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Assessing interacting impacts of artisanal and recreational fisheries in a small Marine Protected Area (Portofino, NW Mediterranean Sea)

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Abstract. Marine Protected Areas (MPAs) have spread across the Mediterranean to protect its rich biodiversity and manage human activities for a more sustainable coastal development. Within MPAs, traditional artisanal fishing is competing for space and resources with increasing recreational fishing, likely leading to interacting ecological effects. Such effects are difficult to unravel, given the multispecies character of both fisheries and the complexity of the food webs upon which they both impact. To address these issues, we developed an Ecopath and EcoTroph trophic model for the Portofino MPA case study (NW Mediterranean), in particular to (1) identify keystone species and assess fishing impact on them; (2) analyze the interacting impact of artisanal and recreational fishing on ecosystem biomass and trophic structure; and (3) assess the impact of recreational fishing on artisanal fishing catches. Two high trophic level predator (HTLP) groups coupled important keystone roles with high sensitivity to fishing pressure and should thus be regarded as "sentinels" to be prioritized for the definition of management actions. Recreational fishing had the widest impact on the food web, strongly impacting HTLP. Simulation of different mortality scenarios for each fishery highlighted that the ecosystem is far from its carrying capacity for HTLP. Forbidding recreational fishing allowed a 24% increase in HTLP biomass and benefited artisanal fishing by increased availability of HTLP catches. Artisanal fishing alone could instead be maintained with a moderate impact on the food web. Overall, Ecopath and EcoTroph modeling is a valuable tool to advise MPA management, but it is essential to increase data availability and quality by developing long-term monitoring programs on key species and on artisanal and recreational fishing.

Key words: artisanal fishing; Ecopath; EcoTroph; food web; high trophic level predators; keystone species; Marine Protected Area; recreational fishing.

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INTRODUCTION

In the last decade, the ecosystem-based management approach has become the major call of action in the marine research context. Ignoring the nature, strength, and complexity of species interactions, single-species approaches have generally failed to cope with the increasing human impacts on the world's oceans, that often cause dramatic changes in marine ecosystems (Roux et al. 2013, Travis et al. 2014). The Mediterranean, hosting an estimated 7% of the world's marine biodiversity (Coll et al. 2010, Coll 2011), exemplifies the scarce success of these approaches: most of its fish stocks are currently overfished (Colloca et al. 2013, Vasilakopoulos et al. 2014, Tsikliras et al. 2015) and irreversible ecosystem changes have occurred in some areas open to fishing (Sala et al. 1998, 2012). The overexploitation of fish stocks also affected traditional activities such as small-scale artisanal fishing by reducing the availability of catches. Artisanal fishing is usually operated by relatively small vessels (<12 m total length, with low-power engine) typically fishing within the first three nautical miles from the coast (Coppola 2006, Guyader et al. 2013). Usually, artisanal fisheries are highly multi-specific (Farrugio et al. 1993) and multi-métier, using a broad range of gears and techniques selected according to seasonal availability of target species (the concept of "métier" denotes a combination of fishing gear, target species, area, and season; Mesnil and Shepherd 1990, Biseau 1998). Such activity has long played a fundamental role in both the economy and society (Farrugio et al. 1993) of the Mediterranean, with considerable cultural and historical significance, but is now declining in many areas with a downward trend in the number of vessels and licenses, catches, and net revenues (Gómez et al. 2006, Guyader et al. 2013, Lloret and Font 2013, Di Franco et al. 2014).

In addition to artisanal fishing, Mediterranean coastal ecosystems are facing a boom in leisure activities, particularly recreational fishing. An increasing number of studies supported the idea that the increasing recreational fishing effort can have similar as, or even higher effects on fish populations than artisanal fishing (Cooke and Cowx 2004, 2006, Lewin et al. 2006). Nonetheless, recreational fishing is not as controlled nor as well investigated as artisanal fishing, especially in the Mediterranean, where it would represent more than 10% of the total fishing catches (Morales-Nin et al. 2005, Font et al. 2012).

To face this situation and in the perspective of an ecosystem-based approach to coastal management (Lubchenco et al. 2003), Marine Protected Areas (MPAs) have spread across the coastal zones of the Mediterranean as a tool to protect the ecosystem and manage human activities for a more sustainable coastal development (Abdulla et al. 2008, Forcada et al. 2008). Where they are well managed and enforced, MPAs have proved to be effective in protecting exploited fish and invertebrate stocks (Goñi et al. 2006, Guidetti et al. 2008, Sala et al. 2012, Mesnildrey et al. 2013), and have in some successful cases helped to enhance artisanal fisheries (Guidetti and Claudet 2010, Fenberg et al. 2012). Nonetheless, Mediterranean MPAs are often small and competition for space and resources is increasingly causing conflicts among artisanal and recreational fishermen. The activity of the latter within MPAs is often less regulated and controlled (Edgar 2011). Artisanal and recreational fishing pressure are indeed likely to have interacting ecological effects, which are difficult to unravel given the multispecies character of both fisheries and the complexity of the protected food webs upon which they both impact (Baskett et al. 2007).

