is certainly needed in order to correctly inform and adjust the current management strategy in Palamós, as well as to set the proper scientific basis to implement it at a larger spatial scale. In addition, the long-term effects of the intensive fishing activities on this resource should be considered.

The objective of this work was to assess the stock of *Aristeus antennatus* exploited by the Catalan fleets in the recent years. We also investigated the long-term effects of the increasing fishing effort on this stock in the last 60 years. The evolution of fishing effort was quantified using days at sea and engine horsepower of shrimp trawlers, integrating and rectifying official data with information obtained by interviews with fishermen. In this study, we provide the first evidence of the remarkable increase of fishing effort that occurred in the Northwest Mediterranean in the second half of the last century. Following to this, we used yearly landings to build an historical series of catch per unit of effort (CPUE). Finally, we performed a stock assessment at two different time periods, 1984-1989 and 2008-2010, using the same methodology and biological parameters, in order to highlight differences in the exploitation status of the red shrimp over a period of twenty-five years.

Methods

Data on the trawling fleets active in Catalonia for the period 1900-2013 were obtained from the Spanish Ministry of Agriculture, Livestock and Fishery. A list of vessels characteristics including harbor of base, period of activity, gross tonnage (GT), gross register tonnage (GRT) and engine horsepower (hp) was provided. From the list, we selected trawlers belonging to the harbors that have a fishery for the red shrimp (Fig. 1). Face to face interviews with fishermen from the different harbors of study were performed in order to obtain the following information: i) which, among the trawlers on the list, were the ones that targeted red shrimp (full time or occasionally); ii) which was the real engine power of such vessels; iii) if any improvement to the engine power of these vessels was performed over time. Unfortunately, not all the fishermen interviewed agreed to provide information on the real engine power of vessels. To estimate a realistic horsepower value for trawlers when no direct information was provided, we investigated the relationship between the real hp values obtained with successful interviews and other vessels characteristics (i.e. GRT and GT). Then, all hp values obtained either by interview or extrapolation were summed to obtain a yearly value of total engine power of trawlers targeting red shrimp in Catalonia.

The total number of days at sea per fishing vessels was available in the records of the Autonomous Government of Catalonia (Tab. 1). The database covered the period 2001-2013 and allowed identifying values regarding specifically trawlers landing red shrimp. Extrapolation of data to the previous years was made considering fishing habits as well as environmental conditions in the area. The average number of days at sea per trawler was fairly stable in the time period 2001-2013, except for the years 2005 and 2006 (Tab. 1). In these years the red shrimp abundance in the fishing grounds was scarce due to exceptionally intense cascading events (Company et al. 2008), and this condition resulted in a lower fishing effort directed to this resource. Strong cascading generating currents reaching the depths of the fishing grounds were also observed in 2012-2013 (Durrieu de Madron et al. 2013), but they had a lesser impact on the fishery compared to previous events. Another cascading event reaching 500 m depth was recorded in 2010, but it had a short duration and no deep-water anomaly was observed in the following year (Puig et al. 2013). Exceptional environmental conditions are the most important factors affecting the number of days at sea in this fishery. In fact, fishing activities in this area are an otherwise routinely activity, strictly organized in daily trips with days at sea established at five per week. Anomalies in the deep-water characteristics following exceptionally strong cascading events (similar to the 2005-2006 events) were also observed in 1971-1972, 1980-1981, 1988-1989 and 1999-2000 (Bethoux et al. 2002, Puig et al. 2013). Thus, the mean value of days at sea per vessel in 2005 and 2006 was used as an estimate of days at sea per vessel in these years. The same method was employed for non-cascading years. Finally, the series of fishing effort directed to the red shrimp was worked out as yearly values of days at sea per fleet engine power (Gulland 1969):

$$Fishing\ Effort\ = (Average\ Days\ at\ Sea\ per\ Vessel) \times (Fleet\ hp)$$

During the interviews, fishermen stressed the importance of the improvements in fishing technology to increase their fishing efficiency. In particular, the technological equipment acquired over the years (use of scanmar, bathymetry data, GPS, etc.) contributed to a precise identification of the most suitable and safe grounds for trawling and the achievement of a near perfect asset of the fishing gear during operations. Therefore, a yearly rate of 1% increase due to technological creep was applied to the series of fishing effort starting from 1980. The 1% ratio used in this work was assumed as a conservative ratio compared to the 3.6 % suggested by Pauly and Palomares (2010).

Table 1. Yearly values of total number of days at sea and average number of days at sea per vessel for the Catalan trawling fleets targeting red shrimp from 2001 to 2013. In 2005 and 2006 (in bold) exceptionally strong cascading events occurred in the study area negatively affecting the red shrimp abundance in the fishing grounds.

Year	Total days at sea	Average days at sea per vessel
2001	11990	98.28
2002	13806	113.16
2003	13344	105.90
2004	15695	122.62
2005	**9876**	**77.16**
2006	**7895**	**59.81**
2007	13033	99.49
2008	15818	121.68
2009	15569	127.61
2010	13177	110.73
2011	13632	118.54
2012	11993	106.13
2013	12033	109.39

Table 2. Total landings of red shrimp (in tonnes) for the Catalan region in the years 1984-1989 and 2008-2010 per sex.

	1984	1985	1986	1987	1988	1989	2008	2009	2010
Males	30	35	24	35	51	88	49	45	30
Females	253	315	212	217	327	265	629	581	456

The historical series of landings was built integrating two different data sources. From 1963 to 1986 data were obtained from Tobar and Sardà (1987), who in turn made reference to the Spanish Ministry of Agriculture, Livestock and Fishery. From 1987 onwards the responsibility of such data collection was transferred to the regional governments. Therefore, from 1987 to 2013 data were obtained from the records of the Autonomous Government of Catalonia. Then, annual CPUE were calculated for the period 1963 – 2013 as:

$$CPUE = \frac{Catches\ (kg)}{Fishing\ Effort}$$

For the stock assessment of *A. antennatus* at two different time periods, we employed two series of size frequencies in the catches proceeding of four Catalan harbors. One series was relative to the period 1984-1989 and the other to the period 2008-2010. The first data were available in literature (Demestre 1990) and were previously analyzed in Demestre and Lleonart (1993). They were obtained by monthly sampling the catches of the trawling fleets of Blanes, Arenys and Barcelona. During the sampling, sex and cephalotorax length of individuals in the catches was recorded. The second data series (2008-2010) was obtained within a monitoring project carried out by the Autonomous Government of Catalonia. Data were obtained by similar methodology as in the previous case, i.e. sampling catches onboard commercial trawlers of three of the main Catalan harbors: Roses, Arenys and Vilanova i la Geltrú. In both cases data obtained with the samplings were assumed to be representative for Catalonia and length frequencies were extrapolated to the landings of the whole region in the respective years. In particular, the sex ratio in the samples was extrapolated to the total landings in order to obtain values of landings per sex (Tab. 2). The average size frequencies in the catches for the two periods were compared using the Kolmogorov-Smirnov (K-S) test.

Data were analyzed by means of pseudo-cohort and yield per recruit analysis using the VIT program (Lleonart and Salat 1997). This method is commonly used in data poor fisheries, as it allows stock assessment when only a few consecutive years of size structured data are available. The VIT basically performs a virtual population analysis (VPA) under the assumption of steady state of the stock (constant recruitment and mortality). This way the age structure of a single year is considered as the age structure of a single cohort ("pseudo-cohort"). We give no further detail on the calculations used by VIT as an extensive description is provided in Lleonart and Salat (1997). This method is widely used for stock assessment in the Mediterranean Sea due to the general availability of poor data series, and it is one of the main methods used for official fishery evaluations within the General Fishery Commission for the Mediterranean (GFCM). We used the same biological parameters for the stock assessment in the two time periods. In particular, the Von Bertalanffy growth parameters were taken from Sardà and Demestre (1987), the natural mortality estimates from Demestre and Martín (1993), and the length weight relationship parameters from Demestre (1990) (Tab. 3). A qualitative evaluation of the stock at each year analyzed was given comparing fishing mortality (F) estimated by the pseudo-cohort analysis with the reference point $F_{0.1}$ calculated by the yield per recruit analysis. Given the differences between females and males in the growth parameters and natural mortality rates, all the analyses were performed for the two sexes separately.

Table 3. Parameters used for the pseudo-cohort analysis. Parameters of the Von Bertalanffy relationship (L_{inf}, k, t_0) are from Sardà and Demestre (1987); parameters of the length-weight relationship (a, b) are from Demestre (1990); natural mortalities (M) are from Demestre and Martín (1993).

	L_{inf}	k	t_0	a	b	M
Males	54	0.25	-0.5	0.004024	2.31769	0.8
Females	76	0.3	-0.07	0.00264	2.46604	0.5

Results

The number of trawlers targeting red shrimp in Catalonia undertook an increasing trend starting from the beginning of the 1950s, reaching a peak in 2006 (Fig. 2). At the beginning of 2013 there were 110 trawlers dedicating effort to this fishery (full time or occasionally). Fishermen from the harbors of Palamós, Blanes, and Tarragona agreed to provide the real engine horsepower values of shrimp trawlers for the respective fleets. From these interviews we found that, in 2013, the engine power of 98% of the shrimp trawlers was misreported in the official records. In fact, the average real engine power was 999 hp, while the average declared was only 457 hp. Our results show that massive misreporting started right after the regulation limiting engine power to 500 hp came into force (BOE 1988) (Fig. 3). After this year, many vessels increased their engine power illegally, although with the implicit permission of the authorities. Illegal and unreported engine power was also observed in most of the newly built vessels incorporating to the fleets. Since 1988, only 13% of shrimp trawlers complied with the law. As a result, in 2013 the total engine power of the shrimp fleets of Palamós, Tarragona and Blanes exceeded of more than double the value reported in the official records (Fig. 3).

The real engine horsepower values collected with the interviews showed a significant linear relationship both with vessels GT and GRT, although the relationship with GT provided a better fit. In particular, the GT-hp relationship was sensibly different when considering shrimp trawlers active before 1988 and after 2000 separately (before 1988: R^2 =0.664, p=0.000; after 2000: R^2=0.751, p=0.000) (Fig. 4). In fact, between 1988 and 2000 all the major changes to engine power of vessels were performed. Thus, after 2000 the average engine power of trawlers of a given GT was higher than before 1988. The linear relationship between real hp and GT was used to estimate the real hp values of shrimp trawlers when we had no direct information from the interviews. Such relationship was applied according to the following rules in order to simulate the temporal pattern unveiled from the harbors investigated: i) official engine power of vessels registered before 1988 was considered real with no need of correction; ii) vessels registered before 1988 and active until after 2000 were considered to have changed their engine power during the years 1988-2000, and a new hp value was estimated using the GT-hp relationship; 3) official engine power of vessels registered after 1988 was considered false and the real value was estimated using the GT-hp relationship.

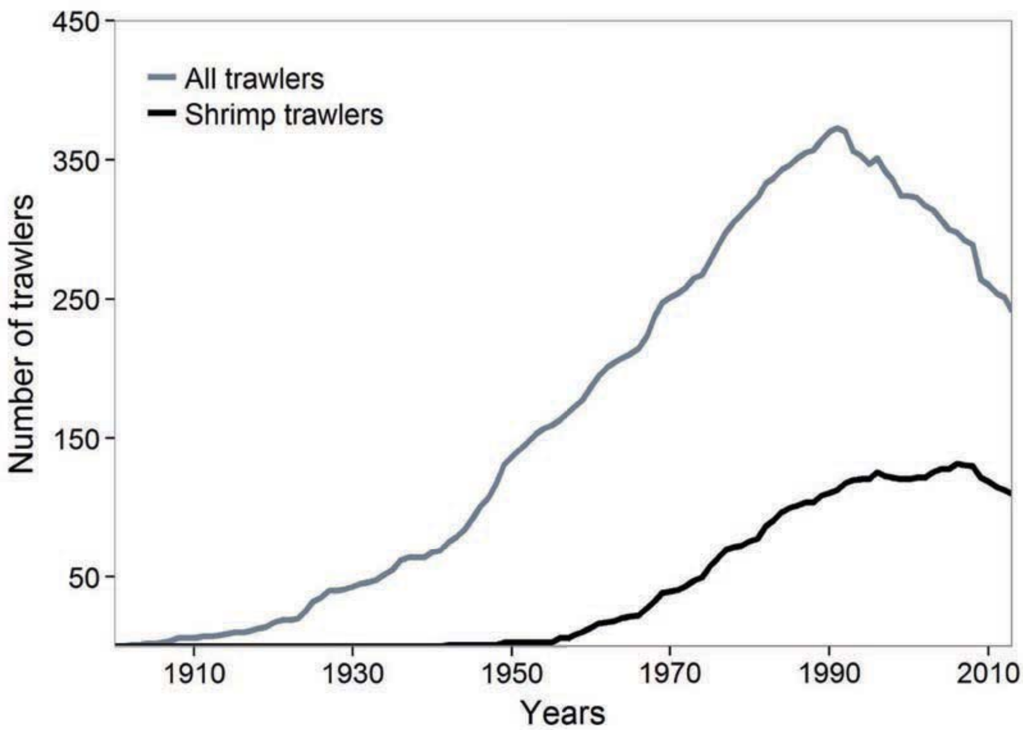

Figure 2. Total number of trawlers and number of trawlers specifically targeting red shrimp (full time or occasionally) in the Catalan region from 1900 to 2013.

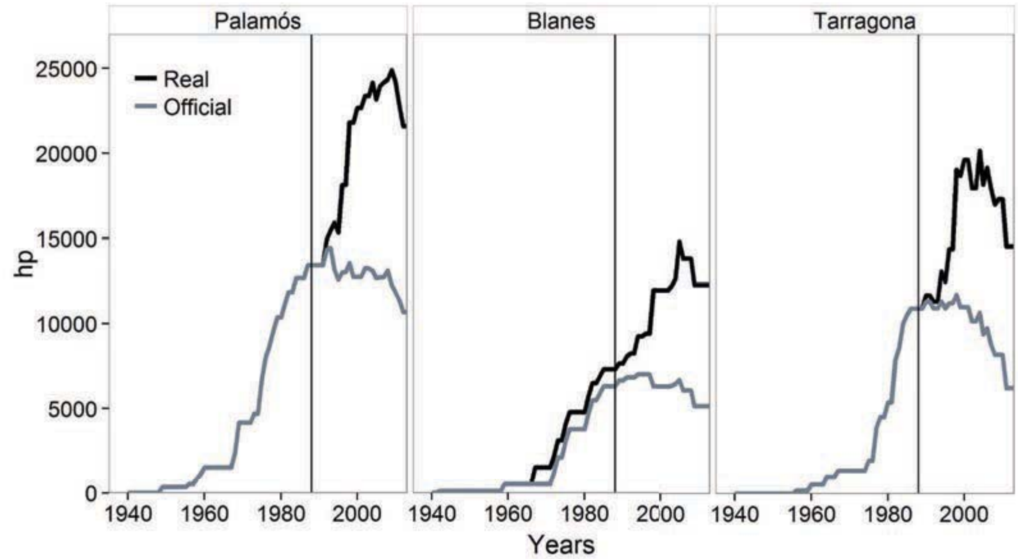

Figure 3. Historical series of total engine power (hp) of the trawling fleets targeting red shrimp for the harbors of Palamós, Blanes and Tarragona (Catalonia). Official vs real values of hp are shown. The vertical lines indicate the year in which the regulation establishing engine power at a maximum of 500 hp came into force (i.e. 1988).

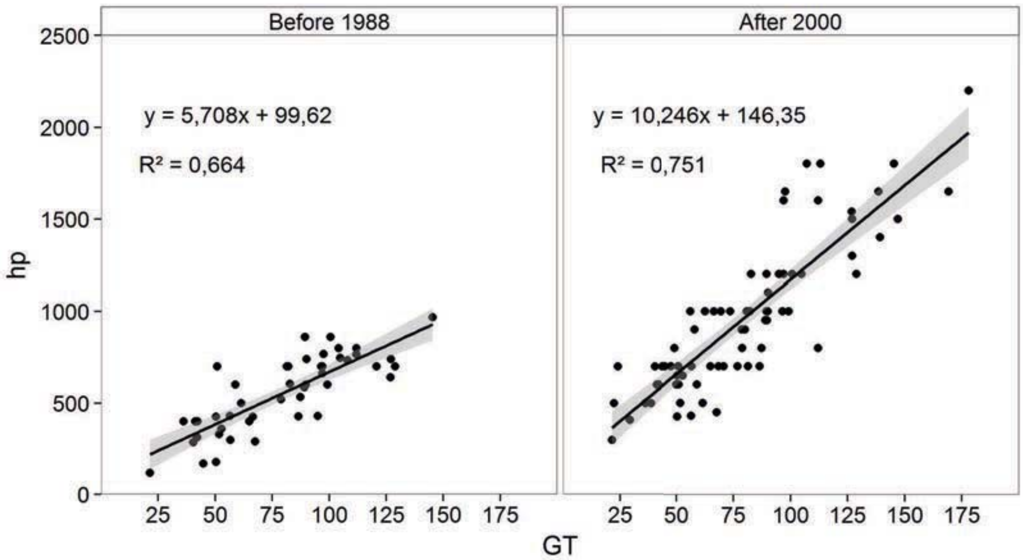

Figure 4. Linear relationship between real engine power (hp) and gross tonnage (GT) of shrimp trawlers in the harbors of Palamós, Blanes and Tarragona (Catalonia). Linear relationships are shown for vessels active before 1988 ($p=0.0000$) and after 2000 ($p=0.0000$) separately. The shaded area corresponds to the 95% confidence interval for the linear regression.

The historical series of total engine power of the Catalan shrimp trawling fleets (obtained using both interview data and estimations) is shown in figure 5. As displayed by the figure, the official records sensibly underestimate the real data starting from 1988, when the curves begin to diverge greatly. After this year, the series of official hp does not show any sign of further increase, while the series of real hp keeps increasing. In 2013, the official value of hp represented only 42% of the real one. The historical evolution of fishing effort including technological creep is shown in figure 6. The curve displays a steep increasing trend starting from the mid-1950s, reaching a maximum in 2009. The minimums in the series correspond to years in which intense cascading events occurred in the study area.

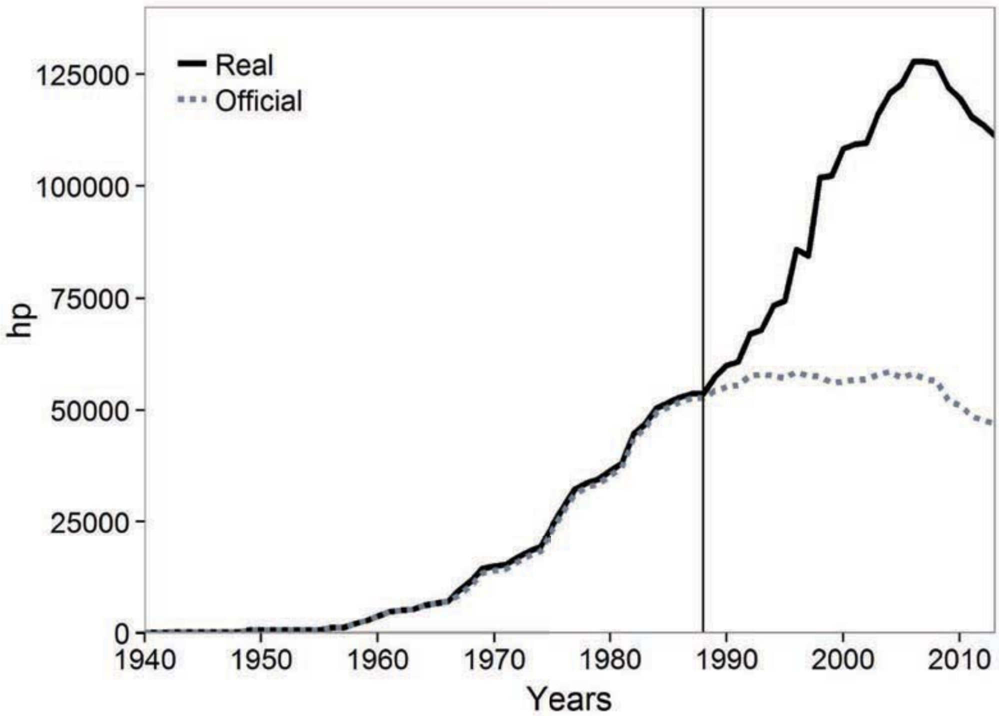

Figure 5. Historical series of total engine power (hp) of the trawling fleets targeting red shrimp in the Catalan region from 1940 to 2013. Official vs real values of hp are shown. The vertical line indicates the year in which the regulation establishing engine power at a maximum of 500 hp came into force (i.e. 1988).

The historical series of landings and CPUE are shown in figure 7 and 8 respectively. The series of landings displays an overall minimum in 1981, when landings for the whole region amounted to only 28.6 tonnes (t), and a maximum in 2008, when landings reached 683 t. A significant increasing trend could be detected over the whole time series (R^2 = 0.247; p=0.0002), although significance and slope of the regression increased if considering years after the modernization of the fleet only (from 1970: R^2 = 0.440; p=0.0000) (Fig. 7). The CPUE series shows an initial increase followed by a steep decrease from 1965 to 1970, when CPUE went from 0.66 kg/hp*day to 0.09 kg/hp*day. After 1970, the series displays a less steep but still overall decreasing trend until 2000, when CPUE undertook a slightly positive trend leading to a value of 0.04 kg/hp*day in 2013.

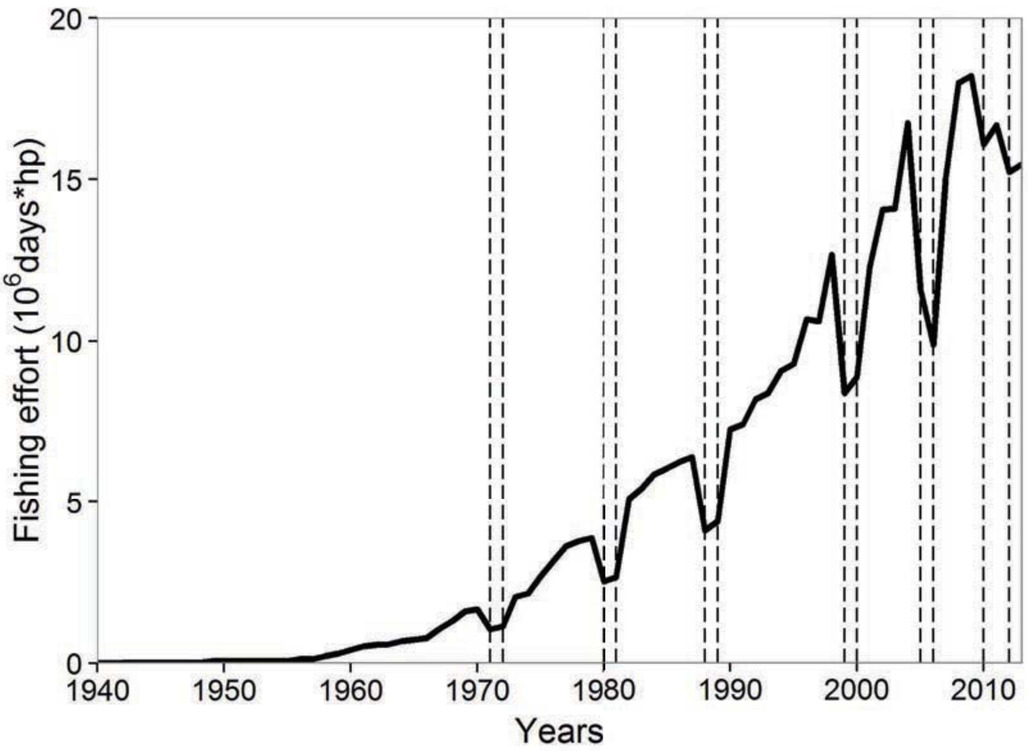

Figure 6. Historical series of fishing effort directed to the red shrimp in Catalonia from 1940 to 2013. The series includes a yearly rate of 1% increase due to technological creep starting from 1980. The dashed lines indicate years in which intense cascading events occurred.

The S-K test did not detect any significant difference in the average size frequencies in the catches between the two time periods considered (1984-1989 and 2008-2010), neither for females nor for males (p > 0.05) (Fig. 9). The results of the pseudo-cohort and yield per recruit analysis are shown in Table 4. According to the pseudo-cohort analysis, the mean population biomass of males was lower than that of females at all years studied, reflecting the sex ratio in the fishing grounds and catches (Sardà et al. 1994a, Sardà et al. 2003a). The mean population biomass of females was considerably lower in the period 1984-1989 compared to 2008-2010, passing from an average of 398 t to an average of 953 t. For males, differences in the estimated values of biomass between the two time periods existed as well, but were not as marked as for females. Biomass of female recruits was higher in the second period of time, too. For males the opposite was true.

Table 4. Results of the pseudo-cohort and yield per recruit analysis shown per year and sex. F0,1/Mean F is the optimum effort factor: if lower than one, the stock is subject to overfishing and *vice versa*.

	1984	**1985**	**1986**	**1987**	**1988**	**1989**	**2008**	**2009**	**2010**
FEMALES									
Mean stock biomass (t)	392	572	416	235	379	393	1067	1068	724
Recruits (t)	67	94	59	90	104	82	114	135	94
Mean Stock Age	1.6	1.7	1.7	1.6	1.5	1.6	1.5	1.6	1.5
Mean Stock Length	28.7	30.3	30.0	29.3	27.6	29.1	27.1	29.1	27.5
Mean F	1.09	1.05	0.88	1.24	1.53	0.96	0.98	1.24	1.29
Y/R (g)	9.39	9.68	8.99	10.39	9.11	9.32	8.14	9.00	8.57
$F_{0.1}$	0.52	0.54	0.52	0.63	0.53	0.5	0.45	0.51	0.49
$F_{0.1}$/Mean F	0.48	0.51	0.59	0.51	0.35	0.52	0.46	0.41	0.38
MALES									
Mean Stock biomass(t)	42	52	40	40	72	145	91	71	48
Recruits (t)	30	35	25	35	48	84	29	42	25
Mean Stock Age	1.6	1.6	1.6	1.6	1.5	1.5	1.1	1.5	1.3
Mean Stock Length	21.7	21.8	22.2	22.0	20.9	21.3	17.7	21.2	19.6
Mean F	1.75	1.90	1.38	1.70	1.15	1.80	0.94	1.70	1.11
Y/R (g)	2.91	2.9	2.78	3.26	2.68	2.63	1.77	2.63	2.26
$F_{0.1}$	0.99	0.93	0.94	1.28	0.92	0.94	0.73	0.87	0.82
$F_{0.1}$/Mean F	0.57	0.49	0.68	0.75	0.8	0.52	0.78	0.51	0.74

Mean fishing mortality (mean F) did not show any particular trend neither within nor between periods, for neither sex. Despite the S-K test not detecting any significant differences in the average length frequencies in the catches, the pseudo-cohort analysis suggests that the mean individual size in the population decreased from the period 1984-1989 to 2008-2010. In fact, average values of cephalothorax length were reduced by more than 1 mm in females (from 29.2 mm to 27.9 mm), and by more than 2 mm in males (from 21.7 mm to 19.5 mm) between the two periods. Females yield per recruit decreased by 10% between 1984-1989 and 2008-2010, passing from an average of 9.48 g to an average of 8.57 g. For males the decline of the yield per recruit was less marked as average values went from 2.86 g to 2.22 g in the two periods respectively. The mean F values exceeded the reference point $F_{0.1}$ at all years and for both sexes, denoting overfishing of the resource in both periods of study (Tab. 4, Fig. 10). For females, overfishing appeared more severe in the second period of time, with the average value of $F_{0.1}$/Mean F going from 0.49 to 0.41 between the two periods.

Discussion

Effective fisheries evaluations and management require the full understanding of the fishing effort directed to the fish stocks and its historical evolution (Hilborn and Walters 1992). Official data are often unable to capture real trends in fishing effort, and the need to improve official statistics through “informed adjustments” has been widely discussed (Anticamara et al. 2011, Ota and Just 2008, Watson et al. 2000). For these reasons the evaluation of official data, with the identification of gaps, biases and misreporting is fundamental in the context of fishery research. In the fishery object of this study, the steep fishing effort increase in the last 25 years was due to a large degree to the increase of trawlers engine power. However, this could not be inferred from the official records due to heavy misreporting. Engine power plays an important role in determining fishing effort and the incorporation of its variations is widely recommended especially when evaluating temporal trends (Anon. 2007a, Gulland 1969). In fact, the size of the fishing gear increases significantly with the trawler engine horsepower (Eigaard et al. 2011). Moreover, according to the fishermen interviewed in this study, a more powerful engine significantly decreases transfer time to the fishing grounds, gaining extra time for trawling on a daily basis. A more powerful vessel also allows fishing in deeper waters expanding the limits of the fishing grounds and increases fishing efficiency in rough weather. In addition, the need to incorporate other descriptors of technological creep that result in a significant increase in fishing efficiency was stressed by many authors (Pauly et al. 2002, Marchal et al. 2006, Marriott et al. 2010, Eigaard et al. 2011).

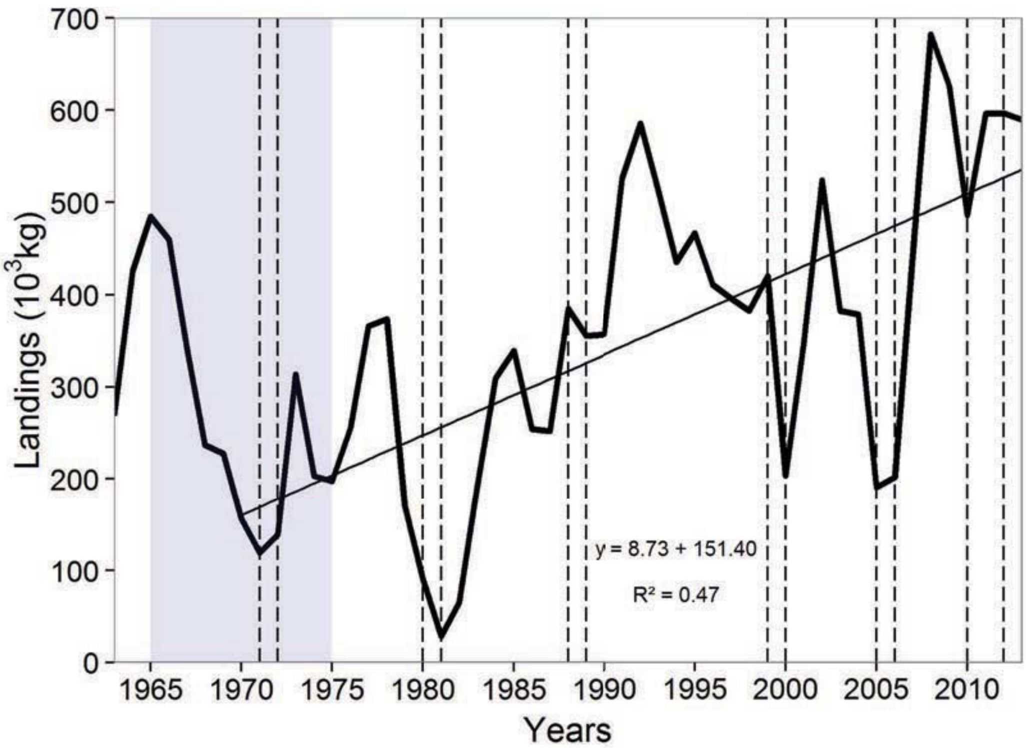

Figure 7. Historical series of red shrimp landings from 1963 to 2013 in Catalonia. The gray area indicates the period of fleet modernization according to Alegret and Garrido (2004). The linear regression for landings in years after fleet modernization is shown (from 1970: p=0.000). The dashed lines indicate the years in which intense cascading events occurred.

The data collected with the interviews were a reliable source of information given the high confidence between the two parties based on years of previous and ongoing collaborations. In fact, when the condition of trust is met, interviews can supply good and high resolution information on fishing practices that might be unavailable otherwise (McCluskey and Lewison 2008). This allowed a careful correction of the official data. The extrapolation to the other Catalan harbors of the results on hp values obtained with the interviews in Palamós, Tarragona and Blanes was justified by similarities in the trawling fleets, fishing habits and socio-economic conditions in these ports. In addition, the number of shrimp trawlers of these harbors represents around 45 % of the total, landing about 50 % of all the red shrimp in the study area. Therefore, these data were considered well representative of the Catalan area and extrapolation to the surrounding ports legitimate.

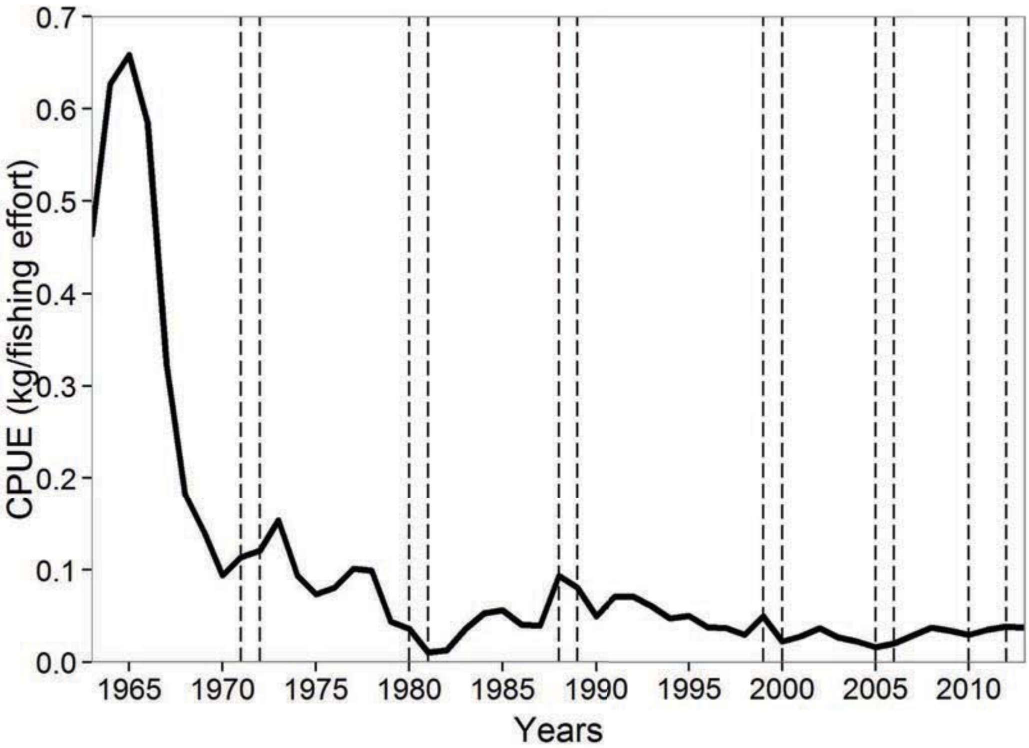

Figure 8. Historical series of red shrimp CPUE from 1963 to 2013 in Catalonia. The dashed lines indicate the years in which intense cascading events occurred.

The series of fishing effort presented in this study shows a steep increasing trend starting from the second half of the last century. It has to be considered that in the first decades of our series (until 1970) the vessels had a lesser efficiency to work in bad weather compared to the present. According to the fishermen interviewed, fishing days in these years were probably less compared to the present. Unfortunately, there were no records available to quantify this difference, and therefore there is a chance that fishing days in the first decades of our series were overestimated. Starting from 2006 and due to unfavorable economic conditions (high gasoil price, declining stocks), several vessels were scrapped and improvements in engine power of active trawlers were avoided. This situation determined the decrease of fishing effort detected in the latest years of our series. A very similar pattern of fleet engine power evolution in the area was previously suggested by Coll et al. (2014), where one Catalan harbor was considered. Similar results were also obtained by a study on a trawling fleet in the Balearic region (Coll et al. 2014). Here, despite a decrease in the number of trawlers, the total engine power doubled its value from the 1970s to the 1900s (Carbonell et al. 1999, Carbonell 2005).

As previously mentioned, the minimums displayed by the landing series were associated to particularly strong cascading events that occurred in the study area (Fig. 7). The hypothesis behind the relatively fast recovery of landings after a minimum is that cascading events enhance recruitment in the following years thanks to the supply of organic matter to the deep basin (Company et al. 2008). In fact, after two or three years from a cascading event, exceptional catches of small individuals are observed. The series of CPUE seems less influenced by the cascading because generally, when exceptional environmental conditions are verified, both landings and fishing effort are reduced. The overall decline of CPUE over the time frame considered suggests a decline in the red shrimp abundance. It has to be beard in mind that inference on stock abundance based on CPUE relies on the assumption of constant catchability. In reality, catchability can be influenced by many factors, such as changes in gear selectivity, technological improvements, fishermen skills and fishing behavior (Harley et al. 2001, Bishop 2006, Maunder et al. 2006). In this work we accounted for a few of these factors in the calculation of CPUE, but a different trend in the resource abundance might be concealed by other factors influencing the catchability. For example, the apparent stabilization of CPUE in the latest years of the series might be due to a decrease in gear selectivity and/or changes in fishermen behavior, which increased the fishing efficiency masking a further reduction of the red shrimp abundance. Unfortunately, we had no fishery independent index to allow a more precise evaluation of the resource abundance.

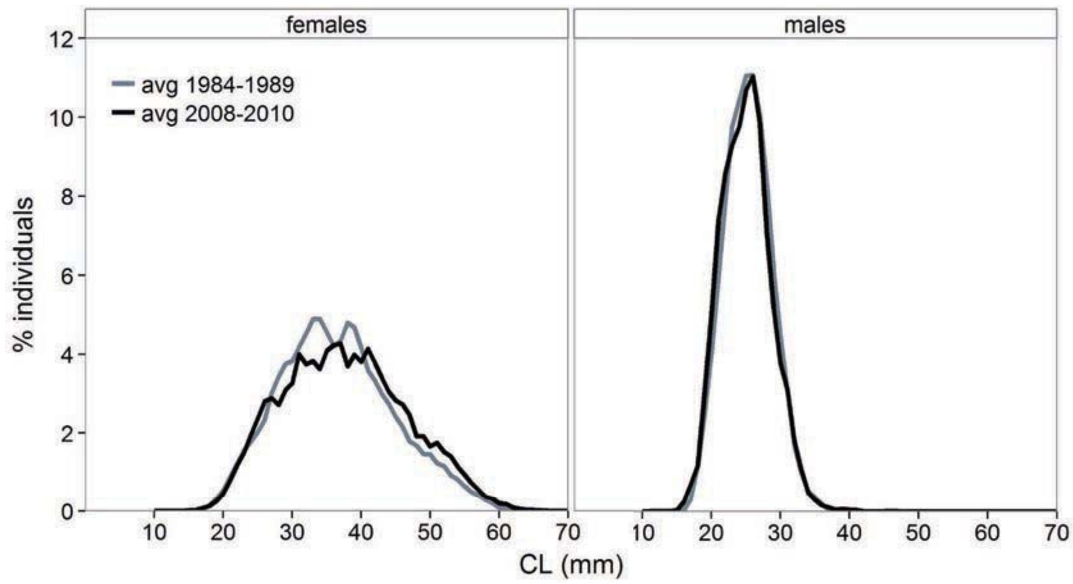

Figure 9. Length frequencies in the catches of red shrimps in the two periods of study (1984 -1989 and 2008-2010), presented per year and sex (CL = cephalothorax length).

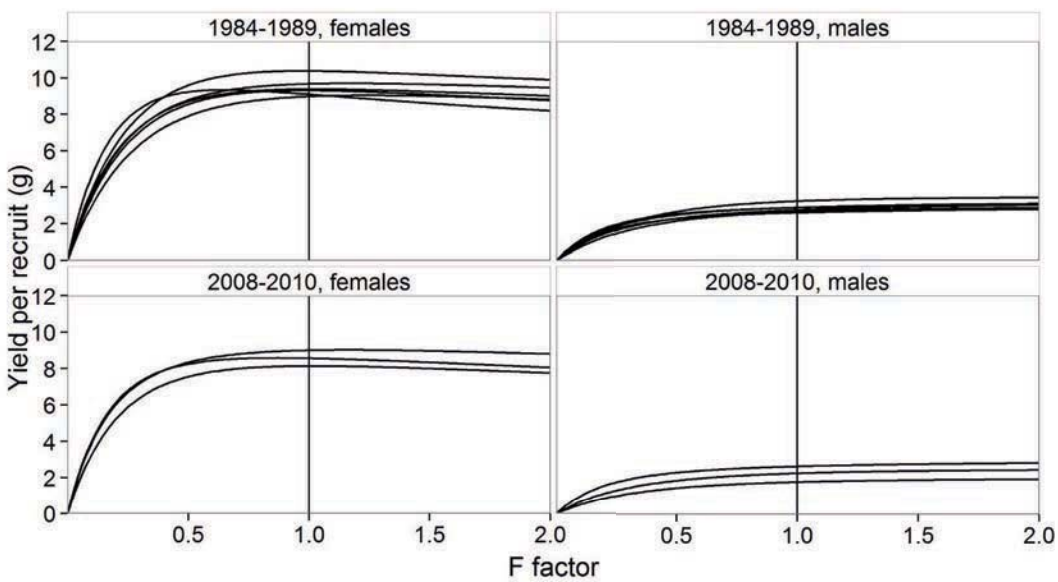

Figure 10. Curves of yield per recruit vs effort factor (i.e. multiplying factor for present level of fishing effort) in the two periods of study (1984-1989 and 2008-2010), presented per year and sex. The black vertical lines indicate the current level of fishing effort.

