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FISH HABITAT MAPPING

Combining GIS and GAMs to identify potential habitats of squid *Loligo vulgaris* in the Northwestern Mediterranean

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Abstract We characterised the most productive areas for the commercial squid *Loligo vulgaris* off the Catalan Coast based on the combined integration of SST and PAR satellite data. We present the distribution of these areas during the most productive months in relation to the spatiotemporal presence of paralarvae of this species off the Catalan Coast. The work is based on Generalised Additive Models (GAMs) that combine the simultaneous analysis of the effect of different environmental explanatory variables from satellite imagery data to obtain the optimal model for paralarvae of the squid. The proposed model helped define the potential Essential Fish Habitat (EFH) for squid paralarvae recruitment, based on the best environmental conditions and is consistent with the higher LPUE observed four months later. The EFH defined for paralarvae recruitment by the model was detected every year in May in the areas both north and central of the Catalan Coast, the same areas where fishing ports evidence the highest commercial yield of squid.

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Essential Fish Habitat Mapping in the Mediterranean

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Introduction

The relationship among the environmental characteristics, the distribution and the reproductive and feeding behaviour of marine organisms are a key research priority that should be investigated to build quantitative predictive models of complex marine ecosystems. Specific habitats for species where they can feed, grow, mature and spawn to sustain their populations are commonly named as Essential Fish Habitat (EFH) as defined by the EC Habitats Directive (Council Directive 92/43/EEC of 21 May 1992 on the Conservation of Natural Habitats and of Wild Fauna and Flora). The characteristics of bottom sediments together with the oceanographic properties of the water are the key points defining the distribution and abundance of species in different marine environments (Valavanis et al., 2004). Knowledge of EFH is very important for the maintenance of sustainable fisheries with a fundamental relationship between quality of habitats and quality of fisheries resources (Benaka, 1999). In order to sustain long-term fisheries production, the protection of EFH is a challenge to be considered by fishery management.

Loligo vulgaris is a valuable resource exploited with three types of fishing gear in the Catalan coast.

Bottom trawl comprises about 90% of total catches of the species while purse seine and different artisanal gear are used for the rest of the catches (Guerra et al., 1994). The distribution of *L. vulgaris* extends along the eastern Atlantic, from the North Sea and British Isles (55° N) to the south-western coast of Africa (20° S), and also throughout the Mediterranean Sea (Guerra, 1992). In the Mediterranean, it is more abundant in waters shallower than 100 m. Generally, it inhabits temperate waters ranging between 12.5 and 20°C and in rather low salinities (Mangold-Wirz, 1963). The species occurs generally within salinity range of 30–36 psu in the North Atlantic (Tinbergen and Verwey, 1945) and slightly higher (37.7–38.15 psu) in the Mediterranean (Salat et al., 1978).

The maturation occurs during the whole year, but may be particularly important in some periods of the year (winter and summer) further south in the Eastern Atlantic, from the Northwest Spanish coast to the Western Sahara (Guerra & Rocha, 1994; Moreno et al., 1994; Raya et al., 1999). In concrete, Mangold-Wirz (1963) found that *L. vulgaris* spawns in the Western Mediterranean during the whole year but with a peak in March–April. The duration of the embryonic development is highly dependent on environmental conditions, mainly temperature and oxygenation (Worms, 1983), and it is usually around 30 days. According to different experimental works, hatching occurs 125 days after spawning at 13°C, 40–45 days after spawning in 12–14°C and 26–27 days after spawning at 22°C (Boletzky, 1979) or 30 days at 17°C according to Mangold-Wirz (1963). The paralarvae of this species have a planktonic life style that lasts around two months (Mangold-Wirz, 1963). Growth of paralarvae is exponential and growth rates are highly influenced by temperature (Villanueva, 2000). Natsukari & Komine (1992) by examination of statolith increments of Mediterranean specimens of *Loligo vulgaris* found that the life span is probably about one year. Lately Arkhipkin (1995) studied the age and growth of *Loligo vulgaris* also by examination of statolith increments from the west Saharan shelf. The author found that maximum age was 396 days (498-mm mantle length).