Ecosystem models could help to shed light on such issues by accounting for the direct and indirect trophic interactions among multiple species (Colléter et al. 2012, Travis et al. 2014). The use of the Ecopath with Ecosim (EwE) modeling software (Christensen and Pauly 1992, Christensen and Walters 2004) has grown significantly in the last 15 years (Fulton 2010, Colléter et al. 2015) and is by now gaining widespread acceptance as a tool to apply the Ecosystem Approach to Management (Coll et al. 2015). The more recent plug-in EcoTroph (Gascuel 2005, Gascuel et al. 2011) provides a simplified representation of ecosystem functioning and allows to evaluate fisheries impacts and analyze the conflicts among interacting fishing fleets (Gasche and Gascuel 2013, Colléter et al. 2014).

Thus, the objective of this study was to show how Ecopath and EcoTroph trophic models can be used to assess impacts of both artisanal and recreational fisheries on the marine food web within a coastal MPA, and to analyze interactions and potential competition between the two different fisheries. As a case study, we focused on the Portofino MPA (Ligurian Sea). This MPA was established with the objective of conserving marine biodiversity around the Portofino promontory, and in the last years has also become the promoter of a sustainable socio-economic development of the area. Traditionally, the area hosted a well-developed artisanal fishing fleet, which, although declining naturally because of the old age of local fishermen, is increasingly competing for space with recreational fishing (Salmona and Verardi 2001, Cattaneo-Vietti et al. 2010, Markantonatou et al. 2014).

We thus approached these issues by building an Ecopath and EcoTroph model for the Portofino MPA. In particular, we aimed at: (1) unraveling species interactions, identifying keystone functional groups in the model area and assessing artisanal and recreational fishing impact on such; (2) analyzing the interacting impacts of both artisanal and recreational fishing on ecosystem biomass and trophic structure; and (3) analyzing the impact of recreational fishing on the quantity and species composition of artisanal fishing catches.

METHODS

Study area

The promontory of Portofino is located 25 km east from Genoa in the Ligurian Gulf and extends over 13 km of coastline (Salmona and Verardi 2001) (Fig. 1). The Portofino MPA was established in 1999 to safeguard the marine biodiversity around the promontory and promote a traditional and sustainable use of its natural resources (Cappanera et al. 2013). Currently, it is the third smallest Italian MPA (374 ha) and is managed by a consortium comprised of the three municipalities of Camogli, Portofino, and Santa Margherita Ligure, the Metropolitan City of Genoa, and the University of Genoa. Similar to other Italian MPAs, it is divided into different subzone types: no-take/no-access A zone, a B zone of general reserve, and a C zone of partial protection, where different restrictions regulate human uses. Artisanal fishing involves 35 operating vessels <10 m in length (MARTE+ 2011, *unpublished data*) and is allowed in zones B and C only for the residents of the three municipalities. This fishery is multi-métier and multi-specific, and fixed nets including gill nets, trammel nets, and combined nets are the mostly used gears (70% of total used gears), followed by longlines and small purse seine (both around 20% of total used gears). Other traditional fishing gears (e.g., *tonnarella* targeting small pelagic, and *mugginara*, specifically targeting mugilids) are allowed during specific periods and are restricted to a single site within zone C of the MPA (Cattaneo-Vietti et al. 2014). Recreational fishing is permitted for residents of the three municipalities under authorization in zones B and C and for non-residents only in zone C. For both recreational and artisanal fishing, other restrictions such as the fishing of some species, spatial closures, prohibitions or modifications of fishing techniques, regulations in fishing effort, and minimum landing sizes are also implemented in the MPA to control the activities, according to the MPA Regulation (2008) (Markantonatou et al. 2014). Trawling is forbidden in the whole MPA.

The modeled surface (57 ha) includes the southern front of the MPA, encompassing zones A and B and two sectors of zone C (Fig. 1), and is characterized mainly by hard bottoms (51% rocky habitat, 31% coralligenous habitat), with some *Posidonia oceanica* meadows and shallow sands (overall 18% of the area). This area supports most of the artisanal and recreational fishing pressure in the MPA, with highest overlap between coralligenous habitat and fishing footprint around 30–40 m depth (Markantonatou et al. 2014). The southern submerged steep cliffs of the promontory and the particular hydrodynamic conditions of the area (Doglioli et al. 2004) create in fact a unique system where rocky reefs, caves, and massive blocks support a very diversified benthic community, including extended coralligenous habitat cover (Cattaneo-Vietti et al. 2010). This, in turn, provides food and shelter for a rich coastal fish community. The hydrodynamic conditions also attract large pelagic fish that are frequently fished in this small area (Cattaneo-Vietti et al. 2014). In the model area, main fishing activities are artisanal fishing with fixed nets and small purse seine, and recreational fishing.

