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Ecosystem structure and fishing impacts in the northwestern Mediterranean Sea using a food web model within a comparative approach

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ABSTRACT

We developed an ecological model to characterize the structure and functioning of the marine continental shelf and slope area of the northwestern Mediterranean Sea, from Toulon to Cape La Nao (NWM model), in the early 2000s. The model included previously modeled areas in the NW Mediterranean (the Gulf of Lions and the Southern Catalan Sea) and expanded their ranges, covering 45,547 km^2, with depths from 0 to 1000 m. The study area was chosen to specifically account for the connectivity between the areas and shared fish stocks and fleets. Input data were based on local scientific surveys and fishing statistics, published data on stomach content analyses, and the application of empirical equations to estimate consumption and production rates. The model was composed of 54 functional groups, from primary producers to top predators, and Spanish and French fishing fleets were considered. Results were analyzed using ecological indicators and compared with outputs from ecosystem models developed in the Mediterranean Sea and the Gulf of Cadiz prior to this study.
Results showed that the main trophic flows were associated with detritus, phytoplankton, zooplankton and benthic invertebrates. Several high trophic level organisms (such as dolphins, benthopelagic cephalopods, large demersal fishes from the continental shelf, and other large pelagic fishes), and the herbivorous salema fish, were identified as keystone groups within the ecosystem. Results confirmed that fishing impact was high and widespread throughout the food web. The comparative approach highlighted that, despite productivity differences, the ecosystems shared common features in structure and functioning traits such as the important role of detritus, the dominance of the pelagic fraction in terms of flows and the importance of benthic–pelagic coupling.

1. Introduction

Global marine catches increased from the 1950s to a maximum of 90 million tonnes at the end of the 1980s. For many years, the total reported global landings have stagnated at around 80 million tonnes per year (FAO, 2012), with another 20 million tonnes of additional illegal/unreported catch (Agnew et al., 2009). This stagnation has occurred despite increased fishing efforts and efficiency, and the geographic and bathymetric expansion of fishing activities (Pauly and Palomares, 2010; Swartz et al., 2010; Watson and Morato, 2013; Watson et al., 2013). The overall limits of sustainable exploitation have long been exceeded (Pitcher and Cheung, 2013; Worm and Branch, 2012).

The Mediterranean Sea has been strongly influenced by human activities since ancient times (Lotze et al., 2011). However, since the industrial revolution these impacts have grown exponentially due to technological improvements in fishing fleets and the demographic explosion in the area (Lotze et al., 2011). The high impact of fishing is evidenced by several stock assessments, indicating that most demersal and pelagic stocks are fully exploited or overexploited (Colloca et al., 2013; GFCM, 2013). In addition, the Mediterranean Sea has been altered by other human effects such as habitat loss and degradation, pollution, climate change, eutrophication, aquaculture and the introduction of alien species (Coll et al., 2010, 2012).

The current situation of exploited resources and marine ecosystems shows that management based on a single species, the dominant one in

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the last 50 years, has not been sufficient to ensure the proper management of exploited resources. Therefore, there is a pressing need to move towards an Ecosystem-based Approach to Fisheries (EAF) (Cochrane and de Young, 2008; Garcia et al., 2003).

The EAF framework has aroused a great interest among the scientific community and new tools have been developed in recent decades, including ecological models and ecological indicators (Link, 2011; Plagányi, 2007). These tools provide a framework for integrating ecological and ecosystem issues into management programs by assessing, for example, the impacts of interactions between species and fisheries and their implications in marine fisheries management.

In the Mediterranean Sea, several ecological models using the *Ecopath with Ecosim* approach (EwE) (Christensen and Walters, 2004) have been developed (Coll and Libralato, 2012). These models have been used for a diversity of applications such as analyzing fishing impacts (Coll et al., 2006a, 2007), comparing ecosystem structure and functioning traits (Hattab et al., 2013; Tsagarakis et al., 2010), exploring management options (Fouzai et al., 2012), assessing the impact of aquaculture (Forestal et al., 2012), evaluating the effects of the environment (Coll et al., 2008; Piroddi et al., 2010) and exploring the effects of invasive species in the food web (Daskalov, 2002).

The NW Mediterranean Sea is exploited by French and Spanish fleets and is one of the most impacted regions in the basin (Coll et al., 2012; Micheli et al., 2013). Previous ecosystem models developed in the study area indicated intense exploitation of the marine ecosystem (Banaru et al., 2013; Coll et al., 2006a) and changes in the trophic structure of the ecosystem (Coll et al., 2008).

In this study, we developed a food web model in a large area of the NW Mediterranean Sea including the Gulf of Lions and part of the Balearic Sea. Previously, various smaller models were developed in this area (Banaru et al., 2013; Coll et al., 2006a), but the new model includes a larger area considering important hydrodynamic events that enhance the connectivity between the two regions. Also included were several submarine canyons of the area, which are mainly located in the Gulf of Lions and the northern part of the Balearic Sea. These canyons play an important ecological role and are associated with important fishing activities (Würtz, 2012). From a fisheries point of view, there are also some 'shared stocks' in the area, which motivated the development of the larger model. Shared stocks include the important commercial populations of hake (*Merluccius merluccius*) and anchovy (*Engraulis encrasicolus*).