Taking into account the life cycle described in the works above, together with our own data, we can assume that the peak of spawning period for the squid in the Catalan coast is basically in March–April, and taking into consideration the prevailing water temperature, hatching of paralarvae will occur mainly in May. The presence of paralarvae in May would contribute to the main peak of landings four months later (September–October).

Fisheries production data have been frequently used to try to identify the general distribution and habitat requirements for both recruitment and spawning areas of the resources to achieve sustainable fisheries within an ecosystem-based approach to management (Sanchez & Martin, 1993; Boyle & Pierce, 1994; Pierce & Guerra, 1994; Sakurai et al., 2000; Denis et al., 2002; Chen et al., 2006). On the other hand, the species requirements on environmental variables that control or limit the above-mentioned life history data deserves serious consideration to integrate the species life cycle and the ecological function.

Monthly landings of *L. vulgaris* show a marked seasonality in Atlantic and Mediterranean areas (Sanchez & Martin, 1993; Guerra et al., 1994). The results of these papers showed that landings were much more increased in summer and autumn than in winter and spring during 1981–1991 and the largest catch was generally obtained in October in the NW Mediterranean. Therefore, the individuals caught in summer-autumn come from the spring hatching. The landings are strongly dependent on the annual recruitment of paralarvae and more specifically on a combination of environmental factors that control paralarvae distribution and abundance within EFH areas where growth and reproduction occurs.

The use of Geographical Information System (GIS) appears as a potential and powerful tool in fisheries management and ecosystem studies to analyse and map the distribution of species and allows combining their biological characteristics, mainly spawning and recruitment, with the environmental features, as shown by several studies (Valavanis et al., 2002, 2004). GIS have been considered to define and characterise the EFH for a great number of marine species (Meaden & Do Chi 1996; Sakurai et al., 2000; Eastwood et al., 2001; Pertierra et al., 2001; Pierce et al., 2002; Valavanis et al., 2004; Koubbi et al., 2006). Development of Generalised Additive Models (GAMs) provides the possibility to model different environmental scenarios, including non-linear responses of biological variables to environmental forcing variables, and to define the optimal areas of potential distribution for the particular stages of the species life