The mean stock biomass estimated by the pseudo-cohort analysis was higher for the period 2008-2010 than for the period 1984-1989. These estimates are highly dependent on catches, which in fact were considerably higher in the second period of time. However, this was most probably due to increased fishing effort (not taken into account in the analysis), rather than increased population biomass. In fact, the increase of fishing effort is likely to have caused an expansion of the fishing grounds, with more powerful vessels fishing at deeper waters increasing the portion of the stock exploited (Coll et al. 2008a). The decrease of the yield per recruit between the two periods of time could result from a change in the selectivity of the fishery and/or a change in the fishing strategy, with smaller individuals living at deeper waters becoming a target of the fishery (Sardà et al. 1994a). It has to be considered that the assumption of steady state implied by the use of the pseudo-cohort analysis is a very constraining one. In fact, variations in the recruitment and mortalities of the red shrimp induced by environmental factors (which occurred in the years considered for stock assessment), are likely to have biased the results. For example, 2008 was a year of enhanced juveniles catches (Company, own unpublished data). Thus, the interpretation of the VIT results should be taken with care. In particular, a comparative study by Ratz et al. (2010) showed that quantitative conclusions from VIT results are particularly sensitive to violations of assumptions, while estimates of $F_{0.1}$ remain in line with estimates from more complex models.

Similarly to the present study, overfishing of the red shrimp was detected by many authors in several areas of the Mediterranean Sea, such as the strait of Ibiza, the Balearic Islands and Sicily (Ragonese and Bianchini 1996, García-Rodríguez and Esteban 1999, Carbonell 2005). The "optimum exploitation" of this resource in Catalonia was only detected when F_{max} was considered as a reference point instead of $F_{0.1}$ (Demestre and Lleonart 1993). In this work we refer to $F_{0.1}$ as it was indicated as a better proxy for F_{msy}

than F_{max}, being consistent with high yield and low risk of collapse in line with a precautionary approach (Gabriel and Mace 1999, Anon. 2007b, Kell and Fromentin 2007).

The point that despite decades of overfishing the stocks of *A. antennatus* have not collapsed yet has been widely discussed (Demestre and Lleonart 1993, Sardà 1993, García-Rodríguez and Esteban 1999, D'Onghia et al. 2005). The rapid growth rate and short life span of this invertebrate species were advocated as factors limiting its sensitivity to intense fishing activities. In addition, the sudden and local shoals fluctuations and the large portion of the population residing in areas outside the fishing grounds might contribute to prevent the collapse of this stock (Demestre and Martín 1993, Sardà et al. 2004, Company et al. 2008). Also, the effects of strong cascading events could work as a natural fishery regulation, periodically lowering the fishing mortality and having a positive effect on the recruitment (Company et al. 2008). However, the historical perspective presented in this work undermines the idea of long-term resilience of this species to the fishing activities. The decrease of the yield per recruit and CPUE over the time frame considered, as well as the reduction of the mean individual length, might in fact be the symptom of population changes induced by the intense exploitation. Our results suggest that fishing effort should be reduced and size at first capture increased, in order to lower fishing mortality to sustainable levels and maximize the yield per recruit. In addition, this study indicates that the long-term effects of the high fishing levels on the red shrimp are yet to be clarified, and that a stock assessment method capable of including fishing effort changes and environmental effects should be developed for this purpose. Finally, our results strongly demonstrate that official data series should be rigorously reviewed before taken into account in fisheries evaluations. In fact, our study shows that fishing effort based on raw official data can be underestimated by more than 50%. We also believe that these results are paradigmatic of many Mediterranean fisheries. Moreover, being most of these fisheries multi specific (with the same vessels targeting different species according to season, prices at market, etc.) the results of this work can be directly applied to the stock assessment of other species, such as European hake, red mullet or Norway lobster.

2.2 The effect of Dense Shelf Water Cascading on the red shrimp population dynamics

The results of this work were presented at the 144th Annual Meeting of the American Fisheries Society in 2014 (Quebec City, Canada). Article in preparation.

Incorporating the effect of dense shelf water cascading in the stock assessment of the deep-sea red shrimp *Aristeus antennatus* in the Northwest Mediterranean Sea.

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Abstract

Accounting for the effects of environmental variability is important for the stock assessment of many fishery resources. The red shrimp *Aristeus antennatus* is one of the most economically important deep-sea demersal resource in the Northwest Mediterranean Sea. In Northeast Spain, it is fished by bottom trawling, and annual landings display high interannual variability. These fluctuations have been related to the effect of strong deep-sea currents generated by dense shelf water cascading (DSWC), which occurs in the area at a decadal scale. Temporary fishery collapses are associated to the occurrence of DSWC and are usually followed by a sharp recovery of the fishery and high catches of small, mostly juvenile individuals in the following years. In this work, we performed a stock assessment for the red shrimp (1963-2015) using a statistical catch age (SCAA) and including the effect of DSWC. In particular, we used the stock assessment model to test different ecological hypotheses on the mechanisms of interaction between the environmental factor and the red shrimp population. The SCAA allowed to use all the available information, including fragmented series of catch at length data and landings by

shrimp market size. Our results show that including the effect of DSWC significantly improves the stock assessment model for this species. DSWC was found to increase punctually and significantly the natural mortality of red shrimps. In addition, overfishing of the stock was detected and the predicted equilibrium MSY was found to be significantly reduced under adverse environmental conditions due to DSWC.

Introduction

Environmental variability has a significant effect on marine resources (Cushing 1982, Botsford et al. 1989, Drinkwater et al. 2003, Overland et al. 2010). In particular, climate induced processes such as changes in temperature, salinity and water circulation have the potential to affect a variety of aspects of the population dynamics of marine species, such as recruitment, abundance, distribution, migration, natural mortality and availability (Ottersen et al. 2004a). The mechanisms through which the interaction between environment and biology occurs are various and complex, and involve a series of direct and indirect effects (Ottersen et al. 2010, Overland et al. 2010). For example, temperature can have direct effects on the physiology of species influencing growth, sexual maturity and reproduction, which has been demonstrated both in pelagic and demersal species (Loeng 1989, Brander 1995, Brander 2000, Ottersen et al. 2004b, Rijnsdorp et al. 2010). On the other hand, water mixing (e.g. upwelling) can create favourable conditions for recruitment, such as enhanced food availability (MacKenzie 2000, Santos et al. 2001, Malta et al. 2016). Water currents also contribute significantly to larval survival in pelagic stages, by carrying them into or away from suitable nursery areas (Calderon-Aguilera et al. 2003, Huggett et al. 2003, Ottersen et al. 2010).

Due to the complexity of the response, it is not always easy to establish unique relationships between environmental condition and a biological response. In fact, the multitude of pathways through which the climate impacts marine populations often makes it difficult to establish univocal connections between climate and ecological response (Ottersen et al. 2004a, Ottersen et al. 2010). In addition, disentangling the effects of fisheries from the effects of environmental fluctuations is often difficult (Rijnsdorp et al. 2010, Rothschild 2000, Rouyer et al. 2014). However, in the case of commercially exploited resources it is particularly important to identify environmental effects, as these can affect greatly the fisheries and should be taken into account to improve the management regimes (Botsford et al. 1989, Jacobson and MacCall 1995, Company et al. 2008). In fact, failing to take into account the relevant environmental effects in the stock assessments can constitute a serious source of error (Ulltang 2003).

The Gulf of Lions in the northwestern Mediterranean Sea is a well-known region where Dense Shelf Water Cascading (DSWC) occurs almost every year, and one of the three known regions in the Mediterranean (Font et al. 1988, Millot 1990, Durrieu de Madron et al. 2005). DSWC is a specific type of buoyancy driven current triggered by particular climate conditions that determine the formation of large quantities of dense surface water (Fohrmann et al. 1998). During winter, in the Gulf of Lion, cold and dry northerly winds induce cooling, salinification and mixing of surface shelf waters. Once denser than the surroundings, this water mass sinks to the shelf bottom and continues to flow down the continental slope. Here, the dense, cold, salty and turbid cascading waters are channelled through an intricate net of submarine canyons carved into the continental shelf of the Gulf of Lions and the Catalan continental margin (northeastern Spain), until they reach the equilibrium depth, usually between 170-800 m (Canals et al. 2006, Millot 1990, Durrieu de Madron et al. 2005). Because of its sensitivity to atmospheric conditions, DSWC displays high interannual variability as for intensity, which related to the volume of dense water formed (Heussner et al. 1996, Canals et al. 2006). One of the strongest and best documented DSWC in this area occurred in 2005, during a particularly cold and dry winter. The dense shelf waters sunk along and across the continental slope, in a cascade that produced down-slope currents up to 85 m/s^{-1} and lasted for more than two months (Canals et al. 2006, Font et al. 2007). In 2005, the dense shelf waters reached depths over 2000 m and spread over the entire northwestern Mediterranean basin, generating a thermohaline and turbidity anomaly in the western Mediterranean deep water

(Puig et al. 2013). During such intense DSWC events, the extremely strong down-slope currents cause erosion and resuspension of surface sediments in the canyons, transporting exceptionally large quantities of organic and inorganic matter (Fohrmann et al. 1998, Canals et al. 2006, Palanques et al. 2006, Puig et al. 2008). Once in the deep-basin, the DSWC waters merge with the open sea convection waters (which occurs in concomitance with DSWC at an off-shore location in the western Mediterranean) creating a bottom-nepheloid layer, characterized by high density and high concentration of suspended particles. This layer can be up to hundreds of meters thick and can persist up to several years after each intense DSWC event, being very likely to affect the deep-sea ecosystems (Puig et al. 2001, Puig et al. 2013). Previous to 2005, another intense DSWC event in the area (reaching almost 2000 m depth) was observed by Bethoux et al. (2002) in 1999. These authors, basing on the study of historical data and the identification of anomalies in the deep-water, inferred that strong DSWC events occur in the northwestern Mediterranean at a quasi-decadal scale.

Company et al. (2008) found that the DSWC in the northwestern Mediterranean were correlated spatially and temporally to the periodical disappearance of the deep-sea red shrimp *Aristeus antennatus* in the fishing grounds in front of the Catalan coast. The red shrimp is one of the main demersal resources in the area, where it is targeted by the trawling fleets of eleven harbours (Maynou et al. 2006, Gorelli et al. 2016a). It is a relatively long lived decapod shrimp, with a life span of 6/7 years for females and 3/4 for males (Sardà and Demestre 1987, Demestre 1990). The early life stages of *Aristeus antennatus* are not entirely known. Reproduction occurs on the open slope in late spring and summer between 600 and 800 m depth. Larvaes in early pelagic development phases were found in the upper water layers over deep-waters (Carbonell et al. 2010), while postlarval individuals (<10 mm cephalotorax length) were mainly found below 1200 m depth, suggesting the existence of ontogenetic migration across the water column during the larval phases (Sardà and Cartes 1997, Sardà et al. 1994a, D'Onghia et al. 2009, Sardà and Company 2012). Juvenile individuals under two years of age (<20 cm cephalotorax length) are mainly present below 1000 m (Sardà and Demestre 1987, Demestre 1990, Sardà et al. 2004, D'Onghia et al. 2005) and progressively move to shallower waters (500-900 m) where fishing occurs (Sardà et al. 2003b, D'Onghia et al. 2005). The population at the depth of the fishing grounds is mainly constituted of adult females, although juvenile individuals can be abundant in certain periods of the year (i.e. in winter). A big portion of the population is thought to dwell at depths beyond the limits of the fishing grounds (Sardà et al. 1994a, Sardà et al. 2003a, Sardà et al. 2004).

The deep-sea red shrimp in Catalonia is fished exclusively by bottom trawling at depths between 500 and 900 m. The main fishing grounds are located along the continental margin of the system of submarine canyons carved in the continental shelf. In 2005, in conjunction with the DSWC, the abundance of red shrimp in the fishing grounds dropped dramatically, and remained close to zero until the cascade of water was over (Company et al. 2008). The landings progressively recovered after 2-3 months from the cessation of DSWC, but overall the landings for 2005 were reduced by more than 50% compared to the previous year. Furthermore, the analysis of the historical series of red shrimp landings in Catalonia showed that marked minimums in the series (comparable to the one in 2005) corresponded to years in which strong DSWC events had occurred (Company et al. 2008, Gorelli et al. 2016a). The minimums were generally followed by a sharp recovery of the catches. Company et al. (2008) also reported a peak in landings of small individuals (< 30 mm cephalotorax length, 1-2 years of age) after 3-5 years from the DSWC event. Following their observations, these authors hypothesized the existence of significant effects of strong DSWC events on the deep-sea red shrimp population, in particular i) an immediate, direct and negative effect on the abundance of this species in the fishing grounds and ii) a delayed, indirect and positive effect the recruitment. In fact, the enhanced availability of nutrients in the deep basin (where the red shrimp recruitment occurs) determined by DSWC might favour the reproductive success of this species.

Other authors have investigated the role of particular hydrodynamic conditions to shape the spatial distribution of the red shrimp in the northwestern Mediterranean Sea, in an attempt to explain the high variability of this species' abundance in the fishing grounds (Bombace 1975, Ghidalia and Bourgois 1961, Puig et al. 2001, Massutí et al. 2008, Maynou 2008, Sardà et al. 2009). However, none has investigated the mechanism of interaction between the environmental effects and the shrimp population, using an *ad hoc* modelling approach.

The objective of this work was to conduct a stock assessment of the red shrimp in Catalonia including the environmental effect of the DSWC, while testing different hypotheses on the mechanisms of interaction between DSWC and red shrimp population. In particular, we formulated two alternate hypotheses to explain the red shrimp disappearance from the fishing grounds during DSWC: a) DSWC increases the shrimps' natural mortality; b) DSWC decreases the shrimps' availability to the fishery by displacing them beyond the fishing grounds limits (i.e. 1000 m depth). We also tested the hypothesis of recruitment enhancement by DSWC. To achieve our objective, we built different models starting from a Statistical Catch at Age (SCAA) (Haddon 2011) and including progressively the environmental effects according to the different ecological hypotheses. The most likely hypothesis was identified through model selection based on the Aikaike information criterion (Aikake 1974, Burnham and Anderson 2004).

Methods

Data for the analysis were collected from different sources: a) a two-year sampling onboard a commercial fishing vessel, b) the official data of the Catalan Fishermen's Associations and c) literature. The sampling was carried out in 2012-2013 onboard a shrimp trawler of the Palamós fleet (the most important harbour for this fishery in Catalonia). Cephalotorax length, sex and sexual maturity of individuals of red shrimp in catch samples were recorded and then expanded to the total catch. Other series of catch at length data obtained from various harbours of Catalonia were available in Demestre and Lleonart (1993) for the years 1984-1989, and from a sampling of the Autonomous Government of Catalonia for the years 2008-2010. In all cases, data were collected by the same research team, with an alike methodology and were considered representative of the whole Catalan area. An additional source of information on catch at length was constituted by the yearly records of catch per market size of the Fishermen's Associations of Roses, Arenys, Blanes and Palamós (four of the most important Catalan harbours) available for the years 1997-2015. These harbours sort and sell the catch into different market size classes that can vary in number from two to four, according to the harbour. For this work, we considered two main market size classes, big (30-60 mm cephalotroax length) and small (20-30 mm cephalotorax length), which allowed accommodating all the available data. An average weight of 11 g and 29 g for small individuals and big individuals respectively was assumed as in Company et al. (2008), to calculate numbers of individuals per market size class. Size frequencies within each market size class were obtained in the 2012-2013 sampling, and were used within the model to predict catch at market size from estimated catch at length (see details below). Total catches and CPUE from 1963 to 2013 were taken from Gorelli et al. (2016a) and updated to 2015 using the same sources of information and methodology. The first seven years of the CPUE series were removed prior to the analysis, as considered too uncertain.

Red shrimp females and males have very different growth characteristics, with males being smaller and with a shorter life span compared females. The sex-specific parameters of the Von Bertallanffy relationship, the age-length keys and the proportion of mature individuals at age were taken from Carbonell (2005). The sex-specific length-weight relationship parameters were found in Demestre (1990), while natural mortality in Demestre and Martín (1993). The estimation of gear selectivity in the fishery object of study was found in Gorelli et al. (2017).

Years in which DSWC had occurred with enough intensity to reach the depth of the fishing grounds (> 500 m depth) and affect the red shrimp population, were identified through different literature sources and considerations. The observation of the latest and best monitored strong DSWC events showed clearly that these tend to occur in “couples” of consecutive years, with the first event being stronger than the second. The most recent events were observed in 2012 and 2013, the first reaching 2000 m depth and the second being slightly less intense (Durrieu de Madron et al. 2013, Puig et al. 2015). In previous years, the exceptionally strong event of 2005 was followed by a milder event (still reaching the deep basin) in 2006. The strong event of 1999 (Bethoux et al. 2002) was also followed by a milder event in 2000 (Puig et al. 2013). Previous events were described in Bethoux et al. (2002) for 1971, 1980, 1988, who analysed the presence of the anomalous “Occasional Bottom Water” in the deep-basin from CTD data. According to our observations, these events were most likely to be followed (or preceded) by a second event. In the case of 1971 and 1980, the anomaly in the deep-waters was detected for two years after the DSWC event, respectively in 1972-1973 and 1981-1982, providing an indication that DSWC also occurred in 1972 and 1981. As for 1988, no clear data were available for that period. However, unpublished CTD data suggest that the strongest DSWC of this couple occurred in 1987. In this study, we modelled and tested the effect of DSWC in: 1971, 1972, 1980, 1981, 1987, 1988, 1999, 2000, 2005, 2006 2012 and 2013.

The SCAA model was conducted on annual time steps from 1963 to 2015 in an Excel spreadsheet. For the baseline model (i.e. without the environmental effects) and for all ages ≥ 2, the predicted number of red shrimp individuals at the start of the year $y + 1$, at age $a + 1$ and sex s ($N_{y+1, a+1, s}$) was derived using the equation:

$$N_{y+1,a+1,s} = N_{y,a,s} \times e^{(-M_s - (F_y \times s_{a,s}))} \quad (1)$$

where M_s is the sex-specific natural mortality, F_y is the yearly fishing mortality and $s_{a,s}$ is the age-specific and sex-specific selectivity.

The number of recruits (i.e. individuals in their first year of age) at the start of the year $y + 1$ (i.e. R_{y+1}) was calculated assuming a Beverton and Holt stock recruitment relationship, which was included in the model in its reparametrized form (Mace and Doonan 1988, Brooks and Powers 2007):

$$R_{y+1} = \frac{4hR_0S_y}{S_0(1-h)+S(5h-1)} + \varepsilon_y \quad (2)$$

Where h, R_0 and S_0 are the stock recruitment relationship parameters, respectively steepness, virgin recruitment and virgin spawning stock biomass to be estimated by the model. S_y is the yearly value of spawning stock biomass, calculated multiplying the number of females per age by the proportion of mature females per age (M_a) and their weight (W_a):

$$S_y = \sum_a (N_{y,f} \times M_a \times W_a) \quad (3)$$

Random deviations from the stock recruitment relationship (ε_y) were estimated only starting from 1984, when catch at length information was available.

Estimated numbers at age were converted into numbers at length using the age-length key. Predicted yearly catch at length per sex ($\hat{C}_{y,a,s}$) were calculated as:

$$\hat{C}_{s,l,y} = \frac{F_y \times s_l}{M_s + (F_y \times s_l)} \times \left(1 - e^{-(M_s + (F_y \times s_l))}\right) \times N_{s,l,y} \tag{4}$$

Catch per market size class ($\widehat{M}_{c,y}$) were worked out using $\hat{C}_{s,l,y}$ and the size frequencies within each market size class obtained in the 2012-2013 sampling.

Predicted total yield, including both males and females, was calculated as:

$$\hat{Y}_y = \sum_l \sum_s \hat{C}_{s,l,y} \times w_{s,l} \tag{5}$$

where $w_{s,l}$ is the sex specific weight at length.

Model predictions of CPUE were calculated as:

$$\widehat{U}_y = q \times \sum_l \sum_s \left(N_{s,l,y} \times w_{s,l}\right) \tag{6}$$

Sex-specific partial recruitment for recruits (PR_1) was included in the model in order to take into account the partial availability ($A_{1,s}$) of this age class to the fishery due to the ontogenetic migrations. For this age class, the selectivity term ($s_{a,s}$) in equations 1 and 4 was substituted by the sex-specific partial recruitment (PR_1):

$$PR_{1,s} = S_{1,s} \times A_{1,s} \tag{7}$$

In particular, in equation 4, the proportion of age 1 individuals in each length class was identified using the age-length key.

After building the baseline model, we started including the effects of DSWC, adding different parameters according to the different ecological hypotheses. The model including the effect of DSWC on natural mortality was built from the baseline model adding an additional natural mortality component, M_c, in years of DSWC. Therefore, sex-specific total natural mortality in years of DSWC (tM_s) was defined as:

$$tM_s = M_s + M_c \tag{8}$$

where M_s is the known sex-specific natural mortality, and M_c the additional parameter to be estimated by the model.

The effect of DSWC on the shrimps' availability was modelled adding the parameter A_c (availability determined by DSWC) to equations 1 and 4 of the baseline model, in DSWC years. In these years, the term for selectivity was substituted by age and sex-specific partial recruitment (PR_a), as:

$$PR_{a,s} = S_{a,s} \times A_c \tag{9}$$

Therefore, for age 1 individuals, partial recruitment in years of DSWC would become:

$$PR_{1,s} = S_{1,s} \times A_{1,s} \times A_c \tag{10}$$

Finally, we included the effect of DSWC on recruitment. To do so, we added the parameter R_c as a multiplicative factor for recruitment (as estimated by the stock recruitment relationship) in the year immediately after a DSWC event. Thus, equation 2 was modified as:

$$R_{y+1} = \frac{4hR_0S_y}{S_0(1-h)+S(5h-1)} \times R_c + \varepsilon_y \tag{11}$$

Model fitting and parameters estimation was carried out using the least squares method, minimizing the sum of the squared residuals (SSQ). The SSQ was obtained summing the square of the log residuals for catch at length, catch at market size, total Yield and CPUE (Doubleday 1976, Haddon 2011):

$$SSQ = \sum_s \sum_l \sum_y \left[\left(Ln\frac{C_{s,l,y}}{\hat{C}_{s,l,y}}\right)\right]^2 + \left\{\sum_c \sum_y \left[\left(Ln\frac{M_{c,y}}{\hat{M}_{c,y}}\right)\right]^2\right\} \times 10 + \left\{\sum_y \left[\left(Ln\frac{Y_y}{\hat{Y}_y}\right)\right]^2\right\} \times 100 + \sum_y \left[\left(Ln\frac{U_y}{\hat{U}_y}\right)\right]^2 \tag{12}$$

A different weighing was applied to the different contributions to the SSQ, reflecting the degree of uncertainty associated to the data.

The best model within our set of models was selected using the Aikake's information criterion (AIC), which takes into account both the goodness of fit and the complexity of the model, i.e. the number of parameters estimated (Aikake 1974). In particular, a small-sample version of AIC, AIC_c, was worked out per each model, as described in Burnham and Anderson (2004):

$$AIC_c = n\times \ln\left(\frac{SSQ}{n}\right) + \frac{2k(k+1)}{n-k-1} \tag{13}$$

where n is the number of observations (sample size) and k is the number of parameters estimated by the model. AIC_c are recommended when $n/k < 40$.

To interpret the AIC_c values, Δ_i were calculated following the methodology described by Burnham and Anderson (2004):

$$\Delta_i = AIC_i - AIC_{min} \tag{14}$$

where AIC_{min} is the minimum of the i AIC values within the candidate set of models. This transformation forces the best model to have $\Delta=0$ and the rest to have positive values. Then, some simple rules of thumb can be used to compare the relative "merits" of the models in the set: models having $\Delta_i \leq 2$ have substantial support (evidence) from the data, those in which $4 \leq \Delta_i \leq 7$ have considerably less support, and models having $\Delta_i > 10$ have essentially no support (Burnham and Anderson 2004).

Finally, we used our best model to estimate the equilibrium MSY and F_{MSY} (projecting the population forward and maximising the yield at the equilibrium by adjusting the F value) in the different environmental conditions.

Results

All the models provided a very good fit to the total yield data and a satisfactory estimation of parameters (Fig. 1, Tab. 1). The fit to the CPUE and catch at market size was not as tight as for the yield for neither model (Fig. 2, 3), as well as the fit to the catch at length data (Fig. 4).

The AIC_c showed that the model including the effect of DSWC on natural mortality was the one receiving the highest support from the data (Tab. 2). In fact, adding the effect of DSWC on natural mortality improved the model fit to the data compared to the baseline model, reducing significantly the SSQ (Tab. 2). In particular, the fit to the total yield and catch at length data was improved significantly (Tab. 2, Fig. 1a, 1c and 4), even though major patterns in residuals for catch at length remained very similar in the two models (Fig. 4). The Δ_i indicated that the model including the effect of DSWC both on natural mortality and recruitment was still supported by the data ($\Delta_i < 2$), but the extra parameter did not bring any significant improvement to the model fit. On the other hand, the model including the effect of cascading on availability did not receive any support from the data, compared to the others.

Table 1. Parameters estimated by the different models. In particular: partial recruitment for age 1 females and males ($P_{1,f}$ and $P_{1,m}$), stock recruit relationship parameters (R_0, S_0, h), catchability (q), and parameters representing the effect of the DSWC on natural mortality (M_c), availability (A_c) and recruitment (R_c). "Baseline" = stock assessment model without any environmental effect; "Cascading A_c" = model including the effect of cascading on availability; "Cascading M_c" = model including the effect of cascading on natural mortality; "Cascading M_c +R_c" = model including the effect of cascading on both natural mortality and recruitment.

	Baseline	Cascading A_c	Cascading M_c	Cascading M_c +R_c
$P_{1,f}$	0.11	0.13	0.09	0.09
$P_{1,m}$	0.84	0.90	0.77	0.76
R_0	74506439	80645940	91343271	94035701
S_0	102.125	102.580	102.132	102.163
h	0.9900	0.9900	0.9893	0.9897
q	0.000003	0.0000027	0.0000027	0.0000028
M_c			0.82	0.77
A_c		0.67		
R_c				0.81

The different models produced quite different reconstructions of the stock, except for the one including the effect of DSWC on natural mortality and recruitment, which provided very similar estimates as the model including the effect on natural mortality alone (Fig. 5, 6 and 7).

Table 2. Log residuals for catch at length, total yield, CPUE and catch per commercial size, total sum of square residuals (SSQ), AIC and Δ_i for the different models. In particular: "Baseline" = stock assessment model without any environmental effect; "Cascading A_c" = model including the effect of cascading on availability; "Cascading M_c" = model including the effect of cascading on natural mortality; "Cascading M_c +R_c" = model including the effect of cascading on both natural mortality and recruitment.

	Baseline	Cascading A_c	Cascading M_c	Cascading M_c+R_c
Catch at length	647.78	665.03	557.42	557.47
Total Yield	19.20	11.72	3.26	2.82
CPUE	16.32	15.94	22.71	23.03
Catch per commercial size	5.64	10.65	11.11	10.53
Total SSQ	688.94	703.34	594.50	593.84
AIC_c	36.63	56.54	-84.84	-83.24
Δ_i	121.47	141.39	0.00	1.60

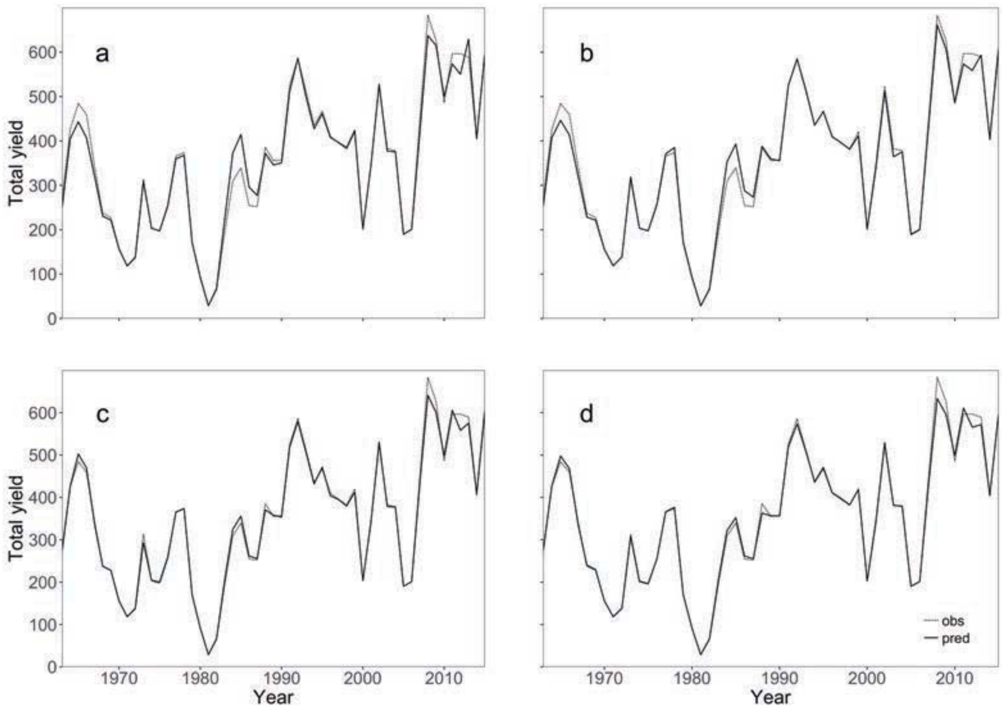

Figure 1. Model predictions of total yield (black line) obtained with the four models. Grey lines indicate the observed values. In particular: a) baseline model (no environmental effect); b) model including the environmental effect on availability (A_c); c) model including the environmental effect on natural mortality (M_c); d) model including the environmental effect on both natural mortality and recruitment (M_c and R_c).

The SSB estimated by the baseline model (Fig. 5a) showed an overall decreasing trend, with high interannual variability. F displayed an overall increasing trend starting from the beginning of the 80s (Fig. 6a). Minimums in the F series corresponded to years of DSWC and were always followed by a steep increase. Recruitment deviations, estimated starting from 1984, determined an extremely variable recruitment (Fig. 7a).

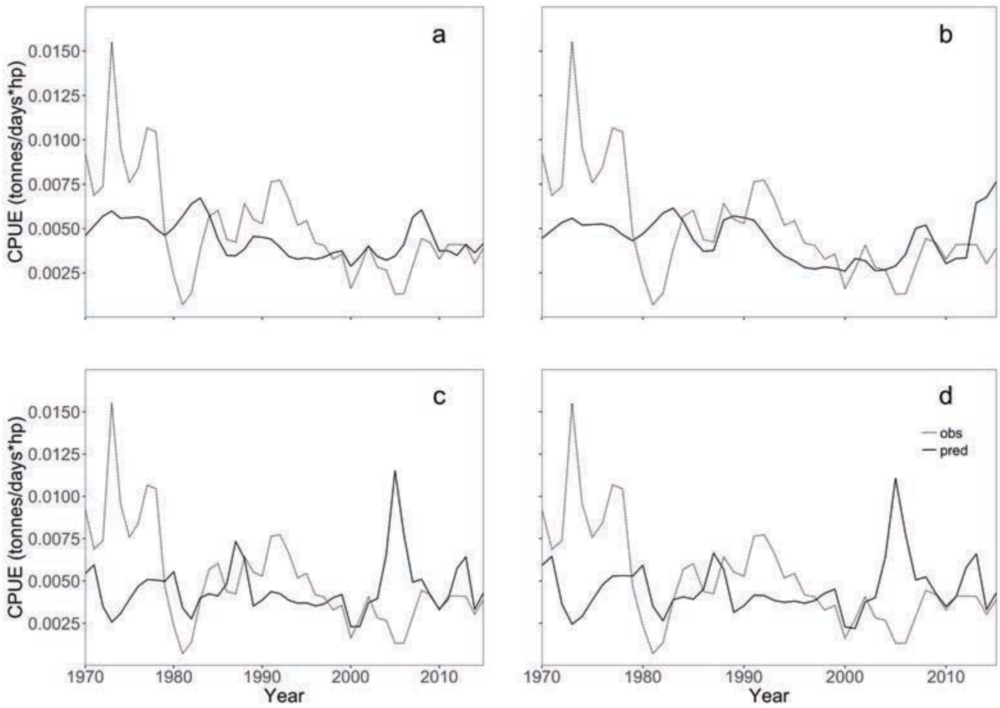

Figure 2. Model predictions of CPUE (black line) obtained with the four models. Grey lines indicate the observed values. In particular: a) baseline model (no environmental effect); b) model including the environmental effect on availability (A_c); c) model including the environmental effect on natural mortality (M_c); d) model including the environmental effect on both natural mortality and recruitment (M_c and R_c).

The model including the effect of DSWC on availability estimated a reduction of more than 30% in the shrimps available to the fishery in DSWC years (A_c = 0,67) (Tab. 1). The series of SSB estimated by this model displayed a similar trend compared to the baseline model, but with overall higher values (Fig. 5b). F displayed a similar trend as for the baseline model (Fig. 6b), while recruitment displayed a considerably higher variability (Fig. 7b).

As indicated by the AIC values, the most likely reconstruction of the population was provided by the model including the effect of DSWC on natural mortality, i.e. our best model. M_c was estimated at 0.82, indicating a dramatic increase of natural mortality for shrimps in years of DSWC (Tab. 1). The SSB still displayed an overall decreasing, fluctuating trend, but this time interannual variability was strictly related to DSWC, with minimums coinciding with years after DSWC events (Fig. 5c). The series of F displayed a similar trend as for the baseline model, with overall lower values (Fig. 6c). Recruitment deviations were very high (Fig. 7c). Adding the effect of DSWC on recruitment to this model did not significantly change the estimates (Fig. 5d, 6d), except slightly for the recruitment, where additional variability was included (Fig. 7d).

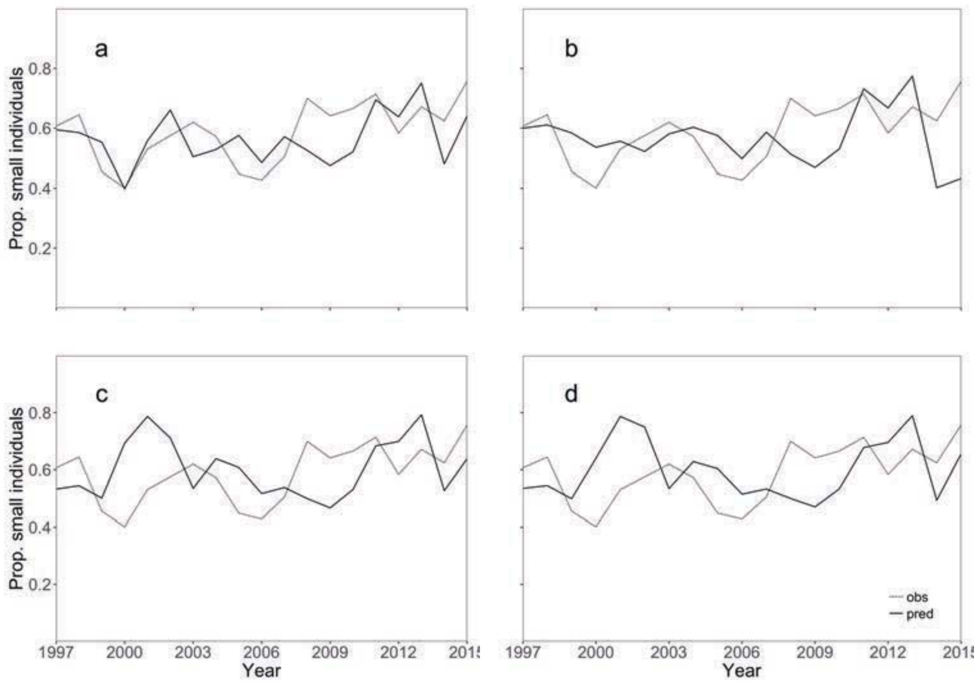

Figure 3. Model predictions of proportion of small individuals in the catches (20-30 mm cephalotorax length) obtained with the four models. Grey lines indicate the observed values. In particular: a) baseline model (no environmental effect); b) model including the environmental effect on availability (A_c); c) model including the environmental effect on natural mortality (M_c); d) model including the environmental effect on both natural mortality and recruitment (M_c and R_c).

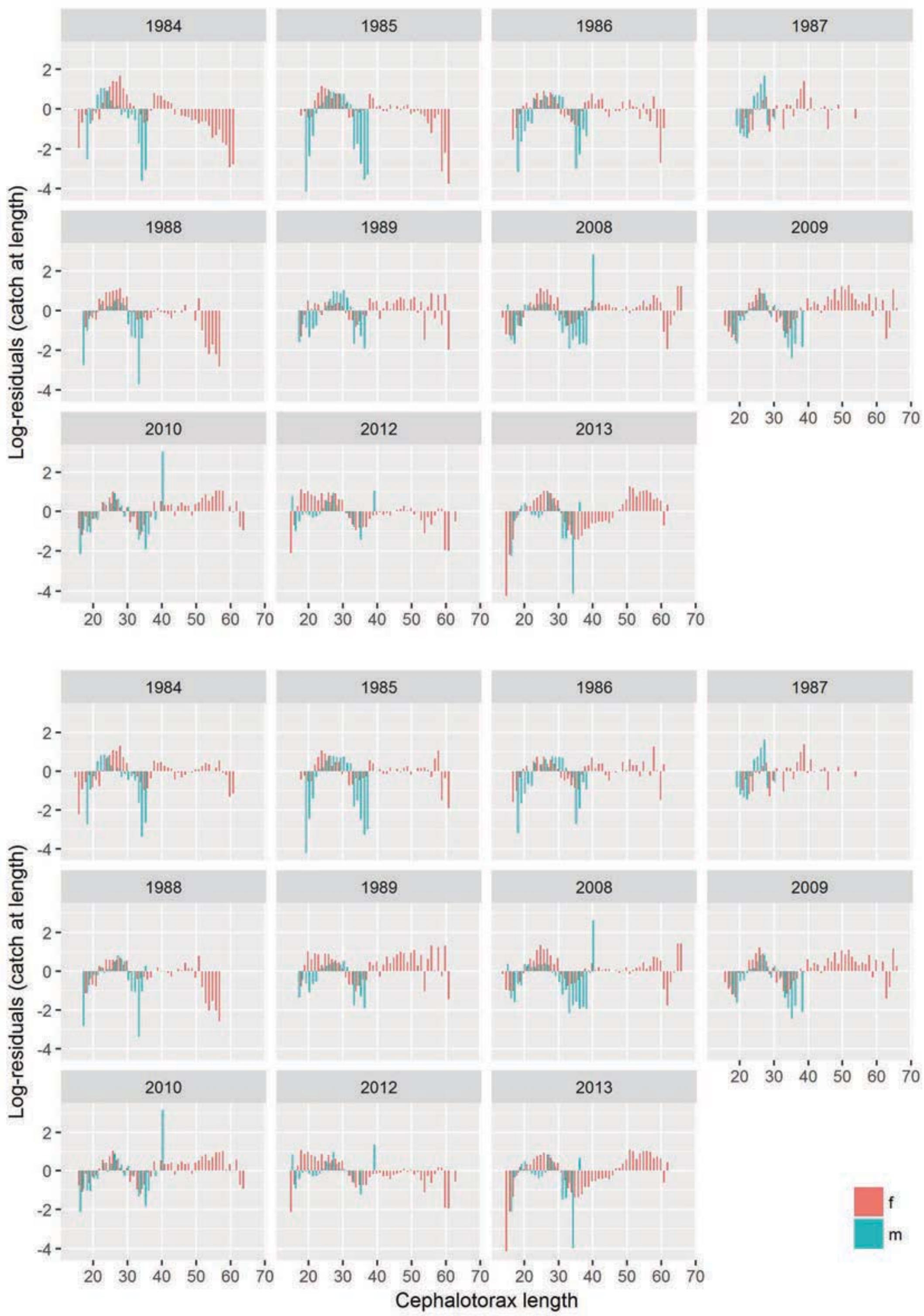

Figure 4. Log residuals (ln(observed/predicted)) of catch at length data for males (blue) and females (pink) for a) the baseline model (no environmental effect) and b) the model including the environmental effect on natural mortality.

Table 1 shows a summary of the estimated parameters. The sex-specific partial recruitment for individuals of one year of age was estimated in a similar way by all models, suggesting a different behaviour for male and female recruits. The steepness of the stock recruitment relationship was very high for all models, indicating that no clear relationship between stock size and recruitment was detected. Large deviations from the stock recruitment relationship were estimated by all models. The maximum sustainable yield (MSY) and the corresponding fishing mortality (F_{MSY}) were estimated at 301.2 tonnes 0.64. Considering that, in 2015, yield was 597 t and fishing mortality 1.31 (average values for the last five years of the series were 557 t and 1.35 respectively), the stock is considered in overexploitation. The equilibrium MSY for years of intense DSWC (calculated taking into account the increase in natural mortality) and the relative fishing mortality was estimated at only 14.2 t and 0.36, indicating that only little harvest may be sustainable in years of adverse environmental conditions.

Discussion

The Statistical Catch at Age is a complex stock assessment method which provides a very flexible framework that can be useful even in data-limited situations (Geromont and Butterworth 2015). Differently to other common modelling approaches (such as Virtual Population Analysis) SCAA allows to use all the available information, including fragmented series of catch at length data and series of catch at market size, covering a temporal range of over 50 years. This allowed us to test the effect of DSWC over a long time frame, which included twelve DSWC events.

In this study, we found that introducing the effect of DSWC on the red shrimp population significantly improved the stock assessment model for this species. In particular, the hypothesis of DSWC affecting the red shrimp population by increasing the shrimps' natural mortality received significantly more support than the hypothesis of DSWC affecting the shrimps' availability to the fishery. The sudden increase in natural mortality explains the disappearance of the shrimps from the fishing grounds observed during DSWC events (Company et al. 2008), and the relative minimums in the yearly landings. There is a large body of literature investigating the correlation between environmental variables and recruitment of marine resources to explain fluctuations of marine populations (Botsford et al. 1997, Rothschild 2000, Santos et al. 2001, Rouyer et al. 2014). In this work, we demonstrate that even the adult population can be strongly affected by the environmental factors.