Ecopath model structure

The species-based Ecopath model and the trophic levels (TLs)-based EcoTroph model were

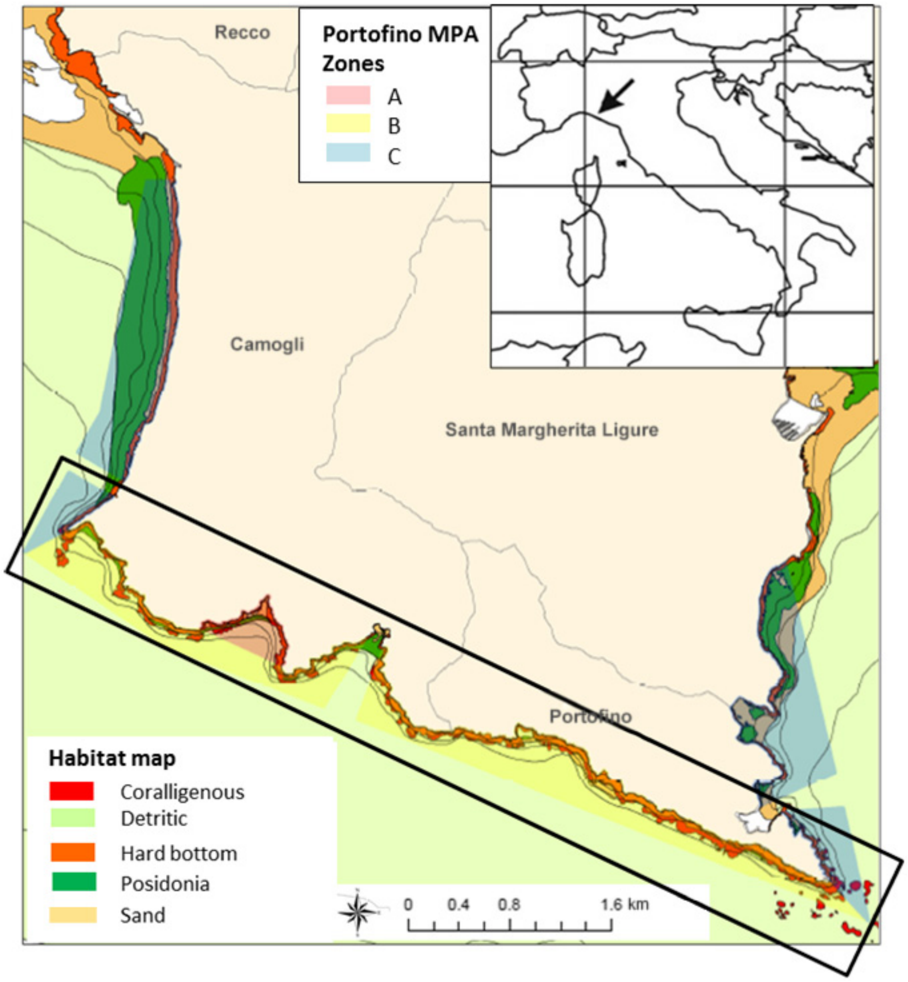

Fig. 1. Habitat map and zoning of the Portofino Marine Protected Area. The modeled area is surrounded by the black rectangle and includes zones A, B, and partially C around the southern front of the promontory. Habitat map retrieved from Diviacco and Coppo (2006, updated to 2012).

used in this study. The Data-Reli toolbox developed by Lassalle et al. (2014) was applied to evaluate data reliability and robustness of the Ecopath model predictions.

Ecopath is a mass-balanced model based on the assumption that the production of one functional group is equal to the sum of all predation, non-predatory losses, exports, biomass accumulations, and catches, as expressed by the following equation:

$$P/B_i \times B_i = P/B_i \times B_i \times (1 - \mathrm{EE}_i) + \sum\nolimits_j (Q/B)_{ji} \times B_i \times \mathrm{DC}_{ji} + Y_i + \mathrm{NM}_i + \mathrm{BA}_i \quad (1)$$

B is the biomass, P/B_i is the production rate, Q/B is the consumption rate, DC_{ji} is the fraction of prey i included in the diet of predator j, NM_i is the net migration of prey i, BA_i is the biomass accumulation of prey i, Y_i is the catch of prey i, and EE_i is the ecotrophic efficiency of prey i, that is, the proportion of production used in the system. The model represents an average situation of the southern front of the Portofino MPA for the period 2007–2014, to ensure that protection effects were already in place. A simplified model structure developed by Prato et al. (2014) for the Port Cros MPA with the intent of standardizing Ecopath modeling for Mediterranean MPAs was used in our study.

The model comprised 33 functional groups, including one group of cetaceans, 17 groups of fish (of which two monospecific groups, *Epinephelus marginatus* and *Sarpa salpa*, were split into ontogenic groups to account for changes in their diet with age), eight benthic invertebrates groups, a group of cephalopods, two zooplankton groups, three primary producers groups, and detritus. More details on the model structure and origins of the input parameters are provided in Appendix S1.

Estimates of catches

The MPA partially monitors artisanal fishing effort and catches. Only available fishing catches within the model area were thus considered, including catches from fixed nets (trammel nets, gill nets, and combined nets), small purse seine, and recreational fishing.

To obtain an annual picture of artisanal fishing catches in the model area, we had to attain from two main sources of data:

1. A data set of fishermen interviews (MARTE+ project, 2011) from which effort in the model area in 1 yr was estimated, computed as total number of boats and days of fishing for fishing metier.
2. The available logbooks from three boats (two boats monitored in 2012, one in 2013–2014), from which catches in kg/d for each fishing métier were estimated.