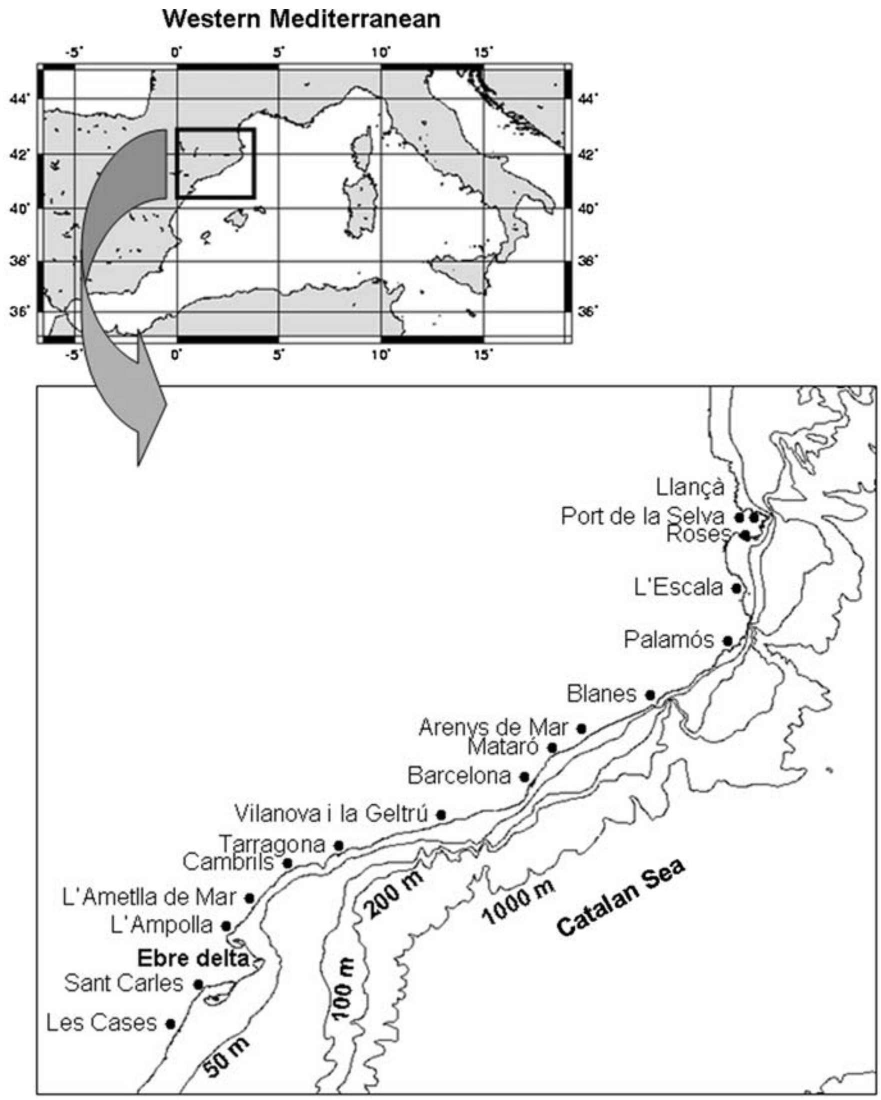

Fig. 1 Location of the study area with the name of the 16 fishing ports where the LPUE are recorded

cycle, e.g. areas of larval development and recruits and adults grounds.

The aim of the present work is to study the relationship between some environmental variables, during the months when paralarvae are more abundant, and the maximum LPUE of *L. vulgaris* in the Catalan coast.

Material and methods

Study area

The Catalan coast within the north-western Mediterranean supports 16 commercial fishing ports where squid are landed. The coast presents a latitudinal temperature gradient with colder waters in the northern part and the southern region starts warming in spring. In general the coast has a narrow continental shelf except in the south around the Ebre Delta (Fig. 1).

Environmental data

Environmental data were collated from internet-based sources by the Hellenic Centre for Marine Research (Brown et al. 2006), and then processed into files suitable for use in a GIS. ArcGIS software was chosen to represent the maps of environmental preferences defining the EFH for squid paralarvae, following the methodology of Valavanis et al. (2002, 2004). The monthly environmental data, for the period January 2000–December 2005, considered for the analyses were: Sea Surface Temperature (SST in °C), Chlorophyll-a (CHLO in mg/m^3), Sea Level Anomaly (SLA in cm) and Photosynthetic Active Radiation (PAR in einstein/m^2/day).

LPUE data

The landings-per-unit-effort (LPUE data) were obtained from the DGPAM (General Direction of Fishing and Maritime Affairs) of the Catalan Government for the period 2000–2005 on a monthly basis. The analysis of the trends in time series of squid LPUE allowed the identification of the best month of squid landings in the Catalan Coast, and the ports with higher yields.

Generalised Additive Models (GAMs) were applied in a quantitative approach on LPUE data for squid *L. vulgaris* at the Catalan Coast (North-Western Mediterranean) using monthly data of the 16 most important ports. The GAMs developed in this work were implemented in R (using Brodgar software package, Highland Statistics Ltd., http://www.brodgar.com). We specified a gamma distribution function for the error structure of the dependent variable (LPUE) with a log link relating the dependent variable to the predictors. The predictor variables were modelled as cubic splines, with a degree of smoothing estimated by the routine mgcv (Wood, 2000). In order to decide which model best fitted the data we used Akaike's Information Criterion (AIC) as goodness-of-fit statistic (Zuur & Pierce, 2004). GAMs were fitted between environmental variables data in spring, when the hatching of paralarvae occurs and the LPUE for the month of peak catches for the period 2000–2005, usually September or October. Three set of environmental variables (April, May and June) were considered to run the model.