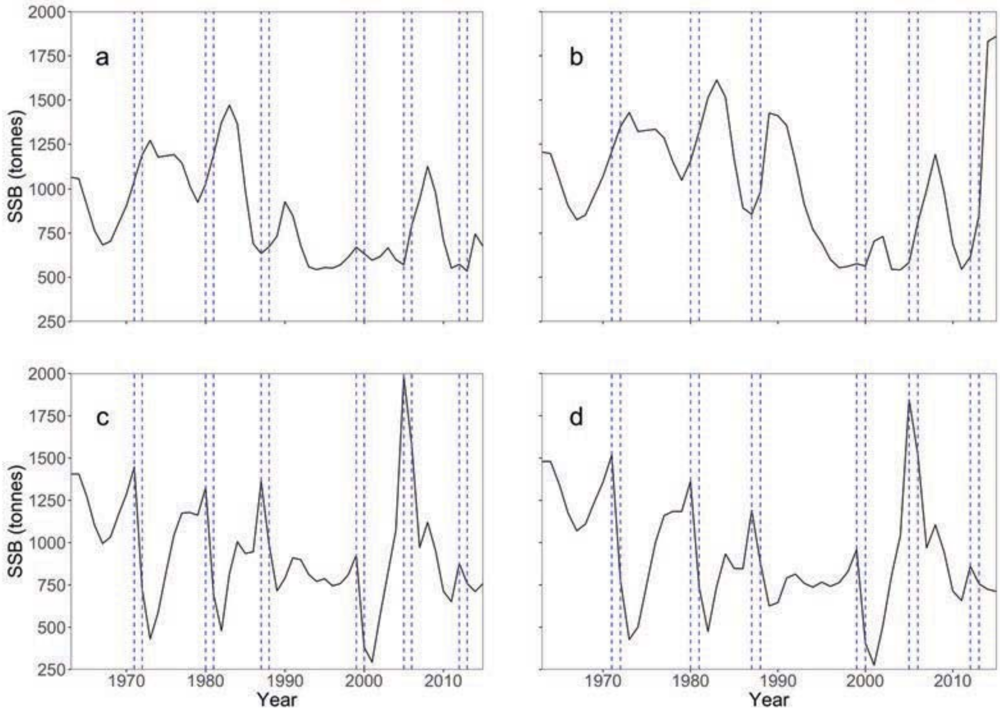

Figure 5. Estimates of spawning stock biomass (SSB) by the four models. In particular: a) baseline model (no environmental effect); b) model including the environmental effect on availability (A_c); c) model including the environmental effect on natural mortality (M_c); d) model including the environmental effect on both natural mortality and recruitment (M_c and R_c). Dashed vertical lines indicate years in which intense DSWC occurred.

The effect of DSWC was not observed on any other commercial species in the area. This is most likely because the other main demersal target species (e.g. *Merluccius merluccius*, *Nephrops norvegicus*, *Mullus barbatus*) are fished at shallower depths, and are not affected by the DSWC currents flowing in the submarine canyons. However, a temporally limited effect of DSWC was observed on the meiofaunal community of species in a submarine canyon of the Catalan continental margin. Samples of sediment collected during the 2005 DSWC showed significantly lower abundance and diversity of meiofauna, compared to samples that were collected only six months after the cascade stopped (Pusceddu et al. 2013).

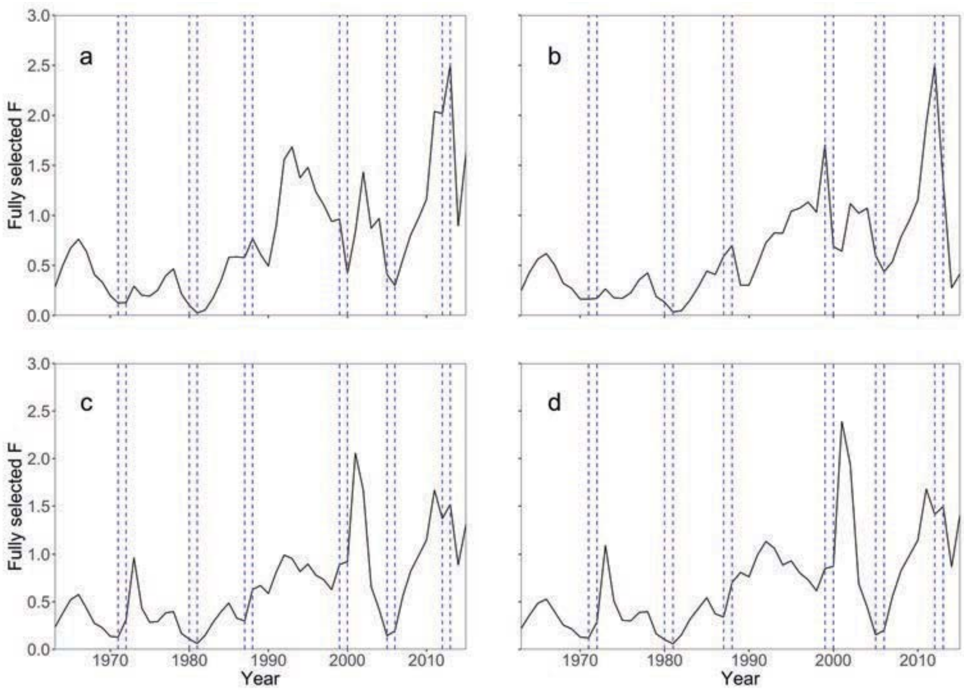

Figure 6. Estimates of fully selected yearly fishing mortality (F) by the four models. In particular: a) baseline model (no environmental effect); b) model including the environmental effect on availability (A_c); c) model including the environmental effect on natural mortality (M_c); d) model including the environmental effect on both natural mortality and recruitment (M_c and R_c). Dashed vertical lines indicate years in which intense DSWC occurred.

High fishing rates are known to exacerbate the effects of environmental factors, with fished stocks fluctuating more, in general, than the unharvested ones (Beddington and May 1977, May et al. 1978, Hsieh et al. 2006). The results of this study show that the deep-sea red shrimp in Catalonia has been in overexploitation since the beginning of the 1990s, with fishing mortality and yield exceeding F_{MSY} and MSY at almost all years. Excessive fishing reduces the survival of mature individuals, leading to age-truncation of the exploited population. Once mainly composed by recruits, the populations cannot buffer the environmental conditions through bet-hedging strategies that are closely related to long-tailed age structures (Hsieh et al. 2006, Anderson et al. 2008, Rouyer et al. 2012). This effect was demonstrated in cod and herring populations, which were found to track environmental variability more closely once their age-structure was truncated (Ottersen et al. 2006, Rouyer et al. 2011). Thus, reducing fishing pressure on the red shrimp population might mitigate the effect of DSWC and the consequent loss of income for the fishers, while improving the overall fishery sustainability.

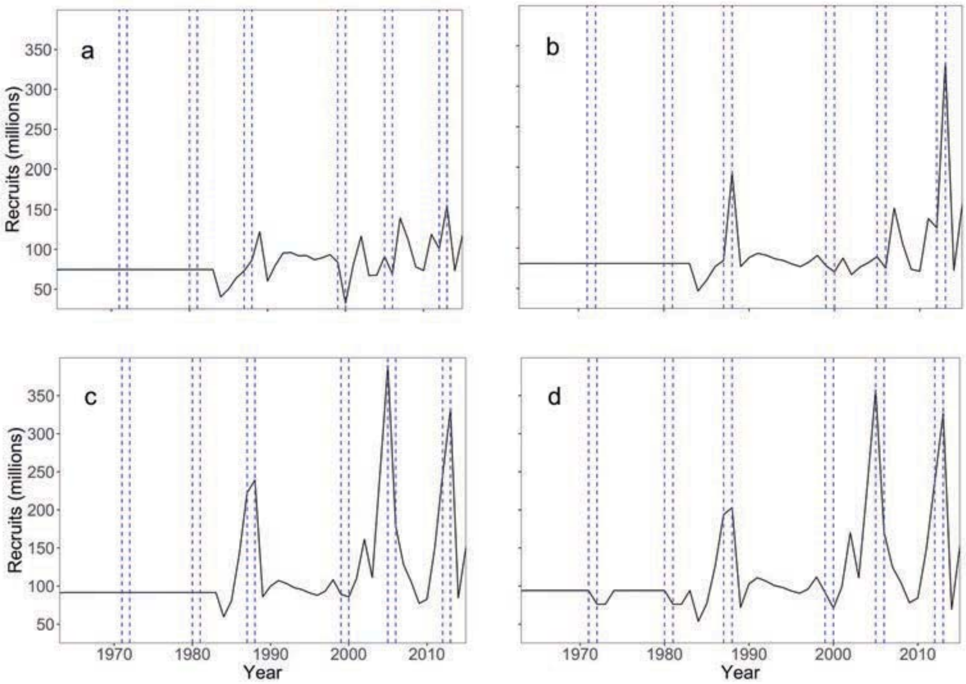

Figure 7. Estimates of recruitment by the four models. In particular: a) baseline model (no environmental effect); b) model including the environmental effect on availability (A_c); c) model including the environmental effect on natural mortality (M_c); d) model including the environmental effect on both natural mortality and recruitment (M_c and R_c). Dashed vertical lines indicate years in which intense DSWC occurred.

Specific measures to maintain a sustainable red shrimp exploitation in years of adverse environmental conditions should also be incorporated in the management strategy. DSWC cannot be predicted, however, since a strong DSWC event can be immediately detected and occurs in the first months of the year, the fishery management in those particular years could be adjusted to take into account the peculiar environmental conditions. In particular, our results show that, due to the increase of natural mortality, predicted equilibrium MSY was considerably reduced in years of DSWC, indicating that only little harvest may be sustainable in years of adverse environmental conditions. Under these conditions, fishing effort should be further reduced to allow the population to rebuild itself, while avoiding an excessive catch of small individuals and growth overfishing. A similar approach was proposed by Jacobson and MacCall (1995) for the pacific Sardine, whose productivity and ability to sustain intense fishing was found to be significantly affected by environmental conditions. The authors found that MSY for this stock was significantly lowered by environmental conditions that prevail when average sea surface temperatures are colder, and suggested that annual cuotas and target exploitation rates should be established taking into account the specific environmental conditions year by year.

In this work, no clear relationship between stock size and recruitment was highlighted for the red shrimp, and large interannual variations in recruitment rates were estimated. This situation is common for shrimp species, where a relatively small population of spawners is sufficient to maintain stock levels, thanks to high fecundity. In these cases, the primary causes of stock fluctuations are usually the environmental effects (Garcia 1983). However, the indirect effect of DSWC on the red shrimp recruitment was not captured by our model. Company et al. (2008) showed that the recovery of the red shrimp landings after a DSWC event was sustained mainly by individuals < 30 mm cephalotorax lenght. However, in our model, the fit to the series of catch at market size was quite poor (Fig. 3) showing that, in fact, the trend in the catch of small individuals after a DSWC was not well captured. The hypothesis that specific climate and oceanographic processes might enhance the recruitment of the red shrimp by increasing the food availability in the deep-basin was previously explored by other authors (Puig et al. 2001, Maynou 2008, Sardà et al. 2009). The fast recovery of red shrimp after a DSWC event could be also explained (aside from the high fecundity and the potential positive effect of DSWC on recruitment) by the fact that a large portion of the population dwells in areas beyond the limits of the fishing grounds. This “reservoir” of individuals might contribute to the renewal of the exploited population through an exchange mechanism (Sardà et al. 2004, D’Onghia et al. 2009).

This study shows that DSWC has a significant effect on the red shrimp population dynamics and provides a quantification of such effect for the first time. We demonstrate the utility of integrated stock assessment models for advancing stock assessment in data-limited situations, and for testing alternate ecological hypotheses. However, given the scarcity of detailed catch at length data available for the stock assessment, uncertainties in the modelling results remain high. Nevertheless, the work presented here includes the best information available at the time of writing, and gives an indication on the stock status and the most likely mechanism of interaction between the red shrimp population and the DSWC.

Further work is needed to identify the factors influencing the red shrimp recruitment and introduce their effects in the stock assessment model for this species. Different oceanographic processes occurring in the northwestern Mediterranean Sea, such as the deep-sea convection, might be involved. Further studies on the larval stages will be useful to formulate informed hypotheses on the mechanisms of interaction between the environment and the early life stages of the red shrimp.

2.3 Fishery discards

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Spatio-temporal variability of discards in the fishery of the deep-sea red shrimp *Aristeus antennatus* in the northwestern Mediterranean Sea: implications for management

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Abstract

In this work we analyzed the spatio-temporal variability of discards in the fishery of the deep-sea red shrimp *Aristeus antennatus* in the Northwest Mediterranean Sea. We sampled fishery discards in the fishing grounds of Palamós (the main harbor for this fishery in the Catalan margin) which are located in different areas of a submarine canyon. We found that the discard ratio in this fishery presented a marked seasonal variability, with a maximum in spring and a minimum in summer. Most of the discarded biomass (almost 96%) was constituted of species with no commercial interest. Within these, the most represented group was elasmobranchs, making up to more than 50% of total discarded biomass. Our findings show that the landing obligation established by the EU will have a low impact in mitigating discards in this fishery, as the vast majority of discards are constituted of non-commercial species that are not specified in the regulation. Alternative management strategies, such as a temporal fishery closure in spring (when

the discard ratio is at its highest) should be considered in order to preserve the vulnerable ecosystem hosted by the submarine canyon.

See original publication in Annex II

Introduction

Fisheries have an impact on the ecosystems at various levels, as fishing operations do not only affect the targeted fish stocks but also a number of species that are caught accidently in the fishing gears. These species are thrown back to the sea, dead or alive, and constitute the fishery discards (Catchpole et al. 2005, Kelleher 2005, Bellido et al. 2011). Discarded species may have no commercial interest or may be valuable species that are unmarketable for different reasons (undersized or damaged individuals, exceeded quotas, etc.). The effect implied by the fishing activities on the environment is major, ranging from ecosystem depletion to habitat destruction and discards account for a great part of the overall impact (Ramsay et al. 1998, Jennings and Kaiser 1998, Sánchez et al. 2000). In fact, up to 60% of the total catch is discarded in some of the most important European trawl fisheries (STECF 2006). In the latest years, after the establishment of the Ecosystem Approach to Fisheries Management (EAFM) as an integrated approach which considers the effects of fisheries on the whole ecosystem (FAO fisheries glossary, http://www.fao.org/fi/glossary/default.asp), the estimation of discards as well as the development of ad hoc management strategies has been regarded as a priority (Catchpole and Gray 2010, Bellido et al. 2011, Hilborn 2011). In Europe, discards are currently a hot topic for fisheries management (Catchpole et al. 2005, Johnsen and Eliasen 2011, Sardà et al. 2013, Condie et al. 2014). They form an important part of the reformed Common Fisheries Policy (CFP), which has established a landing obligation to come into force gradually in the next four years (Regulation (EU) No 1380/2013, 2013). The aim of the landing obligation is to reduce wastage in fishing operations, while incentivizing discards avoidance. In this context, it is important to consider that discards are highly variable both in space and time (Ye et al. 2000, Uhlmann et al. 2013, Pennino et al. 2013). Thus, extensive research on discards in the single fisheries with the identification of factors shaping their spatio-temporal patterns is certainly required in order to improve discards avoidance and selectivity.

In the Mediterranean Sea, trawl fishery is the most important fishery both in terms of volume and economic value of catches (Bas et al. 1984, Abelló et al. 2002). This fishery is generally characterized by high discard ratios and it’s responsible for the bulk of discards (Stergiou et al. 1998, Castriota et al. 2001, Carbonell et al. 2003, Sánchez et al. 2004, Tsagarakis et al. 2008). A recent review by Tsagarakis et al. (2013) identified a wide range of discard ratios within Mediterranean trawling fisheries, ranging from 10% to 90%. Factors acknowledged for affecting discards are various and comprise depth, geographic area, seabed characteristics, season, fishing methods, gear characteristics and cultural factors (Machias et al. 2001, Sartor et al. 2003, Sánchez et al. 2007, Edelist et al. 2011, Pennino et al. 2013). The high diversification of fishing practices and the wide range of environmental characteristics in the Mediterranean Sea place severe difficulties in the way of effective management measures to mitigate discards. This condition is compounded by the extent of several gaps of knowledge (Lleonart and Maynou 2003, Kelleher 2005, Tsagarakis et al. 2013). Thus, a greater effort to quantify discards and identify factors affecting and shaping their patterns is required.

In the Northwest Mediterranean Sea, the most economically important deep-sea trawl fishery is the one targeting the red shrimp *Aristeus antennatus* (Risso, 1816). In the Catalan area (Northeast Spain) this fishery operates in fishing grounds allocated along the margins of a series of submarine canyons carved in the continental margin. Submarine canyons create considerable depths close to the coast while increasing habitat complexity. They also act as major conduits for the transportation and concentration of organic particles (Heussner et al. 1996, Canals et al. 2006, Puig et al. 2013). These characteristics may act in favoring the abundance, biomass and diversity of benthic and pelagic species in the canyons compared to the open slope (Vetter and Dayton 1999). It has also been observed that the higher habitat heterogeneity and the increased food availability in the canyons provide suitable conditions for recruitment of several species of fish and crustaceans (Sardà et al. 1994a, Stefanescu et al. 1994). The importance of submarine canyons in shaping the benthic community of species in the Northwest Mediterranean Sea was assessed in several studies (Sardà et al. 1994b, Ramirez-Llodra et al. 2008). In particular, the relationship between the canyons' topography and the red shrimp seasonal migrations was described in detail (Sardà et al. 2003a, Tudela et al. 2003, Sardà et al. 2004, Sardà et al. 2009), and is well known to the fishers who direct the fishing effort accordingly (Sardà et al. 1997). The vulnerability of these environments to fishing activities has also been pointed out (Ramirez-Llodra et al. 2010). In fact, as deep-sea ecosystems, they are characterized by long lived species with slow growth, late age of maturity and low fecundity, which make them particularly sensitive to the impact of human activities (Koslow et al. 2000). However, no research on the role of the submarine canyons in shaping patterns of fishery discards has been performed so far.

The aim of this work was to broaden our knowledge of fishery discards in a vulnerable environment such as the deep-sea, which is important for fishery management both at European and local level. In particular, we investigate the spatio-temporal discard patterns associated to a submarine canyon in the fishery of the red shrimp in the Northwest Mediterranean Sea. The canyon considered is the Palamós canyon (Fig. 1). The canyon head, wall and open margin of this canyon represent the most heavily trawled fishing grounds for this species in the area, with the Palamós trawling fleet landing about 30% of red shrimp in Catalonia on yearly average (data source: Official fishery statistics from Autonomous Government of Catalonia). Since 2013 the red shrimp fishery in Palamós has been regulated by a local management plan, developed within a co-management framework between fishermen, scientists, local administration and NGOs (BOE 2013). Management measures aim at increasing the fishery sustainability, with particular attention at reducing fishing pressure on small sized individuals of the target species. These measures include, among others, a temporal fishery closure in the canyon head in winter (where shoals of shrimp recruits concentrate) and in increase in gear selectivity. A further improvement in the management plan would be to include ad hoc spatio-temporal management measures to mitigate discards. For this purpose, the specific questions addressed in this work were: (i) does the Palamós submarine canyon and/or the season of the year have an effect on the discard ratio in the fishery studied? (ii) Is there a seasonal or a spatial variability in discards composition? In order to answer these questions we analyzed the composition of catches during a two year sampling onboard a commercial trawler targeting red shrimp in the Palamós canyon.

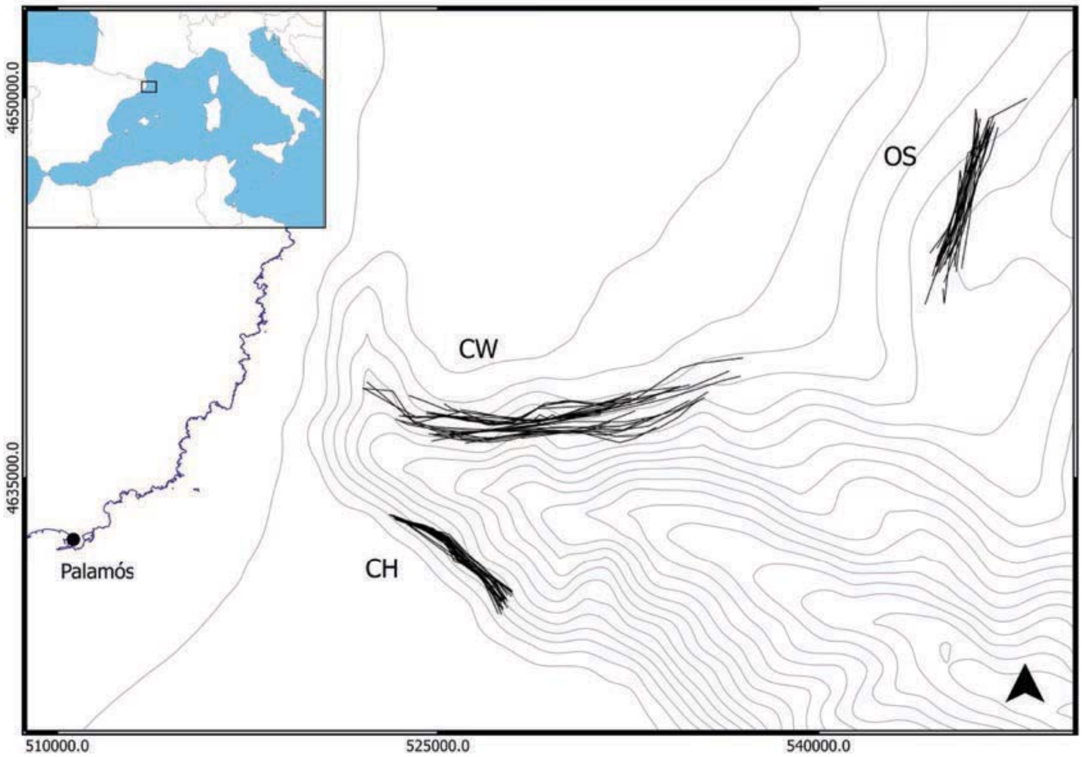

Figure 1. Map representing the Palamós canyon and the three main fishing grounds sampled in this study (CH = canyon head; CW = canyon wall; OS = open slope). Tracks of the sampling tows are shown in the map. Coastline is in blue and bathymetry is displayed every 100 m.

Materials and Methods

Data were collected on a monthly basis from January 2012 to December 2013, during commercial fishing trips onboard a red shrimp trawler of the Palamós' fleet. During each trip we sampled three areas of the Palamós canyon, corresponding to the main fishing grounds for this fishery in Catalonia. These areas were: the canyon head (average depth 426 m; total number of tows: 28), the canyon wall (average depth 504 m; total number of tows: 28) and the open slope, i.e. the area just outside the canyon (average depth 602 m; total number of tows: 26) (Fig. 1). The average tow trawled 0.2 km2 in the canyon head, 0.3 km2 in the canyon wall and 0.2 km2 in the open slope. The start and end position of each tow, as well as the horizontal opening of the net's mouth, were identified by SCANMAR sensors mounted on the trawl's mouth. These data allowed calculation of the area sampled. After each tow fishermen sorted species into three main categories: target (*A. antennatus*), by-catch (non-target species of commercial interest) and discards (species with no commercial interest and/or undersized or damaged individuals of commercial species). We recorded the total weight of the commercial yield onboard, while discarded species were preserved in field coolers for further analysis. Once in the lab, the samples were sorted to species level or to the smallest possible taxonomical level. The biomass and abundance of discards were calculated per taxonomical group and standardized per square kilometer trawled.

Differences in the total weight of discards between fishing grounds and seasons were tested by two-way crossed ANOVA on log transformed data and post-hoc pairwise Tukey test. Before ANOVA was applied (here and in the following analysis) data were tested for normality and homoscedasticity using respectively Shapiro-Wilk's and Bartlett's test. The discard ratio per each tow was calculated as:

$$Discard\ ratio\ = \frac{Discards\ weight}{Discards\ weigth + Commercial\ Catch\ Weigth}$$

Two-way crossed ANOVA and post hoc Tukey test were performed on log transformed data in order to test the effect of fishing ground and season on the discard ratios. Species recovered in the discards were grouped into classes and differences in abundance and biomass for individual classes were tested by two-way crossed ANOVA. The abundance of the discarded species in each tow was used to calculate two diversity indices: total number of species (S) and N90 diversity index. The N90 diversity index was proposed by Farriols et al. (2015). It uses the results of the SIMPER analysis (Clarke and Warwick 2001) and a jackknife resampling to work out the average and dispersion of the number of species contributing to the ninety percent of similarity within each group of samples analyzed. Therefore the N90 takes into account both number of species and community structure for its calculation. It was also shown to be able to detect loss of diversity due to fishing impact where other diversity indices failed (Farriols et al. 2015). The index units, number of species, are straightforward and easy to interpret. Differences in S and N90 between seasons and fishing grounds were tested respectively by two-way crossed ANOVA and Kruskal-Wallis test and post-hoc pairwise tests. Prior to calculation of N90, abundance data were square-root transformed in order to down weight the contribution of the most abundant species to the results (Clarke and Warwick 2001).

Multivariate analyses were performed using the PRIMER software (Clarke and Gorley 2006). Species abundance was used to calculate the Bray-Curtis similarity index between tows. Data were square-root transformed prior to analysis. The similarities within each fishing ground and season in the discards' composition of species were explored by a Multidimensional ordination plot (MDS). Differences between fishing grounds and seasons in the discards' composition of species were tested by ANOSIM, and SIMPER was employed to detect the species accounting for any significant difference.

Results

In this study, a total of 94 species were found in the discards during sampling. Table 1 shows a list of the most common species found, i.e. those accounting for nearly 99% of total abundance and 95% of total biomass. Regarding the remaining 5% of biomass, 62.3% belonged to one species of Elasmobranchia (kitefin shark *Dalatias licha*), 4.6% to one species of Holocephali (rabbit fish *Chimaera monstrosa*), 21.2% to various species of the class Cephalopoda, 10% to Actinopterygii, 0.8% to Gastropoda, 0.7% to Malacostraca and 0.4% to Echinoidea. There were no discards of the target species *A. antennatus*, as there is no minimum landing size (MLS) or catch quota associated with this resource, and any damaged individual was consumed by the fishing crew. Discards of commercial species were limited to a few undersized or damaged specimens of pink glass shrimp (*Pasiphaea multidentata)*, greater fork-beard (*Phycis blennoides)*, norway lobster (*Nephrops norvegicus)*, blue whiting (*Micromesistius poutassou)* and european hake (*Merluccius merluccius)*. These species contributed to less than 4.1% of total discards biomass. The commercial fraction of the fishery comprised the target species *A. antennatus* and a few by-catch species, mainly *Phycis blennoides*, anglerfish *Lophius piscatorius, Micromesistius poutassou, Pasiphaea multidentata* and *Merluccius merluccius*. The total weight of discards ranged between 1 and 109 kg per km^2 trawled, while the commercial yield ranged between 9 and 331 kg per km^2 (Fig. 2). The biomass of discards per km^2 showed a significant decrease in summer compared to the other seasons of the year (ANOVA, F=11.821, df=3, $P<0.001$). No significant differences were detected between fishing grounds (Fig. 3A). The discard ratios ranged between 0.02 and 0.79, with a significant decrease in summer (Kruskal-Wallis, K-S=18.878, df=3, p<0.0001), and no significant difference between fishing grounds (Fig. 3B). The most represented class in terms of biomass in the discards was Chondrichthyes (53% of the total), followed by Actinopterygii (30%), Cephalopoda (9.1%) and Malacostraca (6.5%) (Fig. 4). Classes Echinoidea, Gastropoda and Thaliacea accounted altogether for less than 1.5% of total discards biomass and were grouped into the class "other". Biomass and abundance of all classes except for Cephalopoda showed significant differences between seasons (Tab. 2). Abundance of Chondrichthyes also displayed a significant effect of fishing ground, with individuals being more abundant in the open slope. A total of five individuals of kitefin shark (*Dalatias licha*), a species classified as near threatened by the IUCN (2014), were found in the discards (two individuals in the open slope and three in the canyon head).

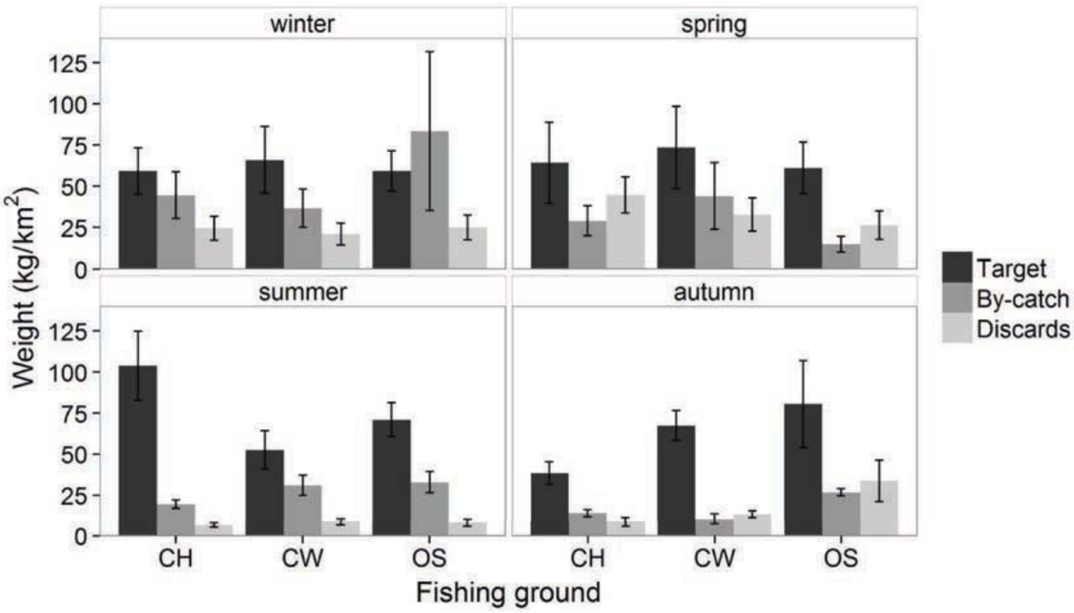

Figure 2. Average weight (kg/km2) and standard error of discards, target species and bycatch species in the catches shown per season and fishing ground (CH = canyon head; CW = canyon wall; OS = open slope).

The number of species in the discards ranged between 2 and 24 and was significantly higher in the canyon wall than in the other fishing grounds (ANOVA, F=7.658, df=2, p<0.01) (Fig. 5A). The N_{90} index ranged between 4 and 18 and differences between fishing grounds, in particular between the canyon wall and the others, were significant (Kruskal-Wallis, K-S=22.5718, df=2, $p<0.05$). As displayed in Figure 5B, the N_{90} was significantly higher in the canyon wall in winter and autumn. An interaction between the factors fishing ground and season seems to be present, although the Kruskal-Wallis test does not allow testing for it and, due to non-normality of data, a two-way ANOVA could not be employed. The MDS ordination plot, where the two-dimensional distance between tows reflects the Bray-Curtis similarity index, is shown in Figure 6. ANOSIM detected significant differences in the species composition of discards both between seasons and fishing grounds. In particular, the pairwise test highlighted significant differences between spring and all other seasons ($p<0.001$), and between the canyon head and the canyon wall and open slope ($p<0.05$ and $p<0.001$ respectively).

The most common species in the discards at all seasons and fishing grounds were the jewel lanternfish (*Lampanyctus crocodilus*), the blackmouth catshark (*Galeus melastomus*) and the small spotted catshark (*Scylorhinus canicula*). *S*pring discards were characterized by higher abundance of these species compared to the other seasons, and a relatively high abundance of the less common actinopterygians species *Trachyrincus scabru*s, *Lepidion lepidion*, *Nezumia aequalis* and *Lepidopus caudatus*. On the other hand, decapod crustacean *Pasiphaea multidentata*, actinopterygians *Notacanthus bonaparte, Mora moro* and *Gadiculus argenteus* were particularly abundant in autumn. According to the SIMPER analysis, the top 10 species contributing to the differences in the species composition of discards between the canyon head and the canyon wall were chondrichthyan *Scylorhinus canicula*, actinopterygian *Capros aper*, *Pasiphaea sivado*, more abundant in the canyon head, and *Lampanyctus crocodilus, Trachyrinchus scabrus*, *Galeus melastomus*, *Pasiphea multidentata*, decapod crustacean *Polycheles typhlops*, *Lepidion lepidion* and *Lepidopus caudatus*, more abundant in the canyon wall. These species accounted for 44% of the total differences. The top 10 species accounting for 47% of the differences between the canyon head and the open slope were *Scylorhinus canicula*, *Trachyrincus scabrus*, *Capros aper*, actinopterygian *Stomias boa boa*, more abundant in the canyon head, and *Lampanyctus crocodilus*, *Galeus melastomus*, *Pasiphaea multidentata*, *Mora moro*, *Nezumia aequalis*, *Lepidion lepidion*, more abundant in the open slope.

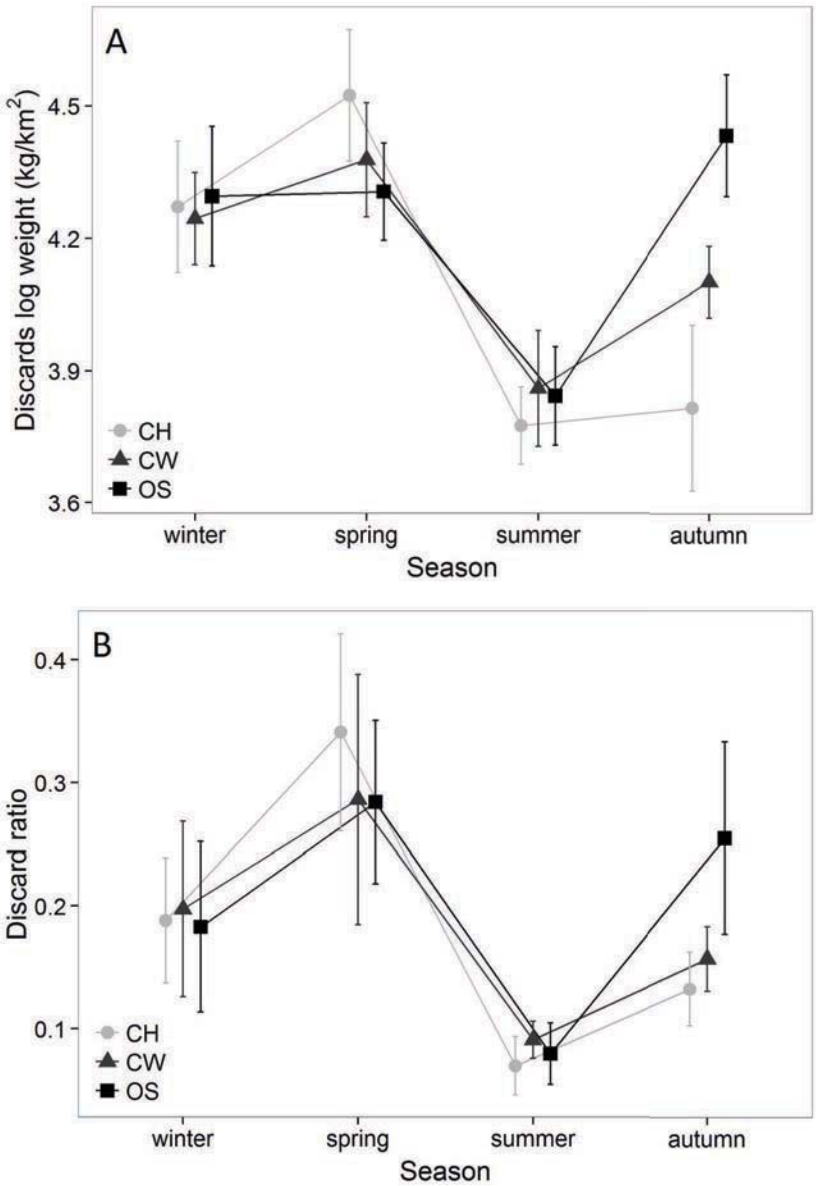

Figure 3. Average value and standard error of log transformed discards weight (A) and discard ratio (B) per season and fishing ground (CH = canyon head; CW = canyon wall; OS = open slope).

Table 1. List of the most common species in the discards (accounting for 99% of total abundance and 95% of total biomass) in the four seasons of the year (Win = winter; Spr = spring; Sum = summer; Aut = autumn) and the three different fishing grounds (CH = canyon head; CW = canyon wall; OS = open slope).

		Average abundance (Individuals/km^2)						
Class	Species	Win	Spr	Sum	Aut	CH	CW	OS
Chondrichthyes	*Galeus melastomus*	28.8	80.7	10.5	44.6	19.9	35.5	87.0
	Scyliorhinus canicula	14.2	22.9	9.4	23.0	29.0	16.4	8.5
	Etmopterus spinax	2.4	4.2	0.9	3.4	3.4	0.0	5.7
Actinopterygii	*Lampanyctus crocodilus*	30.3	142.9	47.7	42.2	41.4	88.6	100.1
	Trachyrincus scabrus	14.4	29.8	3.5	20.0	22.4	23.5	8.3
	Lepidion lepidion	16.0	25.1	5.2	2.8	8.5	13.6	18.1
	Capros aper	0.0	32.3	4.3	1.5	36.5	1.2	0.0
	Notacanthus bonaparte	5.6	2.8	1.3	30.1	0.9	10.6	17.7
	Nezumia aequalis	9.1	15.2	1.1	7.6	4.2	6.8	16.4
	Lepidopus caudatus	2.9	14.6	5.4	4.8	5.0	15.3	2.7
	Mora moro	5.9	5.7	3.8	14.7	0.9	4.5	17.9
	Gadiculus argenteus	0.8	0.9	0.0	23.8	1.8	9.6	7.1
	Conger conger	4.5	4.9	4.3	6.3	2.5	5.7	7.0
	Phycis blennoides	0.3	10.3	4.2	1.4	1.7	7.4	5.8
	Stomias boa boa	3.4	3.9	5.2	6.9	6.4	2.8	5.7
	Coelorhynchus sp.	3.1	8.9	0.8	1.3	9.0	1.7	1.6
	Symphurus sp.	0.8	0.0	0.2	14.8	0.0	8.0	2.9
	Lepidorhombus boscii	1.2	4.5	3.0	3.6	6.0	3.5	0.4
	Chauliodus sloani	0.5	1.5	8.1	2.2	0.8	1.9	6.9
	Helicolenus dactylopterus	3.6	1.3	1.9	1.3	4.4	0.4	0.8
	Hoplostethus mediterraneus	1.2	1.8	1.9	2.1	2.8	1.1	1.5
	Antonogadus megalokynodon	0.2	0.0	0.0	6.1	0.0	4.3	0.0
	Epigonus sp.	0.0	0.1	0.4	4.0	0.0	2.1	1.2
	Argyropelecus hemigymnus	0.0	0.0	0.0	3.9	0.2	0.0	2.8
	Arctozenus risso	0.0	0.0	2.3	0.9	0.2	1.6	0.4
	Alepocephalus rostratus	1.8	0.6	0.7	0.3	0.7	0.6	1.0
	Myctophidae sp.	1.4	0.0	0.0	1.6	0.2	1.1	0.5
	Micromesistius poutassou	1.0	0.6	0.5	0.0	0.4	0.5	0.5
Malacostraca	*Pasiphaea multidentata*	22.3	3.9	4.8	1431.9	9.0	122.6	1001.0
	Pasiphaea sivado	44.7	4.0	28.6	29.6	43.7	23.6	0.0
	Procesa sp.	1.2	2.7	0.0	62.8	0.5	13.5	37.1
	Plesionika martia	0.6	2.5	0.4	52.9	0.7	12.5	29.9
	Solenocera membranacea	0.0	1.2	0.1	42.6	0.0	30.2	0.0
	Meganyctiphanes norvegica	0.0	0.0	0.0	41.9	0.0	28.4	0.0
	Sergestes arcticus	0.0	0.0	0.0	25.1	0.0	3.4	15.9
	Polycheles typhlops	4.8	6.6	2.3	9.6	1.4	10.0	6.2
	Pleisionika edwardsii	11.5	3.6	0.0	0.0	3.0	1.5	5.3
	Nephrops norvegicus	1.0	0.9	0.0	4.6	0.0	4.1	0.5
	Pontocaris lacazei	0.0	1.3	0.9	1.7	0.0	2.7	0.4
	Paromola cuvieri	2.6	1.1	0.3	0.3	1.9	0.7	0.3
	Liocarcinus sp.	0.0	0.1	1.0	1.4	0.7	1.2	0.0
	Parapenaeus longirostris	0.0	1.7	0.0	0.0	1.8	0.0	0.0
	Pagurus alatus	1.8	0.4	0.0	0.5	0.2	0.3	1.3
Cephalopoda	*Histiotheutis reversa*	2.2	0.2	6.3	5.9	1.3	3.0	6.1
	Eledone cirrhosa	5.8	2.0	1.4	0.0	1.8	3.3	0.6
	Histiotheutis bonelli	0.5	3.1	0.8	0.2	0.7	0.6	3.2
	Sepiola rondeletii	0.0	0.5	1.2	2.2	0.8	1.9	0.2
	Todarodes sagittatus	0.5	1.4	0.0	1.3	1.0	1.3	0.3
	Ommastrephidae sp.	1.7	0.9	0.3	0.3	1.4	0.1	0.8
	Bathypolypus sponsalis	1.2	0.3	1.3	0.5	0.4	0.6	1.2
	Octopus salutii	1.1	0.8	0.2	0.0	0.7	0.6	0.3
	Ilex condeitti	1.3	0.0	0.0	1.2	0.2	1.2	0.0
Thaliacea	*Pyrosoma atlanticum*	0.0	5.0	0.0	2.4	0.2	0.2	7.1
	Salpa sp.	5.4	10.4	0.0	0.0	10.8	1.8	0.8

Table 2. Results of two-way ANOVA testing the effect of season and fishing ground on the abundance and biomass of the most common classes of organisms found in the discards. Significance level: * = p<0.05; ** = p<0.01; *** = p<0.001.