Thus, data from the logbooks (kg/d of fishing for each species and fishing métier) were multiplied for the total number of fishing days/yr for the same métier.

Recreational fishermen must fill logbooks concerning catches within the MPA boundaries. From the logbooks, we computed average catches expressed as kg/h within our model area and multiplied for the total number of hours of recreational fishing in the MPA in 1 yr (Cappanera et al. 2013).

To account for the uncertainty in the input fisheries data, we derived alternative data sets using two multiplier coefficients for artisanal fishing catches (0.5 and 2) and seven coefficients (0.5 and from 2 to 7) for recreational fishing catches (characterized by larger uncertainty). Resulting values were then proposed to the evaluation of the MPA staff fishing experts, responsible for the monitoring of artisanal and recreational fishing. For each species, the most realistic estimate according to the expert's knowledge was retained. These expert-modified values were used to build our reference model. Two other models were then built with expert's estimates of catches both multiplied and divided by the coefficient 1.5, and a fourth model was also built with the original logbook's estimates, to identify differences with experts' estimates and highlight data gaps. Accounting for uncertainty, we aimed at highlighting the potential of Ecopath and EcoTroph as a tool for advising MPA management, and thus stress on the urgent need to improve monitoring strategies and increase ecological and fisheries data quality and availability.

Keystone functional groups and fishing impact

The mixed trophic impact routine (MTI) of Ecopath assesses the relative impact of a slight increase in abundance of any group on the biomass of other groups on the food web (Ulanowicz and Puccia 1990, Christensen and Pauly 1992).

Keystone species are defined as the species having the highest and widest impact on the food web despite a low biomass (Power et al. 1996, Piraino et al. 2002). They were identified by applying the new keystonness index developed by Valls et al. (2015). The underlying index equations are detailed in Appendix S2.

Fishing loss (Floss) is an indicator of fishing impact given by the ratio between catches and the production of each functional group (Y/P). After obtaining production (P) from $P/B \times B$, we computed Floss for each functional group, to analyze the impact of fishing on keystone groups.

Finally, we analyzed direct and indirect fisheries impacts on species interactions by computing and cumulatively plotting the MTI index of each fleet. As data availability and quality is the main limitation to EwE, like for any ecosystem model (Lassalle et al. 2014, Prato et al. 2014), data quality was assessed applying the food web diagnostics proposed by Link (2010) and the Data-Reli toolbox developed by Lassalle et al. (2014). Details on the data quality and sensitivity analysis are also provided in Appendix S2.

EcoTroph: interacting fisheries impacts on ecosystem biomass and trophic structure

The EcoTroph model summarizes the ecosystem functioning as a flow of biomass surging up the food web from lower to higher trophic levels, through predation and ontogenic processes. The biomass enters the system at TL = 1, generated by primary producers or recycled from the detritus. For TLs > 2, the biomass is distributed along a continuum of TL due to the diet variability of the various consumers. The resulting biomass distribution is called trophic spectrum (Gascuel 2005). EcoTroph thus allows to simulate various fishing scenarios and their impact on the biomass trophic spectrum. We refer to Appendix S3 for further details on the modeling approach.

For each functional group, accessibility to fishing was defined according to the number of targeted species within the functional group (if none of the species within the group is fished, then the accessibility value is zero). Afterward, we used the ET-transpose routine described in Gascuel et al. (2009) to translate the outputs of the original Ecopath model into an ET model and to build the trophic spectra of the cumulated catches and the trophic spectra of the fishing loss for each fishing fleet.

We simulated the unexploited state of the ecosystem by setting fishing loss (φ) to 0 for all fleets in the ET-diagnosis routine. The current condition and three alternative fishing scenarios were compared to the unexploited state: halved recreational and artisanal fishing effort ($\varphi_\tau = 0.5 \cdot Y_\tau / P_\tau$, where Y_τ is the total catch at trophic level τ to assess the impact that a reduction in the fishing effort could have on the ecosystem), no recreational fishing ($\varphi_\tau = Y_\tau^{\mathrm{com}} / P_\tau$, where Y_τ^{com} is the catch of commercial fisheries only, at trophic level τ), and double artisanal and recreational fishing ($\varphi_\tau = 2 \cdot Y_\tau / P_\tau$, where Y_τ is the total catch at trophic level τ to assess the impact that an increase in the fishing effort could have in the ecosystem).

Finally, we plotted artisanal and recreational fisheries' mixed impact on accessible biomass, TL of the accessible biomass, catches of the artisanal fishery, and mean TL of the artisanal fishery's catch.

RESULTS

Food web structure

The pedigree index of the balanced model was 0.49 (balancing details provided in Appendix S4). Biomass estimates were available for 60% of the groups (including most of the higher trophic levels, and the primary producers), while the remaining 40% (benthic compartments) were estimated by the model (Table 1). Biomasses of fish, invertebrates, and primary producers were respectively 2%, 15%, and 83% of total biomass in the system (5126 $\mathrm{tons \cdot km^{-2} \cdot yr^{-1}}$ including *Posidonia oceanica*).