Results

In order to test the hypothesis proposed in the present study considering that LPUE (response variable) depends on the environment characteristics of the post-hatching period when paralarvae are present, GAM techniques were used to model squid abundance (LPUE) as a function of the climatic variables in spring. The LPUE data series showed a clear seasonal pattern, with a strong autumn peak centred mainly in September.

Table 1 Environmental variables: SST, Sea Surface Temperature; PAR, Photosynthetic Active Radiation; CHLO, Chlorophyll-a. DF, Degrees Freedom; n.s., no significant; DE, Deviance Explained; AIC, function

Month	DF	Variables (*P*-value)	DE	AIC
April	74	SST ($P < 0.05$), PAR (n.s.)	0.19	560.66
May	74	SST ($P < 0.001$), PAR ($P < 0.05$)	0.39	531.16
June	74	SST ($P < 0.05$), CHLO (n.s.)	0.37	534.10

Model results are summarised in Table 1. The AIC function indicates a better fit of the response variable at the month of peak catches with May climatic parameters. GAM explained 39% of the deviance of the abundance of the squid. Two explanatory variables were significant: SST ($P < 0.001$) and PAR ($P < 0.05$) (Fig. 2). SST was the most important explanatory variable, as it represented 32% of the explained deviance. The range of positive values for this parameter is between 15.18 and 17.53°C. SST showed a strong negative effect at temperatures higher than 17.53°C. The favourable range for PAR is between 43.94 and 52.89 einstein/m^2/day. The other environmental variables were not significant.

The inter-annual variations on squid EFH, defined as areas where the positive effects of SST and PAR overlapped in May for 2000–2005, were obtained by combining the SST and PAR layers with GIS (Fig. 3). The best climatic conditions for squid recruitment were predicted in both the north and the central part of the study area every year, from the ports of Llançà to Cambrils (see Fig. 1), while these optimal conditions only appeared in the Ebre delta area in the years 2002, 2004 and, less evidently, in 2005. In accordance with our hypothesis, these conditions were reflected in the historical LPUE data (Fig. 4). North and central ports showed higher LPUE than those closer to Ebre delta. Nevertheless, a slightly higher LPUE was reported in the south area (Fig. 4) during years 2002, 2004 and 2005, in agreement with the climatic pattern found in the study area (Fig. 3). Despite the differences on yield between northern and southern areas, LPUE data

