



Fishing inside or outside? A case studies analysis of potential spillover effect from marine protected areas, using food web models



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ABSTRACT

Marine protected areas (MPAs) are implemented worldwide as an efficient tool to preserve biodiversity and protect ecosystems. We used food web models (Ecopath and EcoTroph) to assess the ability of MPAs to reduce fishing impacts on targeted resources and to provide biomass exports for adjacent fisheries. Three coastal MPAs: Bonifacio and Port-Cros (Mediterranean Sea), and Bamboung (Senegalese coast), were used as case studies. Pre-existing related Ecopath models were homogenized and ecosystem characteristics were compared based on network indices and trophic spectra analyses. Using the EcoTroph model, we simulated different fishing mortality scenarios and assessed fishing impacts on the three ecosystems. Lastly, the potential biomass that could be exported from each MPA was estimated. Despite structural and functional trophic differences, the three MPAs showed similar patterns of resistance to simulated fishing mortalities, with the Bonifacio case study exhibiting the highest potential catches and a slightly inferior resistance to fishing. We also show that the potential exports from our small size MPAs are limited and thus may only benefit local fishing activities. Based on simulations, their potential exports were estimated to be at the same order of magnitude as the amount of catch that could have been obtained inside the reserve. In Port Cros, the ban of fishing inside MPA could actually allow for improved catch yields outside the MPA due to biomass exports. This was not the case for the Bonifacio site, as its potential exports were too low to offset catch losses. This insight suggests the need for MPA networks and/or sufficiently large MPAs to effectively protect juveniles and adults and provide important exports. Finally, we discuss the effects of MPAs on fisheries that were not considered in food web models, and conclude by suggesting possible improvements in the analysis of MPA efficiency.

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1. Introduction

Human activities are causing unprecedented changes to marine ecosystems, partly through both direct and indirect fishing effects (Halpern et al., 2008; Jackson et al., 2001). The increase in demand for seafood has led to a substantial expansion of fisheries through all the oceans and marine habitats (Pauly et al., 2002; Swartz et al., 2010), at all depths (Morato et al., 2006; Pauly et al., 2003), and toward lower trophic levels (Essington et al., 2006; Pauly et al., 1998). These changes in exploitation cause major changes in biological assemblages and,

ultimately, lead to biodiversity losses that may disrupt ecosystem functioning and alter the sustainability of the goods and services provided by the many marine environments that currently support human welfare (Lotze et al., 2006; Pauly and Watson, 2005; Worm et al., 2006).

To protect marine biodiversity and counteract human impacts on marine ecosystems, one intuitive management strategy is to close certain parts of the ocean to fishing. This solution has been employed since the Middle Ages where European kings controlled and closed access to certain streams (Hoffmann, 1996), and was advised as a management tool for fisheries by Hérubel (1912) over a century ago. Nowadays, marine protected areas (MPAs) are implemented worldwide as a tool for an ecosystem approach to fisheries (EAF; Garcia et al., 2003), and to meet the objectives defined by the Convention on Biological Diversity (CBD). In 2004, the CBD reached a consensus among partners such that 10% of each ecoregion would be protected before 2010, the final objective being the creation of a network

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of protected areas covering the major part of biodiversity by 2012 (CBD, 2004).

MPAs are viewed as an effective tool benefiting habitats and fish populations. Not only can they drive increases in the mean size, density, abundance, and species diversity of the various fish populations within their boundaries (Lester et al., 2009; Molloy et al., 2009; Mosquera et al., 2000), but MPAs may also benefit adjacent fisheries through mechanisms such as adult and juvenile fish emigration (“spillover effect”; Rowley, 1994), or pelagic egg and larval exports (Harrison et al., 2012; Pelc et al., 2009, 2010). However, the magnitude of this biomass export from MPAs, its role in sustaining fisheries, and its composition are still poorly known.

Ecosystem modeling approaches can provide support for answering these questions. Among ecosystem models, Ecopath with Ecosim (EwE; Christensen and Walters, 2004; Christensen et al., 2005) has been applied numerous times to model MPAs and their trophic functioning (30 applications registered in EcoBase; Colléter et al., 2013b). However, only a few of these models focused on the potential role of MPAs in sustaining fisheries (e.g. Le Quesne et al., 2008), their contribution at a larger scale (e.g. Mauritanian shelf; Guénette et al., 2014), and the potential export of fish biomass from the reserve (Valls et al., 2012).

Based on available case studies, the current study used trophodynamic modeling tools to investigate trophic functioning and the potential spillover effect of three different MPA ecosystems, which have been previously modeled using EwE. We employed two types of modeling approach: (i) Ecopath (Christensen and Pauly, 1992; Polovina, 1984) to compare outcomes (model derived indicators) of the three case studies and to estimate the fish biomass potential export (i.e. the potential spillover effect) from each MPA, and (ii) EcoTroph (Gascuel, 2005; Gascuel and Pauly, 2009) to derive additional indicators, to simulate the impact of hypothetical fisheries inside the MPAs, and to estimate the biomass of fish that could potentially be caught by these fisheries (i.e. catch losses). We compared these estimates to the potential exports for each reserve (i.e. the fish biomass not used in the trophic network and so possibly emigrating). We concluded with a discussion on the potential spillover effects, and possible improvements in the analysis of MPA efficiency.