The analysis of the energy fluxes and biomass repartition (Fig. 2) allowed to discern among a main bentho-pelagic path, connecting primary producers and detritus to the higher trophic levels in the food web through the benthic compartments, and a pelagic path connecting phytoplankton, zooplankton, planktonivorous fish, and pelagics. Cephalopods played an important role in connecting the pelagic and bentho-pelagic paths, showing a high degree of connections with benthic invertebrates, planktonivorous fish, and high trophic level predators.

Fish biomass was high in the modeled system (91.6 $\mathrm{tons \cdot km^{-2} \cdot yr^{-1}}$), which supported in particular very high biomasses of the Diplodus+ group (29 $\mathrm{tons \cdot km^{-2} \cdot yr^{-1}}$) and also significant biomass of the high trophic level predator groups Amberjack&dentex+ and Dusky grouper. Planktonivorous fish were also important (15 $\mathrm{tons \cdot km^{-2} \cdot yr^{-1}}$ for Sand smelts+ and 8 $\mathrm{tons \cdot km^{-2} \cdot yr^{-1}}$ for Horse mackerels+), being preys of many higher trophic level groups, thus connecting the pelagic pathway to the bentho-pelagic one.

Artisanal and recreational fisheries catches were respectively 53% and 47% of total landings, estimated to be 10 $\mathrm{tons \cdot km^{-2} \cdot yr^{-1}}$, corresponding to 9% of total fish and fished invertebrates biomass.

Keystone groups and species interactions

The keystonness analysis (Fig. 3) showed that three groups played an especially important role in the functioning of the food web: Amberjack&dentex+, Large-scaled scorpionfishes+, and the Small dusky grouper. These groups held negative impacts on the food web through direct predation, but triggered also positive cascade effects on some species, by releasing them from meso-predation (Fig. 4). Amberjack&dentex+ had the overall largest trophic impact. Its significant negative impact on both the Horse mackerels+ and the Small dusky grouper highlighted the connection of Amberjack&dentex+ with both the pelagic and bentho-pelagic pathways. Positive

Table 1. Parameters of the balanced Ecopath model.

No.	Group name	TL	*B*	*P*/*B*	*Q*/*B*	EE	*P*/*Q*	*F*	*Y* Fix. nets	*Y* S.p.seine	*Y* Rec.	Disc. Fix. nets
1	Dolphins	4.95	0.03	0.07	13.49	**0.00**	**0.01**	–	–	–	–	–
2	Small tunas+	4.64	**1.23**	0.35	8.19	0.50	**0.04**	0.18	0.11	0.00	0.10	0.00
3	Amberjack&dentex+	4.31	6.00	0.47	3.58	**0.65**	**0.13**	0.27	0.14	0.45	1.06	0.00
4	Dusky grouper L	4.39	4.60	0.18	0.81	**0.00**	**0.22**	–	–	–	–	–
5	Dusky grouper M	4.26	1.26	0.47	1.66	**0.13**	**0.28**	0.06	0.08	0.00	0.00	0.00
6	Dusky grouper S	3.98	0.62	1.34	4.40	**0.09**	**0.30**	–	–	–	–	–
7	Large-scaled scorpionfishes+	3.79	2.50	0.54	4.62	**0.68**	**0.12**	0.21	0.19	0.00	0.32	0.00
8	Scorpionfishes&combers+	3.69	1.18	0.65	6.60	**0.97**	**0.10**	0.27	0.03	0.00	0.29	0.00
9	Stripped red mullets+	3.72	**2.14**	0.88	7.84	0.70	**0.11**	0.05	0.05	0.00	0.06	0.00
10	Horse mackerels+	3.76	**8.09**	0.97	7.57	0.90	**0.13**	0.03	0.00	0.18	0.03	0.00
11	Sand smelts+	3.53	15.11	0.83	10.41	**0.43**	**0.08**	0.06	0.00	0.62	0.24	0.00
12	Pagellus	3.45	0.31	0.67	6.96	**0.79**	**0.10**	0.41	0.03	0.00	0.10	0.00
13	Diplodus+	3.08	29.70	0.73	6.46	**0.24**	**0.11**	0.11	1.40	0.00	1.94	0.00
14	Gobies+	3.26	**6.00**	1.12	8.54	0.90	**0.13**	0.01	0.00	0.00	0.06	0.00
15	Wrasses+	3.23	2.49	0.96	9.56	**0.75**	**0.10**	0.03	0.02	0.00	0.05	0.00
16	Mullets	2.32	1.17	0.36	14.99	**0.39**	**0.02**	0.01	0.00	0.00	0.01	0.00
17	Salema S	2.35	3.17	0.95	5.30	**0.25**	**0.18**	–	–	–	–	–
18	Salema L	2.00	6.10	0.60	2.54	**0.64**	**0.24**	0.31	0.00	1.84	0.04	0.00
19	Decapods+	2.65	**12.61**	2.64	18.89	0.90	**0.14**	0.01	0.14	0.00	0.00	0.00
20	Cephalopods	3.61	3.43	2.34	**7.80**	0.70	0.30	0.13	0.05	0.00	0.40	0.00
21	Zooplankton L	3.02	**3.12**	22.71	60.47	0.95	**0.38**	–	–	–	–	–
22	Zooplankton S	2.10	**7.52**	35.44	109.43	0.95	**0.32**	–	–	–	–	–
23	Sea worms	2.31	**40.16**	2.58	15.27	0.95	**0.17**	–	–	–	–	–
24	Macrofauna+	2.16	**49.71**	4.10	47.60	0.90	**0.09**	–	–	–	–	–
25	Echinoderms+	2.36	**21.38**	0.59	1.67	0.50	**0.35**	–	–	–	–	–
26	Suspensivores+	2.19	**74.23**	2.63	11.20	0.90	**0.23**	–	–	–	–	–
27	Gorgonians	2.23	500.80	0.20	0.53	**0.02**	**0.38**	–	–	–	–	–
28	Sea urchins	2.15	64.95	0.57	2.70	**0.60**	**0.21**	–	–	–	–	–
29	Meiofauna	2.00	**19.84**	10.00	**33.33**	0.95	0.30	–	–	–	–	–
30	Posidonia	1.00	3674.0	0.55	–	**0.24**	–	–	–	–	–	–
31	Seaweeds	1.00	557.00	4.43	–	**0.14**	–	–	–	–	–	–
32	Phytoplankton	1.00	7.14	179.60	–	**0.46**	–	–	–	–	–	–
33	Detritus	1.00	65.25	–	–	**0.28**	–	–	–	–	–	–