Variable	Class	Factor	df	Sum sq.	Mean sq.	F value	p	Sig.
Biomass	Chondrichthyes	Season	3	4.678	1.5595	4.798	0.00462	**
		Fishing ground	2	1.199	0.5996	1.845	0.16693	
		Season*Fishing ground	6	1.666	0.2776	0.854	0.53370	
		Residuals	60	19.502	0.3250			
	Actinopterygii	Season	3	2.892	0.9640	6.006	0.00115	**
		Fishing ground	2	0.391	0.1957	1.219	0.30239	
		Season*Fishing ground	6	0.716	0.1194	0.744	0.61641	
		Residuals	63	10.111	0.1605			
	Malacostraca	Season	3	14.45	4.817	3.430	0.0221	*
		Fishing ground	2	4.15	2.074	1.477	0.2361	
		Season*Fishing ground	6	3.58	0.597	0.425	0.8598	
		Residuals	64	89.89	1.405			
	Cephalopoda	Season	3	13.20	4.398	2.631	0.0575	
		Fishing ground	2	5.88	2.938	1.757	0.1807	
		Season*Fishing ground	6	7.23	1.206	0.721	0.6339	
		Residuals	64	106.99	1.672			
Abundance	Chondrichthyes	Season	3	3.381	1.1269	6.396	0.00078	***
		Fishing ground	2	1.247	0.6234	3.538	0.03527	*
		Season*Fishing ground	6	0.956	0.1593	0.904	0.49826	
		Residuals	60	10.571	0.1762			
	Actinopterygii	Season	3	3.905	1.3018	8.353	0.0001	***
		Fishing ground	2	0.898	0.4489	2.880	0.0635	
		Season*Fishing ground	6	0.862	0.1437	0.922	0.4852	
		Residuals	63	9.818	0.1558			
	Malacostraca	Season	3	11.56	3.855	5.326	0.00244	**
		Fishing ground	2	2.83	1.414	1.953	0.15015	
		Season*Fishing ground	6	4.22	0.703	0.971	0.45221	
		Residuals	64	46.32	0.724			
	Cephalopoda	Season	3	0.578	0.1926	0.699	0.556	
		Fishing ground	2	0.757	0.3784	1.374	0.261	
		Season*Fishing ground	6	1.226	0.2044	0.742	0.618	
		Residuals	64	17.631	0.2755			

Discussion

The average discard ratio observed in this study was 0.2, similar to values obtained in other studies on deep-sea trawl fisheries in the Northwest Mediterranean Sea (Sartor et al. 2003, Sánchez et al. 2004). In fact, a discard ratio of 0.2 was found in a previous study in the Catalan area and a discard ratio ranging between 0.2 and 0.3 was found in the

Tyrrhenian Sea. The relatively low discard ratio found in these fisheries is associated with the high depths where they operate (>400 m). Trawl fisheries operating on the continental shelf at lower depths are usually associated with higher discard ratios (Sánchez et al. 2004, Tsagarakis et al. 2013). In the Balearic Islands, the discard ratio in deep-sea shrimp fisheries was a little bit higher, around 0.4, but diminished with depth (Moranta et al. 2000). Our results also highlighted a marked seasonal variability in the discard ratios. Their value was particularly high in spring, with 80% of discard ratios higher than 0.4 being registered in late March, April and May. These values were mostly due to the occurrence of a high discards biomass in these months. Moreover, yields of the target species *A. antennatus* can be considerably reduced in the same months, contributing to the resulting high discard ratios. In fact, submarine currents (cascading) that occur in the study area in late winter/early spring can be particularly strong in some years and have been associated to extremely low catches of *A. antennatus* (Company et al. 2008). On the other hand, particularly low values of discard ratios were observed in summer. This is a favorable time for the fishery of the red shrimp in Catalonia, due to the high yields of the target species and the greatest proportion of big individuals in the catches, which are sold at a higher price in the market (Sardà et al. 1994a).

The multivariate analysis showed that the species composition of discards in the canyon head was significantly different from the other fishing grounds, and the highest number of species was found in the canyon wall. Similar patterns in the community of species of the Blanes submarine canyon (a few miles south of the Palamós canyon, supporting a similar fishing activity) were highlighted in a previous study by Ramirez-Llodra et al. (2010). In fact, these authors found significant differences in the benthic community between locations inside and outside the canyon, and they also found that diversity was higher inside the canyon than on the open slope. Similarly to our study, these authors found a scarce or null abundance of sessile faunal groups, such as echinoderms, gastropods, bivalves and cnidarian. These groups were found to be common in other submarine canyons in the Catalan area (Cartes 1998, Ramirez-Llodra et al. 2008), but are particularly sensitive to fishing pressure with consistent loss of abundance in heavily trawled areas (Auster et al. 1996, De Juan et al. 2013). The fact that in this study we found that diversity of species in the canyon head, the most embedded area of the canyon, was reduced compared to the canyon wall might be an indicator of fishing impact in this highly productive and heavily trawled area. In fact, the canyon head is the closest fishing ground to the coast and is the principal target of fishing boats in winter and early spring when the weather is rough and shoals of red shrimp concentrate in this area (Tudela et al. 2003).

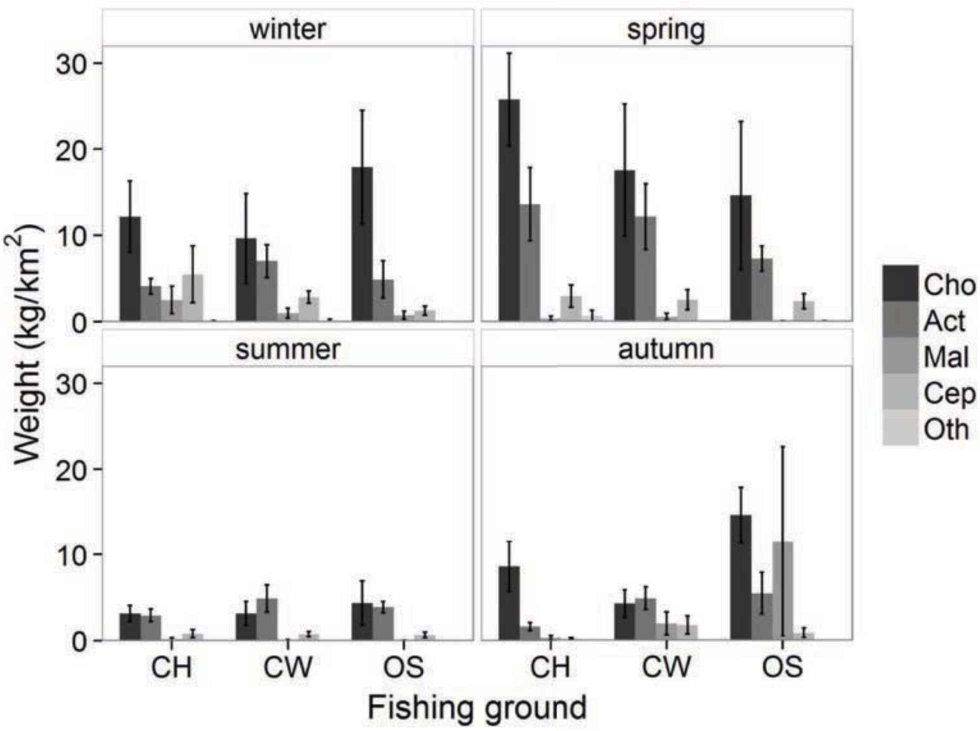

Figure 4. Average biomass (kg/km2) and standard error of the different classes of organisms found in the discards per season and fishing ground (Cho = Chondrichthyes; Act = Actinopterygii; Mal = Malacostraca; Cep = Cephalopoda; Oth = other; CH = canyon head; CW = canyon wall; OS = open slope).

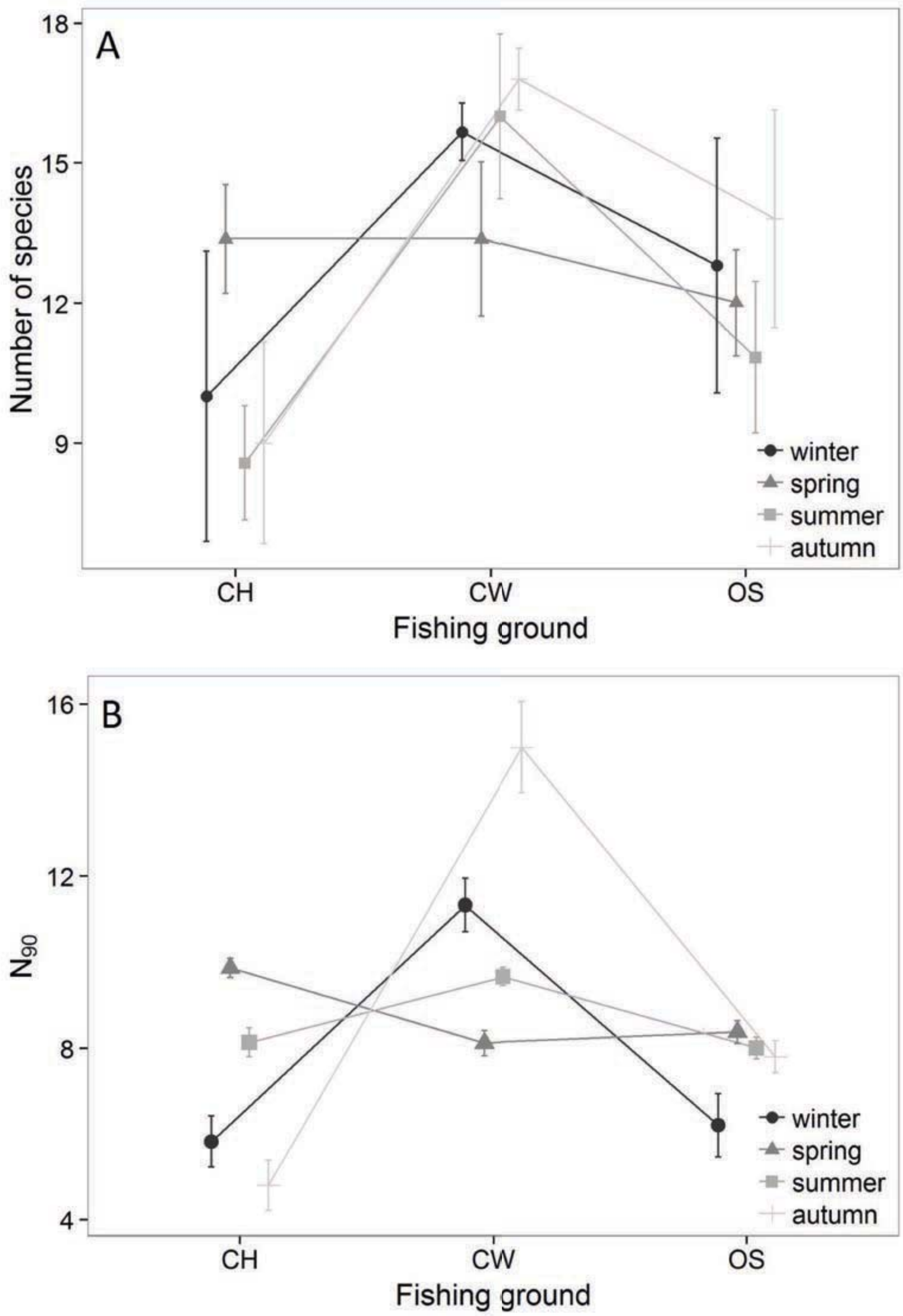

Figure 5. Average value and standard error of total number of species (A) and N90 diversity index (B) in the discards per season and fishing ground (CH = canyon head; CW = canyon wall; OS = open slope).

It stands out from our results that the vast majority of discards in this fishery (≈ 96%) was constituted by non-commercial species belonging to different taxa. In particular, more than half (53%) of discards was constituted by Chondrichthyes, which are vulnerable species because of their biological traits and k-selection life history (Pennino et al. 2013). This includes the nearly threatened species *Dalatias licha* (IUCN 2014). The mortality introduced at various levels of the ecosystem by the catch of unwanted species might imply serious consequences for the health of the submarine canyon's communities. For these reasons an effective management to reduce discards in this fishery is required.

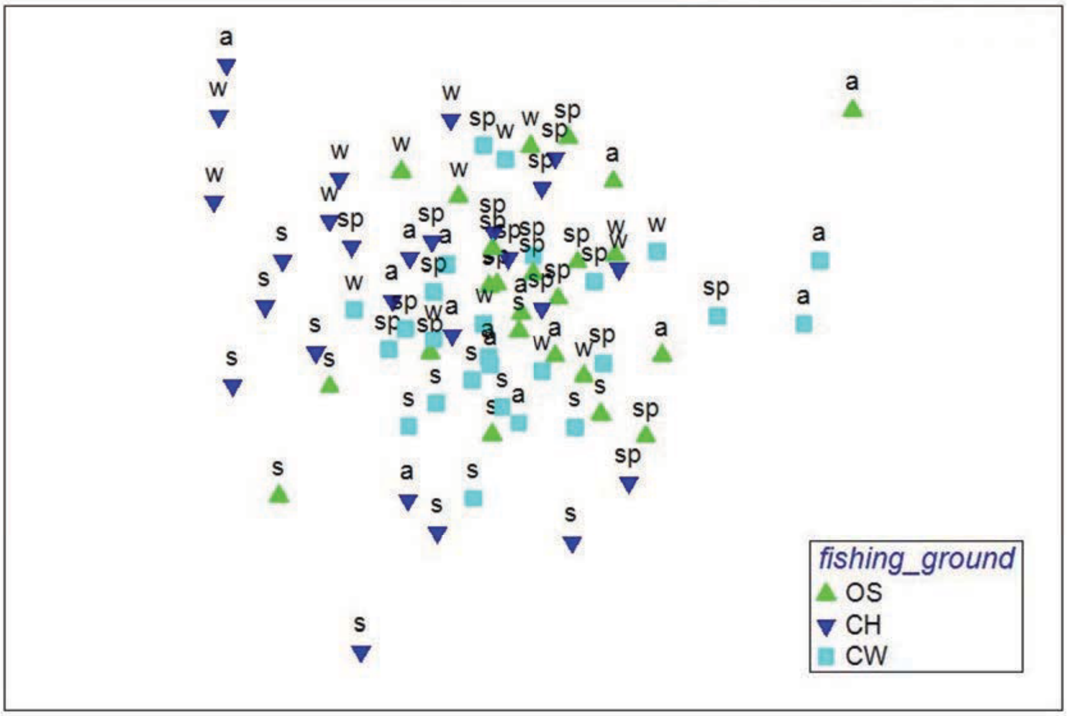

Figure 6. MDS ordination plot of the single hauls (CH = canyon head; CW = canyon wall; OS = open slope. W = winter; sp = spring; s = summer; a = autumn).

When the landing obligation required by the Common Fisheries Policy of the EU will come into force, all catches of commercial species managed through catch quotas or MLS (except for those used as live baits) will be subject to mandatory landing (Regulation (EU) No 1380/2013, 2013). In the Mediterranean, as there are no fisheries managed through catch quotas, except for the blue fin tuna, the landing obligation will apply to species managed through MLS at EU level (Article 15 of Regulation (EU) No 1380/2013, 2013). However, according to our findings, this regulation will have an extremely low impact on the fishery studied, as nearly 96% of the total discards are constituted of non-commercial species that are not affected by the landing obligation at all. Our results show that the landing obligation will only prevent discarding an average of 0.9 kg/km^2 of undersized or damaged individuals of few commercial species. Our study confirms that the main reason for discarding in the Mediterranean Sea is the lack of commercial interest in many of the species caught (Sánchez et al. 2004, Tsagarakis et al. 2013, Catchpole et al. 2013). For this reason, the benefits of implementing the landing obligation in the Mediterranean Sea have been questioned by other authors (Sardà et al. 2013, Catchpole et al. 2013, García-Rivera et al. 2015).

If reducing discards is a priority within the CFP, a different management strategy, not solely based on commercial species, must be designed in order to address the particular characteristics of Mediterranean fisheries. In northern Europe, *ad hoc* spatio-temporal fishery closures were highlighted as one of the most efficient management strategies to mitigate discards (Catchpole et al. 2005, Catchpole and Gray 2010, Johnsen and Eliasen 2011, Condie et al. 2014). For example, the Norwegian fisheries in the Barents Sea (Bjørnar 1996) successfully reduced discard ratio of haddock and cod by implementing a system of real time closures, i.e. temporarily forbidding fishing in specific areas where the amount of unwanted catches was forecasted to exceed a certain limit. In Kuwait, the shrimp trawling successfully reduced the catch of unwanted species introducing a spatial fishery closure in the Kuwait bay (Ye et al. 2000).

In the fishery studied, a temporal fishery closure might be an appropriate management strategy given the high seasonal pattern of discard ratios. The closure should include at least the fishing grounds inside the canyon, which is the area hosting the greatest diversity and most vulnerable to the impact of fishing activities. A one-month fishery closure in winter is already in place in the three fishing grounds studied, and it aims to preserve the red shrimp juveniles. Our suggestion is that this closure is prolonged for a few weeks through spring in order to address the discard issue in the canyon head and wall. The effectiveness of this measure in mitigating overall discards in the fishery should be monitored in time, as well as the potential occurrence of unintended results such as fishing effort shifts and reduced catch of target species (O'Keefe et al. 2013). In fact, a spatio-temporal closure is not costless to the fishermen, as it might imply loss of fishing opportunities. Moreover, the canyon head and wall are the closest fishing grounds to the coast, which considerably reduces the cost of fuel for fishing trips. On the other hand, submarine canyons are unique environments, home to the recruitment of many species (Stefanescu et al. 1994, Sardà and Cartes 1997, Tyler and Ramirez-Llodra 2002, Sardà et al. 2004, Ramirez-Llodra et al. 2010), which are threatened by anthropogenic activities and should be preserved in order to maintain their ecological value.

2.4 Gear selectivity

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Improving codend selectivity in the fishery of the deep-sea red shrimp *Aristeus antennatus* in the Northwest Mediterranean Sea

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Abstract

The deep-sea red shrimp *Aristeus antennatus* is one of the most valuable demersal resources in Catalonia (Northeast Spain). Palamós is the most important harbor for this fishery in the area. Here, a management plan published in 2013 established the use of a 40 mm square mesh codend (40s), replacing the previously employed 50 mm diamond mesh (50d). The objective was to decrease the amount of juveniles in the catches, but the regulation did not bring the expected results. In this study, we measured and compared the selectivity of the 50d and 40s in this fishery. In addition, we experimented the use of a 50 mm square mesh (50s). According to our results, the 40s had a lower 50% selection length (L_{50}) compared the 50d, while the 50s had a substantially higher L_{50} than the other two. A transition analysis showed an increase of yield per recruit after the second year from a hypothetical implementation of the 50s. Our conclusion is that the 40s does not display a higher selectivity than the 50d, explaining (at least partially) the failure to reach the management objective in Palamós. Conversely, the use of a 50s would significantly benefit the fishery, increasing gear selectivity and Y/R.

Introduction

Gear selectivity regulation is an important tool for fisheries management that can be efficiently implemented to maintain the catch within sustainable boundaries and to mitigate the overall impact of fisheries on the ecosystems (Sardà et al. 2006, Suuronen and Sardà 2007, Coll et al. 2008b). In fact, through the regulation of size at first capture, improvements in gear selectivity are expected to reduce the capture of juveniles and increase the yield per recruit of targeted species, while reducing the total amount of discards (Armstrong et al. 1990, MacLennan 1992)

In bottom trawl fisheries, the main factors influencing gear selectivity are the codend mesh size and shape (Robertson and Stewart 1988, Reeves et al. 1992). In particular, a diamond-shaped mesh displays a tendency to stretch and close under tension, reducing its effective selectivity as the codend fills with the catch. Conversely, a square-shaped mesh tends to stay opened during a tow, displaying an overall higher selectivity for most species than a diamond-shaped mesh of same nominal size (Robertson and Stewart 1988, Sala et al. 2008).

The deep-sea red shrimp *Aristeus antennatus* (Risso, 1816) is one of the most economically important demersal resources in the Northwest Mediterranean Sea. In Catalonia (Northeast Spain) this resource is fished exclusively by bottom trawling and makes up to 50% of the incomes for the local Fishermen's Associations (Maynou et al. 2006, DGPAM 2017). In particular, medium and big size individuals ($\geq$ 30 mm cephalothorax length (CL)) reach a much higher price in the market compared to smaller individuals, i.e. 42 Euros/kg vs. 16 Euros/kg respectively (average values for years 2010-2015; data from selling bills of the Fishermen's Association of Palamós, Catalonia). Size at first maturity for the red shrimp was estimated at 27 mm CL for females and 24 mm

CL for males (Sardà and Demestre 1987). However, there is no official minimum landing size for this fishery.

Starting from 2008, the total amount (as well the proportion) of small individuals in the catches increased dramatically in several harbors of Catalonia. In Palamós, the most important harbor for this fishery in the area, yearly catches of small individuals surpassed those of big individuals and remained particularly high at almost all years (Fig. 1, data from landing statistics of the Fishermen's Association of Palamós). The process behind this sudden shift in the catch composition of red shrimp is still unclear. The main hypothesis is that it derives from a combination of unusually high recruitment events triggered by specific environmental conditions, i.e. particularly strong dense shelf water cascading events (Company et al. 2008), and growth overfishing (Gorelli et al. 2016a).

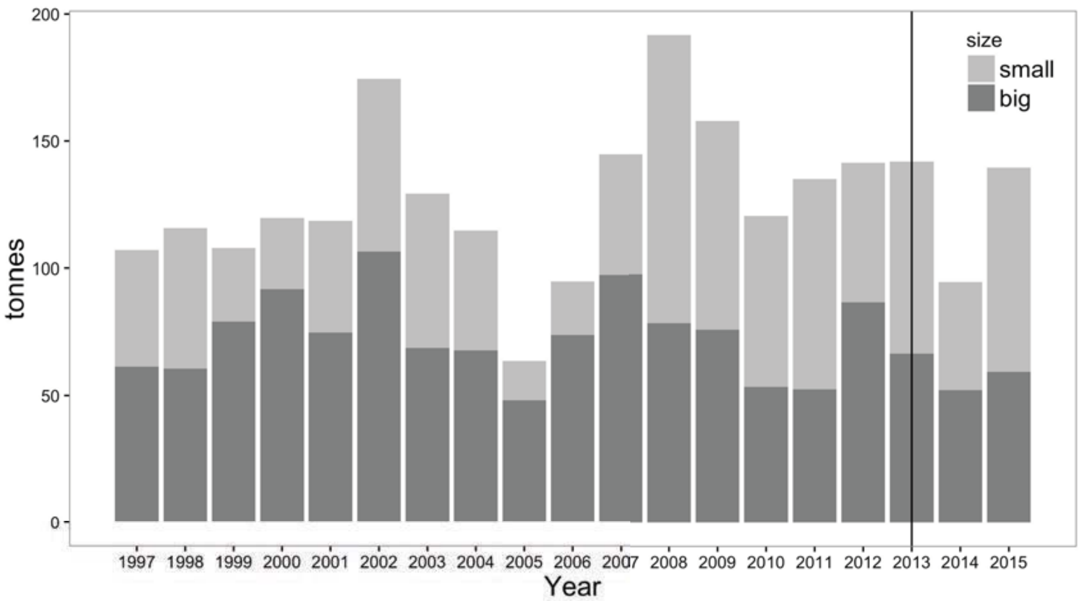

Figure 1. Catches of red shrimp (tonnes) for the trawling fleet of Palamós shown per commercial size class: small individuals (< 30 mm cephalothorax length) in light grey and medium/big individuals (≥ 30 mm cephalothorax length) in dark grey. The vertical line indicates the starting year of full implementation of the 40 mm square mesh codend, i.e. 2013. Previously, the 50 mm diamond mesh codend was used. Note that from 2008 onwards the proportion of small individuals in the catches is above 50% at almost all years.

In 2013, the Fishermen's Association of Palamós adopted a long-term management plan for the fishery of the red shrimp, with the collaboration and approval of the Catalan regional government and the Spanish central administration (BOE 2013). The objective of the plan was to increase the sustainability of the fishery (both economic and biological), with particular attention to the reduction of fishing pressure on the smallest individuals of the targeted stock. The new regulation established the use of a 40 mm square mesh codend instead of the 50 mm diamond mesh codend previously used in the fishery. Other measures in the management plan included a two-month fishery closure in winter/spring (when shoals of juveniles appear in the fishing grounds) and a reduction of 20% (along the 5-years duration of the management plan) in the number of vessels operating in the red shrimp fishing grounds. The plan came officially into force in May 2013. Nevertheless, the fleet started self-regulating more than a year in advance. In fact, the transition from the 50 mm diamond mesh to the 40 mm square mesh started in March 2012 and was completed by May 2013. It is worth noting that the whole management plan was established without any previous scientific evaluation of the fishery. Thus, the measures were adopted as a precaution in order to avoid severe overfishing and to increase the average size of individuals in the catch. The expected outcome in the short term was a reduction in the amount of small individuals in the catches. In the medium and long term, an increase in the yield per recruit and the overall profitability of the fishery was expected.

In this study, we measured and compared the selectivity of three different codend mesh configurations in the fishery of the deep-sea red shrimp: a) the 50 mm diamond mesh (from now on, 50d), used prior to the implementation of the management plan; b) the 40 mm square mesh (40s), fully implemented from mid-2013 and used up to date, and c) the 50 mm square mesh (50s), not used at present in the fishery and included in the analysis to assess the potential improvements in gear selectivity. Furthermore, we simulated the evolution of yield per recruit (Y/R) and biomass per recruit (B/R) after a hypothetical implementation of the 50s. Our objective was to assess the effectiveness of the selectivity regulation adopted in Palamós and to provide the necessary scientific evidence to support any future management decision regarding gear selectivity in this fishery.

Materials and methods

Sampling was carried out onboard a commercial shrimp trawler of the Palamós fleet, with 68.5 t GT and 700 hp engine power. The standard covered codend method (Wileman et al. 1996) was employed to assess the selectivity of the three mesh configurations. The cover had a mesh size of 12 mm (stretched), and was attached directly to the funnel end of the net. In order to maintain a good flow of water and avoid masking the codend meshes, the cover was 1.5 m wider and longer than the codends. The three codends were made of a 3 mm thick nylon twine. Experimental tows with the three codends were carried out on the commercial fishing grounds for red shrimp traditionally exploited by the Palamós fleet (Fig. 2), which are located at depths between 300 and 900 m. The average towing speed was two knots. The overall performance of the gear (door spread, mouth opening and towing depth) was monitored using acoustic sensors (Scanmar AS, Asgardstrand, Norway). The mean effective towing duration was 1 hour and 40 minutes. Catch sampling focused on *A. antennatus,* which is the only target species in this fishery and constitutes the majority of the catches (Gorelli et al. 2016b). The cephalothorax length (CL) of individuals in the codend and cover was measured with a precision of 0.1 mm. When catches were too large to measure each individual, representative subsamples were measured instead. Experimental tows with the 50d were performed during January 2012 - March 2012, while experimental tows with the 40s during May 2012 - December 2013 (these data were part of a catch sampling for stock assessment). In May - June 2016, the 50s was tested and a few more tows using the 50d were performed. Although the landings of red shrimp display a yearly peak in summer, the species is targeted during the whole year and its abundance in the fishing grounds at all times allowed a representative sampling for the three codends tested.

The size selectivity of the three mesh configurations was modeled using a standard logistic curve:

$$r(l) = \frac{e^{(a+b\times l)}}{1 + e^{(a+b\times l)}}$$

where r(l) is the probability that a fish of length l, if contacting the gear, will be retained.

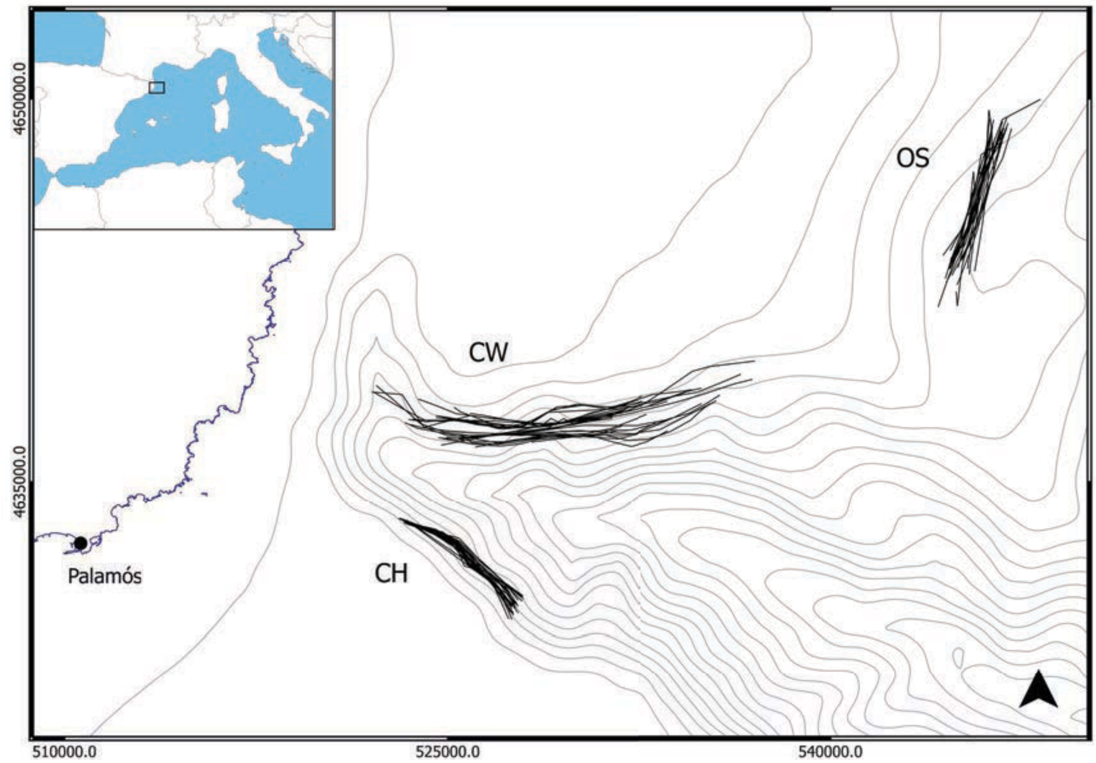

Figure 2. Map of the study area, i.e. the main fishing grounds for red shrimp exploited by the trawling fleet of Palamós (Catalonia, NE Spain). The fishing grounds are located on the margins of a submarine canyon (CH = canyon head; CW = canyon northern wall; OS = open slope). Tracks of the experimental tows are shown in the map.

The logistic parameters (*a*, intercept, and *b*, slope) were estimated using a mixed-effects logistic model (Fryer 1991). The mixed-effects model takes into account both within- and between-haul variability. The latter occurs between deployments of the same fishing gear and is due to the effect of uncontrolled variables (Millar and Fryer 1999, Reeves et al. 1992). This method ensures the proper estimation of parameters uncertainties, avoiding spurious statistical significance. In order to fit the mixed-effects logistic model, we used the *glmer* function in the *lme4* R package. The 50% selection length (L_{50}, i.e. the length at which 50% of the fish contacting the gear will be retained) and the selection range (SR) with associated standard errors were calculated as in Wileman et al. (1996). In particular:

$$L_{50} = -\frac{a}{b}$$

$$SR = L_{75} - L_{25} = \frac{2 \times \ln(3)}{b}$$

In order to simulate the effect of changing mesh configuration from 40s to 50s, a transition analysis using the software VIT was performed (Lleonart and Salat 1997). First, we ran a pseudo-cohort analysis using the length frequencies obtained with the 40s and the 50s separately. Parameters used in the analysis are shown in Table 1. Then, we ran a transition analysis to simulate the effect on Y/R and B/R of shifting current fishing mortalities (obtained with the 40s) to fishing mortalities obtained with the 50s. Details on the pseudo-cohort analysis and the transition analysis are described in Lleonart and Salat (1997). Females and males of red shrimp have very different biological parameters (Sardà and Demestre 1987, Demestre 1990, Demestre and Martín 1993). Females grow larger than males and are more abundant in the fishing grounds. In our sampling, females made around 80% of total catch weights, while constituting nearly 100% of individuals in the medium/big size class. Adult males fell almost completely in the small size class. For these reasons, the transition analysis was performed on females only.

Table 1. Parameters used for the pseudo-cohort analysis for red shrimp females. Parameters of the Von Bertalanffy relationship (L_{inf}, k, t_0) are from Sardà and Demestre (1987); parameters of the length-weight relationship (a, b) are from Demestre (1990); natural mortality (M) is from Demestre and Martín (1993). Fterm is the terminal fishing mortality for the pseudo-cohort analysis, assumed as in Demestre and Lleonart (1993).

L_{inf}	k	t_0	a	b	M	Fterm
76	0.3	-0.07	0.00264	2.46604	0.5	2

Results

A total of 99 valid experimental tows were performed in this study: 16 employing the 50d, 66 with the 40s, and 17 using the 50s (Tab. 2). The average catch weight of *A. antennatus* in the experimental hauls was 11.5 kg for the 50d, 15.3 for the 40s and 17.5 for the 50s. The length range and frequency of individuals encountering the gear during the tows was very similar for the three mesh configurations (Fig.3).

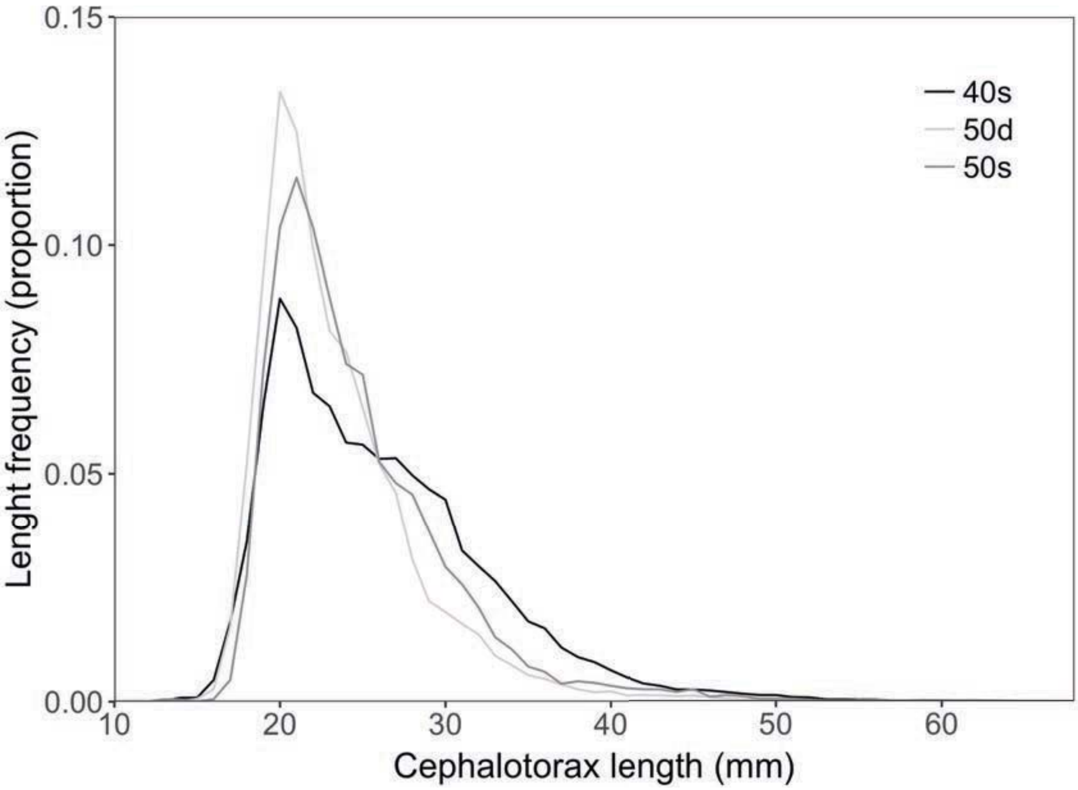

Figure 3. Length frequency of individuals encountering the gear in the experimental tows for the three mesh configurations: 50 mm diamond (50d), 40 mm square (40s) and 50 mm square (50s).

Table 2. Number of valid hauls per mesh configuration (50d = 50 mm diamond; 40s = 40 mm square; 50s = 50 mm square). Total number of individuals retained in the codend and cover per mesh configuration are also displayed.

	50d	40s	50s
N of valid hauls	16	66	17
N of individuals in codend	21462	87899	27750
N of individuals in cover	17913	31378	41399

Selectivity curves for individual hauls carried out with the three different codends are shown in Figure 4. Mean logistic parameters, *a* and *b*, displayed significant differences among mesh configurations (Tab. 3, Fig. 5). In particular, the pairwise test showed that significant differences in the steepness occurred among the 40s and the other two. As for the intercept, significant differences occurred among the 50d and the other two (Tab. 3). Significant logistic parameters allowed the estimation of mean SR and L_{50} (Tab. 4). The 40s displayed the lowest L_{50} among the three mesh configurations (21.1 mm). In particular, the difference between the 40s and the 50d was minimal (1.5 mm), while the difference between 40s and 50s was more substantial (5.1 mm) (Tab. 4, Fig. 5). The 40s displayed the narrowest selection range (5.7 mm), while the other two mesh configurations had a similar SR (7.7 and 7.2 for the 50d and 50s, respectively).

The expected Y/R after a hypothetical implementation of the 50s showed an initial decrease of 10.75%, passing from 4.93 g to 4.40 g after one year. Starting from the second year, the model suggested a recovery and a subsequent increase of the Y/R, reaching a maximum value of 5.38 g after 9 years (corresponding to an increase of 9.13% compared to the initial value) (Fig. 6). As shown in Figure 6, after five years the Y/R was already very close to the maximum. The B/R showed a gradual increase, passing from an initial value of 4.79 g to a maximum value of 6.28 g after nine years from the hypothetical 50s implementation. This corresponded to a percentage increase of 31. Similarly to the Y/R, after five years the B/R was already very close to the maximum.

Table 3. Logistic parameters (a and b) estimated by the mixed-effects model for the three mesh configurations (50d = 50 mm diamond; 40s = 40 mm square; 50s = 50 mm square), standard errors (se) and pairwise comparison between mesh configurations. The asterisk indicates significant P values, i.e. < 0.05.

	Estimate	se	P value	
a 50d	-6.45	0.54	< 0.001	*
b 50d	0.29	0.02	< 0.001	*
a 40s	-8.11	0.27	< 0.001	*
b 40s	0.38	0.01	< 0.001	*
a 50s	-8.02	0.51	< 0.001	*
b 50s	0.31	0.02	< 0.001	*
a 40s - a 50d	-1.66	0.60	< 0.01	*
a 50s - a 50d	-1.57	0.74	< 0.05	*
a 40s - a 50s	-0.09	0.58	> 0.1	
b 40s - b 50s	0.08	0.02	< 0.001	*
b 50d – b 50s	-0.02	0.03	> 0.1	
b 40s - b 50d	0.1	0.02	< 0.001	*

Table 4. Mean estimates of 50% selection length (L_{50}), selection range (SR) and associated standard errors (se) for the three mesh configurations (50d = 50 mm diamond; 40s = 40 mm square; 50s = 50 mm square).

	50d	se	40s	se	50s	se
L_{50}	22.6	0.4	21.1	0.3	26.2	0.5
SR	7.7	0.4	5.7	0.2	7.2	0.2

Discussion

In this study, we found that shifting from a diamond to a square mesh does not assure a higher selectivity regardless of the nominal mesh size. In fact, the 40s displayed a smaller L_{50} compared to the 50d. Similar results were obtained for other species in the Eastern Mediterranean Sea (Aydin et al. 2011). This reason might explain (at least partially) the failure to reduce the catch of small individuals attempted in Palamós by replacing the 50d with the 40s. In fact, the annual series of catches per commercial size (Fig. 1) shows that the catch of small individuals was not significantly reduced after 2013, when the 40s was fully adopted by the trawling fleet. On the other hand, the 50s was found to be significantly more selective than the 50d (higher L_{50} and smaller SR). Square mesh codends were proven significantly more selective than diamond mesh codends of same nominal size in several other Mediterranean fisheries and for a diversity of species (Guijarro and Massutí 2006, Sala et al. 2008, Tosunoglu et al. 2009).

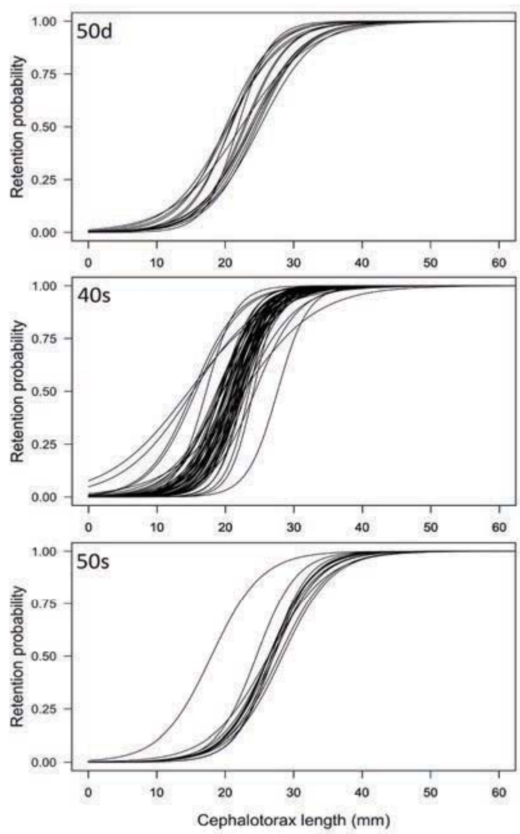

Figure 4. Selectivity curves of individual hauls for the 50 mm diamond mesh (50d), 40 mm square mesh (40s) and 50 mm square mesh (50s).