2. Material and methods

2.1. MPA case studies and Ecopath models

The Ecopath with Ecosim software and model (EwE, version 6.2.0.262; Christensen and Walters, 2004; Christensen et al., 2005) are used worldwide to analyze trophic interactions and quantify trophic flows in aquatic ecosystems. An Ecopath model comprises a set of functional groups (each representing a species or group of species) that are linked by trophic interactions. The model assumes the trophic network to be in a steady state during the studied period, and consequently a mass-balance where the production of the group is equal to the sum of all predations, non-predatory losses, exports, biomass accumulations and catches (Eq. (1)):

$$B_i \times \left(\frac{P}{B}\right)_i = \sum_{j=1}^N B_j \times \left(\frac{Q}{B}\right)_j \times DC_{ji} + \left(\frac{P}{B}\right)_i \times B_i \times (1-EE_i) + Y_i + EX_i + BA_i \quad (1)$$

where N is the number of groups in the model, B the biomass, P/B the production rate, Q/B the consumption rate, DC_{ji} the diet matrix representing the fraction of prey i in the diet of predator j, EX the net export, BA the biomass accumulation, Y the catch, and EE the ecotrophic efficiency, i.e. the fraction of production which is used in the system. EE must be less than or equal to one under the assumption of mass-balance. Assuming that there is no export and no biomass accumulation, and the catches are known, only three of the four parameters B, P/B, Q/B and EE have to be set initially for each group. The Ecopath mass-balance

algorithm estimates the value of the remaining parameter. Ecopath software computes mass-balance by solving the system of equations for the unknown parameters of all groups. It also calculates the trophic level (TL, Eq. (2)) of each group, which characterizes their position within ecosystem’s food web (Lindeman, 1942; Odum and Heald, 1975):

$$\tau_j = 1 + \sum_i (DC_{ji} \times \tau_i) \quad (2)$$

where τ_j is the TL of predator j and τ_i the TL of its prey. The trophic level of primary producers is equal to 1.

We focused on three MPAs, for all of which Ecopath models have previously been built: two on the French Northwestern Mediterranean coast and one on the Senegalese coast (Fig. 1). We used available models and associated trophic spectra to analyze common features, especially regarding potential relative fishing impacts and biomass exports, in these three contrasting MPAs (Table 1):

- The *Bonifacio Strait Natural Reserve* was created in 1999. It covers approximately 800 km² and is characterized by a predominantly rocky substrate and *Posidonia oceanica* seagrass beds at shallow depths (Pluquet, 2006). Artisanal and recreational fishing activities are allowed in some parts of the MPA. The Ecopath model we adapted was originally developed by Albouy et al. (2010) for the years 2000–2001.
- The *Port-Cros MPA* is a small insular reserve created in 1963. The MPA has a total area of 12.9 km², and 30% of which is covered by seagrass meadows. As in Bonifacio, small-scale fishing activities are permitted with specific restrictions in some parts of the MPA (Cadiou et al., 2009). The Ecopath model we adapted was originally developed by Valls et al. (2012) for the years 1998–2008.
- The *Bolong de Bamboung* is a small saline tributary of the Sine Saloum estuary. The MPA covers 6.8 km² including 4.7 km² of intertidal banks. The bolong has been monitored since 2003 (Albaret, 2003) and fishing has been prohibited since 2004. Two Ecopath models were developed for this site by Colléter et al. (2012): one for 2003, when fishing was still allowed, and one for the 2006–2008 period, after the establishment of the MPA. Given the context of this work, the latter was used.

The three Ecopath models were developed within a French national program (ANR-Amphore) with the objectives of modeling trophic networks and assessing the effectiveness of MPAs. Their structure differed in order to properly reflect each ecosystem and its typical characteristics, but their construction satisfied common criteria (Table 1). These Ecopath models included all the biological ecosystem components using 32 trophic groups for Bonifacio, 41 for Port-Cros, and 31 for Bamboung. The ratio of the number of fish trophic groups to present fish species was in the same order of magnitude for the three models (21% for Port-Cros and Bonifacio, 25% for Bamboung). Mediterranean models were more detailed for invertebrate compartments since more information was available. The input data (especially biomass estimates) for the models came mostly from field studies (see details in Albouy et al., 2010; Colléter et al., 2012; Valls et al., 2012). Biomasses estimated by EwE concerned 34% of the groups for Port-Cros, 31% for Bonifacio, and 26% for Bamboung. These biomasses referred almost exclusively to the secondary consumer groups, for which biomass estimations were rare. On the contrary, fish biomass estimations were of good quality, as they mostly came from field studies corresponding to the modeled periods (see Tables S1, S2, and S3 for parameter details).

We homogenized the pre-existing models by adjusting some of the model input parameters. We adapted the two kinds of initial Ecopath parameters that could be standardized without affecting the structure of the models: 1. The assimilation efficiency (U/Q), which is an estimate of the fraction of the food that is not assimilated (i.e. consisting of urine and feces) and directed to the detritus, was set to the same value for similar functional groups: 0.11 for carnivorous fishes, cephalopods and

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