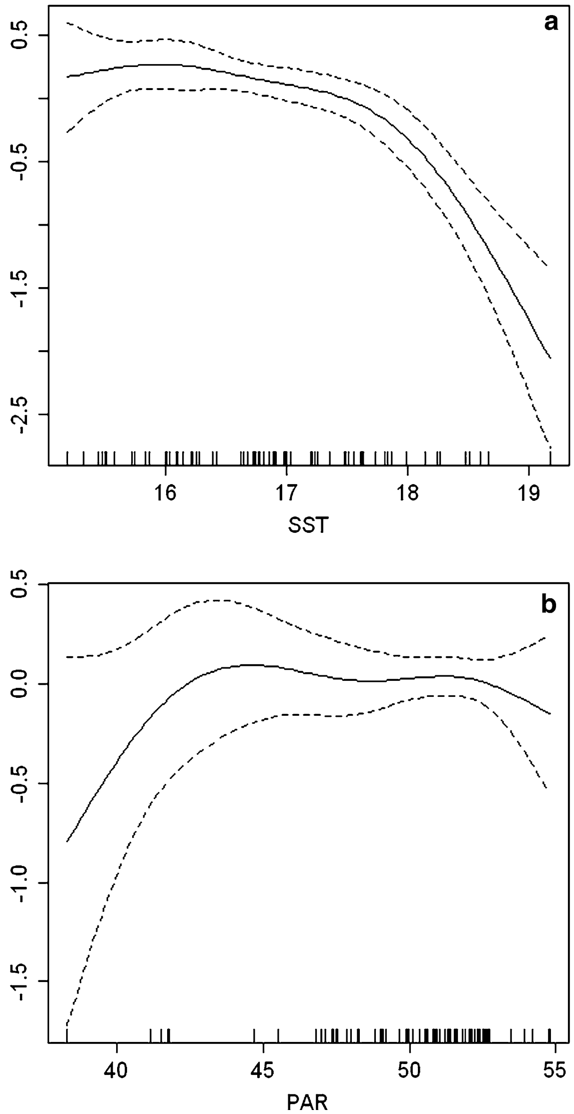

Fig. 2 GAM plot for *Loligo vulgaris* LPUE showing the effect of (**a**) May SST (Sea Surface Temperature) and (**b**) May PAR (Photosynthetic Active Radiation) on squid abundance (maximum LPUE)

series showed a clear seasonal pattern characteristic of the species, with a strong autumn peak centred mainly in September in both areas (Fig. 4).

Discussion

The study characterised the most productive regions for the commercial squid *Loligo vulgaris* off the Catalan Coast based on the combined integration of

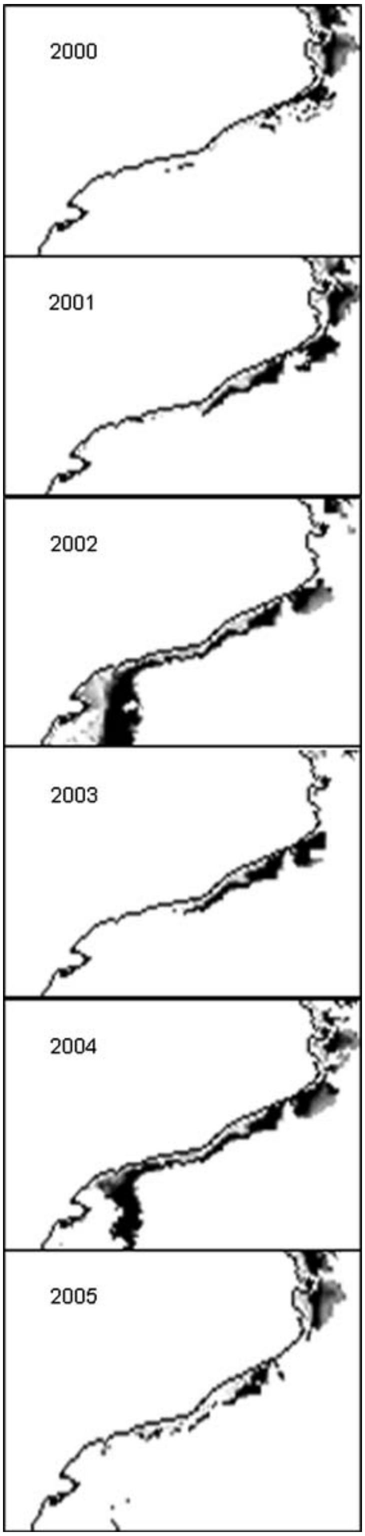

Fig. 3 GIS-based EFH maps of paralarvae *Loligo vulgaris* in Catalan coast (NW Mediterranean) in May 2000–2005