The improvement in selectivity associated to the 50s is substantial in terms of L_{50}. The initial decrease in the simulated Y/R after the adoption of this codend is recovered relatively rapidly (after only two years), and Y/R keeps improving in the following years. At the same time, the simulated B/R starts increasing immediately after the implementation of the 50s, and keeps increasing in the following years. It is important to highlight that an increase in the average size of individuals in the catch might translate into a substantial economic advantage (given the high price of big red shrimp individuals) even without a significant increase of the total yield. Thus, the adoption of the 50s might contribute to improve the overall economic and biological sustainability of the fishery, contributing to achieve the management objectives set in Palamós. At the same time, it has to be noted that the L_{50} of the 50s is still slightly below the size at first maturity of females. In this context, other measures to protect juveniles (such as the fishery closure already in place in Palamós during two months in winter/spring) should be implemented to complement the selectivity increase. Further experimentation of other mesh configurations is also recommended.

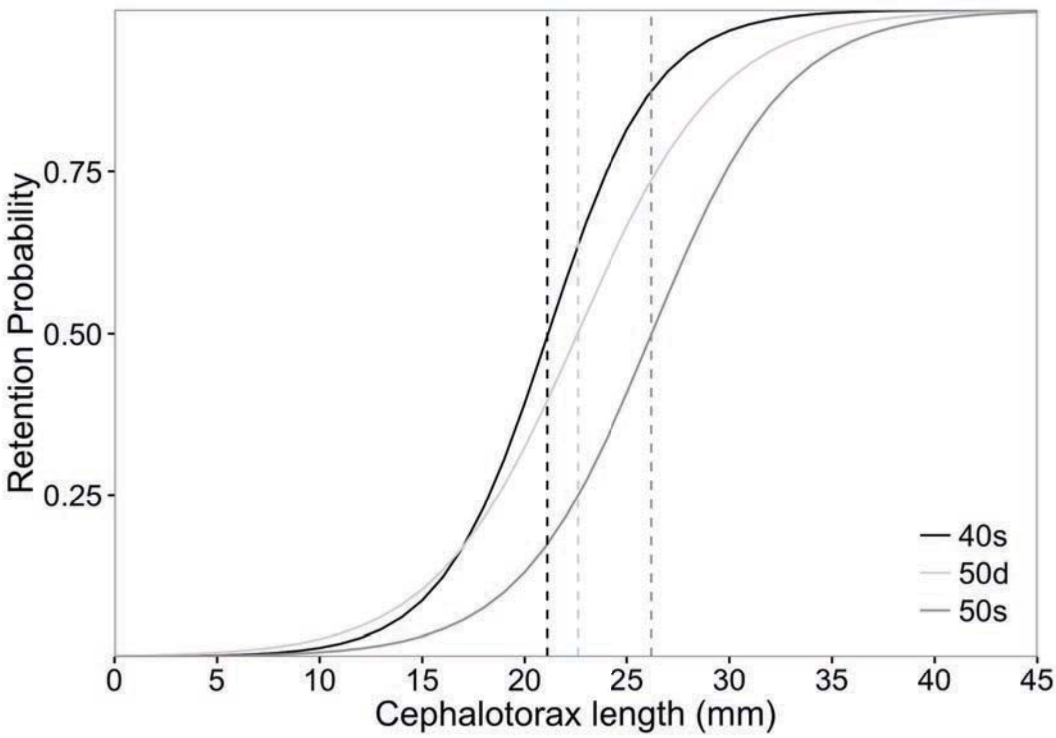

Figure 5. Mean selectivity curves for the 50 mm diamond mesh (50d), 40 mm square mesh (40s) and 50 mm square mesh (50s), obtained taking into account between-haul variability. The vertical dashed lines indicate the L50 for the three mesh configurations (black = 40s, light grey = 50d, dark grey = 50s).

Finally, our study highlights the importance and the need for scientific evidence to support the adoption of management measures. The investment made by the Fishermen's Association of Palamós to change the codend mesh configuration from 50d to 40s did not bring any beneficial effect to the fishery. A previous evaluation and comparison of the selectivity of the two mesh configurations would have prevented this loss of economic resources. In fact, the implementation of management measures without previous knowledge or estimate of their effects might result in unexpected outcomes, such as potential disadvantages for the fishery, economic loss and no contribution to the achievement of the established management objectives.

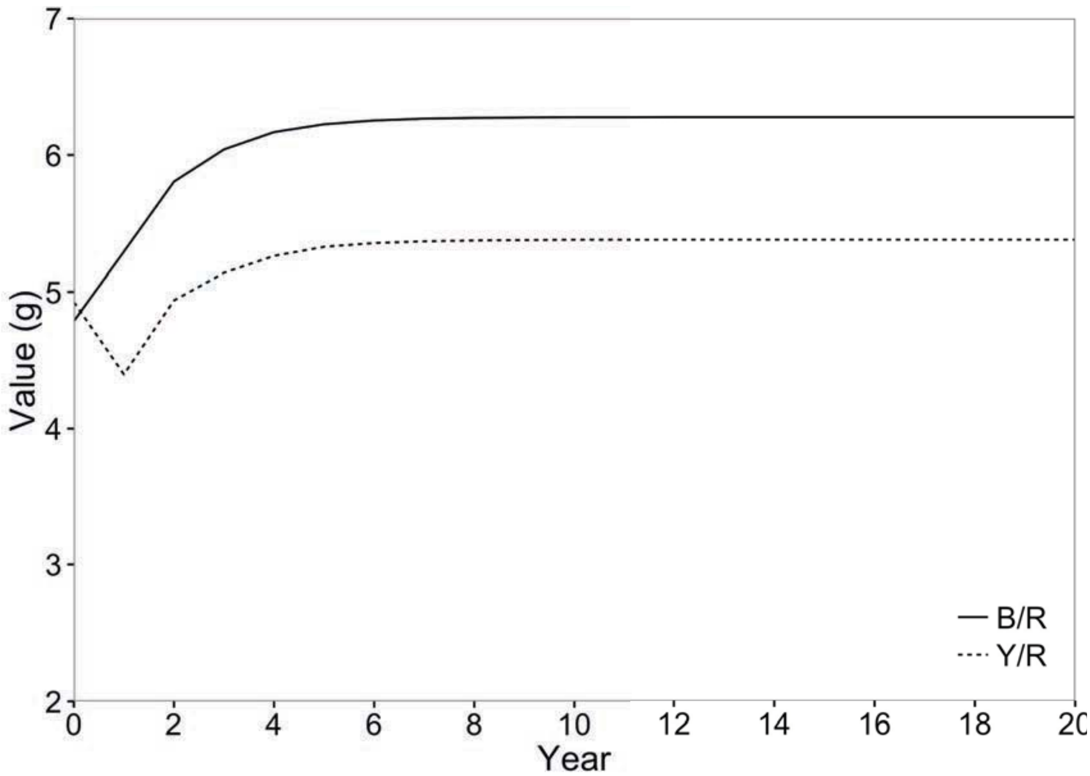

Figure 6. Simultated effects on the yield per recruit (Y/R, dotted line) and biomass per recruit (B/R, black line) in the red shrimp fishery after shifting mesh configuration from 40 mm square mesh to 50 mm square mesh. The y-axis represents the values in grams of yield per recruit and biomass per recruit.

2.5 Summary of Results

Chapter 2.1

Historical series of fishery data

The number of trawlers targeting the red shrimp in Catalonia undertook an increasing trend starting from the 1950s and peaked in 2006 with 132 trawlers (Fig. 2 of chapter 2.1). In 2013, there were 110 trawlers targeting this resource in the area.

The results of the interviews to fishermen showed that in 2013 the horse power of the shrimp trawling fleet in Palamós, Tarragona and Blanes (three of the most important harbors of the area) was misreported in the official records (Fig. 3 of chapter 2.1). In fact, the average declared value of hp for a shrimp trawler in these harbors was 457 hp (just under the law limitation of 500 hp), while the average real value was 999 hp. A significant linear relationship between the vessels' real engine power and gross tonnage (GT) was found (Fig. 4 of chapter 2.1) and was used to estimate engine power for the Catalan fleets not covered by the interviews. The results showed that, in 2013, the total hp for the Catalan fleet targeting the red shrimp was about 111,000 hp, more than double the official value (Fig. 5 of Chapter 2.1).

The time series of fishing effort (1950-2013) directed to the red shrimp in Catalonia (Fig. 6 of chapter 2.1) showed a steep increasing trend starting from the mid-1950s and reached a maximum in 2009.

The historical series of landings (1963-2013) (Fig. 7 of chapter 2.1) showed considerable inter-annual variability, with an overall minimum in 1981 (28.6 t) and a maximum in 2008 (683 t). A significant increasing trend was detected over the whole time series. Nevertheless, the significance and slope of the regression increased when considering the years after the motorization of the fleet alone (i.e. after 1970).

The CPUE time series (1963-2013) (Fig. 8 of chapter 2.1) showed an initial increase followed by a steep decrease from 1965 to 1970, when CPUE went from 0.66 kg/hp*day to 0.09 kg/hp*day. From 1970 to 2000, the series displayed a less steep but still overall decreasing trend. After 2000, the CPUE undertook a slightly positive trend leading to a value of 0.04 kg/hp*day in 2013.

Stock status evolution from the period 1984-1989 to 2008-2010.

Population estimates from the pseudo-cohort analysis are shown in Table 4 of chapter 2.1. The stock assessment detected overfishing at all years considered (1984-1989 and 2008-2010), for both sexes. For females, overfishing worsened in the second period of time, with the average value of $F_{0.1}/Mean\,F$ going from 0.49 to 0.41 (Tab. 4 of chapter 2.1). Similarly, the yield per recruit analysis showed that the Y/R decreased by 10% between the two time periods, passing from an average value of 9.48 g to an average value of 8.57. For males, the decline in the yield per recruit was less marked, with average values being 2.86 g and 2.22 g in the two time periods respectively (Tab. 4, Fig. 10 of chapter 2.1).

Chapter 2.2

Test of different ecological hypotheses and model selection

All the models provided a very good fit to the total yield data and a satisfactory estimation of parameters (Fig. 1, Tab. 1 of chapter 2.2). The fit to the catch at length data, CPUE, catch at market size was not as good as for the yield for neither model (Fig. 2, 3, 4 of chapter 2.2).

The AICc values showed that the model including the effect of DSWC on natural mortality was the one receiving the highest support from the data (Tab. 2 of chapter 2.2). In fact, adding the effect of DSWC on natural mortality improved the model fit compared to the baseline model, reducing significantly the SSQ (Tab. 2 of chapter 2.2). In particular, the fit to the total yield and catch at length data was improved significantly (Tab. 2, Fig. 1a, 1c, 4 of chapter 2.2), even though main residuals patterns for catch at length remained very similar in the two models (Fig. 4 of chapter 2.2). The Δi indicated that the model including both the effect of DSWC on natural mortality and recruitment was still supported by the data (Δi < 2). However, the extra parameter representing the effect of DSWC on recruitment did not bring any significant improvement to the model fit. On the other hand, the model including the effect of cascading on availability did not receive any support from the data.

Model estimates and reference points

The different models produced quite different reconstructions of the stock (Fig. 5, 6 and 7 of chapter 2.2). As indicated by the AIC values, the best population estimates were provided by the model including the effect of DSWC on natural mortality.

$M_{c,}$ the natural mortality component due to cascading, was estimated at 0.82, indicating that natural mortality in year of cascading is increased by more than 100% for shrimps of both sexes (Tab. 1 of chapter 2.2). The spawning stock biomass (1963-2015) displayed an overall decreasing trend, with marked fluctuations. The high inter-annual variability of SSB was strictly related to DSWC, with minimums coinciding with years after DSWC events (Fig. 5c of chapter 2.2). The series of fishing mortality (1963-2015) displayed an increasing trend starting from the beginning of the 1980s. Minimums in the F series corresponded to years of DSWC and were always followed by a steep increase (Fig. 6c of chapter 2.2). Recruitment deviations from the Beverton and Holt stock recruitment relationship determined an extremely variable recruitment (Fig. 7c of chapter 2.2). The steepness of the stock recruitment relationship was very high, indicating that no clear relationship between stock size and recruitment was detected.

The sex-specific partial recruitment estimated for individuals of one year of age was very different between sexes (Tab. 1 of chapter 2.2), suggesting a different behaviour of male and female recruits.

The maximum sustainable yield (MSY) and the corresponding fishing mortality (F_{MSY}) were estimated at 301.2 tonnes 0.64. Considering that, in 2015, the yield was 597 t and the fishing mortality 1.31, the stock is considered in overexploitation. The equilibrium MSY for years of intense DSWC was estimated at only 14.2 t, indicating that only very little harvest may be sustainable in years of adverse environmental conditions (F_{MSY} in years of cascading = 0.36).

Chapter 2.3

Spatio-temporal patterns in discards weights and ratios

The total weight of discards ranged between 1 and 109 kg/km^2, while the commercial catch ranged between 9 and 331 kg/km^2 (Fig. 2 of chapter 2.3). The discard ratios ranged between 0.02 and 0.79, with an average value of 0.2. Both discarded biomass and discard ratio showed a significant decrease in summer compared to the other seasons, and no significant difference among fishing grounds (corresponding to different areas of the submarine canyon) (Fig. 3a, 3b of chapter 2.3). In addition, discard ratios displayed a peak in spring.

Discards composition in relationship to the Palamós submarine canyon

A total of 94 species were found in the discards of the red shrimp fishery in Palamós (Tab. 1 of chapter 2.3). There were no discards of the target species *Aristeus antennatus*, as there is no minimum landing size (MLS) established for this resource, and any damaged individual is consumed by the fishing crew. Discards of other commercial species were very small, contributing by less than 4.1% to the total discarded biomass.

These were limited to a few undersized or damaged specimens of pink glass shrimp (*Pasiphaea multidentata),* greater fork-beard (*Phycis blennoides),* norway lobster (*Nephrops norvegicus),* blue whiting (*Micromesistius poutassou)* and european hake (*Merluccius merluccius)*.

The majority of discards (≈ 96%) was constituted of non-commercial species. The list of the most common species found in the discards (i.e. those accounting for 99% of total abundance and 95% of total biomass) is found in Table 1 of chapter 2.3. In terms of biomass, the most represented class was Chondrichthyes, making 53% of the total, followed by Actinopterygii (30%), Cephalopoda (9.1%) and Malacostraca (6.5%) (Fig. 4 of chapter 2.3). The biomass and abundance of all classes (except for Cephalopoda) showed significant differences between seasons (Tab. 2 of chapter 2.3). In addition, the abundance of Chondrichthyes also varied significantly according to the fishing ground, being higher in the open slope.

Five individuals of kitefin shark (*Dalatias licha*), a species classified as near threatened by the IUCN, were found in the discards in this study.

ANOSIM (Analysis of Similarities) detected significant differences in the species composition of discards, both between seasons and fishing grounds. In particular, the pairwise test highlighted significant differences between spring and all other seasons ($p<0.001$), and between the canyon head and the canyon wall and open slope ($p<0.05$ and $p<0.001$ respectively).

The number of species in the discards ranged between 2 and 24, while the N_{90} index ranged between 4 and 18. Both diversity indexes were significantly higher in the canyon wall than in the other fishing grounds (Fig. 5a, 5b of chapter 2.3). In particular, N_{90} in the canyon wall was particularly high in autumn.

Chapter 2.4

Selectivity estimation for the different codend mesh configurations

The selectivity of the three codend mesh configurations tested (40 mm square mesh - 40s; 50 mm diamond mesh - 50d; 50 mm square mesh - 50d) displayed considerable inter-haul variability (Fig. 4 of chapter 2.4). The mean logistic parameters estimated using the mixed-effects logistic model, *a* and *b*, displayed significant differences among mesh configurations (Tab. 3, Fig. 5 of chapter 2.4). The 40s displayed the lowest 50% selection length (21.1 mm) while the 50s displayed the highest L_{50} (26.2 mm) (Tab. 4, Fig. 5 of chapter 2.4). The 40s had the narrowest selection range (5.7 mm), while the other two mesh configurations had a similar SR (7.7 and 7.2 for the 50d and 50s, respectively).

Transition analysis

The expected Y/R after a hypothetical implementation of the 50s showed an initial decrease of 10.75%. Starting from the second year, the model predicted a recovery and a subsequent increase of the Y/R, reaching a maximum increase of 9.13% (compared to the initial value) after nine years (Fig. 6 of chapter 2.4). Nevertheless, after five years the Y/R was already very close to the maximum. The B/R showed a gradual increase, reaching a maximum increase of 31% after nine years from the hypothetical 50s implementation (Fig. 6 of chapter 2.4). Similarly to the Y/R, after five years the B/R value was already very close to the maximum.

3. General Discussion

Trends in the historical series of fishery data (1950-2013)

The historical series of fishing effort reconstructed in chapter 2.1 displayed a steep increasing trend starting from the second half of the last century until 2009. In particular, the increase of fishing effort in the last 25 years of the series was largely due to the increase of the trawlers engine power. However, this could not be inferred from the official records, due to the heavy misreporting that started after 1988, when the regulation limiting the trawlers' engine power to 500 hp came into force. Taking into account the engine horsepower and its variations in the computation of fishing effort is widely recommended, especially when evaluating temporal trends (Anon. 2007a, Gulland 1969). In fact, the size of the fishing gear increases significantly with the trawlers engine power (Eigaard et al. 2011). Moreover, as confirmed by the fishermen interviewed in this study, a more powerful engine significantly increases fishing efficiency in rough weather and decreases transfer time to the fishing grounds, gaining extra time for trawling on a daily basis. In addition, a more powerful vessel allows fishing in deeper waters, expanding the limits of the fishing grounds and increasing the portion of the stock exploited (Coll et al. 2008a).

Starting from 2009, the increasing trend in fishing effort was reversed. Around this year, due to unfavorable economic conditions (high gasoil price, declining stocks) and declining stocks abundance, several vessels were scrapped and improvements in engine power of active trawlers were avoided. This determined the decrease of fishing effort detected in the latest years of the time series.

A very similar pattern of fleet engine power evolution in the Catalan area was previously suggested by Coll et al. (2014), where one Catalan harbor was considered. Similar results were also obtained within a study on a trawling fleet in the Balearic region (Coll et al. 2014). Here, despite a decrease in the number of trawlers, the total engine power doubled its value from the 1970s to the 1900s (Carbonell 2005, Carbonell et al. 1999).

The decline of CPUE over the time frame considered (1963-2015) suggests a decline in the red shrimp abundance. It has to be beard in mind that CPUE can be considered an index of abundance only under the assumption of constant catchability, or when factors influencing catchability are removed from its computation (Hinton and Maunder 2003). In this work, the series of CPUE was calculated taking into account some of the main factors affecting catchability over time, i.e. vessels' engine power and technological creep. However, catchability can be influenced by several more factors, such as changes in gear selectivity, fishermen skills and fishing behavior (Bishop 2006, Harley et al. 2001, Maunder et al. 2006). Thus, an increase in fishing efficiency might have resulted in a stabilization of CPUE, masking a further reduction in the red shrimp abundance in the latest years of the series.

The time series of landings (1963-2015) and fishing effort, displayed high inter-annual variability. As already suggested by Company et al. (2008), such variability was found to be strictly related to the occurrence of Dense Shelf Water Cascading (DSWC) events in the area. In fact, minimums in the series of landings and fishing effort coincided with years when particularly strong cascading events occurred.

Stock status evolution (from 1984-1989 to 2008-2010) using pseudo-cohort and yield per recruit analysis

In contrast with the abundance trends inferred from the CPUE time series, the estimates of stock biomass from the stock assessment were considerably higher for the period 2008-2010 than for the period 1984-1989. However, the biomass estimates from the pseudo-cohort analysis are highly dependent on catches, which, due increased fishing effort, were higher in the second period of time. However, the pseudo-cohort analysis does not use any index of abundance and/or fishing effort in its calculations, and therefore their effects on catches and stock abundance are not taken into account.

Overfishing of the stock was detected at all years studied. For females, overfishing was more severe in the second period of time, and Y/R showed a decrease among the two time periods considered. According to the results of the most recent year studied (i.e. 2008), fishing mortality should be decreased by more than 60% to reach the level of the reference point $F_{0.1}$.

As already pointed out by Company et al. (2008), the results obtained in chapter 2.1 highlighted that the red shrimp fishery is highly influenced by the occurrence of DSWC, which periodically reduces the abundance of the shrimps in the fishing grounds. This process is very likely to violate the steady state assumption (i.e. constant mortality and constant recruitment) underlying the pseudo-cohort and yield per recruit analysis. In particular, a study by Ratz et al. (2010) showed that the quantitative estimations from pseudo-cohort analysis are very sensitive to violations of this assumption, while trends in fishing mortalities and estimates of $F_{0.1}$ are less affected. Therefore, stock assessment results obtained in chapter 2.1 should be treated with care and quantitative conclusions should be avoided (especially over distant time periods). However, the overfishing and the declining trends of Y/R and CPUE detected in this chapter clearly indicated the need to improve the stock assessment and management for this species in the area.

Stock assessment using SCAA and quantification of environmental effects.

The results obtained in chapter 2.1 highlighted the need to assess the deep-sea red shrimp in Catalonia using a stock assessment model free from the steady state assumption and able to take into account the evolution of CPUE and the effect of the environmental factors.

The Statistical Catch at Age (SCAA) used in chapter 2.2 is a complex stock assessment method which provides a very flexible framework that can be useful even in data-limited situations (Geromont and Butterworth 2015). Differently from other commonly used modelling approaches (such as Virtual Population Analysis), SCAA allowed to use all the available information, including fragmented time series of catch at length data and series of catch at market size, covering a temporal range of over 50 years. This allowed to include and test the effect of DSWC over a long time frame, which included twelve DSWC events. Given the scarcity of detailed catch at length data available for the stock assessment, uncertainties in the modelling results remain high. However, the SCAA was performed using the best available data, and provides an indication on the stock status and the most likely mechanism of interaction between the red shrimp population and the DSWC.

The results showed that the DSWC has a significant effect on the red shrimp population dynamic, dramatically increasing its natural mortality. Taking into account this effect significantly improved the stock assessment model for this species. The sudden increase in natural mortality explains the disappearance of the shrimps from the fishing grounds observed during DSWC events (Company et al. 2008), as well as the relative minimums in the yearly landings.

No clear relationship between stock size and recruitment was estimated by the model. This is quite common for shrimp species where, due to their high fecundity, even a small population of spawners is sufficient to maintain stock levels. Usually, in these cases, the primary causes of recruitment fluctuations are the environmental effects (Garcia 1983). The hypothesis that specific climate and oceanographic processes might enhance the recruitment of the red shrimp by increasing the food availability in the deep-basin was previously explored by several authors (Puig et al. 2001, Maynou 2008, Sardà et al. 2009). Company et al. (2008) showed that, in the Catalan area, the proportion and number of small individuals of red shrimp (< 30 mm cephalotorax length) in the catches increased considerably after intense DSWC events. In fact, in the years following the 2005-2006 cascading events, the recovery in the catches was mainly sustained by small individuals (Fig. 1 of chapter 2.4). However, the positive effect of DSWC on the red shrimp recruitment was not captured by the model developed in this thesis. Instead, high inter-annual variability in recruitment, with no correlation with cascading events, were estimated. This might be due to the fact that there was not enough information in the data to relate recruitment rates and DSWC event, as too few years of catch at length were available. In addition, there might be other environmental processes, such as the deep-sea convection, influencing the recruitment of the red shrimp in the area.

The reference points estimated by the SCAA showed that the stock of *Aristeus antennatus* in Catalonia is in overfishing, confirming the results of the pseudo-cohort and Y/R analysis obtained in chapter 2.1. The results also showed that, due to the increase in natural mortality, predicted equilibrium MSY for years of DSWC was considerably reduced, indicating that only little harvest may be sustainable in years of adverse environmental conditions.

High fishing rates are known to lower the resilience of exploited populations, exacerbating the effects of environmental factors (Beddington and May 1977, May et al. 1978, Hsieh et al. 2006). In fact, populations that are subject to excessive fishing rates and that, as a result, are composed mainly by recruits are known to track the environmental fluctuations more closely than the unexploited ones (Ottersen et al. 2006, Anderson et al. 2008, Rouyer et al. 2011). Therefore, reducing fishing pressure on the red shrimp might mitigate the negative effect of DSWC on the resource abundance (and fishery incomes), while improving the overall fishery sustainability.

Overfishing of *A. antennatus* was detected by many authors in several areas of the Mediterranean Sea, such as the strait of Ibiza, the Balearic Islands and Sicily (Relini and Relini Orsi 1987, Ragonese and Bianchini 1996, García-Rodríguez and Esteban 1999, Carbonell 2005). The point that, despite decades of overfishing, the stocks of red shrimp have not collapsed yet has been widely discussed (Demestre and Lleonart 1993, D'Onghia et al. 2005, García–Rodríguez et al. 1999, Sardà, 1993). The rapid growth rate and high fecundity of this invertebrate species were advocated as factors limiting its sensitivity to intense fishing activities. The periodical recruitment enhancement by DSWC was also considered as a possible factor to contrast the negative effects of overfishing (as well as the negative effect of DSWC itself) (Company et al. 2008). In addition, the large portion of the population residing in the deep-basin, beyond the limits of the fishing grounds, might act as a "reservoir" of individuals contributing to prevent the collapse of this stock (Demestre and Martín 1993, Company et al. 2008, Sardà et al., 2004, Marra et al. 2015). However, the results obtained in chapters 2.1 and 2.2 indicate that overfishing of the red shrimp in the last decades has led to a reduction in the stock abundance, catch rates and average individual size. An appropriate management strategy should be adopted to assure a sustainable and profitable fishery in the long term.

Patterns in fishery discards

The average discard ratio observed in the fishery of the dee-sea red shrimp was 0.2, similarly to other deep-sea trawl fisheries in the northwestern Mediterranean Sea (Sartor et al. 2003, Sánchez et al. 2004). The relatively low discard ratio found in these fisheries is associated with the high depths where they operate (>400 m). Trawl fisheries operating on the continental shelf at lower depths are usually associated with higher discard ratios (Sánchez et al. 2004, Tsagarakis et al. 2013).

The discard ratios in this fishery displayed a marked seasonal variability. Their value was particularly high in spring, with 80% of discard ratios higher than 0.4 being observed in late March, April and May. These values were mostly due to the occurrence of a high discarded biomass in these months. Moreover, yield of the target species *A. antennatus* can be considerably reduced in the same months, due to the effects of DSWC, contributing to the resulting high discard ratios. On the other hand, particularly low values of discard ratios were observed in summer. This is a favorable time for the fishery of the red shrimp in Catalonia, given the high yields of the target species and the greatest proportion of big individuals in the catches, which are sold at a higher price in the market (Sardà et al. 1994a).

The results obtained in chapter 2.3 confirmed that the main reason for discarding in the Mediterranean Sea is the lack of commercial interest in many of the species caught (Sánchez et al. 2004, Tsagarakis et al. 2013, Catchpole et al. 2013). In fact, the great majority of discards in this fishery (≈ 96%) is constituted by non-commercial species, with more than half (53%) belonging to the family Chondrichthyes. These are particularly vulnerable species because of their biological traits and k-selection life history (Pennino et al. 2013). Discarded species in this fishery include the nearly threatened species *Dalatias licha* (IUCN 2014).

In a previous study by Ramirez-Llodra et al. (2010), the species diversity of the Blanes submarine canyon (a few miles south of the Palamós canyon, supporting a similar fishing activity) was found to be higher at locations inside the canyon compared to the locations outside. The results of this study show that the discards' diversity of species in in the canyon head, the most embedded area of the canyon, was reduced compared to the canyon wall. This might be an indicator of fishing impact in this highly productive and heavily trawled area. In fact, the canyon head is the closest fishing ground to the coast and is the principal location for fishing vessels in winter and early spring, when the weather is rough and shoals of red shrimp concentrate in this area (Tudela et al. 2003). Similarly to Ramirez-Llodra et al. (2010), in this study a scarce or null abundance of sessile faunal groups (such as echinoderms, gastropods, bivalves and cnidarian) was found in the discards. These groups are usually common in other submarine canyons in the Catalan area (Cartes 1998, Ramirez-Llodra et al. 2008), but are particularly sensitive to fishing pressure displaying consistent loss of abundance in heavily trawled areas (Auster et al. 1996, De Juan et al. 2013).

The Common Fisheries Policy of the EU has established a landing obligation for all commercial species regulated through catch quotas or minimum landing size (Regulation (EU) No 1380/2013, 2013), with the aim to disincentive and reduce discards in European fisheries. According to the findings of this study, this regulation will have an extremely low impact on the fishery of the red shrimp in the northwestern Mediterranean, as nearly 96% of the total discarded biomass is constituted of non-commercial species that are not affected by the landing obligation at all. The results of this thesis show that the landing obligation will only prevent discarding an average of 0.9 kg/km^2 of undersized or damaged individuals of few commercial species. For similar reasons, the benefits of implementing the landing obligation in the Mediterranean Sea have been questioned by other authors (Sardà et al. 2013, Catchpole et al. 2013, García-Rivera et al. 2015).

A different management strategy, tailored at the specific, local characteristics of the red shrimp fishery should be adopted to actually mitigate discards and help preserving the submarine canyons ecosystem.

Gear selectivity

Gear selectivity regulation is an important tool for fisheries management that can be efficiently implemented to reduce the catch of small individuals, diminish the overall fishing mortality and reduce the amount of fishery discards. Through the regulation of size at first capture, improvements in gear selectivity are expected to increase the yield per recruit of targeted species (Armstrong et al. 1990, MacLennan 1992).

The results obtained in this thesis showed that shifting from a diamond to a square mesh in the red shrimp fishery does not assure a higher selectivity regardless of the nominal mesh size. In fact, the 40 mm square mesh (40s) displayed a smaller L_{50} compared to the 50 mm diamond mesh (50d). Similar results were obtained for other species in the Eastern Mediterranean Sea (Aydin et al. 2011). On the other hand, the 50 mm square mesh (50s) was found to be significantly more selective than the 50d (higher L_{50} and smaller SR). Square mesh codends were proven significantly more selective than diamond mesh codends of same nominal size in several other Mediterranean fisheries and for a diversity of species (Campos et al. 2002, Bahamón et al. 2006, Guijarro and Massutí 2006, Sala et al. 2008, Tosunoglu et al. 2009).

The simulated evolution of Y/R after the hypothetical adoption of the 50s shows an initial decrease that is recovered relatively rapidly (after only two years), and a subsequent increase of more than 9% in the following years. At the same time, the simulated B/R starts increasing immediately after the implementation of the 50s, and keeps increasing in the following years. It is important to notice that, given the high price of big individuals of red shrimp compared to the small ones, an increase in the average size of individuals in the catch would translate into a substantial economic advantage even without a significant increase in the total yield. Thus, the adoption of the 50s might contribute to improve the overall economic and biological sustainability of the fishery. At the same time, it has to be noted that the L_{50} of the 50s is still slightly below the size at first maturity of females. In this context, other measures to protect juvenile individuals (such as fishery closures) should be implemented to complement the selectivity increase. Further experimentation of other mesh configurations is also recommended.

Management advice for the red shrimp fishery in Catalonia

The results obtained in this thesis suggest the need to implement a management strategy in the fishery of the red shrimp in the Catalan area to: a) reduce the fishing effort to a sustainable level; b) increase gear selectivity and protect juvenile individuals; c) decrease the peak of discards in spring and d) mitigate, as far as possible, the negative effect of DSWC. The expected outcomes of such management strategy would be, in the short term, an increase in the CPUE and a decrease in the amount of juvenile, immature individuals in the catches. In the medium/long term, an improvement of the stock status and an increase in the biomass per recruit and yield per recruit is expected, as well as a reduction in the overall impact of the fishery in the deep-sea canyon ecosystem.

In particular, the fishing pressure directed to the shoals of small red shrimp individuals should be reduced. These shoals tend to form in winter/spring (Sardà et al. 1994b, Sardà et al. 1997, Tudela et al. 2003) especially inside the canyons, and are particularly abundant after a cascading event (Company et al. 2008). Given their aggregating behavior, *ad hoc* spatio-temporal fishery closures could be an effective measure to protect juvenile individuals in this fishery. In addition, an increase in the gear selectivity is recommended, as small individuals are present in the fishing grounds at all seasons, in different proportions and abundances. Chapter 2.4 showed that the L_{50} of the currently employed codends (22.6 mm CL for the 50d and 21.1 mm CL for the 40s) is inappropriate to decrease the amount of small, immature individuals in the catches. On the other hand, the 50s would improve significantly the selectivity, bringing L_{50} to 26.2 mm CL, and would provide an increase of about 9% in the Y/R within 5 years from its adoption. At the same time, it has to be noted that the L_{50} of the 50s is still slightly below the size at first maturity of females, and further experimentation of other mesh configurations is also recommended.

Given that the price per kilo of the red shrimp increases greatly with the individuals' size, shifting the fishing pressure to the bigger size classes, thus increasing the Y/R, would be particularly beneficial for this fishery. In addition, overfishing and the related age-truncation effect generally increase the sensitivity of the exploited populations to the environmental effects. Therefore, reestablishing a balanced age-structure would likely improve the red shrimp population resilience and capability to buffer the negative effect of DSWC.

F_{MSY} and MSY based on the SCAA were estimated at 0.64 and 301.2 t respectively, indicating that both fishing mortality and catches should be reduced by approximately 50% (as of 2015). The yield per recruit analysis estimated that, as of 2008, fishing mortality should be reduced by 60% to reach the optimal level ($F_{0.1}$). In addition, the predicted equilibrium MSY in years of DSWC was estimated at only 14.2 t, indicating that only little harvest may be sustainable in years of adverse environmental conditions. Therefore, specific measures to maintain a sustainable red shrimp exploitation in years of DSWC should be incorporated in the management strategy. Under these conditions, fishing effort should be further reduced to allow the population to rebuild itself.

The average discard ratio found in the red shrimp fishery is low compared to other trawl fisheries. However, it shows a marked seasonal pattern, with a significant peak in spring. The submarine canyons where this fishery occurs are vulnerable environments creating habitat complexity, hosting great diversity and home to the recruitment of many species (Stefanescu et al. 1994, Sardà and Cartes 1997, Tyler and Ramirez-Llodra 2002, Sardà et al. 2004, Ramirez-Llodra et al. 2010). Discards in this fishery are almost exclusively constituted of non-commercial deep-sea species, which, due to their life history characteristics, are particularly sensitive to the impact of fisheries. Therefore, the impact of anthropogenic activities should be minimized, in order to maintain the ecological value of canyons. *Ad hoc* spatio-temporal fishery closures were highlighted as one of the most efficient management strategies to mitigate fishery discards by several authors (Catchpole et al. 2010, Bellido et al. 2011, Johnsen and Eliasen. 2011, Condie et al. 2014). In the fishery studied, a temporal fishery closure might in fact be an appropriate measure to mitigate the peak in discards occurring in spring. The closure should include at least the fishing grounds inside the canyon, which is the area hosting the greatest diversity and being most vulnerable to the impact of fishing activities. In addition, an increase in gear selectivity would contribute to the overall reduction of discards.

The management plan established in Palamós in mid-2013 aimed at reducing the fishing effort and decreasing the amount of small individuals in the catches. The fishing effort was successfully reduced (Fig. 1) thanks to a reduction of 20% in the number of red shrimp trawlers and to the introduction of a two-months fishery closure in winter/spring. In particular, the fishery closure aimed at protecting the shoals of juvenile individuals that aggregate in the fishing grounds in these months. In addition, the use of a 40 mm square mesh coded was established, replacing the 50 mm diamond mesh codend previously employed. However, there was no significant reduction in the proportion of small individuals in the catches in the years after the implementation of the management plan (Fig. 1 of chapter 2.4). In fact, as it was demonstrated in this thesis, the 40s does not display a higher size selectivity for red shrimp than the 50d. In addition, it has to be noted that in 2012 and 2013 DSWC occurred, and the abundance of small individuals in the fishing grounds was particularly high in the following years.

The management plan adopted in Palamós did not explicitly include the issue of fishery discards, but the two-month fishery closure in winter/spring might as well serve to tackle this issue, since it implies that the fishing grounds inside the canyon will remain closed to all vessels. However, following the principles of the ecosystem approach to fisheries management (Garcia et al. 2003, Dimech et al. 2014) the discards reduction and the preservation of the canyon's ecosystem should be regarded as a primary management objective, which should be formally stated in the management plan.

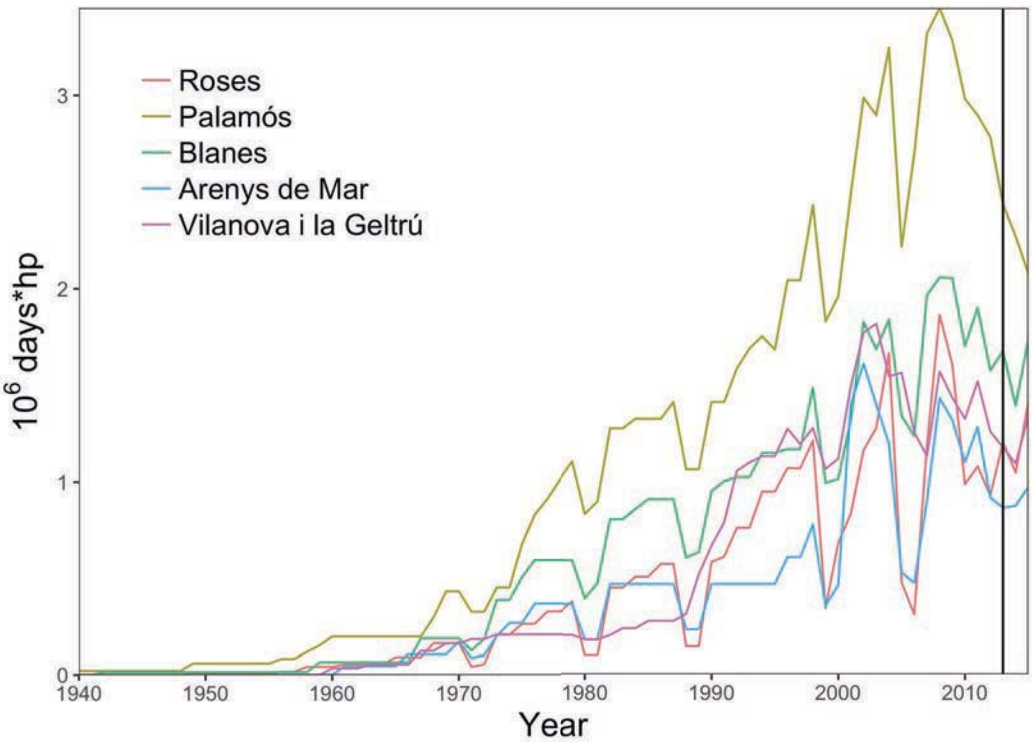

Figure 1. Historical series (1940-2015) of fishing effort directed to the red shrimp in various Catalan ports. The vertical line indicates the year of publication of the management plan in Palamós (i.e. 2013). Notice how, after 2013, Palamós succeeds in keeping the effort decreasing while it is increasing in all the other ports.

The results of this thesis show that, although some of the measures should be adjusted, the management strategy adopted in Palamós was overall appropriately designed to tackle some of the main issues threatening the sustainability of the red shrimp fishery in Catalonia. However, if only implemented in this harbor, the recommended management measures will probably have only a limited and local impact (e.g. increasing CPUE and reducing the amount of juvenile individuals in the catches of Palamós), and will be unlikely to improve the overall stock status, thus failing to achieve the long term management objectives. In addition, a monitoring plan to regularly assess the stock status and the performance of the selected management measures should be established and regarded as an integral part of the management strategy.

In this work, the red shrimp stock exploited by the Catalan fleets was considered as a single assessment and management unit. This assumption was justified by the similarities in the trawling fleets, fishing habits and socio-economic conditions for all the Catalan harbors exploiting this resource. Here, the main fishing fleets targeting red shrimp develop their activities on the continental margins of the Catalan submarine canyons, with similar implications for the environment. In addition, the influence of DSWC and the landings patterns, with their annual and inter-annual fluctuations, appear to be synchronous in the whole area. For these reasons, the management objectives and strategy implemented in Palamós could be easily replicated and adopted in the other Catalan harbors, thus contributing to improve the stock status and the overall sustainability of the fishery.

4. Conclusions

This thesis constitutes a thorough evaluation of the deep-sea red shrimp fishery in the Catalan area (northwestern Mediterranean Sea), providing the basis to inform an *ad hoc* management strategy aiming at the sustainable exploitation of this resource. It is the first study investigating the mechanism of interaction between the dense shelf water cascading (DSWC) and the red shrimp population. Furthermore, the effect of the DSWC is quantified and included in a stock assessment model. This thesis also provides the first evidence and quantification of the remarkable increase of fishing effort in the northwestern Mediterranean Sea in the last decades. In addition, it presents a characterization of fishery discards in relationship to the vulnerable environment of the submarine canyons, and a comparative analysis of gear selectivity. The main conclusions deriving from this study can be summarized as follows:

1. Fishing effort directed to the red shrimp in the Catalan area underwent a steep increasing trend starting in the second half of the last century up to 2009, while CPUE decreased. Inter-annual variability in fishing effort and landings appear to be strictly related to DSWC events.