Notes: Parameters in boldface were obtained through the mass-balance calculations of the model. TL, trophic level; *B*, biomass; *P*/*B*, production-to-biomass ratio; *Q*/*B*, consumption-to-biomass ratio; EE, ecotrophic efficiency; *F*, fishing mortality; *Y*, fishing catches; S.p.seine, small purse seine; Rec., recreational fishing; Disc. Fix. Nets, discards fixed nets.

indirect effects of Amberjack&dentex+ mainly concerned benthic invertebrates groups (Sea urchins, Macrofauna+, Suspensivores+, and Decapods+), which were released from meso-predation (diverse effects+; Fig. 4).

The Small dusky grouper and Large-scaled scorpionfishes+ negatively impacted many necto-benthic fish groups. A slight increase in Large scaled scorpionfish+ biomass led to large indirect positive effects, mainly favoring Cephalopods+, Decapods+, Large zooplankton, and Gobies+ (Fig. 4).

Cephalopods+ also had a high KS score (Fig. 3), showing the largest overall positive impact on the food web. Indeed, they are preferred preys of the Medium and Large dusky groupers and also release several invertebrates (diverse effects+ in Fig. 4, including Sea urchins, Gorgonians, Suspensivores+, Macrofauna+, and Echinoderms+) from the meso-predation of Decapods, Diplodus+, and Sand smelts+, all preys of Cephalopods+. Some negative effects on necto-benthic fish were also unraveled (e.g., on Large scaled scorpionfish+ and Scorpionfish&combers+) due to indirect competition for preys (Fig. 4).

Fishing impact on keystone groups and on species interactions

Analysis of fishing loss rates showed that six groups encompassed a high fishing pressure,