With this new modeling effort we aimed to develop a useful modeling tool to contribute to the fisheries management in the region through an ecosystem approach. In this study, we present the new ecological model and use it to update previous knowledge of the area by:

a) Characterizing the structure and functioning of the ecosystem during the early 2000s;

b) Assessing the impact of fishing activity on the ecosystem using ecological indicators; and

c) Comparing the results with other food web models developed in several areas of the Mediterranean Sea and adjacent waters of the Gulf of Cadiz.

2. Material and methods

2.1. Study area and period

Despite the fact that the Mediterranean Sea is considered an oligotrophic region, the NW Mediterranean is a rather productive area (Bosc et al., 2004; Estrada, 1996). This is due to the upwelling activity influenced by wind conditions and the fresh water inputs from the Rhone and Ebro Rivers (Agostini and Bakun, 2002; Salat, 1996). General marine circulation is characterized by the presence of the wide Northern current running along the continental slope from the Ligurian Sea to the continental shelf of the Balearic Sea (Millot, 1999).

Several parts of the area have been identified as important ecological habitats, and spawning and nursery areas, for small pelagic and demersal fish (Lleonart et al., 2008; Palomera et al., 2007). Moreover, this area is home to abundant seabird colonies, such as in the Gulf of Lions and the Ebro Delta (Arcos et al., 2009; Cadiou et al., 2004). Several species of mammals and sea turtles are also present in the area (Gómez de Segura et al., 2006a,b).

Mediterranean fisheries are characterized by multi-specificity (targeting a variety of fish and invertebrate species), particularly in the demersal regime, and use of a large number of landing sites (Lleonart and Maynou, 2003). Catches are landed on a daily basis and are made near the coast, on the continental shelf down to the mid-continental slope. Three different types of fleets can be identified: artisanal, industrial and semi-industrial (Farrugio and Papaconstantinou, 1998). Although the artisanal fleet is still important, the most important fleets are semi-industrial and industrial, composed of bottom trawlers, purse seiners and longliners, and include the tuna fishery (Lleonart and Maynou, 2003).

This study includes the Gulf of Lions and part of the Balearic Sea, specifically the continental shelf and upper slope from Toulon (France) to Cabo de la Nao (Spain) (Fig. 1). The NW Mediterranean Sea model (NWM model) represents the early 2000s and covers an area of 45.547 km^2, with depths from 0 to 1000 m.

The selection of the bathymetry in the model is justified for fishery and biological reasons. The limit of 0–50 m represents an important feeding area for most species or functional groups and is essential for the inclusion in the model of *Posidonia oceanica*, macrophytes and microphytobenthos, and the artisanal fleet. The limit of 1000 m is the boundary at which bottom trawling fleet is allowed to operate (Regulation EC 1967/2006).

The northern and southern boundaries are justified because part of the northern Catalonia (Spain) fishing fleets exploits the fishing resources in the Gulf of Lions (Aldebert et al., 1993; Lleonart et al., 2008), resulting in a number of shared stocks, as is the case of hake and anchovy. The hydrodynamic events in the region indicate connectivity between the Gulf of Lions and the Balearic Sea, due to the general southward circulation mainly illustrated by anchovy larvae transport (Ospina-Alvarez et al., 2012; Sabatés et al., 2001). The model does not include the Balearic Islands as this area has different ecological and fisheries features (Quetglas et al., 2012) and is considered another GSA (Geographical Sub-Areas) for management purposes by the General Fisheries Commission for the Mediterranean (GFCM).

2.2. Modeling approach

The food web model of the NWM was constructed using the *Ecopath with Ecosim* (EwE) software version 6.3 (Christensen and Walters, 2004; Christensen et al., 2008). We used the static Ecopath model that provides a "snapshot" of the trophic flows in the ecosystem during a specific period. The Ecopath model is parameterized with two master equations for each functional group or "box" in the model: one describes the biological production and the other describes the energy balance. A functional group consists of ontogenic fractions of a species, single species or groups of species sharing common ecological traits such as habitat or feeding (Christensen et al., 2008).

The first equation of the production of each functional group (i) is:

$$P_i = \sum_j B_j \cdot M2_{ij} + Y_i + E_i + BA_i + P_i \cdot (1 - EE_i) \quad (1)$$

where $M2_{ij}$ is the predation mortality caused by the biomass of the predators (B_j); Y_i are exports from the system due to fishing activity; E_i is the net migration rate (emigration − immigration); BA_i is the biomass accumulation in the ecosystem; and $P_i \cdot (1 - EE_i)$ is other natural mortality excluding predation ($M0$). $M0$ is a catch-all term including all mortality not elsewhere included, e.g. mortality due to disease or old