2. Basing fishing effort estimation on raw official data leads to an underestimation of more than 50%. This is due to misreporting of vessels engine power in the official records. Official data series should be rigorously reviewed before taken into account in fisheries evaluations. The linear relationship between the trawlers gross tonnage and real horse power found in this study can be used to estimate the real trawlers' engine power in similar fisheries where misreporting occurs.

3. DSWC occurring in the northwestern Mediterranean has an effect on the deep-sea red shrimp population by increasing its natural mortality. Taking into account this effect significantly improves the stock assessment model for this species.

4. The red shrimp in the Catalan area is in overfishing. Catches and fishing

mortality should be reduced by 50% to achieve the level of MSY and relative fishing mortality. In particular, the predicted equilibrium MSY was considerably reduced in years of DSWC, indicating that only little harvest may be sustainable in years of adverse environmental conditions. In these years, fishing effort should be further reduced.

5. Estimates of spawning stock biomass (1963-2015) show a general declining trend, with great inter-annual variability related to DSWC events. The yield per recruit decreased by 10% between the 1980s and recent years (2005-2008).

6. The Statistical Catch at Age model is a very flexible method that can be useful to overcome data sparsity and scarcity that is common in several Mediterranean fisheries. In this study, it was also useful to test alternate ecological hypotheses. However, the scarcity of detailed catch at length data make the model results presented in this study uncertain.

7. Discard ratios in this fishery are low in average compared to other trawl fisheries and display a minimum in summer and a peak in spring. Most of the discarded biomass is constituted of non-commercial species. The landing obligation established by the EU will have a low impact in mitigating the discards in this fishery, since non-commercial species are not affected by the regulation at all. In this regard, *ad hoc* management measures should be adopted.

8. The 40 mm square mesh (40s) and the 50 mm diamond (50d) mesh currently employed in this fishery have a low selectivity for red shrimp. In particular, the 40s has a lower 50% selection length compared to the 50d, i.e. 21.1 mm and 22.6 mm respectively. On the other hand, the 50 mm square mesh experimented in this thesis would significantly increase the 50% selection length (26.2 mm) and improve the yield per recruit by about 9% within 5 years form its implementation.

9. A fishery management aiming at the long term sustainable and profitable exploitation of the red shrimp in Catalonia should include measures to: reduce overfishing, increase yield per recruit and CPUE, lower the peak of discards in spring, buffer the negative effect of the DSWC. This could be achieved by decreasing fishing effort, reducing the fleet overcapacity, protecting the aggregations of small individuals, and increasing the gear selectivity. In particular, this study indicates that a fishery closure in winter/spring, when shoals of juvenile individuals form in the fishing grounds inside the canyons and the discard ratio reaches a peak, would be particularly appropriate. The mitigation of overfishing is also likely to increase the red shrimp resilience to the effects of DSWC.

10. The management measures adopted in Palamós with the management plan published in 2013 were fundamentally in line with the advice arising from this study, although they failed to improve gear selectivity. However, in order to obtain a significant impact on the stock status, the recommended management strategy should be adopted and implemented also by the other Catalan harbors, which share similar fishing habits, socio-economic and environmental conditions with Palamós.

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6. Annexes

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Fishing Effort Increase and Resource Status of the Deep-Sea Red Shrimp *Aristeus antennatus* (Risso 1816) in the Northwest Mediterranean Sea Since the 1950s

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ABSTRACT

The deep-sea red shrimp *Aristeus antennatus* is one of the most valuable demersal resources for bottom trawl fishery in the Mediterranean Sea. Nevertheless, this fishery lacks specific management at Mediterranean level, data availability is sparse and official records are often unreliable. In particular, misreporting of trawlers engine power is a widespread issue, complicating the process of fish stock assessments. In Catalonia (Northeast Spain), the red shrimp is particularly important and the stock has been traditionally exploited. The aim of this study was to investigate the long-term effects of intense fishing activities on this resource. For this purpose, we built a reliable series of fishing effort and catch per unit of effort (CPUE), integrating official data with information obtained by interviews to fishermen. Stock assessment at two different time periods, 1984–1989 and 2008–2010, was performed. In this study, we provide the first evidence of the remarkable increase of fishing effort in the Northwest Mediterranean Sea in the last decades. Overfishing of the red shrimp was detected at all years studied. A decrease in the yield per recruit and mean individual length over the two time periods considered was also detected. In addition, the CPUE presented a marked decreasing trend, indicating a possible reduction in the resource abundance. Our results show that an appropriate fishery management for this resource is needed, and should aim at reducing fishing mortality and increasing yield per recruit. These objectives could be achieved by reducing fishing effort and increasing size at first capture.

KEYWORDS
Stock assessment; fishing effort; CPUE; historical data; bottom trawling

1. Introduction

The deep-sea red shrimp *Aristeus antennatus* is among the most important target species for demersal trawl fishery in the Mediterranean Sea. The bathymetrical distribution of this species ranges between 100 and 3,000 m depth (Sardà et al., 2004), with a large portion of the stock dwelling at depths beyond the fishing grounds limits (1,000 m depth). Biology and ecology of this species have been widely studied, except for the larval phase that is still largely unknown (Carbonell et al., 2010). It displays marked sexual dimorphism for secondary sexual characters and growth characteristics. Females have a longer life span compared to males (five to six years versus three to four years) and can reach a maximum cephalothorax length of 76 mm, while males reach a maximum of 54 mm (Sardà and Demestre, 1987; Demestre, 1990). It is a highly appreciated sea food and a very high value species at market, reaching peaks of more than 200 €/kg during holidays. It is actively targeted by bottom trawlers mainly at depths between 350 and 900 m in various areas of the western and central Mediterranean Sea (Fiorentino et al., 1998; Carbonell et al., 1999; D'Onghia et al., 2005). Catches are mainly made up of females, which dominate the population at the depth range of the fishing grounds, where they constitute 70% of the population (Sardà et al., 1994; Sardà et al., 2003). There are no discards for this species, and all the catches are landed.

Many authors agree on the overexploitation status of the red shrimp in the Mediterranean Sea (Ragonese and Bianchini, 1996; García-Rodríguez and Esteban, 1999; Carbonell, 2005). However, the stock assessment process is often complicated by the general scarcity and unreliability of official fishery data (Lleonart and Maynou, 2003). One example is constituted by the engine power of the Spanish Mediterranean trawling fleets. Here, a national regulation establishes since 1988 a maximum engine power of 500 hp for trawlers (BOE, 1988). Unfortunately, compliance to this regulation has always been extremely low and misreporting in the official records extremely common. Although it is recognized that fishing effort in the area has increased significantly in the last decades mainly due to the modernization of fleets (Alegret and Garrido, 2004; Coll et al., 2014), no attempt to rectify the official records quantifying such increase

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was performed so far. In addition, despite the economic importance of the red shrimp and the risks related to intense and unregulated fishing activities, no specific national or international fishery management for this resource has been established, not even a minimum landing size.

In Catalonia (Northeast Spain), the red shrimp is an extremely important resource for the local fishermen associations (Figure 1), which rely to a large degree on the incomes from this fishery (Maynou et al., 2006). Here, this species constitutes 3% of total landings while making 21% of economic incomes on a yearly average (Official fishery statistics from Autonomous Government of Catalonia). Landings of this species in the area are characterized by marked inter annual fluctuations, with minimums associated with the occurrence of an oceanographic process known as dense shelf water cascading (DSWC; Company et al., 2008). DSWC in the area occurs when coastal surface waters on the wide shelf of the Gulf of Lions become denser than surrounding waters and cascade downslope, until reaching their equilibrium depth (Canals et al., 2006; Puig et al., 2013). In particularly dry, windy, and cold winters the cascading is exceptionally intense and generates currents reaching depths >500 m, creating a thermo-haline and turbidity anomaly in the deep waters. This anomaly is believed to increase the shrimps mortality and/or decrease their availability in the fishing grounds leading to a drastic reduction in their abundance and a temporary fishery collapse (Company et al., 2008).

The last stock assessment available in literature for the red shrimp in the Catalan area dates back to the period 1984–1989, when size structured data were sampled and analyzed in Demestre and Lleonart (1993). These authors defined the red shrimp at an optimum level of exploitation. Starting in 2013, Palamós, the most important harbor for this fishery in Catalonia, implemented a local management plan for the red shrimp fishery (BOE, 2013). The measures included in the management plan aim at reducing the fishing effort and preserving red shrimp juveniles by (i) reducing the number of vessels allowed in the fishing grounds, (ii) performing a fishery closure in winter (when shoals of small individuals form in the fishing grounds), and (iii) establishing the use of a more selective mesh size (40 mm square mesh instead of 50 mm diamond mesh). However, a more recent stock assessment is certainly needed in order to correctly inform and adjust the current management strategy in Palamós, as well as to set the proper scientific basis to implement it at a larger spatial scale. In addition, the

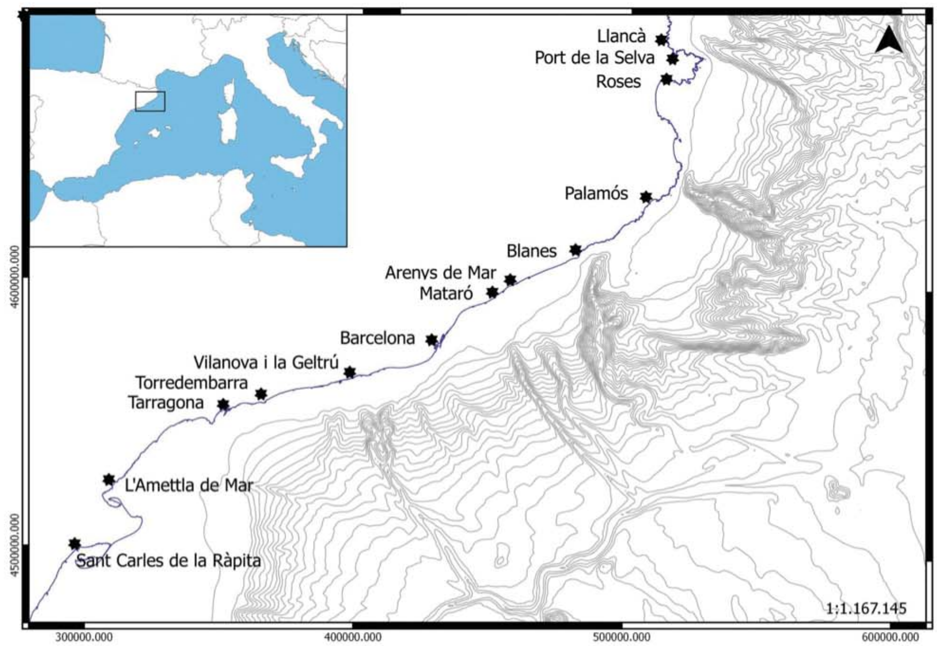

Figure 1. Map of the Catalan coast (NE Spain). The fishing harbors with a trawling fleet targeting red shrimp are shown.

long-term effects of the intensive fishing activities on this resource should be considered.

The objective of this work was to assess the stock of *A. antennatus* exploited by the Catalan fleets in the recent years. We also investigated the long-term effects of the increasing fishing effort on this stock in the last 60 years. The evolution of fishing effort was quantified using days at sea and engine horsepower of shrimp trawlers, integrating and rectifying official data with information obtained by interviews with fishermen. In this study, we provide the first evidence of the remarkable increase of fishing effort that occurred in the Northwest Mediterranean Sea in the second half of the last century. Following to this, we used yearly landings to build a historical series of catch per unit of effort (CPUE). Finally, we performed a stock assessment at two different time periods, 1984–1989 and 2008–2010, using the same methodology and biological parameters, in order to highlight differences in the exploitation status of the red shrimp over a period of 25 years.

2. Methods

Data on the trawling fleets active in Catalonia for the period 1900–2013 were obtained from the Spanish Ministry of Agriculture, Livestock and Fishery. A list of vessels' characteristics including harbor of base, period of activity, gross tonnage (GT), gross register tonnage (GRT), and engine horsepower (hp) was provided. From the list, we selected trawlers belonging to the harbors that have a fishery for the red shrimp (Figure 1). Face to face interviews with fishermen from the different harbors of study were performed in order to obtain the following information: (i) which, among the trawlers on the list, were the ones that targeted red shrimp (full time or occasionally); (ii) which was the real engine power of such vessels; (iii) if any improvement to the engine power of these vessels was performed over time. Unfortunately, not all the fishermen interviewed agreed to provide information on the real engine power of vessels. To estimate a realistic horsepower value for trawlers when no direct information was provided, we investigated the relationship between the real hp values obtained with successful interviews and other vessels characteristics (i.e., GRT and GT). Then, all hp values obtained either by interview or extrapolation were summed to obtain a yearly value of total engine power of trawlers targeting red shrimp in Catalonia.

The total number of days at sea per fishing vessels was available in the records of the Autonomous Government of Catalonia (Table 1). The database covered the period 2001–2013 and allowed identifying values regarding specifically trawlers landing red shrimp. Extrapolation of data to the previous years was made considering fishing habits as well as environmental conditions in the area. The average number of days at sea per trawler was fairly stable in the time period 2001–2013, except for the years 2005 and 2006 (Table 1). In these years the red shrimp abundance in the fishing grounds was scarce due to exceptionally intense cascading events (Company et al., 2008), and this condition resulted in a lower fishing effort directed to this resource. Strong cascading generating currents reaching the depths of the fishing grounds were also observed in 2012–2013 (Durrieu de Madron et al., 2013), but they had a lesser impact on the fishery compared to previous events. Another cascading event reaching 500 m depth was recorded in 2010, but it had a short duration and no deep-water anomaly was observed in the following year (Puig et al., 2013). Exceptional environmental conditions are the most important factors affecting the number of days at sea in this fishery. In fact, fishing activities in this area are an otherwise routinely activity, strictly organized in daily trips with days at sea established at five per week. Anomalies in the deep-water characteristics following exceptionally strong cascading events (similar to the 2005–2006 events) were also observed in 1971–1972, 1980–1981, 1988–1989, and 1999–2000 (Bethoux et al., 2002; Puig et al., 2013). Thus, the mean value of days at sea per vessel in 2005 and 2006 was used as an estimate of days at sea per vessel in these years. The same method was employed for non-cascading years. Finally, the series of fishing effort directed to the red shrimp was worked out as yearly values of days at sea

Table 1. Yearly values of total number of days at sea and average number of days at sea per vessel for the Catalan trawling fleets targeting red shrimp from 2001 to 2013. In 2005 and 2006 (in bold) exceptionally strong cascading events occurred in the study area negatively affecting the red shrimp abundance in the fishing grounds.

Year	Total days at sea	Average days at sea per vessel
2001	11,990	98.28
2002	13,806	113.16
2003	13,344	105.90
2004	15,695	122.62
2005	**9,876**	**77.16**
2006	**7,895**	**59.81**
2007	13,033	99.49
2008	15,818	121.68
2009	15,569	127.61
2010	13,177	110.73
2011	13,632	118.54
2012	11,993	106.13
2013	12,033	109.39

per fleet engine power (Gulland, 1969):

$$Fishing\ Effort = (Average\ Days\ at\ Sea\ per\ Vessel) \times (Fleet\ hp).$$

During the interviews, fishermen stressed the importance of the improvements in fishing technology to increase their fishing efficiency. In particular, the technological equipment acquired over the years (use of scanmar, bathymetry data, GPS, etc.) contributed to a precise identification of the most suitable and safe grounds for trawling and the achievement of a near perfect asset of the fishing gear during operations. Therefore, a yearly rate of 1% increase due to technological creep was applied to the series of fishing effort starting from 1980. The 1% ratio used in this work was assumed as a conservative ratio compared to the 3.6% suggested by Pauly and Palomares (2010).

The historical series of landings was built integrating two different data sources. From 1963 to 1986, data were obtained from Tobar and Sardà (1987), who in turn made reference to the Spanish Ministry of Agriculture, Livestock and Fishery. From 1987 onward the responsibility of such data collection was transferred to the regional governments. Therefore, from 1987 to 2013 data were obtained from the records of the Autonomous Government of Catalonia. Then, annual CPUE were calculated for the period 1963–2013 as

$$CPUE = \frac{Catches(kg)}{Fishing\ Effort}.$$

For the stock assessment of *A. antennatus* at two different time periods, we employed two series of size frequencies in the catches proceeding of four Catalan harbors. One series was relative to the period 1984–1989 and the other to the period 2008–2010. The first data were available in literature (Demestre, 1990) and were previously analyzed in Demestre and Lleonart (1993). They were obtained by monthly sampling the catches of the trawling fleets of Blanes, Arenys, and Barcelona. During the sampling, sex and cephalothorax length of individuals in the catches was recorded. The second data series (2008–2010) was obtained within a monitoring project carried out by the Autonomous Government of Catalonia. Data were obtained by similar methodology as in the previous case, i.e., sampling catches onboard commercial trawlers of three of the main Catalan harbors: Roses, Arenys, and Vilanova i la Geltrú. In both cases data obtained with the samplings were assumed to be representative for Catalonia and length frequencies were extrapolated to the landings of the whole region in the respective years. In particular, the sex ratio in the samples was extrapolated to the total landings in order to obtain values of landings per sex (Table 2). The average size frequencies in the catches for the two periods were compared using the Kolmogorov–Smirnov (K-S) test.

Data were analyzed by means of pseudo-cohort and yield per recruit analysis using the VIT program (Lleonart and Salat, 1997). This method is commonly used in data poor fisheries, as it allows stock assessment when only a few consecutive years of size structured data are available. The VIT basically performs a virtual population analysis (VPA) under the assumption of steady state of the stock (constant recruitment and mortality). This way the age structure of a single year is considered as the age structure of a single cohort ("pseudo-cohort"). We give no further detail on the calculations used by VIT as an extensive description is provided in Lleonart and Salat (1997). This method is widely used for stock assessment in the Mediterranean Sea due to the general availability of poor data series, and it is one of the main methods used for official fishery evaluations within the General Fishery Commission for the Mediterranean (GFCM). We used the same biological parameters for the stock assessment in the two time periods. In particular, the Von Bertalanffy growth parameters were taken from Sardà and Demestre (1987), the natural mortality estimates from Demestre and Martín (1993), and the length weight relationship parameters from Demestre (1990) (Table 3). A qualitative evaluation of the stock at each year analyzed was given comparing fishing mortality (F) estimated by the pseudo-cohort analysis with the reference point $F_{0.1}$ calculated by the yield per recruit analysis. Given the differences between females and males in the growth parameters and natural mortality rates, all the analyses were performed for the two sexes separately.

3. Results

The number of trawlers targeting red shrimp in Catalonia undertook an increasing trend starting from the beginning of the 1950s, reaching a peak in 2006 (Figure 2). At the beginning of 2013, there were 110 trawlers dedicating effort to this fishery (full time or occasionally). Fishermen from the harbors of Palamós, Blanes, and Tarragona agreed to provide the real engine

Table 2. Total landings of red shrimp (in tonnes) for the Catalan region in the years 1984–1989 and 2008–2010 per sex.

	1984	1985	1986	1987	1988	1989	2008	2009	2010
Males	30	35	24	35	51	88	49	45	30
Females	253	315	212	217	327	265	629	581	456

Table 3. Parameters used for the pseudo-cohort analysis. Parameters of the Von Bertalanffy relationship (L_{inf}, k, t_0) are from Sardà and Demestre (1987); parameters of the length-weight relationship (a, b) are from Demestre (1990); natural mortalities (M) are from Demestre and Martín (1993).

	L_{inf}	k	t_0	a	b	M
Males	54	0.25	−0.5	0.004024	2.31769	0.8
Females	76	0.3	−0.07	0.00264	2.46604	0.5

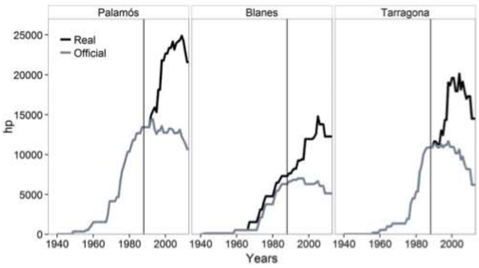

Figure 3. Historical series of total engine power (hp) of the trawling fleets targeting red shrimp for the harbors of Palamós, Blanes, and Tarragona (Catalonia). Official versus real values of hp are shown. The vertical lines indicate the year in which the regulation establishing engine power at a maximum of 500 hp came into force (i.e., 1988).

horsepower values of shrimp trawlers for the respective fleets. From these interviews we found that, in 2013, the engine power of 98% of the shrimp trawlers was misreported in the official records. In fact, the average real engine power was 999 hp, while the average declared was only 457 hp. Our results show that massive misreporting started right after the regulation limiting engine power to 500 hp came into force (BOE, 1988; Figure 3). After this year, many vessels increased their engine power illegally, although with the implicit permission of the authorities. Illegal and unreported engine power was also observed in most of the newly built vessels incorporating to the fleets. Since 1988, only 13% of shrimp trawlers complied with the law. As a result, in 2013 the total engine power of the shrimp fleets of Palamós, Tarragona, and Blanes exceeded of more than double the value reported in the official records (Figure 3).

The real engine horsepower values collected with the interviews showed a significant linear relationship both with vessels GT and GRT, although the relationship with GT provided a better fit. In particular, the GT–hp relationship was sensibly different when considering shrimp trawlers active before 1988 and after 2000 separately (before 1988: $R^2 = 0.664$, $p = 0.000$; after 2000: $R^2 = 0.751$, $p = 0.000$) (Figure 4). In fact, between 1988 and 2000 all the major changes to engine power of vessels were performed. Thus, after 2000 the average engine power of trawlers of a given GT was higher than before 1988. The linear relationship between real hp and GT was used to estimate the real hp values of shrimp trawlers when we had no direct information from the interviews. Such relationship was applied according to the following rules in order to simulate the temporal pattern unveiled from the harbors investigated: (i) official engine power of vessels registered before 1988 was considered real with no need of correction; (ii) vessels registered before 1988 and active until after 2000 were considered to have changed their engine power during the years 1988–2000, and a new hp value was estimated using the GT–hp relationship; (iii) official engine power of vessels registered after 1988 was considered false and the real value was estimated using the GT–hp

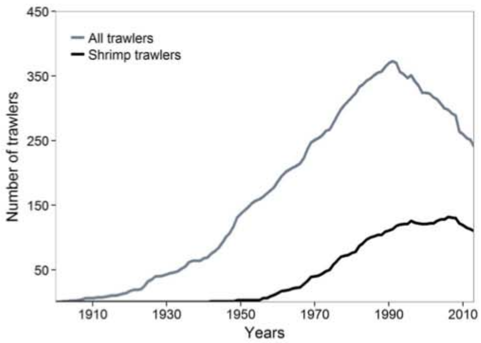

Figure 2. Total number of trawlers and number of trawlers specifically targeting red shrimp (full time or occasionally) in the Catalan region from 1900 to 2013.

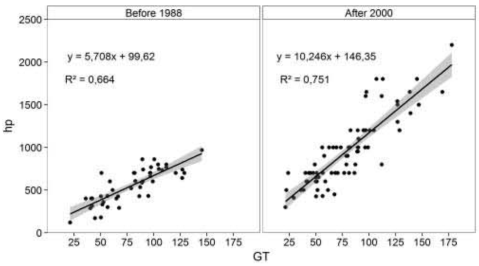

Figure 4. Linear relationship between real engine power (hp) and gross tonnage (GT) of shrimp trawlers in the harbors of Palamós, Blanes, and Tarragona (Catalonia). Linear relationships are shown for vessels active before 1988 ($p = 0.0000$) and after 2000 ($p = 0.0000$) separately. The shaded area corresponds to the 95% confidence interval for the linear regression.

relationship. The historical series of total engine power of the Catalan shrimp trawling fleets (obtained using both interview data and estimations) is shown in Figure 5. As displayed by the figure, the official records sensibly underestimate the real data starting from 1988, when the curves begin to diverge greatly. After this year, the series of official hp does not show any sign of further increase, while the series of real hp keeps increasing. In 2013, the official value of hp represented only 42% of the real one. The historical evolution of fishing effort including technological creep is shown in Figure 6. The curve displays a steep increasing trend starting from the mid-1950s, reaching a maximum in 2009. The minimums in the series correspond to years in which intense cascading events occurred in the study area.

The historical series of landings and CPUE are shown in Figures 7 and 8, respectively. The series of landings displays an overall minimum in 1981, when landings for the whole region amounted to only 28.6 tonnes (t), and a maximum in 2008, when landings reached 683 t. A significant increasing trend could be detected over the whole time series ($R^2 = 0.247$; $p = 0.0002$), although significance and slope of the regression increased if considering years after the modernization of the fleet only (from 1970: $R^2 = 0.440$; $p = 0.0000$) (Figure 7). The CPUE series shows an initial increase followed by a steep decrease from 1965 to 1970, when CPUE went from 0.66 kg/hp*day to 0.09 kg/hp*day. After 1970, the series displays a less steep but still overall decreasing trend until 2000, when CPUE undertook a slightly positive trend leading to a value of 0.04 kg/hp*day in 2013.

The S-K test did not detect any significant difference in the average size frequencies in the catches between the two time periods considered (1984–1989 and 2008–2010), neither for females nor for males ($p > 0.05$) (Figure 9). The results of the pseudo-cohort and yield per recruit analysis are shown in Table 4. According to the pseudo-cohort analysis, the mean population biomass of males was lower than that of females at all years studied, reflecting the sex ratio in the fishing grounds and catches (Sardà et al., 1994; Sardà et al., 2003). The mean population biomass of females was considerably lower in the period 1984–1989 compared to 2008–2010, passing from an average of 398 t to an average of 953 t.

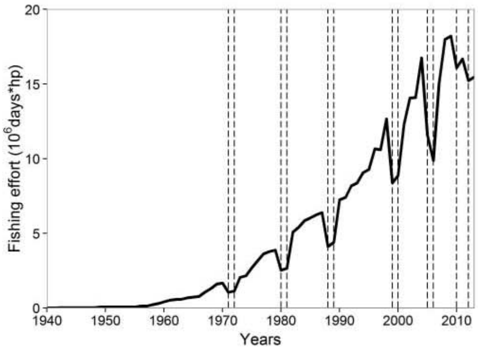

Figure 6. Historical series of fishing effort directed to the red shrimp in Catalonia from 1940 to 2013. The series includes a yearly rate of 1% increase due to technological creep starting from 1980. The dashed lines indicate years in which intense cascading events occurred.

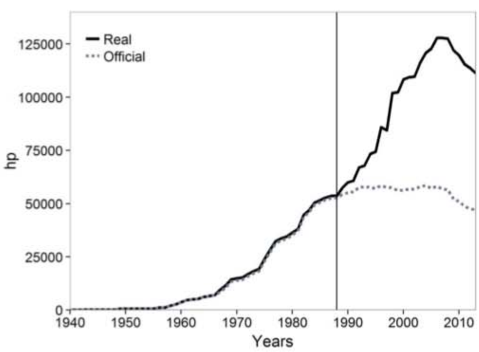

Figure 5. Historical series of total engine power (hp) of the trawling fleets targeting red shrimp in the Catalan region from 1940 to 2013. Official versus real values of hp are shown. The vertical line indicates the year in which the regulation establishing engine power at a maximum of 500 hp came into force (i.e., 1988).

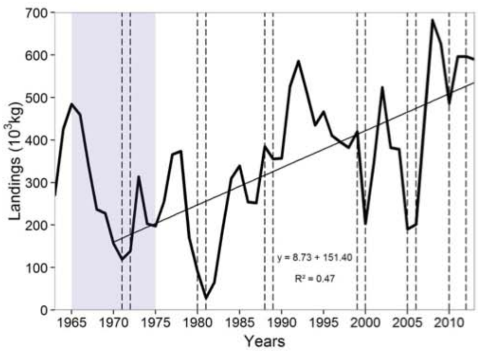

Figure 7. Historical series of red shrimp landings from 1963 to 2013 in Catalonia. The gray area indicates the period of fleet modernization according to Alegret and Garrido (2004). The linear regression for landings in years after fleet modernization is shown (from 1970: $p = 0.000$). The dashed lines indicate the years in which intense cascading events occurred.

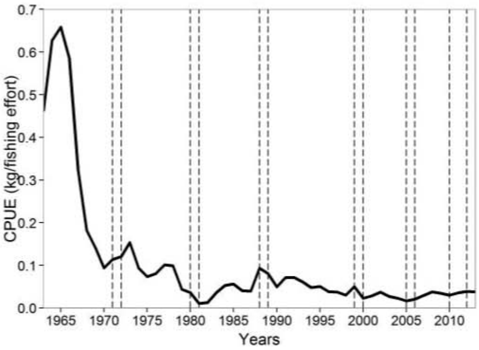

Figure 8. Historical series of red shrimp CPUE from 1963 to 2013 in Catalonia. The dashed lines indicate the years in which intense cascading events occurred.

For males, differences in the estimated values of biomass between the two time periods existed as well, but were not as marked as for females. Biomass of female recruits was higher in the second period of time, too. For males the opposite was true. Mean fishing mortality (mean *F*) did not show any particular trend neither within nor between periods, for neither sex. Despite the S-K test not detecting any significant differences in the average length frequencies in the catches, the pseudo-cohort analysis suggests that the mean individual size in the population decreased from the period 1984–1989 to 2008–2010. In fact, average values of cephalothorax length were reduced by more than 1 mm in females (from 29.2 mm to 27.9 mm), and by more than 2 mm in males (from 21.7 mm to 19.5 mm) between the two periods. Females yield per recruit decreased by 10% between 1984–1989 and 2008–2010, passing from an average of 9.48 g to an average of 8.57 g. For males, the decline of the yield per recruit was less marked as average values went from 2.86 g to 2.22 g in the two periods respectively. The mean F values exceeded the reference point $F_{0.1}$ at all years and for both sexes, denoting overfishing of the resource in both periods of study (Table 4, Figure 10). For females, overfishing appeared more severe in the second period of time, with the average value of $F_{0.1}$/Mean F going from 0.49 to 0.41 between the two periods.

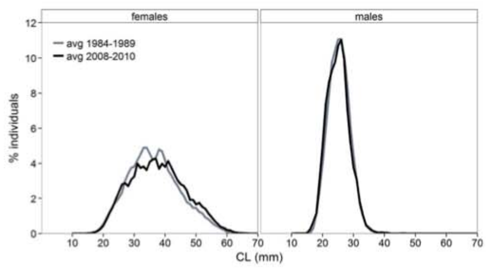

Figure 9. Length frequencies in the catches of red shrimps in the two periods considered for stock assessment (1984–1989 and 2008–2010), presented per year and sex (CL = cephalothorax length).

Table 4. Results of the pseudo-cohort and yield per recruit analysis shown per year and sex. $F_{0,1}$/Mean *F* is the optimum effort factor: if lower than one, the stock is subject to overfishing and vice versa.

	1984	1985	1986	1987	1988	1989	2008	2009	2010
Females									
Mean stock biomass (t)	392	572	416	235	379	393	1067	1068	724
Recruits (t)	67	94	59	90	104	82	114	135	94
Mean stock age	1.6	1.7	1.7	1.6	1.5	1.6	1.5	1.6	1.5
Mean stock length	28.7	30.3	30.0	29.3	27.6	29.1	27.1	29.1	27.5
Mean *F*	1.09	1.05	0.88	1.24	1.53	0.96	0.98	1.24	1.29
Y/R (g)	9.39	9.68	8.99	10.39	9.11	9.32	8.14	9.00	8.57
$F_{0.1}$	0.52	0.54	0.52	0.63	0.53	0.5	0.45	0.51	0.49
$F_{0.1}$;/Mean *F*	0.48	0.51	0.59	0.51	0.35	0.52	0.46	0.41	0.38
Males									
Mean stock biomass (t)	42	52	40	40	72	145	91	71	48
Recruits (t)	30	35	25	35	48	84	29	42	25
Mean stock age	1.6	1.6	1.6	1.6	1.5	1.5	1.1	1.5	1.3
Mean stock length	21.7	21.8	22.2	22.0	20.9	21.3	17.7	21.2	19.6
Mean *F*	1.75	1.90	1.38	1.70	1.15	1.80	0.94	1.70	1.11
Y/R (g)	2.91	2.9	2.78	3.26	2.68	2.63	1.77	2.63	2.26
$F_{0.1}$	0.99	0.93	0.94	1.28	0.92	0.94	0.73	0.87	0.82
$F_{0.1}$/Mean *F*	0.57	0.49	0.68	0.75	0.8	0.52	0.78	0.51	0.74

4. Discussion

Effective fisheries evaluations and management require the full understanding of the fishing effort directed to the fish stocks and its historical evolution (Hilborn and Walters, 1992). Official data are often unable to capture real trends in fishing effort, and the need to improve

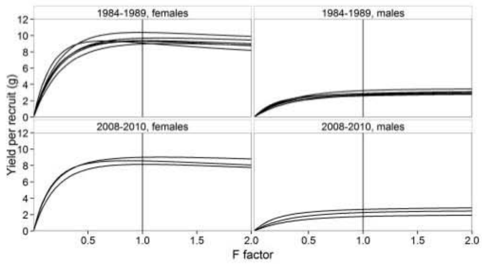

Figure 10. Curves of yield per recruit versus effort factor (i.e., multiplying factor for present level of fishing effort) in the two periods considered for stock assessment (1984–1989 and 2008–2010), presented per year and sex. The black vertical lines indicate the current level of fishing effort.

official statistics through "informed adjustments" has been widely discussed (Watson et al., 2000; Ota and Just, 2008; Anticamara et al., 2011). For these reasons, the evaluation of official data with the identification of gaps, biases, and misreporting is fundamental in the context of fisheries research. In the fishery object of this study, the steep fishing effort increase in the last 25 years was due to a large degree to the increase of trawlers engine power. However, this could not be inferred from the official records due to heavy misreporting. Engine power plays an important role in determining fishing effort and the incorporation of its variations is widely recommended especially when evaluating temporal trends (Gulland, 1969; Anonymous, 2007a). In fact, the size of the fishing gear increases significantly with the trawler engine horsepower (Eigaard et al., 2011). Moreover, according to the fishermen interviewed in this study, a more powerful engine significantly decreases transfer time to the fishing grounds, gaining extra time for trawling on a daily basis. A more powerful vessel also allows trawling in deeper waters (expanding the limits of the fishing grounds) and increases fishing efficiency in rough weather. In addition, the need to incorporate other descriptors of technological creep that result in a significant increase in fishing efficiency was stressed by many authors (Pauly et al., 2002; Marchal et al., 2006; Marriott et al., 2010; Eigaard et al., 2011).

The data collected with the interviews were a reliable source of information given the high confidence between the two parties based on years of previous and ongoing collaborations. In fact, when the condition of trust is met, interviews can supply good and high resolution information on fishing practices that might be unavailable otherwise (McCluskey and Lewison, 2008). This allowed a careful correction of the official data. The extrapolation to the other Catalan harbors of the results on hp values obtained with the interviews in Palamós, Tarragona, and Blanes was justified by similarities in the trawling fleets, fishing habits, and socio-economic conditions in these ports. In addition, the number of shrimp trawlers of these harbors represents around 45% of the total in the study area, landing about 50% of all red shrimp. Therefore, these data were considered well representative of the Catalan area and extrapolation to the surrounding ports legitimate.

The series of fishing effort presented in this study shows a steep increasing trend starting from the second half of the last century. It has to be considered that in the first decades of our series (until 1970), the vessels had a lesser efficiency to work in bad weather compared to the present. According to the fishermen interviewed, fishing days in these years were probably less compared to the present. Unfortunately, there were no records available to quantify this difference, and therefore there is a chance that fishing days in the first decades of our series were overestimated. Starting from 2006 and due to unfavorable economic conditions (high gasoil price, declining stocks), several vessels were scrapped and improvements in engine power of active trawlers were avoided. This situation determined the decrease of fishing effort detected in the latest years of our series. A very similar pattern of fleet engine power evolution in the area was previously suggested by Coll et al. (2014), where one Catalan harbor was considered. Similar results were also obtained on a trawling fleet in the Balearic region (Coll et al., 2014). Here, despite a decrease in the number of trawlers, the total engine power doubled its value from the 1970s to the 1900s (Carbonell et al., 1999; Carbonell, 2005).

As previously mentioned, the minimums displayed by the landing series were associated with particularly strong cascading events that occurred in the study area (Figure 7). The hypothesis behind the relatively fast recovery of landings after a minimum is that cascading enhances recruitment in the following years thanks to the supply of organic matter to the deep basin (Company et al., 2008). In fact, after two or three years from a cascading event, exceptional catches of small individuals are observed. The series of CPUE seems less influenced by the cascading because generally, when exceptional environmental conditions are verified, both landings and fishing effort are reduced. The overall decline of CPUE over the time frame considered suggests a decline in the red shrimp abundance. However, it has to be beard in mind that inference on stock abundance based on CPUE relies on the assumption of constant catchability. In reality, catchability can be influenced by many factors, such as changes in gear selectivity, technological improvements, fishermen skills, and fishing behavior (Harley et al., 2001; Bishop et al., 2006; Maunder et al., 2006). In this work, we accounted for a few of these factors in the calculation of CPUE, but a different trend in the resource abundance might be concealed by other factors influencing the catchability. For example, the apparent stabilization of CPUE in the latest years of the series might be due to a decrease in gear selectivity and/or changes in fishermen behavior, which increased the fishing efficiency masking a further reduction of the red shrimp abundance. Unfortunately, we had no fishery independent index to allow a more precise evaluation of the resource abundance.

The mean stock biomass estimated by the pseudo-cohort analysis was higher for the period 2008–2010 than for the period 1984–1989. These estimates are highly dependent on catches, which in fact were considerably higher in the second period of time. However, this was most probably due to increased fishing effort (not taken into account in the analysis), rather than increased population biomass. In fact, the increase of fishing effort is likely to have caused an expansion of the fishing grounds, with more powerful vessels fishing at deeper waters increasing the portion of the stock exploited (Coll et al., 2008). The decrease of the yield per recruit between the two periods of time could result from a change in the selectivity of the fishery and/or a change in the fishing strategy, with smaller individuals living at deeper waters becoming a target of the fishery (Sardà et al., 1994). It has to be considered that the assumption of steady state implied by the use of the pseudo-cohort analysis is a very constraining one. In fact, variations in the recruitment and mortalities of the red shrimp induced by environmental factors (which occurred in the years considered for stock assessment) are likely to have biased the results. For example, 2008 was a year of enhanced juveniles catches (Company, own unpublished data). Thus, the interpretation of the VIT results should be taken with care. In particular, a comparative study by Ratz et al. (2010) showed that quantitative conclusions from VIT results are particularly sensitive to violations of assumptions, while estimates of $F_{0.1}$ remain in line with estimates from more complex models.

Similarly to the present study, overfishing of *A. antennatus* was detected by many authors in several areas of the Mediterranean Sea, such as the strait of Ibiza, the Balearic Islands, and Sicily (Ragonese and Bianchini, 1996; García-Rodríguez and Esteban, 1999; Carbonell, 2005). The "optimum exploitation" of this resource in Catalonia was only detected when F_{max} was considered as a reference point instead of $F_{0.1}$ (Demestre and Lleonart, 1993). In this work, we refer to $F_{0.1}$ as it was indicated as a better proxy for F_{msy} than F_{max}, being consistent with high yield and low risk of collapse in line with a precautionary approach (Gabriel and Mace, 1999; Anonymous, 2007b; Kell and Fromentin, 2007).

The point that despite decades of overfishing the stocks of *A. antennatus* have not collapsed yet has been widely discussed (Demestre and Lleonart, 1993; Sardà, 1993; García-Rodríguez et al., 1999; D'Onghia et al., 2005). The rapid growth rate and short life span of this invertebrate species were advocated as factors limiting its sensitivity to intense fishing activities. In addition, the sudden and local shoals fluctuations and the large portion of the population residing in areas outside the fishing grounds might contribute to prevent the collapse of this stock (Demestre and Martín, 1993; Sardà et al., 2004; Company et al., 2008). Also, the effects of strong cascading events could work as a natural fishery regulation, periodically lowering the fishing mortality and having a positive effect on the recruitment (Company et al., 2008). However, the historical perspective presented in this work undermines the idea of long-term resilience of this species to the fishing activities. The decrease of the yield per recruit, CPUE and mean individual length over the time frame considered might in fact be the symptom of population changes induced by the intense exploitation. Our results suggest that fishing effort should be reduced and size at first capture increased, in order to lower fishing mortality to sustainable levels and maximize the yield per recruit. In addition, this study indicates that the long-term effects of the high fishing levels on the red shrimp are yet to be clarified, and that a stock assessment method capable of including fishing effort changes and environmental effects should be developed for this purpose. Finally, our results strongly demonstrate that official data series should be rigorously reviewed before taken into account in fisheries evaluations. In fact, our study shows that fishing effort based on raw official data can be underestimated by more than 50%. We also believe that these results are paradigmatic of many Mediterranean fisheries. Moreover, being most of these fisheries multi specific (with the same vessels targeting different species according to season, prices at market, etc.) the results of this work can be directly applied to the stock assessment of other species, such as European hake, red mullet, or Norway lobster.

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Spatio-temporal variability of discards in the fishery of the deep-sea red shrimp *Aristeus antennatus* in the northwestern Mediterranean Sea: implications for management

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Summary: In this work we analysed the spatio-temporal variability of discards in the fishery of the deep-sea red shrimp *Aristeus antennatus* in the northwestern Mediterranean Sea. We sampled fishery discards in the fishing grounds of Palamós (the main harbour for this fishery on the Catalan margin), which are located in several areas of a submarine canyon. We found that the discard ratio in this fishery showed a marked seasonal variability, with a maximum in spring and a minimum in summer. Most of the discarded biomass (almost 96%) were of species with no commercial interest. Within these, the most represented group was elasmobranchs, making up to more than 50% of total discarded biomass. Our findings show that the landing obligation established by the EU will have a low impact in mitigating discards in this fishery, as the vast majority of discards are non-commercial species that are not specified in the regulation. Alternative management strategies, such as a temporary fishery closure in spring (when the discard ratio reaches its maximum), should be considered in order to preserve the vulnerable ecosystem hosted by the submarine canyon.

