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An ecosystem model of an exploited southern Mediterranean shelf region (Gulf of Gabes, Tunisia) and a comparison with other Mediterranean ecosystem model properties

Tarek Hattab [a,b,*], Frida Ben Rais Lasram [a], Camille Albouy [b,c], Mohamed Salah Romdhane [a], Othman Jarboui [d], Ghassen Halouani [a,b], Philippe Cury [b], François Le Loc'h [b]

[a] UR 03AGRO1 Ecosystèmes et Ressources Aquatiques, Institut National Agronomique de Tunisie, 43 Avenue Charles Nicolle, 1082 Tunis, Tunisia
[b] UMR 212 Ecosystèmes Marins Exploités (IRD-IFREMER-UMII) Avenue Jean Monnet, BP 171, 34203 Sète, France
[c] UMR 5119 ECOSYM (CNRS-UM2-IRD-IFREMER-UM1), Université de Montpellier 2, CC 093, 34095 Montpellier, France
[d] LR11INSTM01, Laboratoire Sciences Halieutiques, Institut National des Sciences et Technologies de la Mer, Centre de Sfax, B.P 1035, 3018 Sfax, Tunisia

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ABSTRACT

In this paper, we describe an exploited continental shelf ecosystem (Gulf of Gabes) in the southern Mediterranean Sea using an Ecopath mass-balance model. This allowed us to determine the structure and functioning of this ecosystem and assess the impacts of fishing upon it. The model represents the average state of the ecosystem between 2000 and 2005. It includes 41 functional groups, which encompass the entire trophic spectrum from phytoplankton to higher trophic levels (e.g., fishes, birds, and mammals), and also considers the fishing activities in the area (five fleets). Model results highlight an important bentho-pelagic coupling in the system due to the links between plankton and benthic invertebrates through detritus. A comparison of this model with those developed for other continental shelf regions in the Mediterranean (i.e., the southern Catalan, the northern-central Adriatic, and the northern Aegean Seas) emphasizes similar patterns in their trophic functioning. Low and medium trophic levels (i.e., zooplankton, benthic molluscs, and polychaetes) and sharks were identified as playing key ecosystem roles and were classified as keystone groups. An analysis of ecosystem attributes indicated that the Gulf of Gabes is the least mature (i.e., in the earliest stages of ecosystem development) of the four ecosystems that were compared and it is suggested that this is due, at least in part, to the impacts of fishing. Bottom trawling was identified as having the widest-ranging impacts across the different functional groups and the largest impacts on some commercially-targeted demersal fish species. Several exploitation indices highlighted that the Gulf of Gabes ecosystem is highly exploited, a finding which is supported by stock assessment outcomes. This suggests that it is unlikely that the gulf can be fished at sustainable levels, a situation which is similar to other marine ecosystems in the Mediterranean Sea.

1. Introduction

The Mediterranean Sea, the widest and deepest semi-enclosed sea on earth, has been strongly influenced by human activities for millennia (Lotze et al., 2011). Exploitation of marine resources has been a significant component in this historical relationship and overutilization along the continental shelf has occurred at different times (Tudela, 2004). For example, localized depletions of fish populations were recorded during Roman times (Hughes, 1994; Radcliffe, 1921). Indeed, fishing may induce a number of direct effects on marine ecosystems including a reduction in fish abundance, biomass and species richness (for Mediterranean examples see Harmelin et al., 1995; Tudela, 2004). Indirectly, fishing can disrupt ecosystem functioning, leading to changes in biological assemblages and impacts on marine ecosystem services (Worm et al., 2006). At present, the most significant threats to Mediterranean ecosystems in addition to fishing are pollution, eutrophication, habitat loss, the introduction of alien species, and climate change (Coll et al., 2010). The complexity of marine ecosystem dynamics and the difficulties associated with single-species management have led to a shift towards an ecosystem approach to fisheries (EAF). It is recognized that this approach could lead to the sustainable exploitation of fish stocks (Cochrane and De Young, 2008; Cury et al., 2005; Garcia et al., 2003). However, modern fisheries management strategies were developed after World War II, particularly in the north-western region of the Mediterranean (Farrugio et al., 1993) and it is still at an early stage of development across the broader basin. Mediterranean fisheries are typically multi-species and multi-gear, particularly the demersal fisheries that are composed of numerous small- to medium-sized boats (Farrugio et al., 1993). This diversity brings additional difficulties to the task of

* Corresponding author at: UMR 212 Ecosystèmes Marins Exploités (IRD-IFREMER-UMII) Avenue Jean Monnet, BP 171, 34203 Sète, France. Tel.: +216 22772973.
E-mail address: hattab.tarek@gmail.com (T. Hattab).