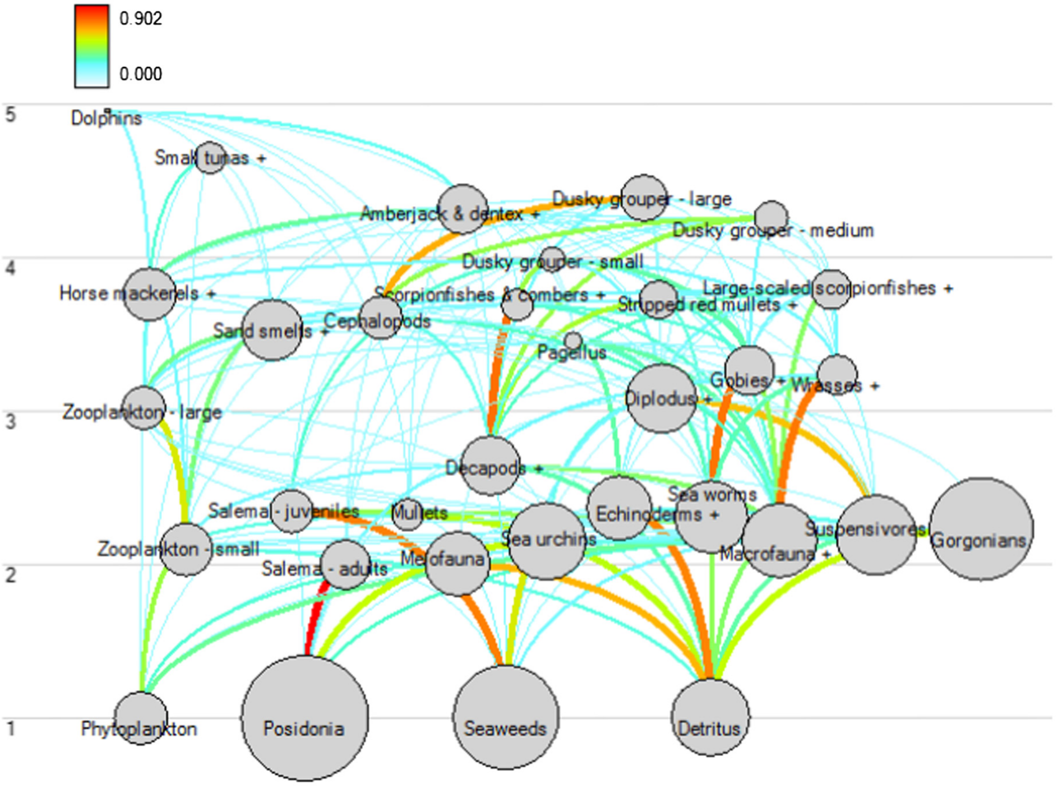

Fig. 2. Flow diagram of the modeled ecosystem. Size of the nodes is proportional to the logarithm of the biomass of the functional groups. Lines represent the flux of energy among groups. Colors are proportional to the magnitude of the flux.

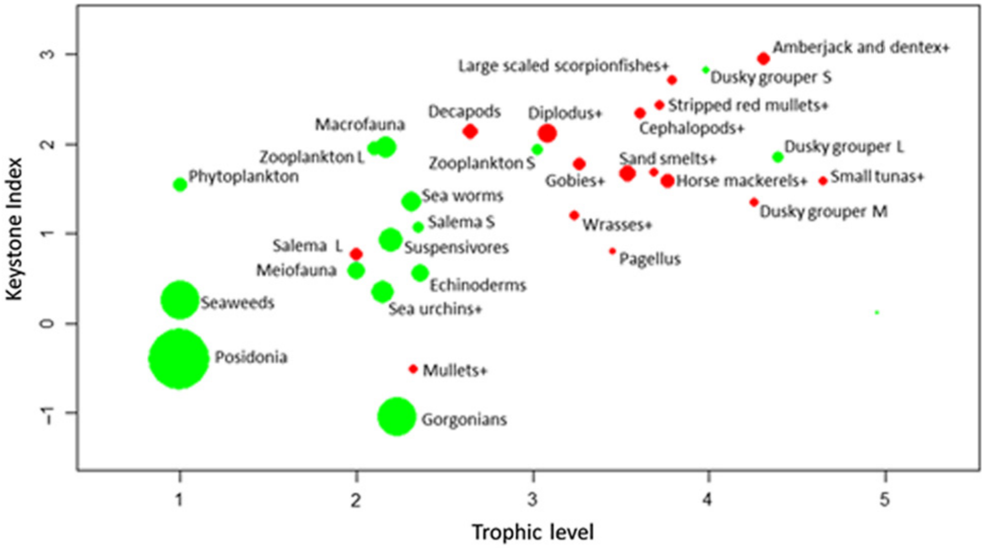

Fig. 3. Functional groups plotted against keystone index and trophic level. Size of the bubbles is scaled to the biomass of the group.

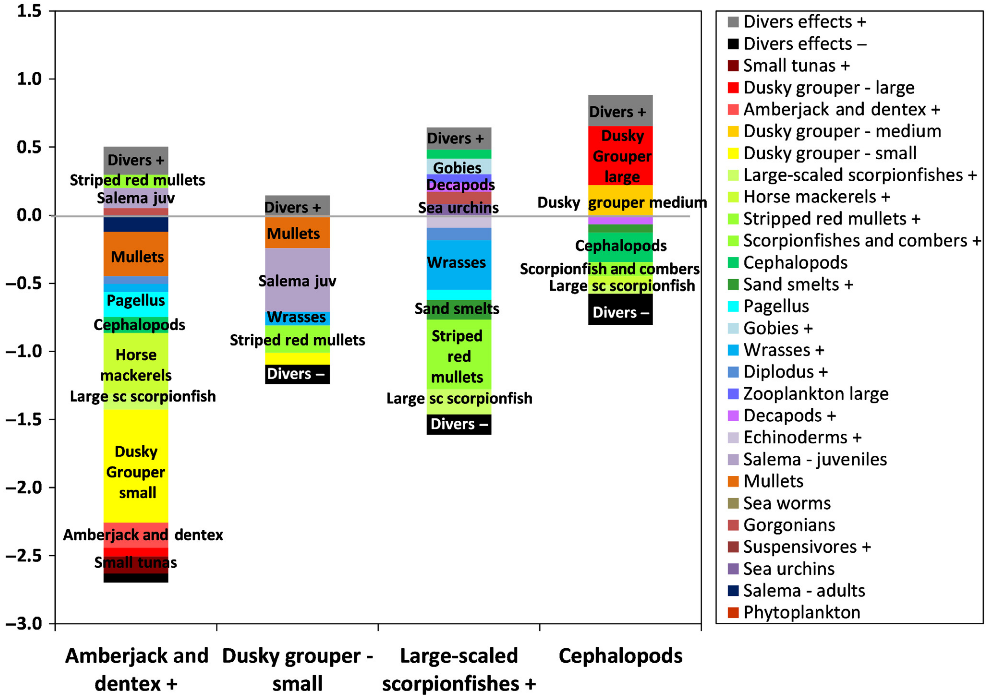

Fig. 4. Cumulative plot of the mixed trophic impact indices of the species with highest keystonness scores. Values on the positive axis represent positive impacts of the keystone groups on each functional group in the food web, and values on the negative axis represent negative impacts. Impacts <0.05 were grouped together under diverse effects (both negative and positive).

with annual catch higher than 35% of their natural production (Fig. 5). Among these six groups, two were keystone species: the Amberjack&dentex+ and the Large-scaled scorpionfishes+.