Keywords: Northwestern Mediterranean; trawl fishery; fishery discards; fisheries impact; deep-sea; *Aristeus antennatus*.

Variabilidad espacio-temporal de los descartes en la pesquería de la gamba roja de profundidad *Aristeus antennatus* en el mar Mediterráneo Noroccidental: implicaciones para la gestión

Resumen: En este estudio se analizó la variabilidad espacio-temporal de los descartes en la pesquería de la gamba roja de profundidad *Aristeus antennatus* en el mar Mediterráneo Noroccidental. Para ello se muestrearon las capturas obtenidas en los caladeros de Palamós (el mayor puerto para esta pesquería en Cataluña), que están localizados en diferentes áreas adyacentes a un cañón submarino. Nuestros resultados demuestran que la proporción de descartes en las capturas de esta pesquería presenta una marcada variabilidad estacional, con un máximo en primavera y un mínimo en verano. La mayoría de la biomasa de los descartes (casi el 96%) está constituida por especies sin ningún interés comercial. Entre éstas, el grupo más representado es el de los elasmobranquios, que constituye más del 50% de la biomasa total de los descartes. Nuestros resultados indican que la obligación de desembarcar las capturas establecida por la UE tendrá un impacto bajo en disminuir los descartes en esta pesquería, ya que la gran mayoría de los descartes está constituida por especies no comerciales que no están especificadas en la regulación. Medidas de gestión alternativas, como el establecimiento de una veda en primavera (cuando la proporción de descartes llega a su máximo) deberían considerarse para preservar el ecosistema vulnerable de este cañón submarino.

Palabras clave: Mediterráneo Noroccidental; pesca de arrastre; descartes; impacto de la pesca; mar profundo; *Aristeus antennatus*.

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INTRODUCTION

Fisheries have an impact on the ecosystems at various levels, as fishing operations affect not only the targeted fish stocks but also a number of species that are caught accidently in the fishing gears. These species are thrown back to the sea, dead or alive, and constitute the fishery discards (Catchpole et al. 2005, Kelleher 2005, Bellido et al. 2011). Discarded species may have no commercial interest or may be valuable species that are unmarketable for different reasons (undersized or damaged individuals, exceeded quotas, etc.). The effect of fishing activities on the environment is great, ranging from ecosystem depletion to habitat destruction, and discards account for a great part of the overall impact (Ramsay et al. 1998, Jennings and Kaiser 1998, Sánchez et al. 2000). In fact, up to 60% of the total catch is discarded in some of the most important European trawl fisheries (STECF 2006). In the last few years, after the establishment of the Ecosystem Approach to Fisheries Management as an integrated approach which considers the effects of fisheries on the whole ecosystem (FAO fisheries glossary, http://www.fao.org/fi/glossary/default.asp), estimating discards and developing ad hoc management strategies have been regarded as a priority (Catchpole and Gray 2010, Bellido et al. 2011, Hilborn 2011). In Europe, discards are currently a hot topic for fisheries management (Catchpole et al. 2005, Johnsen and Eliasen 2011, Sardà et al. 2013, Condie et al. 2014). They form an important part of the reformed Common Fisheries Policy (CFP), which has established a landing obligation that will come into force gradually in the next four years (European Union 2013). The aim of the landing obligation is to reduce wastage in fishing operations while incentivizing discard avoidance. In this context, it is important to consider that discards are highly variable in both space and time (Ye et al. 2000, Uhlmann et al. 2013, Pennino et al. 2014). Extensive research on discards in single fisheries with the identification of factors shaping their spatio-temporal patterns is therefore required in order to improve discard avoidance and selectivity.

In the Mediterranean Sea, trawl fishery is the most important fishery in terms of both volume and economic value of catches (Bas et al. 1984, Abelló et al. 2002). This fishery is generally characterized by high discard ratios and it is responsible for the bulk of discards (Stergiou et al. 1998, Castriota et al. 2001, Carbonell et al. 2003, Sánchez et al. 2004, Tsagarakis et al. 2008). A recent review by Tsagarakis et al. (2013) identified a wide range of discard ratios within Mediterranean trawling fisheries, ranging from 10% to 90%. Factors acknowledged for affecting discards are various and comprise depth, geographic area, seabed characteristics, season, fishing methods, gear characteristics and cultural factors (Machias et al. 2001, Sartor et al. 2003, Sánchez et al. 2007, Edelist et al. 2011, Pennino et al. 2014). The high diversification of fishing practices and the wide range of environmental characteristics in the Mediterranean Sea place severe difficulties in the way of effective management measures to mitigate discards. This condition is compounded by several major gaps in knowledge (Lleonart and Maynou 2003, Kelleher 2005, Tsagarakis et al. 2013). A greater effort to quantify discards and identify factors affecting and shaping their patterns is therefore required.

In the northwestern Mediterranean Sea, the most economically important deep-sea trawl fishery is the one targeting the red shrimp *Aristeus antennatus* (Risso, 1816). In the Catalan area (northeast Spain) this fishery operates in fishing grounds allocated along the margins of a series of submarine canyons carved into the continental margin. Submarine canyons create considerable depths close to the coast and increase habitat complexity. They also act as major conduits for the transportation and concentration of organic particles (Heussner et al. 1996, Canals et al. 2006, Puig et al. 2013). These characteristics may favour the abundance, biomass and diversity of benthic and pelagic species in the canyons compared with the open slope (Vetter and Dayton 1999). It has also been observed that the higher habitat heterogeneity and the increased food availability in the canyons provide suitable conditions for recruitment of several species of fish and crustaceans (Sardà et al. 1994b, Stefanescu et al. 1994). The importance of submarine canyons in shaping the benthic community of species in the northwestern Mediterranean Sea was assessed in several studies (Sardà et al. 1994a, Ramirez-Llodra et al. 2008). In particular, the relationship between the topography of the canyons and the red shrimp seasonal migrations was described in detail (Sardà et al. 2003, Tudela et al. 2003, Sardà et al. 2004, Sardà et al. 2009) and is well known to the fishers who direct the fishing effort accordingly (Sardà et al. 1997). The vulnerability of these environments to fishing activities has also been pointed out (Ramirez-Llodra et al. 2010). In fact, as deep-sea ecosystems, they are characterized by long-lived species with slow growth, late age of maturity and low fecundity, which make them particularly sensitive to the impact of human activities (Koslow et al. 2000). However, no research on the role of the submarine canyons in shaping patterns of fishery discards has been performed so far.

The aim of this work was to broaden our knowledge of fishery discards in the vulnerable environment of the deep sea, which is important for fishery management both at European and local level. In particular, we investigate the spatio-temporal discard patterns associated with a submarine canyon in the fishery of the red shrimp in the northwestern Mediterranean Sea. The canyon considered is the Palamós Canyon (Fig. 1). The canyon head, wall and open margin of this canyon are the most heavily trawled fishing grounds for this species in the area, with the Palamós trawling fleet landing about 30% of red shrimp in Catalonia on a yearly average (data source: Official fishery statistics from the Catalan government). Since 2013 the red shrimp fishery in Palamós has been regulated by a local management plan developed within a co-management framework between fishermen, scientists, local administration and NGOs (BOE 2013). Management measures aim to increase the fishery sustainability, paying particular attention to reducing fishing pressure on small-sized individuals of the target species. These measures include a temporary fishery closure at the canyon head (where shoals of shrimp recruits con-

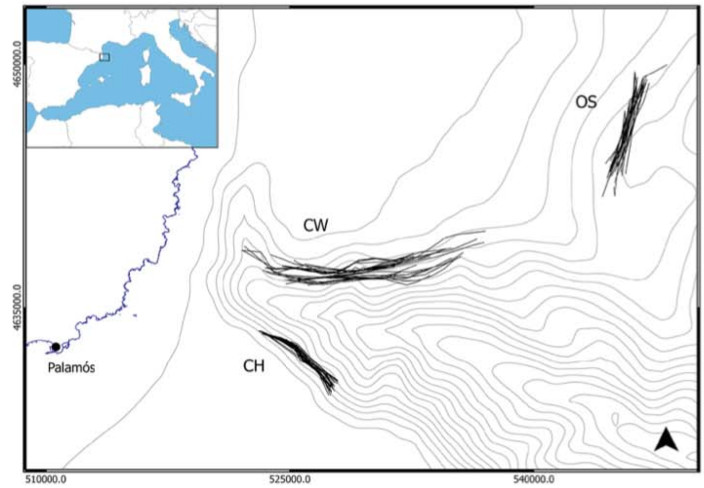

Fig. 1. – Map representing the Palamós canyon and the three main fishing grounds sampled in this study (CH, canyon head; CW, canyon wall; OS, open slope). Tracks of the sampling tows are shown in the map. Coastline is in blue and bathymetry is displayed every 100 m.

centrate) in winter and an increase in gear selectivity. A further improvement in the management plan would be to include ad hoc spatio-temporal management measures to mitigate discards. For this purpose, the specific questions addressed in this work were (i) whether the Palamós submarine canyon and/or the season of the year have an effect on the discard ratio in the fishery studied; and (ii) whether there is a seasonal or spatial variability in discards composition. In order to answer these questions, we analysed the composition of catches during a two-year sampling onboard a commercial trawler targeting red shrimp in the Palamós canyon.

MATERIALS AND METHODS

Data were collected on a monthly basis from January 2012 to December 2013, during commercial fishing trips onboard a red shrimp trawler of the Palamós fleet. During each trip we sampled three areas of the Palamós canyon corresponding to the main fishing grounds for this fishery in Catalonia. These areas were the canyon head (average depth, 426 m; total number of tows, 28), the canyon wall (average depth, 504 m; total number of tows, 28) and the open slope, i.e. the area just outside the canyon (average depth, 602 m; total number of tows, 26) (Fig. 1). The average tow trawled 0.2 km^2 at the canyon head, 0.3 km^2 at the canyon wall and 0.2 km^2 on the open slope. The start and end position of each tow, as well as the horizontal opening of the net's mouth, were identified by SCANMAR sensors mounted on the trawl's mouth. These data allowed calculation of the area sampled. After each tow fishermen sorted species into three main categories: target (*A. antennatus*), by-catch (non-target species of commercial interest) and discards (species with no commercial interest and/or undersized or damaged individuals of commercial species). We recorded the total weight of the commercial yield onboard, while discarded species were preserved in field coolers for further analysis. Once in the lab, the samples were sorted to species level or to the smallest possible taxonomical level. The biomass and abundance of discards were calculated per taxonomical group and standardized per square kilometre trawled.

Differences in the total weight of discards between fishing grounds and seasons were tested by two-way crossed ANOVA on log-transformed data and post-hoc pairwise Tukey test. Before ANOVA was applied (here and in the following analysis) data were tested for normality and homoscedasticity using Shapiro-Wilk's and Bartlett's test, respectively. The discard ratio per tow was calculated as:

$$\text{Discard ratio} = \frac{\text{Discards weight}}{\text{Discards weight} + \text{Commercial catch weight}}$$

Two-way crossed ANOVA and post-hoc Tukey tests were performed on log-transformed data in order to test the effect of fishing ground and season on the discard ratios. Species recovered in the discards were grouped into classes, and differences in abundance and biomass of individual classes were tested by two-way crossed ANOVA. The abundance of the discarded species in each tow was used to calculate two diversity indices: total number of species (S) and N_{90} diversity index. The N_{90} diversity index was proposed by Farriols et al. (2015). It uses the results of the SIMPER analysis (Clarke and Warwick 2001) and a jackknife resampling to work out the average and dispersion of the number of species contributing to the 90% similarity within each group of samples analysed. Therefore, the N_{90} takes into account both number of species and community structure for its calculation. It was also shown to be able to detect loss of diversity due to fishing impact where other diversity indices failed (Farri-

Table 1. – List of the most common species in the discards (accounting for 99% of total abundance and 95% of total biomass) in the four seasons of the year (Win, winter; Spr, spring; Sum, summer; Aut, autumn) and the three different fishing grounds (CH, canyon head; CW, canyon wall; OS, open slope).

		Average abundance (Individuals km^{-2})						
Class	Species	Win	Spr	Sum	Aut	CH	CW	OS
Chondrichthyes	*Galeus melastomus*	28.8	80.7	10.5	44.6	19.9	35.5	87.0
	Scyliorhinus canicula	14.2	22.9	9.4	23.0	29.0	16.4	8.5
	Etmopterus spinax	2.4	4.2	0.9	3.4	3.4	0.0	5.7
Actinopterygii	*Lampanyctus crocodilus*	30.3	142.9	47.7	42.2	41.4	88.6	100.1
	Trachyrincus scabrus	14.4	29.8	3.5	20.0	22.4	23.5	8.3
	Lepidion lepidion	16.0	25.1	5.2	2.8	8.5	13.6	18.1
	Capros aper	0.0	32.3	4.3	1.5	36.5	1.2	0.0
	Notacanthus bonaparte	5.6	2.8	1.3	30.1	0.9	10.6	17.7
	Nezumia aequalis	9.1	15.2	1.1	7.6	4.2	6.8	16.4
	Lepidopus caudatus	2.9	14.6	5.4	4.8	5.0	15.3	2.7
	Mora moro	5.9	5.7	3.8	14.7	0.9	4.5	17.9
	Gadiculus argenteus	0.8	0.9	0.0	23.8	1.8	9.6	7.1
	Conger conger	4.5	4.9	4.3	6.3	2.5	5.7	7.0
	Phycis blennoides	0.3	10.3	4.2	1.4	1.7	7.4	5.8
	Stomias boa boa	3.4	3.9	5.2	6.9	6.4	2.8	5.7
	Coelorhynchus sp.	3.1	8.9	0.8	1.3	9.0	1.7	1.6
	Symphurus sp.	0.8	0.0	0.2	14.8	0.0	8.0	2.9
	Lepidorhombus boscii	1.2	4.5	3.0	3.6	6.0	3.5	0.4
	Chauliodus sloani	0.5	1.5	8.1	2.2	0.8	1.9	6.9
	Helicolenus dactylopterus	3.6	1.3	1.9	1.3	4.4	0.4	0.8
	Hoplostethus mediterraneus	1.2	1.8	1.9	2.1	2.8	1.1	1.5
	Antonogadus megalokynodon	0.2	0.0	0.0	6.1	0.0	4.3	0.0
	Epigonus sp.	0.0	0.1	0.4	4.0	0.0	2.1	1.2
	Argyropelecus hemigymnus	0.0	0.0	0.0	3.9	0.2	0.0	2.8
	Arctozenus risso	0.0	0.0	2.3	0.9	0.2	1.6	0.4
	Alepocephalus rostratus	1.8	0.6	0.7	0.3	0.7	0.6	1.0
	Myctophidae sp.	1.4	0.0	0.0	1.6	0.2	1.1	0.5
	Micromesistius poutassou	1.0	0.6	0.5	0.0	0.4	0.5	0.5
Malacostraca	*Pasiphaea multidentata*	22.3	3.9	4.8	1431.9	9.0	122.6	1001.0
	Pasiphaea sivado	44.7	4.0	28.6	29.6	43.7	23.6	0.0
	Procesa sp.	1.2	2.7	0.0	62.8	0.5	13.5	37.1
	Plesionika martia	0.6	2.5	0.4	52.9	0.7	12.5	29.9
	Solenocera membranacea	0.0	1.2	0.1	42.6	0.0	30.2	0.0
	Meganyctiphanes norvegica	0.0	0.0	0.0	41.9	0.0	28.4	0.0
	Sergestes arcticus	0.0	0.0	0.0	25.1	0.0	3.4	15.9
	Polycheles typhlops	4.8	6.6	2.3	9.6	1.4	10.0	6.2
	Pleisionika edwardsii	11.5	3.6	0.0	0.0	3.0	1.5	5.3
	Nephrops norvegicus	1.0	0.9	0.0	4.6	0.0	4.1	0.5
	Pontocaris lacazei	0.0	1.3	0.9	1.7	0.0	2.7	0.4
	Paromola cuvieri	2.6	1.1	0.3	0.3	1.9	0.7	0.3
	Liocarcinus sp.	0.0	0.1	1.0	1.4	0.7	1.2	0.0
	Parapenaeus longirostris	0.0	1.7	0.0	0.0	1.8	0.0	0.0
	Pagurus alatus	1.8	0.4	0.0	0.5	0.2	0.3	1.3
Cephalopoda	*Histiotheutis reversa*	2.2	0.2	6.3	5.9	1.3	3.0	6.1
	Eledone cirrhosa	5.8	2.0	1.4	0.0	1.8	3.3	0.6
	Histiotheutis bonelli	0.5	3.1	0.8	0.2	0.7	0.6	3.2
	Sepiola rondeletii	0.0	0.5	1.2	2.2	0.8	1.9	0.2
	Todarodes sagittatus	0.5	1.4	0.0	1.3	1.0	1.3	0.3
	Ommastrephidae sp.	1.7	0.9	0.3	0.3	1.4	0.1	0.8
	Bathypolypus sponsalis	1.2	0.3	1.3	0.5	0.4	0.6	1.2
	Octopus salutii	1.1	0.8	0.2	0.0	0.7	0.6	0.3
	Ilex condeitti	1.3	0.0	0.0	1.2	0.2	1.2	0.0
Thaliacea	*Pyrosoma atlanticum*	0.0	5.0	0.0	2.4	0.2	0.2	7.1
	Salpa sp.	5.4	10.4	0.0	0.0	10.8	1.8	0.8

ols et al. 2015). The index units, number of species, are straightforward and easy to interpret. Differences in S and N_{90} between seasons and fishing grounds were tested by two-way crossed ANOVA and Kruskal-Wallis tests and by post-hoc pairwise tests, respectively. Prior to calculation of N_{90}, abundance data were square-root transformed in order to downweight the contribution of the most abundant species to the results (Clarke and Warwick 2001).

Multivariate analyses were performed using the PRIMER software (Clarke and Gorley 2006). Species abundance was used to calculate the Bray-Curtis similarity index between tows. Data were square-root transformed prior to analysis. The similarities within each fishing ground and season in the species composition of discards were explored by a multidimensional ordination plot (MDS). Differences between fishing grounds and seasons in the species composition of discards were tested by ANOSIM, and SIMPER was employed to detect the species accounting for any significant difference.

RESULTS

In this study, a total of 94 species were found in the discards during sampling. Table 1 shows a list of the most common species found, i.e. those accounting for nearly 99% of total abundance and 95% of total bio-

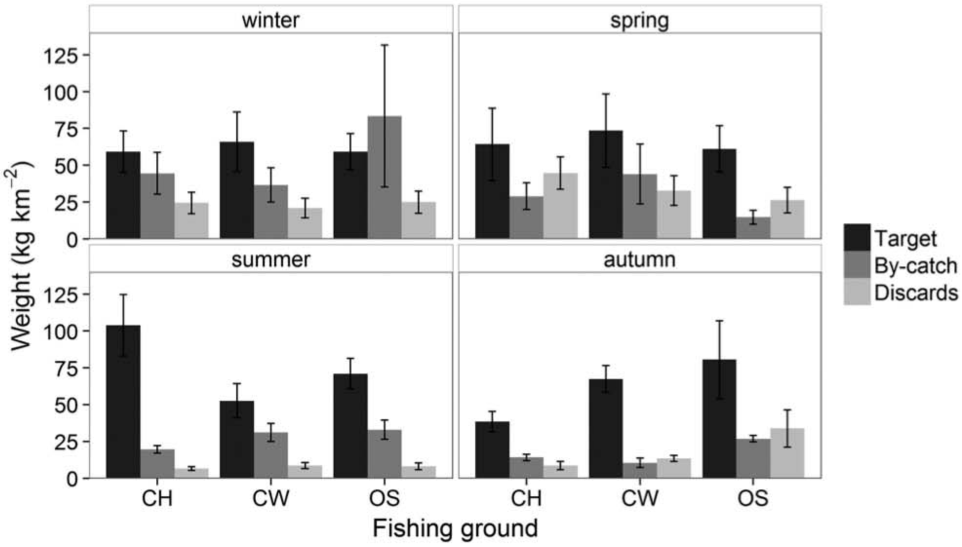

Fig. 2. – Average weight (kg km^{-2}) and standard error of discards, target species and bycatch species in the catches shown per season and fishing ground (CH, canyon head; CW, canyon wall; OS, open slope).

mass. Regarding the remaining 5% of biomass, 62.3% belonged to one species of Elasmobranchia (kitefin shark *Dalatias licha*), 4.6% to one species of Holocephali (rabbit fish *Chimaera monstrosa*), 21.2% to various species of the class Cephalopoda, 10% to Actinopterygii, 0.8% to Gastropoda, 0.7% to Malacostraca and 0.4% to Echinoidea. There were no discards of the target species *A. antennatus,* as there is no minimum landing size (MLS) or catch quota associated with this resource, and any damaged individual was consumed by the fishing crew. Discards of commercial species were limited to a few undersized or damaged specimens of pink glass shrimp (*Pasiphaea multidentata*), greater fork-beard (*Phycis blennoides*), Norway lobster (*Nephrops norvegicus*), blue whiting (*Micromesistius poutassou*) and European hake (*Merluccius merluccius*). These species accounted for less than 4.1% of total discarded biomass. The commercial fraction of the fishery comprised the target species *A. antennatus* and a few by-catch species, mainly *Phycis blennoides,* anglerfish *Lophius piscatorius, Micromesistius poutassou, Pasiphaea multidentata* and *Merluccius merluccius*. The total weight of discards ranged between 1 and 109 kg per km^2 trawled, while the commercial yield ranged between 9 and 331 kg per km^2 (Fig. 2). The biomass of discards per km^2 showed a significant decrease in summer compared with the other seasons of the year (ANOVA, F=11.821, df=3, P<0.001). No significant differences were detected between fishing grounds (Fig. 3A). The discard ratios ranged between 0.21 and 0.97, with a significant decrease in summer (Kruskal-Wallis, K-S=18.878, df=3, p<0.0001) and no significant difference between fishing grounds (Fig. 3B). The most represented class in terms of biomass in

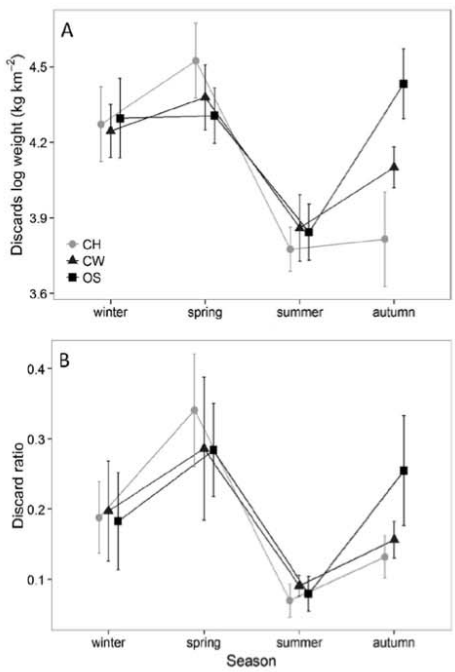

Fig. 3. – Average value and standard error of log-transformed discard weight (A) and discard ratio (B) per season and fishing ground (CH, canyon head; CW, canyon wall; OS, open slope).

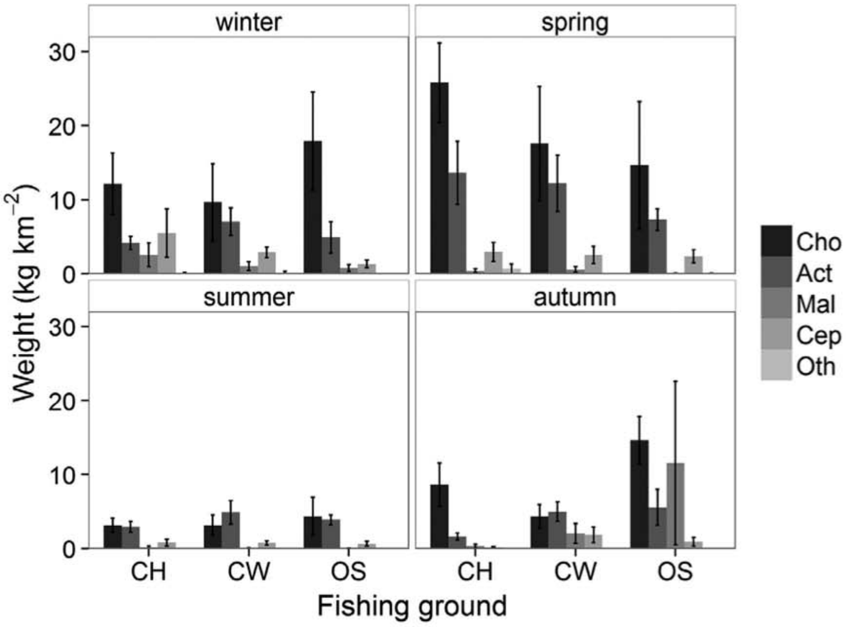

Fig. 4. – Average biomass (kg km^{-2}) and standard error of the different classes of organisms found in the discards per season and fishing ground (Cho, Chondrichthyes; Act, Actinopterygii; Mal, Malacostraca; Cep, Cephalopoda; Oth, other; CH, canyon head; CW, canyon wall; OS, open slope).

Table 2. – Results of two-way ANOVA testing the effect of season and fishing ground on the abundance and biomass of the most common classes of organisms found in the discards. Significance level: * = p<0.05; ** = p<0.01; *** = p<0.001.

Variable	Class	Factor	df	Sum sq.	Mean sq.	F value	p	Sig.
Biomass	Chondrichthyes	Season	3	4.678	1.5595	4.798	0.00462	**
		Fishing ground	2	1.199	0.5996	1.845	0.16693	
		Season*Fishing ground	6	1.666	0.2776	0.854	0.53370	
		Residuals	60	19.502	0.3250			
	Actinopterygii	Season	3	2.892	0.9640	6.006	0.00115	**
		Fishing ground	2	0.391	0.1957	1.219	0.30239	
		Season*Fishing ground	6	0.716	0.1194	0.744	0.61641	
		Residuals	63	10.111	0.1605			
	Malacostraca	Season	3	14.45	4.817	3.430	0.0221	*
		Fishing ground	2	4.15	2.074	1.477	0.2361	
		Season*Fishing ground	6	3.58	0.597	0.425	0.8598	
		Residuals	64	89.89	1.405			
	Cephalopoda	Season	3	13.20	4.398	2.631	0.0575	
		Fishing ground	2	5.88	2.938	1.757	0.1807	
		Season*Fishing ground	6	7.23	1.206	0.721	0.6339	
		Residuals	64	106.99	1.672			
Abundance	Chondrichthyes	Season	3	3.381	1.1269	6.396	0.00078	***
		Fishing ground	2	1.247	0.6234	3.538	0.03527	*
		Season*Fishing ground	6	0.956	0.1593	0.904	0.49826	
		Residuals	60	10.571	0.1762			
	Actinopterygii	Season	3	3.905	1.3018	8.353	0.0001	***
		Fishing ground	2	0.898	0.4489	2.880	0.0635	
		Season*Fishing ground	6	0.862	0.1437	0.922	0.4852	
		Residuals	63	9.818	0.1558			
	Malacostraca	Season	3	11.56	3.855	5.326	0.00244	**
		Fishing ground	2	2.83	1.414	1.953	0.15015	
		Season*Fishing ground	6	4.22	0.703	0.971	0.45221	
		Residuals	64	46.32	0.724			
	Cephalopoda	Season	3	0.578	0.1926	0.699	0.556	
		Fishing ground	2	0.757	0.3784	1.374	0.261	
		Season*Fishing ground	6	1.226	0.2044	0.742	0.618	
		Residuals	64	17.631	0.2755			

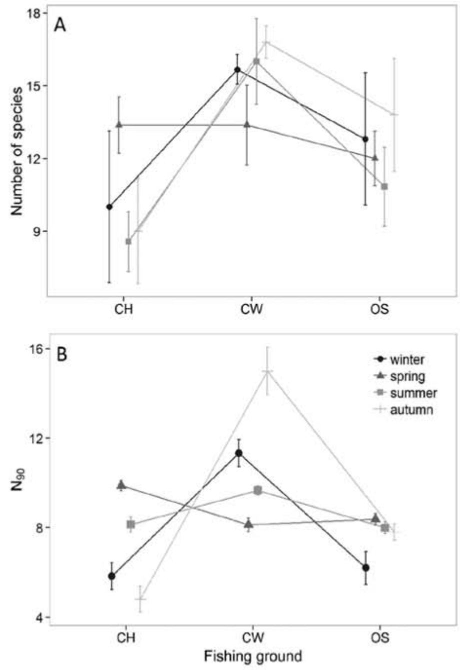

Fig. 5. – Average value and standard error of total number of species (A) and N_{90} diversity index (B) in the discards per season and fishing ground (CH, canyon head; CW, canyon wall; OS, open slope).

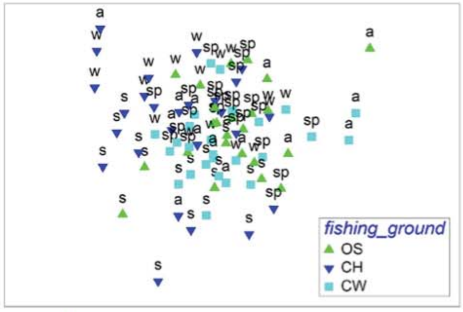

Fig. 6. – MDS ordination plot of the single hauls (CH, canyon head; CW, canyon wall; OS, open slope; w, winter; sp, spring; s, summer; a, autumn).

the discards was Chondrichthyes (53% of the total), followed by Actinopterygii (30%), Cephalopoda (9.1%) and Malacostraca (6.5%) (Fig. 4). Classes Echinoidea, Gastropoda and Thaliacea accounted together for less than 1.5% of total discarded biomass and were grouped into the class "other". Biomass and abundance of all classes except for Cephalopoda showed significant differences between seasons (Table 2). Abundance of Chondrichthyes also displayed a significant effect of fishing ground, with individuals being more abundant on the open slope. A total of five individuals of kitefin shark (*Dalatias licha*), a species classified as near threatened by the IUCN (2014), were found in the discards (two individuals on the open slope and three at the canyon head).

The number of species in the discards ranged between 2 and 24 and was significantly higher in the canyon wall than in the other fishing grounds (ANOVA, F=7.658, df=2, $p<0.01$) (Fig. 5A). The N_{90} index ranged between 4 and 18 and differences between fishing grounds, in particular between the canyon wall and the others, were significant (Kruskal-Wallis, K-S=22.5718, df=2, $p<0.05$). As displayed in Figure 5B, the N_{90} was significantly higher in the canyon wall in winter and autumn. An interaction between the factors fishing ground and season seems to be present, although the Kruskal-Wallis test does not allow testing for it and, due to non-normality of data, a two-way ANOVA could not be employed. The MDS ordination plot, where the two-dimensional distance between tows reflects the Bray-Curtis similarity index, is shown in Figure 6. ANOSIM detected significant differences in the species composition of discards both between seasons and fishing grounds. In particular, the pairwise test highlighted significant differences between spring and all other seasons ($p<0.001$), and between the canyon head and the canyon wall and open slope ($p<0.05$ and $p<0.001$, respectively).

The most common species in the discards at all seasons and fishing grounds were the jewel lanternfish (*Lampanyctus crocodilus*), the blackmouth catshark (*Galeus melastomus*) and the small spotted catshark (*Scylorhinus canicula*). Spring discards were characterized by higher abundance of these species compared with the other seasons, and a relatively high abundance of the less common actinopterygian species *Trachyrincus scabrus, Lepidion lepidion, Nezumia aequalis* and *Lepidopus caudatus*. On the other hand, the decapod crustacean *Pasiphaea multidentata,* actinopterygians *Notacanthus bonaparte, Mora moro* and *Gadiculus argenteus* were particularly abundant in autumn. According to the SIMPER analysis, the top 10 species contributing to the differences in the species composition of discards between the canyon head and the canyon wall were the chondrichthyans *Scylorhinus canicula*, the actinopterygians *Capros aper, Pasiphaea sivado*, more abundant at the canyon head, and *Lampanyctus crocodilus, Trachyrinchus scabrus, Galeus melastomus, Pasiphea multidentata*, and the decapod crustaceans *Polycheles typhlops, Lepidion lepidion* and *Lepidopus caudatus*, more abundant in the canyon wall. These species accounted for 44% of the total differences. The top 10 species accounting for 47% of the differences between the canyon head and the open slope were *Scylorhinus canicula, Trachyrincus scabrus, Capros aper*, the actinopterygian *Stomias boa boa*, more abundant at the canyon head, and *Lampanyctus crocodilus, Galeus melastomus, Pasiphaea multidentata, Mora moro, Nezumia aequalis, Lepidion lepidion*, more abundant on the open slope.

DISCUSSION

The average discard ratio observed in this study was 0.2, similar to values obtained in other studies on deep-sea trawl fisheries in the northwestern Mediterranean Sea (Sartor et al. 2003, Sánchez et al. 2004). In fact, a discard ratio of 0.2 was found in a previous study in the Catalan area and a discard ratio ranging between 0.2 and 0.3 was found in the Tyrrhenian Sea. The relatively low discard ratio found in these fisheries is associated with the high depths where they operate (>400 m). Trawl fisheries operating on the continental shelf at lower depths are usually associated with higher discard ratios (Sánchez et al. 2004, Tsagarakis et al. 2013). In the Balearic Islands, the discard ratio in deep-sea shrimp fisheries was a little bit higher, around 0.4, but diminished with depth (Moranta et al. 2000). Our results also highlighted a marked seasonal variability in the discard ratios. Their value was particularly high in spring, with 80% of discard ratios higher than 0.4 being observed in late March, April and May. These values were mostly due to the occurrence of a high discarded biomass in these months. Moreover, yields of the target species *A. antennatus* can be considerably reduced in the same months, contributing to the resulting high discard ratios. In fact, submarine currents (cascading) that occur in the study area in late winter/early spring can be particularly strong in some years and have been associated with extremely low catches of *A. antennatus* (Company et al. 2008). On the other hand, particularly low discard ratios were observed in summer. This is a favourable time for the fishery of the red shrimp in Catalonia, due to the high yields of the target species and the greater proportion of big individuals in the catches, which are sold at a higher price in the market (Sardà et al. 1994b).

The multivariate analysis showed that the species composition of discards at the canyon head was significantly different from that in the other fishing grounds, and the highest number of species was found at the canyon wall. Similar patterns in the community of species of the Blanes submarine canyon (a few miles south of the Palamós canyon, supporting a similar fishing activity) were highlighted in a previous study by Ramirez-Llodra et al. (2010). In fact, these authors found significant differences in the benthic community between locations inside and outside the canyon, and they also found that diversity was higher inside the canyon than on the open slope. Similarly to our study, these authors found a low or null abundance of sessile faunal groups, such as echinoderms, gastropods, bivalves and cnidarian. These groups were found to be common in other submarine canyons in the Catalan area (Cartes 1998, Ramirez-Llodra et al. 2008) but are particularly sensitive to fishing pressure with consistent loss of abundance in heavily trawled areas (Auster et al. 1996, De Juan et al. 2013). The fact that in this study we found that diversity of species at the canyon head, the most embedded area of the canyon, was reduced compared with diversity at the canyon wall might be an indicator of fishing impact in this highly productive and heavily trawled area. In fact, the canyon head is the closest fishing ground to the coast and is the principal target of fishing boats in winter and early spring when the weather is rough and shoals of red shrimp concentrate in this area (Tudela et al. 2003).

It stands out from our results that the vast majority of discards in this fishery (≈96%) consisted of non-commercial species belonging to a variety of taxa. In particular, more than half (53%) of the discards were Chondrichthyes, which are vulnerable species because of their biological traits and k-selection life history (Pennino et al. 2013). The discards include the nearly threatened species *Dalatias licha* (IUCN 2014). The mortality introduced at various levels of the ecosystem by the catch of unwanted species might imply serious consequences for the health of the submarine canyon's communities. For this reason, effective management to reduce discards in this fishery is required.

When the landing obligation required by the CFP of the EU comes into force, all catches of commercial species managed through catch quotas or MLS (except for those used as live baits) will be subject to mandatory landing (European Union 2013). In the Mediterranean, as there are no fisheries managed through catch quotas, except for the blue fin tuna, the landing obligation will apply to species managed through MLS at EU level (Article 15 of Regulation (EU) No 1380/2013, [European Union 2013]). However, according to our findings, this regulation will have an extremely low impact on the fishery studied, as nearly 96% of the total discards consist of non-commercial species that are not affected by the landing obligation at all. Our results show that the landing obligation will only prevent discarding of an average of 0.9 kg km^{-2} of undersized or damaged individuals of few commercial species. Our study confirms that the main reason for discarding in the Mediterranean Sea is the lack of commercial interest in many of the species caught (Sánchez et al. 2004, Tsagarakis et al. 2013, Catchpole et al. 2013). For this reason, the benefits of implementing the landing obligation in the Mediterranean Sea have been questioned by other authors (Sardà et al. 2013, Catchpole et al. 2013, García-Rivera et al. 2015).

If reducing discards is a priority within the CFP, a different management strategy, not solely based on commercial species, must be designed in order to address the particular characteristics of Mediterranean fisheries. In northern Europe, ad hoc spatio-temporal fishery closures have been highlighted as one of the most efficient management strategies for mitigating discards (Catchpole et al. 2005, Catchpole and Gray 2010, Johnsen et al. 2011, Condie et al. 2014). For example, the Norwegian fisheries in the Barents Sea (Bjørnar 1996) successfully reduced the discard ratio of haddock and cod by implementing a system of real-time closures, i.e. temporarily forbidding fishing in specific areas where the amount of unwanted catches was forecast to exceed a certain limit. In Kuwait, the shrimp trawling fishery successfully reduced the catch of unwanted species by introducing a spatial fishery closure in the Kuwait bay (Ye et al. 2000).

In the fishery studied, a temporal fishery closure might be an appropriate management strategy given the high seasonal pattern of discard ratios. The closure should include at least the fishing grounds inside the canyon, which is the area hosting the greatest diversity and the most vulnerable to the impact of fishing activities. A one-month fishery closure in winter is already in place in the three fishing grounds studied, and it aims to preserve the red shrimp juveniles. Our suggestion is that this closure should be prolonged for a few weeks in spring in order to address the discard issue at the canyon head and wall. The effectiveness of this measure for mitigating overall discards in the fishery should be monitored over time, considering the potential occurrence of unintended results such as fishing effort shifts and reduced catch of target species (O'Keefe et al. 2013). In fact, a spatio-temporal closure is not costless to the fishermen, as it might imply loss of fishing opportunities. Moreover, the canyon head and wall are the closest fishing grounds to the coast, so the cost of fuel for fishing trips is considerably reduced. On the other hand, submarine canyons are unique sites for the recruitment of many species (Stefanescu et al. 1994, Sardà and Cartes 1997, Tyler and Ramirez-Llodra 2002, Sardà et al. 2004, Ramirez-Llodra et al. 2010), which are threatened by anthropogenic activities and should be preserved in order to maintain their ecological value.

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Marine Stewardship Council Science Series

Management strategies for the fishery of the red shrimp *Aristeus antennatus* in Catalonia (NE Spain)

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Abstract

Red shrimp (*Aristeus antennatus*) is the most important demersal resource in the Northwest Mediterranean. In Northeast Spain it is fished by bottom trawling and constitutes a large part of the income for local fishermen's associations. In Palamós, the most important harbour for this fishery in the area, a management plan regulating this fishery was established in May 2013, aiming to reduce fishing effort and protect juveniles. We investigate whether the management strategy adopted in Palamós is appropriate and how it could be improved according to the stock status and fishery characteristics. For this purpose we analyze the trends of several historical series of data including fishing effort, landings, catch per unit effort (CPUE) and size frequencies in the catches. We found that fishing effort directed to this species has increased massively starting form the second half of the last century, accompanied by a marked decline in CPUE. Overfishing of the stock has been evident since 1984. Given the results obtained in this work, we consider the management strategy recently established in Palamós will be appropriate to achieve the aim of sustainability for the red shrimp fishery.

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Introduction

The red shrimp *Aristeus antennatus* is one of the most important target species for trawl fisheries in the western and central Mediterranean. It is a deep-sea shrimp found from depths of 100 m to 3000 m (Sardà *et al.*, 2004). It is widely distributed across the whole Mediterranean although it decreases eastwards, as the abundance of another deep-sea red shrimp species, *Aristaeomorpha foliacea*, increases.

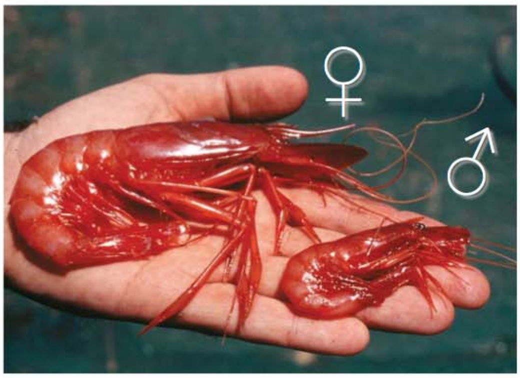


Figure 1. Red shrimp individuals: female on the left and male on the right. In this species the two sexes display marked differences in growth characteristics.

The biology and ecology of this species has been widely studied, except for the larval phase which is still largely unknown (Carbonell *et al.*, 2010). *A. antennatus* displays marked sexual dimorphism, in terms of secondary sexual characters and growth characteristics. Females have a longer life span compared to males, 4/5 years against 3/4 years respectively, and can reach up to 76 mm cephalothorax length, against 54 mm for males (Sardà and Demestre, 1987, Demestre 1990) (Figure 1).