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managing fisheries (Papaconstantinou and Farrugio, 2000) and puts fisheries research in the context of "composite fisheries" (Farrugio et al., 1993). This is especially true in Tunisia (Jabeur et al., 2000) where, though artisanal fisheries remain important, most fleets have developed to a semi-industrial level. These fleets intensively exploit the continental shelf and upper slopes of the basin. A general assessment suggests that most Mediterranean demersal stocks are fully exploited or overexploited, and some pelagic stocks also show overexploitation trends (ICCAT, 2003; Lleonart and Maynou, 2003; Papaconstantinou and Farrugio, 2000).

Evidence shows that the effects of fishing in the Mediterranean Sea go far beyond the isolated impacts on overfished target species, threatened non-commercial species, or sensitive habitats (Tudela, 2004). The ecosystem effects of fishing are also obvious at the systemic level, as evidenced by the massive ecological footprint of fishing and its marked effects on the structure of food webs (CIESM, 2000; Tudela, 2004). Therefore, a holistic approach should be adopted if these ecosystem-scale fisheries-driven changes to the structure and functioning of marine ecosystems are to be addressed (Tudela, 2004).

The shift towards an ecosystem approach has led to a demand for tools capable of managing information on ecosystem interactions. Consequently, trophic network models of aquatic ecosystems are increasingly appearing in the literature. By providing an integrative image of the structure, functioning, and dynamics of ecosystems, modeling can be a useful tool to advance our knowledge of food web theory. It is an approach that has been increasingly used in fisheries management to assess possible ecosystem responses to different impacts and to explore alternative sustainable use scenarios (Coll and Libralato, 2012). Among the different modeling tools available, Ecopath with Ecosim (EwE; Christensen and Walters, 2004; Polovina, 1984) is used worldwide for aquatic ecosystems (Plagányi, 2007). However, due to the limited quantity and quality of data for lower trophic levels, EwE predominantly focuses on the upper trophic levels and the effects of fishing on commercially-targeted species (Steele, 2009).

The EwE approach explicitly considers trophic links between ecosystem components and allows fishing activities to be studied within an ecosystem context. This allows a number of critical analyses to be performed including: (1) a comparison of ecosystem structure and functioning (e.g., Coll and Libralato, 2012; Tsagarakis et al., 2010) (2) the derivation of emergent properties (e.g., Pauly and Christensen, 1995); (3) an assessment of the impacts arising from human activities (e.g., Albouy et al., 2010; Mackinson et al., 2009; Shannon et al., 2008); and (4) the analysis of marine resource management options (e.g., Araújo et al., 2008; Criales-Hernandez et al., 2006; Libralato et al., 2010). In the Mediterranean Sea, 40 Ecopath models have been fully developed and documented (Coll and Libralato, 2012), primarily in the north, for a range of systems including the continental shelf, upper slopes, lagoons and coastal zone. To date, no models have been developed for the southern Mediterranean Sea.

This study will be the first to use a mass-balanced Ecopath model to describe an exploited shelf ecosystem in the southern Mediterranean Sea. The study area, the Gulf of Gabes, is the second-widest area of continental shelf in the Mediterranean Sea. The gulf is characterized by a shallow slope, a soft bottom, and high fish diversity that combine to make it the most important fishing area in Tunisia (Najar et al., 2010). Intense fishing activity in the Gulf of Gabes began in the early 1980s. Large fluctuations in landings followed and catches have progressively declined since the late 1990s (Najar et al., 2010) mainly due to decreases in demersal stocks. The area currently supports 60% of the national fleet operations and contributes 42% (42,000 t) of the annual national fish production (DGPA, 2007). Catches in the gulf are dominated by benthic cephalopods such as cuttlefish or octopus (e.g., *S. officinalis*, *O. vulgaris*), the caramote prawn (*Melicertus kerathurus*), the round sardinella (*Sardinella aurita*), the European pilchard (*Sardina pilchardus*), mullet (*Mullus barbatus* and *Mullus surmuletus*), and Sparidae (e.g., *Diplodus annularis*).