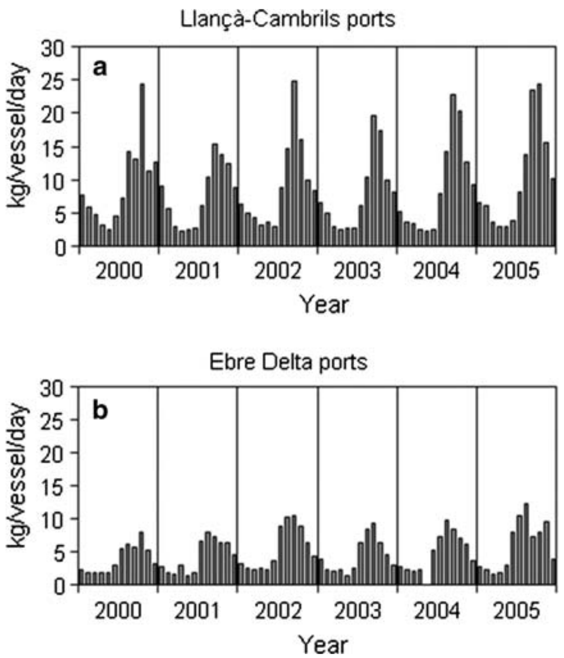

Fig. 4 Monthly *Loligo vulgaris* LPUE for 2000–2005 to the north and central fishing ports, Llançà to Cambrils (**a**) and to the Ebre River ports (**b**)

SST and PAR satellite data. The variability in abundance of fishery species may be attributed to several factors. However, in short-lived species such as cephalopods, abundance is highly influenced by the environmental conditions, which affect recruitment (Boyle & Rodhouse, 2005). The average temperature on March in the studied period is 12.87°C and at this temperature hatching would be 40–45 days (according to Boletzky, 1979), after spawning occurred, in March–April (Mangold-Wirz, 1963). Therefore, the temperature in May, month in which the paralarvae would hatch, is crucial for the success of the annual recruitment, reflected in the maximum catches in autumn. The seasonal variation in fisheries catches depends mainly on survival during the pre-recruitment months (Denis et al. 2002). Lloret & Lleonart (2002) found, in the north part of the same study area, that strong seasonal pattern in recruitment of *L. vulgaris* (about 12 cm mantle length) is reflected by high seasonal landings.

Due to their short life span and rapid growth rates, cephalopods growth and abundance are thought to be especially sensitive to changes in environmental conditions such as sea water temperature (Boyle & Pierce, 1994). The optimal range of PAR found in the present study is high (43.9–52.9 einstein/m^2/day). The expression PAR designates the spectral range of solar light that is useful to terrestrial plants in the process of photosynthesis. PAR measurements are also used to calculate the euphotic depth in the ocean. The depth of the euphotic zone can be greatly affected by seasonal turbidity. *Loligo vulgaris*, as other cephalopods, is a visual predator (Messenger, 1968; Boucher-Rodoni et al., 1987) meaning that the species would prefer clear water to live in and grow. In the study area, the most turbid area is defined by the influence of Ebre River that is also the area with lower landings and PAR.

The range of temperatures found in May suggested that less warm weather conditions favour subsequent landing in autumn. The model shows a negative effect with values of temperature higher than 17.53°C in agreement with the result found by Challier et al. (2005) for *L. forbesi*. In some areas, such as in the coastal waters of the Thracian Sea (Eastern Mediterranean), temperature has been found to be highly significant for beach-seine catches of *L. vulgaris*, conditioning inshore–offshore movements of the species during autumn and winter (Lefkaditou et al., 1998). Valavanis et al. (2002) found that geodistribution of potential spawning grounds in selected areas suggested that the species prefer to spawn closer to the coast when sharp-rocky coastline is present and away from the coast when a smooth-sandy beach is present. In the present study, the species presented higher LPUE in the north and central coast of the study area. The north area and part of the central consists mainly of a rocky coast with dominant sand and sandy-muddy bottom substrates (Fig. 1).

Loligo vulgaris couples their life pattern with the environmental features and takes also advantages from the hydrographic characteristic of the area. The fishing grounds for squids are mainly located in the north and central part of the Catalan coast where the EFH for paralarvae are optimal. The reported low LPUE in the south part could be related with the exportation/migration of paralarvae from north to south following the north–south current water that circulates parallel to the coast (Sabates & Maso, 1990).

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