In Catalonia (NE Spain), *A. antennatus* is fished exclusively by bottom trawling at depths ranging from 300 m to 900 m. In the northern part of the region, the fishing grounds are located along the heads, margins and slopes of a system of submarine canyons, whose geomorphology influences the ecological behavior of this species. Reproduction occurs from late spring to early summer, when aggregations made up mainly of mature females form on the mid-slope at depths between 600 m and 800 m. In autumn and winter, density on the mid-slope decreases and aggregations of juveniles appear at shallower depths in the submarine canyon heads (areas of high productivity where food availability is enhanced) between 500 m and 600 m, (Sardà *et al.*, 1994, Sardà *et al.*, 1997, Tudela *et al.*, 2003, Sardà *et al.*, 2003, Sardà *et al.*, 2004). These aggregations are actively targeted by the fishermen and contribute to keeping their income stable throughout the year (Sardà *et al.*, 1994, Sardà *et al.*, 1997).

However, the landings of red shrimp are highly variable both within and between years. These fluctuations have been related to the ecology and tendency to form aggregations and also to the strong environmental influence of currents (Canals *et al.*, 2006, Company *et al.*, 2008). These currents form periodically in the area, and have been shown to play an important role in lowering the abundance of the red shrimp in the fishing grounds and enhancing recruitment in the following years. The red shrimp is a high value species at market reaching peaks of 200 €/kg during particular periods such as Christmas or summer holidays. Catches are mainly constituted of females (80-90% in weight), which dominate the population at the depth range of the fishing grounds, where they make up 70% of the population (Sardà *et al.*, 2003, Sardà *et al.* 1994, Sardà *et al.*, 2004). By virtue of their larger size, females are also more valuable.

The red shrimp fishery is an extremely important one for the Fishermen's Associations in the region, which rely in great part on this fishery for their income. Even though it is economically important, there is no European or national level official management established for its exploitation, not even a minimum landing size (MLS).

The city of Palamós (located 100 km north of Barcelona) is one of the main fishing ports of the Catalan coast for *A. antennatus*. Here, this resource makes up to 10% of the total landings (by weight) for the trawling fleet but constitutes 50% of total income. In the whole region the red shrimp is renowned as "Gamba de Palamós" (Palamós shrimp). In recent years, a collaboration between scientists of the Institute of Marine Sciences of Barcelona, Fishermen's Association of Palamós and the Autonomous Government of Catalonia has been established to seek the sustainable exploitation of this resource. The first important result from this collaboration was the official publication in May 2013 of a management plan at local level regulating the fishing activities in the red shrimp fishing grounds off the port of Palamós and fishing capacity of its trawling fleet. It is the first plan of its kind for the Mediterranean Sea, and includes several measures to reduce fishing effort and preserve the juvenile population. The technical measures established by the plan include: fishery closure during two months in winter when juveniles are in the fishing grounds; use of a more selective mesh size (40 mm square instead of 50 mm diamond); reduction of the number of trawlers in the fleet. The plan will have a five-year duration from the date of its publication, and was implemented by the whole fleet from the first months of 2012, more than one year before the final publication of the Management Plan by the Spanish Government (Boletín Oficial del Estado 2013).

The aim of this work was to investigate whether the management strategy adopted in Palamós is appropriate and how that could be improved according to the stock status and fishery characteristics. For this purpose we analyzed several historical series of data for the red shrimp fishery, including fishing effort, landings, CPUE and size frequencies of catches. The selectivity of the mesh size recently adopted in Palamós (40 mm square) is also analyzed and compared with the selectivity of the previously used mesh size (50mm diamond).

Fishing effort, landings, CPUE assessment and historical evolution of the fleet

Assessment and description of the evolution of fishing effort, landings and catch per unit of effort (CPUE) is fundamental for the understanding of a fishery and its correct management. The aim of this section is to quantify the fishing effort applied to the stock of red shrimp per year in a reliable manner, and then to use this series to calculate CPUE using official landings data.

Methods

To build a historical series of fishing effort, data were obtained from the Ministry of Agriculture, Livestock and Fishery records on the fishing fleets of all the ports of Catalonia from the beginning of the last century to June 2013. These data provided information on the individual vessels such as, type of vessel, period of activity, vessel size, and engine horse power (hp). Data were filtered for trawlers that mainly target red shrimp.

A historical series of fishing effort was then built by summing the engine hp values of selected trawlers per year and by port. However, the hp values are often under-reported when they exceed the 500hp limit set by law. Also, changes to engine power after vessel construction (usually increases) are not reported at all, so evolution of fishing effort is impossible to outline comprehensively. Therefore, we corrected the official values of hp per vessel by conducting personal interviews with members of the Fishermen's Associations. We refer to this corrected series as "real fishing effort". In addition, a 1% yearly increase due to improved fishing technology was applied to the series of real fishing effort starting from 1980. Historical series of CPUE were calculated as kg/hp, using the real hp values corrected per technology increase and the historical series of landings of *A. antennatus* per port. The historical series of landings were supplied by the Autonomous Government of Catalonia.

Results and discussion

Results were calculated for the ports of Palamós and Blanes, two of the main ports of Catalonia for the fishery of the *A. antennatus*. From interviews we found that, out of the 59 vessels checked for the two ports (40 for Palamós and 19 for Blanes), there were only 8 cases where the real engine power coincided with the value reported in the official list. The official data and real data series started to diverge in 1955 for Palamós and 1966 for Blanes. Also, 42.5% of vessels in this study had increased their engine power beyond the legal limit after construction, and these changes were not reported in the official dataset. Most of the increases in engine power at both ports were made between 1990 and 2000, when socio-economic conditions in the area were more favorable. In June 2013, the real value of total hp for the trawling fleet targeting red shrimp was 21600 hp in Palamós and 12270 hp in Blanes (Figure 2). Hp values based on official data were in both cases less than half, cf. 10679 hp and 5147 hp, for Palamós and Blanes respectively. In 1950, when no differences between official and real vessel power were detected in either of the two ports, the total engine power of the fleet targeting shrimp was 330 hp in Palamós and 120 in Blanes. The percentage increase in total hp from 1950 to 2013 for Palamós was of a 6445% according to real data, and of a 3618% according to official data. Considering technological improvements, the fishing capacity of Palamós has increased by 8782%. For Blanes, the percentage increase according to real data has been 10125%, while according to official data it was a 4189%. Including technological improvements, the percentage increase for this port was 13405%. Total landings of *A. antennatus* were available until 2012 starting from 1963 for Palamós and from 1983 for Blanes (Figure 3). Both ports show high inter-annual fluctuations. In Blanes, landings show a decline from 1983, while in Palamós, apart from a steep decline from 1963 to 1981, no clear trend can be detected. The historical series of CPUE (kg/hp) displays declining trend in both ports. In Palamós, the average value of CPUEs for the decade 1963-1972 was 27.9 kg/hp. In the decade 2003-2012 it had dropped to 4.1 kg/hp. In Blanes, the average value for the decade 1983-1992 was 8.3 kg/hp, and in the last decade of the series, 2003-2012, it had dropped to 3.8 kg/hp (Figure 3).

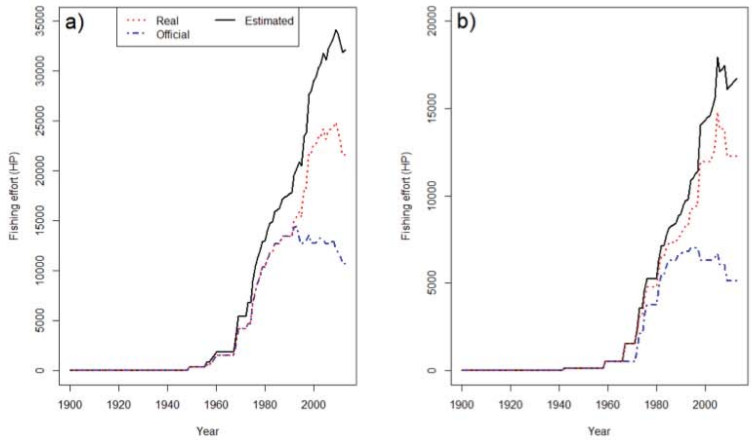


Figure 2. Historical time series of fishing effort for trawlers targeting red shrimp for the ports of a) Palamós and b) Blanes (NW Mediterranean). Official hp values were obtained from governmental sources; real from personal interviews at each Fishermen Association; Estimated real hp adding an 1% of annual increase (starting from 1980) after new technological equipment to fishing vessels, such as net sensors, bathymetry data, etc.

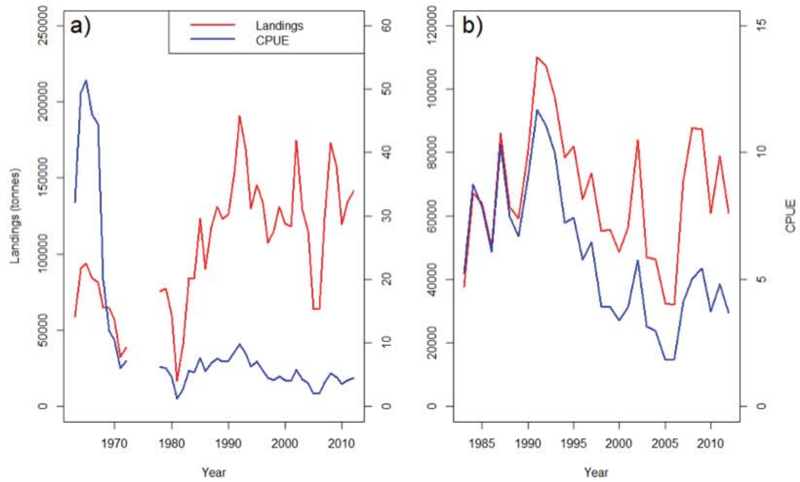


Figure 3. Historical series of landings of *A. antenntus* and CPUEs for the ports of a) Palamós and b) Blanes

Stock assessment

Stock assessment is an analytical procedure that aims to evaluate the state of an exploited stock. Usually, fishery and biological data are used to estimate population parameters, such as biomass, recruitment, fishing mortality and other reference points, through a mathematical model. Our goal here was to assess the state of this fishery in 2012 using data from a survey in Palamós, and to compare its status in recent years to that of twenty years ago using data from four other ports of Catalonia.

Methods

Data for the stock assessment were collected from sampling carried out every two / three weeks onboard a fishery trawling vessel from Palamós harbour between January 2012 and December 2013. The study area was the submarine canyon of Palamós, around which the fishing grounds for *A. antennatus* are located. Three sampling stations were chosen corresponding to three fishing grounds at different levels of the canyon: Rostoll, on the canyon head (average depth 431 m); Sant Sebastiá, on the canyon wall (average depth 498 m); and Gamba de Llevant, on the adjacent northern open slope (average depth 598 m). One trawl per fishing ground every day of sampling was performed using commercial fishing gear. For the first 5 months of 2012, a 50 mm diamond mesh codend was used. Afterwards, the gear was changed to a 40 mm square mesh, according to the newly implemented Management Plan. Sampling stations were chosen in order to capture the population fluctuations of abundance at different levels of the canyon in different times of the year due to the ecological behavior of the red shrimp. The data were collected on the cephalotorax length (from the orbital margin to the mid posterior edge of the cephalothorax), sex, sexual maturity, and total weight of catches. For the analysis, we used only data relative to 2012 as the series relating to 2013 was not yet completed. In addition, similar data collected during a previous survey carried out by the Autonomous Government of Catalonia during years 2008-2010 were evaluated. Here, data were collected onboard trawlers from three other ports of Catalonia, Blanes, Arenys and Vilanova. Another similar data series for the period 1984-1989, relative to the catches of the fishing fleets of Blanes, Arenys and Barcelona , was obtained from the literature (Demestre, 1990).

For the analysis, length frequency distributions were combined to include catches from the whole of Catalonia, and assumed to be representative of the region. The analysis of the three data series allows investigation of the status of the fishery of the red shrimp in 2012 and comparison with its status in recent years and 20 years ago. The method used for stock assessment was the pseudo-cohort analysis, followed by a yield per recruit analysis, both performed using the program VIT (Lleonart & Salat 1997). The pseudo-cohort analysis is a method especially developed for stocks in data-poor situations, when only one or a few consecutive years of data are available. The model uses age or length structured data, total catches and certain biological parameters. In return, it provides estimates of population biomass, mean age and length and fishing mortality (F). For this model to be applied, the equilibrium of the stock (constant mortality and recruitment) has to be assumed. Then, the yield per recruit analysis, based on the pseudo-cohort analysis results, calculates the yield per recruit value at the current value of F. It also provides a reference point for F which corresponds to the level of fishing mortality at which the yield per recruit would be optimized, or the optimum level of exploitation. The reference point calculated by the yield per recruit analysis is the $F_{0.1}$, which is considered a good proxy for F_{msy} (the F providing the maximum sustainable yield) (Gabriel & Mace, 1999). The biological information required for the analysis was available in literature, in particular: the Von Bertalanffy growth parameters (L_{inf}, k, t_0) in Sardà and Demestre (1987), natural mortality estimates (M) in Demestre and Martín (1993), and the estimates of the length-weight relationship parameters (a, b) in Demestre (1990) (Table 1). Given the biological differences between females and males (growth and natural mortality rates), all the analysis were performed separately for the two sexes.

Table 1. Parameters used for the Pseudo-Cohort analysis. These include the parameters of the Von Bertalanffy equation (L_{inf}, k, t_0), the parameters of the length-weigth relationship (a,b), and natural mortality (M)

	L_{inf}	k	t_0	a	b	M
Males	54	0,25	-0,5	0,004024	2,31769	0,8
Females	76	0,3	-0,07	0,00264	2,46604	0,5

Results and discussion

The mean length frequency distributions in the catches of *A. antennatus* for each period of study are shown in Figure 4. The length frequency distribution for females in 2012 looks narrower and shifted to lower size values with respect to the two other periods. In fact, the value of mean size for females was 30.7 mm in 2012, 37.6 mm in 2008-2010 and 36.5 mm in 1984-1989. For males, mean size values were 23.9 mm, 25.0 mm and 25.3 mm, for the periods 2012, 2008-2010 and 1984-1989 respectively.

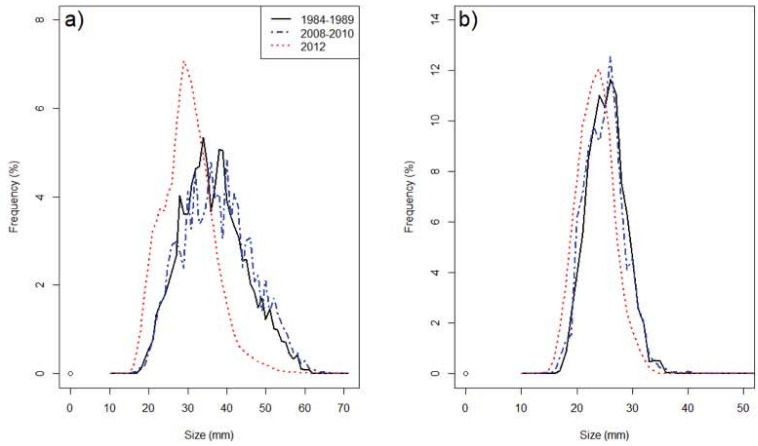


Figure 4. Average length (or size) frequency distributions in the catches for the three periods of study (1984 – 1989, 2008 – 2010 and 2012) shown for a) females and b) males.

Results of the Pseudo-cohort analysis and yield per recruit analysis are shown in Table 2. Results are reported per year, for both sexes. Mean population age and length of females in 2012 was smaller than for any other year studied. For the same year and sex, estimated mean F was greater than for any other year. Also, for females in 2012, estimates of population mean biomass was smaller than catches. Mean biomass is the value of biomass present at sea in average at each moment of the year: If catches are over this level, it means that at the end of the year, it has been fished more than the overall input from recruitment and growth to the population. The same was not true for any of the other data series, denoting a higher level of exploitation for this year.

The historical series of yield per recruit values for females shows a tendency to decrease from 1984 to present, showing the lowest value in 2012. The comparison of $F_{0.1}$ with the current value of mean F ($F_{0.1}$/Mean F) highlights a situation of overexploitation of the resource (both sexes) in all years studied, even though the level of overexploitation (the gap between mean F and the $F_{0.1}$ reference point) is bigger in 2012 than for any other year studied. The biological differences between the two sexes in *A. antennatus* lead to a difference in the degree at which they are affected by the fishery and in their overall response. In fact, the results obtained for females are not always obtained for males. However, females constitute the great majority of catches and according to General Fishery Commission for the Mediterranean guidelines evaluations for management purpose should be based on the most abundant sex in the captures.

In general, the results for 2012 are quite different from the other years studied. This is probably due to the fact that the 2012 data series, unlike all the others, was obtained sampling exclusively one port, cf. Palamós. This port has got one of the biggest fleets targeting mainly red shrimp in the region. Juveniles are specifically targeted, especially in winter, when there are aggregations of young shrimp in the canyon head. Our results suggest that the fishery of the red shrimp in Palamós has specific characteristics, and it's probably not representative of the catches from the rest of the Catalan region. In particular, our findings on the length frequency distribution of the catch and yield per recruit highlight the extent of pressure on the smallest sizes of the population, stressing the need for a specific management in order to preserve the juveniles. Increasing size at first capture is actually one of the most efficient measures to increase yield per recruit values (Sparre & Venema, 1998). The measures included in the management plan, such as mesh size regulation and a winter fishery closure, are going some way towards this, even though long terms effects such as the increase in population mean size and yield per recruit values will require a monitoring of the stock in the following years to be detected.

Table 2. Results of the pseudo-cohort and yield per recruit analysis for Catalonia shown per year and for females and males separately

	1984	1985	1986	1987	1988	1989	2008	2009	2010	2012
FEMALES ♀										
Mean pop biomass(t)	392.33	571.91	416.26	234.81	378.96	393.48	1066.91	1068.31	724.07	453.88
Tot. Catch (t)	253	315	212	217	327	265	628.86	580.85	455.72	495.94
Mean Age	1.581	1.712	1.699	1.586	1.481	1.604	1.49	1.63	1.50	1.23
Mean Length	28.727	30.394	30.04	29.267	27.608	29.079	27.13	29.13	27.53	23.92
Mean F	1.086	1.051	0.879	1.239	1.525	0.961	0.98	1.24	1.29	1.57
Y/R	9.39	9.68	8.99	10.39	9.11	9.32	8.14	9	8.57	7.53
$F_{0,1}$	0.52	0.54	0.52	0.63	0.53	0.5	0.45	0.51	0.49	0.42
$F_{0,1}$/Mean F	0.48	0.51	0.59	0.51	0.35	0.52	0.46	0.41	0.38	0.27
MALES ♂										
Mean pop biomass(t)	42.35	51.76	40.1	40.34	72.18	145.36	90.55	70.84	48.01	131.92
Tot. Catch (tons)	30	35	24	35	51	88	48.52	44.63	30.38	100.65
Mean Age	1.59	1.598	1.644	1.603	1.489	1.537	1.13	1.52	1.34	1.27
Mean Length	21.769	21.842	22.155	21.955	20.927	21.312	17.72	21.21	19.60	19.11
Mean F	1.745	1.903	1.38	1.703	1.151	1.802	0.94	1.70	1.11	1.61
Y/R	2.91	2.9	2.78	3.26	2.68	2.63	1.77	2.63	2.26	2.41
$F_{0,1}$	0.99	0.93	0.94	1.28	0.92	0.94	0.73	0.87	0.82	0.72
F0,1/Mean F	0.57	0.49	0.68	0.75	0.8	0.52	0.78	0.51	0.74	0.45

Mesh size selectivity

The regulation of the mesh size of the cod end is a useful management tool, as it usually facilitates an increase in size at first capture, thus preserving juveniles, improving yield per recruit values and reducing discards. In an effort to improve size selectivity, the management plan approved for Palamós establishes the use of a 40 mm square mesh instead of the 50 mm diamond mesh which is more commonly used in the Mediterranean. The objective of this section is to analyze the differences in the selectivity of the two different meshes used.

Methods

In order to compare the mesh size selectivity of 50 mm diamond mesh (50d), and the 40 mm square mesh (40s), we used the "covered end method" (Pope *et al.*, 1975). This method employs a net cover placed over the cod end of the commercial gear to determine the amount of fish of different sizes that escape through the meshes of the cod end. The selectivity of the gear can then be determined by comparing the amount and sizes of the fish in the cod end with those of the fish in the cover.

Figure 5. Pictures of the two mesh sizes tested for selectivity: a) 50 mm diamond and b) 40 mm square mesh. c) shows the codend covered with a 3 mm mesh size net in order to determine selectivity of the gear

The mathematical expression used to describe the gear selection per size of individuals is a sigmoid curve, known as "gear selection ogive". The simplest mathematical expression for this curve is: $S_L=1/(1+\exp(S_1-S_2*L)$, where S_L is the proportion of individuals of size L retained in the code end and S_1 and S_2 are constants (Sparre & Venema, 1998). Experimental data were collected onboard a commercial trawler of the fishing fleet of Palamós. Eleven trawls were made using the 50d during four different fishing trips, while nine trawls during three fishing trips were made using the 40s. The cephalothorax length of individuals in the cod end and in the cover was measured following the methodology in section 3. Only trawls with at least 200 individuals were kept for the analysis: 7 trawls for the 50d and 9 for the 40s were left. The logistic curve parameters were estimated fitting the experimental data and the selection ogives per each trawl were plotted. The values of L_{25}, L_{50} and L_{75}, the cephalothorax length at which respectively 25%, 50% and 75% of individuals are retained in the cod end, were then calculated per each mesh kind and compared by t-test.

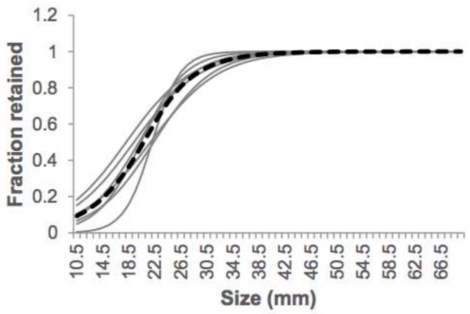
Results and discussion

During the experimental trawls a total of 15421 individuals entered the 50d cod end, and a total of 22000 entered the 40s. Of those, respectively 58.2% and 53.8% were retained by the cod end. The gear selection ogives for each trawl for both meshes are shown in Figure5, where the average curves are also plotted. Average values of L_{25} and L_{50} were both bigger for the 40s than for the 50d, and the difference between values was bigger for the L_{25} estimate. Average values of L_{75} were almost coincident (Table 3). These results suggest a higher selectivity at small sizes for the 40s mesh compared to the 50d (higher values of L_{25} and L_{50}), and an equal efficiency in retaining the bigger individuals (similar L_{75}). Despite that, comparison of average values of parameters obtained for the two mesh kinds was made by means of t-test and no significant difference was found. However, the p value for L_{25} (0.079) was very close to threshold of significance, (0.05).

Table 3. Average values and standard error of L_{25}, L_{50} and L_{75} for the 50 mm diamond mesh and the 40 mm square mesh. P values for the t-test performed to compare the average values for the two meshes are shown

	50 mm diamond mesh		40 mm square mesh		
	$\overline{X}$	s.e.	$\overline{X}$	s.e.	p value
L_{25}	15.9	4.9	18.2	2.2	0.079
L_{50}	20.6	3.1	21.6	1.0	0.137
L_{75}	25.2	3.6	25.0	0.6	0.725

6a)



6b)

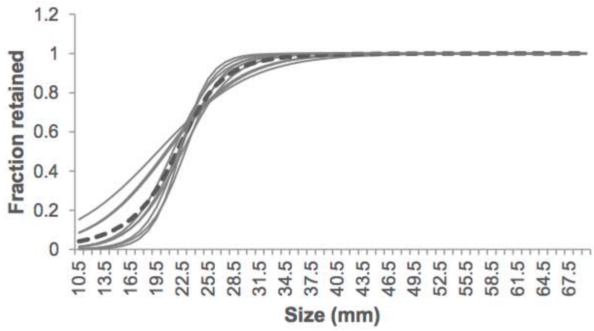


Figure 6. Selection ogives for the a) 50 mm diamond mesh and b) the 40 mm square mesh for each tow. The average curves for each mesh size are also shown

The lower variability in the estimates of parameters for the 40s (smaller standard error) suggests better selectivity for this mesh kind compared to the 50d. It has been pointed out by several authors how the diamond shaped meshes stretch and elongate under tension, as the cod end fills with fish (Robertson & Stewart, 1988). This reduces the probability of the fish of certain body sizes escaping, causing variability in gear selectivity. In contrast, square-shaped meshes remain open when towing increasing size selectivity (Reeves *et al.*, 1992; Petrakis & Kostantinos, 1997). The data show that the percentage of individuals that manage to escape through the square mesh is bigger than for the diamond mesh and this portion is made up of smaller individuals. These smaller individuals have the lowest price in the market but are important to preserve with a view to increasing the mean size of the population and catches, the yield per recruit values, and eventually the incomes for the fishery in the long term.

Conclusions

- The fishing effort for the red shrimp in Blanes and Palmós displayed a spectacular increase in the second half of the last century, increasing its value of about 80 times in average. However, fishing effort is profoundly underestimated in official data.
- CPUE for the two ports studied indicated a declining trend in recent decades, while landings remained stable.
- Overfishing of the resource in Catalonia was detected for all years assessed between 1984 and 2012. This result is consistent with the high values of fishing effort and declining CPUE detected in Blanes and Palamós over this time period.
- In Palamós in 2012 we found higher fishing pressure on the small size classes of the population compared with other years and ports studied. Here, we also detected higher fishing mortality, lower Y/R value, and a higher degree of overfishing.
- The 40 mm square mesh adopted in Palamós with the new regulation was more selective at small size classes while displaying the same efficiency in retaining larger individuals when compared to the 50 mm diamond mesh that was previously employed.
- The management strategy adopted in Palamós aiming to reduce fishing effort is appropriate given the high levels of effort, low CPUEs and persistent overfishing status of the resource detected over the last few decades. Measures adopted in order to protect juveniles are also appropriate, given the high level of fishing pressure on small size classes and low levels of Y/R detected for this port.

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Seasonal mapping of landings per size class for the fishery of the deep-sea red shrimp *Aristeus antennatus* in NE Spain using Vessels Monitoring System data and daily landings.

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INTRODUCTION

The red shrimp *Aristeus antennatus* is the most important deep-sea demersal resource in the NW Mediterranean. In NE Spain it is fished by bottom trawling (Fig.1) at the depths between 200 m and 900 m, and the fishing grounds are allocated around the margins of a system of submarine canyons, where it constitutes the only target species (Fig.2). This fishery is characterized by marked seasonality, with higher levels of landings occurring in summer [1]. Combining Vessel Monitoring System data (VMS) with daily landings has the potential to substitute logbook data for stock evaluations, avoiding human error or misreporting. Also, when landings per size class are available, this approach allows the identification of the critical areas and/or periods for the exploitation of the smallest size classes in the population, constituting the basis for specific management decisions such as the establishment of protected areas or temporary fishery closures. The main objective of this study was to map and investigate the spatiotemporal distribution of the landings per size class of red shrimp in the fishing grounds of two of the main fishing ports of NE Spain, Blanes and Palamós.

Figure 1. Shrimp trawling vessel of the fishing fleet of Palamós (NE Spain).

Figure 2. Fishing grounds for red shrimp off the fishing ports of Palamós and Blanes (NE Spain).

MATERIALS AND METHODS

The study area is constituted by the fishing grounds of the fishing ports of Blanes and Palamós (NE Spain). We obtained VMS data of trawlers of the two ports from the Spanish Ministry of Agriculture, Livestock and Fishery for the years 2007-2012. Daily landings per vessel and commercial size class of individuals were supplied by the local Fishermen Associations. Data analysis was performed according to the following protocol:

- VMS data points were filtered for speed (< 4 knots) and depth (>200 m and < 900 m) to select points corresponding to actual fishing activity;
- Daily landings of red shrimp per size class were associated to the filtered VMS data. VMS data that had no corresponding red shrimp landings were discarded to strictly select points associated to the fishery of the red shrimp;
- VMS points were crossed with the fishing grounds locations. All the fishing trips in which vessels had been fishing in more than one fishing ground were excluded from the analysis (around 10% of points), as to associate landings to fishing ground strictly.

The red shrimp landings are divided in different commercial size classes (Fig.3). For the analysis we grouped into two classes: small and big. The small size class includes mainly juveniles: females of age >1 and < 2,5, and males of age 2 and 3. To convert landings (kg) into number of individuals we used the mean weight of individuals per size class: 11 g for small and 29 for big [2]. We also used data from a biological survey in the fishing grounds of Palamós (2012-2013) to check the size frequency of the commercial size classes. Finally, maps of total landings and percentage of small size class individuals in the landings were made using QGIS [3]. A grid polygon layer of half mile squares (0,85746 km) was overlaid to the data points and used to sum values within each square.

Figure 3. Different commercial size classes of red shrimp

RESULTS

1. Total landings

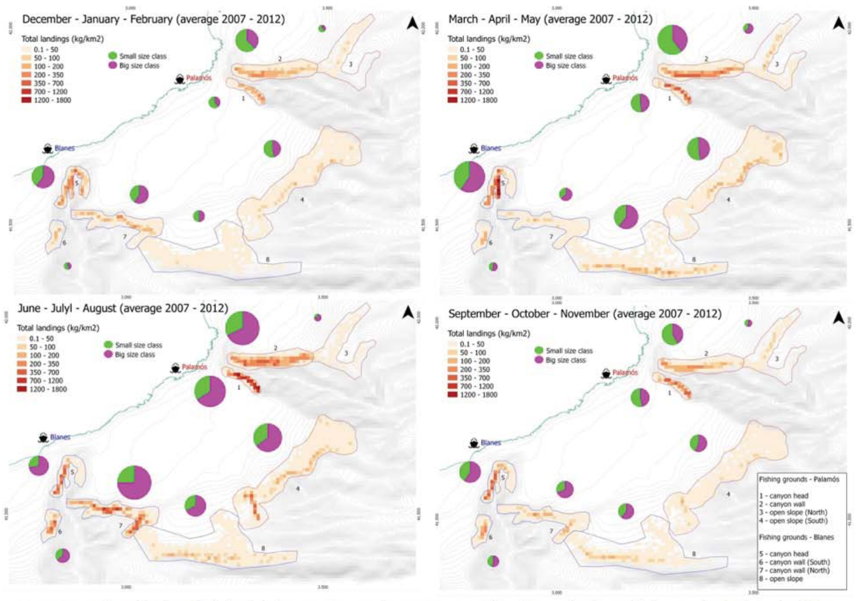

Figure 4. Map of total landings (kg) of red shrimp per trimester (average 2007-2012) for the trawling fleets of Blanes and Palamós in the different fishing grounds. Pie charts area is proportional to total landings.

- Blanes and Palamós show a similar pattern of total landings distribution in the fishing grounds around the canyon margins;
- High spatial density of landings in the canyon heads and walls all year round;
- Increase of landings on the open slope in spring and summer;
- Biggest amount of landings in summer, with the lowest proportion of small size class.

2. Proportion of small size class individuals in the landings

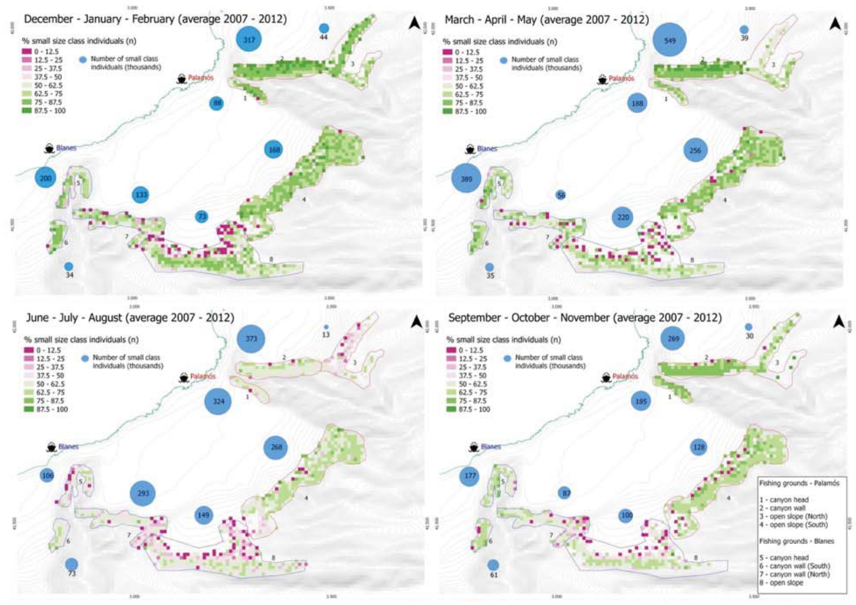

Figure 5. Map of percentage of small size class individuals (number) of red shrimp in the captures per trimester (average 2007-2012) for the trawling fleets of Blanes and Palamós in the different fishing grounds. Pie charts area is proportional to total number of individuals.

- Palamós displays an overall bigger proportion of small size class individuals in the landings;
- For both ports, the biggest proportion of small individuals occurs in winter and spring in the canyon heads and walls ;
- In Palamós, the length frequency of small size class individuals in winter (Fig.6) is shifted to smaller values compared to the other fishing grounds (average cephalotorax size canyon head: 22 mm; canyon wall: 24 mm; open slope: 24 mm)

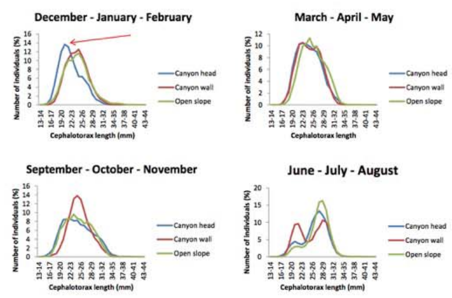

Figure 6. Length frequency distribution of small size class individuals in the captures in the different fishing grounds of Palamós (canyon head, canyon wall and open slope). Data from biological survey.

3. Comparing the fishing pattern of the two ports: differences and management strategy

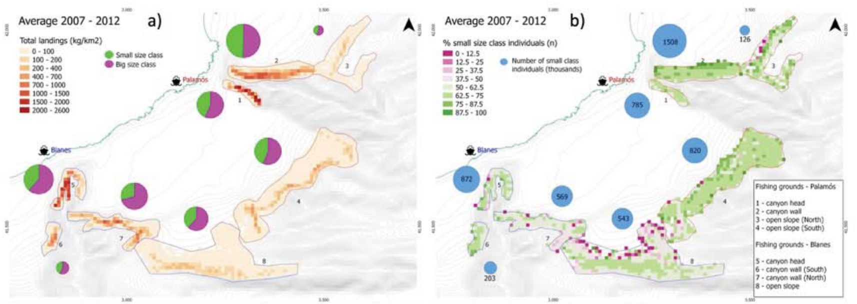

Figure 7. Map of total landings in kg (a) and percentage of small size class individuals in number (b) of red shrimp in the captures as average of the years 2007-2012 for the trawling fleets of Blanes and Palamós in the different fishing grounds. Pie charts area is proportional to total landings (a) and total number of individuals (b).

- Overall amount and distribution of landings is very similar for Palamós and Blanes;
- Palamós displays a bigger presence of small size class individuals in the landings compared to Blanes, both in weight and number;
- Biggest catches of small individuals occur in the canyon heads and walls.

MANAGEMENT STRATEGY

In 2012 the trawling fleet of Palamós has implemented a long term management plan for the fishery of the red shrimp aiming at reducing fishing effort and preserving juveniles. The measures established by the management strategy include: use of 40 mm square mesh (instead of 50 mm diamond); fishery closure in winter; reduce number of trawlers.

CONCLUSIONS

- The methodological approach used in this study permitted the identification of VMS data points deriving from vessels specifically targeting red shrimp. It also allowed the link of the landings and their size structure with the single fishing grounds in the different seasons of the year, allowing spatiotemporal based management decisions.
- The pattern of distribution of landings is similar for the ports of Palamós and Blanes, displaying in both cases high density of landings in the canyon heads and walls;
- In the canyon heads and walls we found the biggest proportion of small size class individuals in the landings, especially in winter and spring, corroborating results of previous ecological studies [4] [5] at a finer spatiotemporal scale;
- The smallest individuals in the landings are caught in the canyon head in winter;
- The management plan recently implemented in Palamós aiming at reducing fishing pressure on the smaller size classes of the population is appropriate according to the results of this study;
- Given the similarities of the fishing pattern between Palamós and Blanes, it would be recommendable to extend the fishery management established in Palamós to Blanes

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Effects of bottom trawling on fish foraging and feeding

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The effects of bottom trawling on benthic invertebrates include reductions of biomass, diversity and body size. These changes may negatively affect prey availability for demersal fishes, potentially leading to reduced food intake, body condition and yield of fishes in chronically trawled areas. Here, the effect of trawling on the prey availability and diet of two commercially important flatfish species, plaice (*Pleuronectes platessa*) and dab (*Limanda limanda*), was investigated over a trawling intensity gradient in the Irish Sea. Previous work in this area has shown that trawling negatively affects the condition of plaice but not of dab. This study showed that reductions in local prey availability did not result in reduced feeding of fish. As trawling frequency increased, both fish and prey biomass declined, such that the ratio of fish to prey remained unchanged. Consequently, even at frequently trawled sites with low prey biomass, both plaice and dab maintained constant levels of stomach fullness and gut energy contents. However, dietary shifts in plaice towards energy-poor prey items were evident when prey species were analysed individually. This, together with a potential decrease in foraging efficiency due to low prey densities, was seen as the most plausible cause for the reduced body condition observed. Understanding the relationship between trawling, benthic impacts, fish foraging and resultant body condition is an important step in designing successful mitigation measures for future management strategies in bottom trawl fisheries.

1. Introduction

Demersal fisheries using otter and beam trawls are widespread over shelf seas, and typically use heavy ground ropes and chains to drive fish and crustaceans from the seabed into nets. Physical disturbance from such fisheries can cause significant changes in benthic invertebrate abundance, biomass, production and species richness [1–4]. While many invertebrate species are negatively affected by demersal trawling, other more resilient species may show little response [5], resulting in anthropogenically modified benthic species assemblages. Changes in benthic composition may subsequently affect the quality and quantity of prey for demersal, benthivorous fish species [6–9]. The general response to a reduction in benthic biomass as a consequence of demersal trawling is thought to decrease the overall carrying capacity for demersal fishes through reduced prey availability [10]. The response of individual fish species will, however, depend on the susceptibility of its prey to fishing disturbance [8]. Negative effects can be expected if fishing leads to a reduction in the biomass of preferred prey [1,7,11], whereas no effect or a positive effect may be expected if the prey is not influenced or benefits from the fishing activity, e.g. (if its prey profits from scavenging on organisms that are damaged by the trawl or competitive release from trawl-sensitive competitors) [12–14].

The response of individual fish species could also be shaped by their feeding strategy and the prey species they preferentially feed on. For example, fish species

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Assessing Fishing and Marine Biodiversity Changes Using Fishers' Perceptions: The Spanish Mediterranean and Gulf of Cadiz Case Study

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Abstract

Background: The expansion of fishing activities has intensively transformed marine ecosystems worldwide. However, available time series do not frequently cover historical periods.

Methodology: Fishers' perceptions were used to complement data and characterise changes in fishing activity and exploited ecosystems in the Spanish Mediterranean Sea and Gulf of Cadiz. Fishers' interviews were conducted in 27 fishing harbours of the area, and included 64 fishers from ages between 20 to >70 years old to capture the experiences and memories of various generations. Results are discussed in comparison with available independent information using stock assessments and international convention lists.

Principal Findings: According to fishers, fishing activity substantially evolved in the area with time, expanding towards deeper grounds and towards areas more distant from the coast. The maximum amount of catch ever caught and the weight of the largest species ever captured inversely declined with time. Fishers (70%) cited specific fishing grounds where depletion occurred. They documented ecological changes of marine biodiversity during the last half of the century: 94% reported the decline of commercially important fish and invertebrates and 61% listed species that could have been extirpated, with frequent mentions to cartilaginous fish. Declines and extirpations were in line with available quantitative evaluations from stock assessments and international conventions, and were likely linked to fishing impacts. Conversely, half of interviewed fishers claimed that several species had proliferated, such as cephalopods, jellyfish, and small-sized fish. These changes were likely related to trophic cascades due to fishing and due to climate change effects. The species composition of depletions, local extinctions and proliferations showed differences by region suggesting that regional dynamics are important when analysing biodiversity changes.

Conclusions/Significance: Using fishers' perceptions, fishing and ecological changes in the study area were documented. The recovery of local ecological knowledge provides valuable information complementing quantitative monitoring and evaluation surveys.

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Introduction

From coastal areas to the open seas, human activities impact marine ecosystems [1,2]. In the past, human impacts on marine ecosystems were mainly due to exploitation of marine resources and fishing. These activities diversified with time and currently include other impacts such as habitat degradation, pollution and eutrophication, climate change, and the invasion of non-indigenous species [3–6]. These impacts have an effect on the biodiversity and abundance of marine resources [7–9], and on marine ecosystem structure and functioning [10,11].

The Mediterranean Sea is one of the most impacted marine ecosystems worldwide [5,12–14]. Exploitation and habitat loss are the main human activities shaping its biodiversity changes [12]. Fishing impacts are notable and several commercial species are highly exploited or overexploited [15,16]. Non-commercial species have also shown important declines [16,17].

Additionally, the impact of widely distributed factors such as climate change or the invasion of non-indigenous species is steadily increasing [18–20]. Human impacts are distributed in a heterogenic way along the Mediterranean Sea and many areas are subjected to multiple impacts simultaneously [13]. Some of the