Several indicators suggest that the Gulf of Gabes ecosystem is being depleted. For example, the yield per hour rate has decreased from 75 kg h^{-1} in the 70s to 30 kg h^{-1} in the 90s (Hattour, 1991). At a species level, a number of commercially-targeted demersal species have been reported as overexploited. These include the surmullet (*M. surmuletus*; Ben Mariem et al., 1994), red mullet (*M. Barbatus*; Gharbi et al., 2004), common pandora (*Pagellus erythrinus*; Ghorbel and Bouain, 1992; Ghorbel et al., 1997; Jarboui and Ghorbel, 1998), and bluefish (*Pomatomus saltatrix*; Dhieb et al., 2007). The large amounts of discards associated with fishing activities in the area are also of significant concern (Ben Mariem and Gharbi, 1988; Gharbi and Ben Meriem, 1996; Jarboui and Zamouri, 2004). To address these issues, this study aims to: (1) describe the main structural and functional traits of the Gulf of Gabes ecosystem; (2) analyze the ecological role of the main trophic groups; (3) assess the ecosystem impacts of fishing; and (4) compare the properties of this ecosystem with several other Mediterranean Ecopath models.

2. Materials and methods

2.1. The study area

The Gulf of Gabes is located in the southern Mediterranean Sea and covers the second-widest continental shelf area (35,900 km^2; Fig. 1). The gulf is characterized by unique geomorphological, climatic and oceanographic conditions. The gulf basin is very shallow, reaching only 50 m depth 110 km offshore. A depth of 200 m is not reached until 400 km from the coastline. This particular bathymetric pattern makes the gulf very sensitive to atmospheric conditions (Natale et al., 2006). The annual water temperature cycle is very pronounced (range: 13 °C to 29 °C) (Ben Ismail Hammouda et al., 2010) and these variations influence the composition of the phytoplankton community. Consequently, different trophic regimes have been observed: the warmer and saltier Mediterranean Mixed Water and the Modified Atlantic Water are characterized by mesotrophy, while the Transition Water separating these two water masses is observed to be oligotrophic (Ben Hassen et al., 2008). The gulf's tidal amplitude is also unusual with tides reaching 1.8 m height, the highest in the Mediterranean (Sammari et al., 2006).

Favorable geomorphological and climatic conditions have combined to support one of the most productive ecosystems in the Mediterranean Sea (Papaconstantinou and Farrugio, 2000), which has significant economic and ecological importance. The gulf supports high fisheries productivity and serves as a nursery, feeding, and breeding ground for numerous populations of fishes and crustaceans. For example, ecological succession has resulted in one of the most extensive seagrass communities (*Posidonia oceanica*) in the Mediterranean Sea (Batisse and Jeudy de Grissac, 1998), which provides a major nursery site for several marine species (Francour, 1997). Due to its importance, the ecosystem of the Gulf of Gabes has been extensively studied during the last few decades. Its continental shelf was selected in this study to develop a mass-balance model. Within the gulf, we modeled the area within a depth range of 20 and 200 m (Fig. 1). This encompassed a total area of 25,000 km^2 of soft sediment bottom. This area is where the trawlers and purse seiners mainly operate, as well as a few of the artisanal fishers. The model was developed to represent an average situation in the Gulf of Gabes ecosystem, using data from 2000 to 2005.

2.2. Mass-balance modeling approach

The Ecopath with Ecosim (EwE) software (Version 6.2; www.ecopath.org; Christensen and Walters, 2004) was used in this study to assess the trophic functioning of the Gulf of Gabes. In EwE, trophic interactions between functional groups (i.e., single species or groups of species sharing similar ecological features) are described by a set of linear equations that ensure the mass balance of ecosystems and quantify