The direct and indirect effects of each fishery were then unraveled in the MTI analysis (Fig. 6). The recreational fishing fleet had the strongest total impact on the food web. Species directly targeted by this fishery were the high trophic level groups Small tunas+, Amberjack&dentex+, and Large scaled scorpionfish+. Several groups, such as the Small and medium dusky grouper, Horse mackerels+, Wrasses+, and many benthic invertebrates, were indirectly favored by this fishery due to the release from the predation of high trophic level predators.

Artisanal fishing with fixed nets negatively impacted the Medium dusky grouper, partly because of direct fishing and partly because of competition, because many species targeted by fixed nets were also preys of the Medium dusky grouper. Sea urchins and most benthic invertebrates (except Decapods+) were also favored by an increase in this fishery. Artisanal fishing with small purse seine had the lowest overall trophic impact, with a large negative impact mainly on Salemas and Amberjack&dentex+, and a consequent positive impact on the Small dusky grouper and benthic invertebrates.

Fishing impacts on ecosystem trophic structure and fleet interactions

The analysis of the MTI also highlighted the competition between recreational fishing and artisanal fishing with fixed nets, with the former having the largest indirect impact on the latter (Fig. 6).

Indeed, the catch trophic spectra of the three fleets overlapped particulary on trophic levels >3.5 (Fig. 7a). Recreational fishing catches targeted trophic levels >3 (mean TL catch = 3.56), while artisanal fixed nets catches concentrated mainly around TL 3 (mean TL catch = 3.35). Small purse seine fishing extracted high biomasses at TL

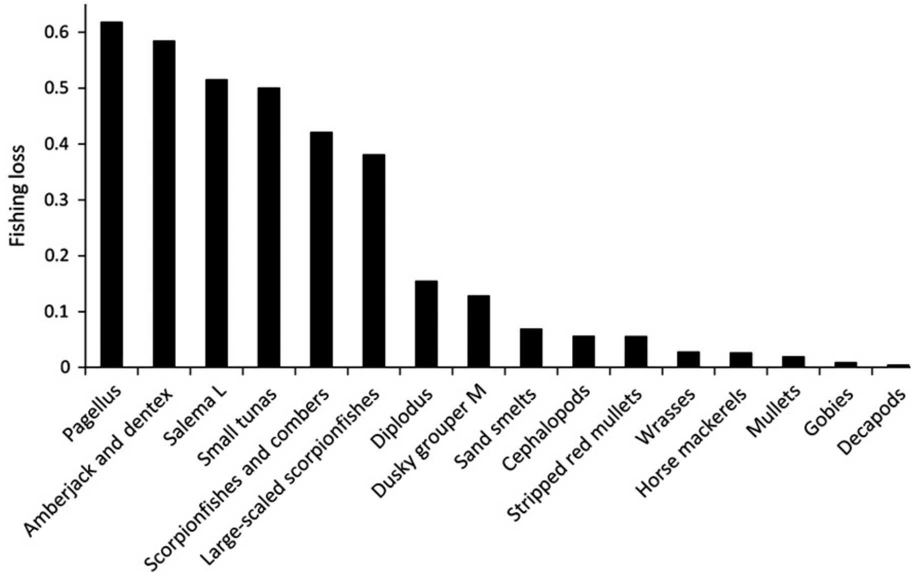

Fig. 5. Fishing loss rate for each functional group. Fishing loss = Y/P.

2 (Salemas), and also at TL > 3.5 (mean TL catch = 2.75). The overlap of the three fisheries on high trophic levels resulted in the strongest fishing losses for TL > 4, due to the lower turnover rates of these predators (Fig. 7b). On the contrary, high catches at TL 2 and 3 did not translate into strong fishing impact.

When confidence intervals were added according to the two alternative estimates provided by the MPA fishery experts, results were consistent. When the analysis was run on the model based on non-corrected logbook fishing data, fishing loss by recreational fishing was consistently lower, due to an underestimation of total fishing catches (Appendix S5: Fig. S1). However, the general trend of major impact on high trophic levels was maintained.

Simulation of fishing scenarios (Fig. 8) showed that the system was far from its unexploited condition for the higher trophic level groups (TL > 4). In the unexploited state, the biomass of these groups would be 44% higher than current biomass. Halving the effort of both artisanal and recreational fishing led to a 19% increase in the total biomass of high trophic level fish. When only recreational fishing mortality was set to 0, a 24% increase in the total biomass of high trophic level fish was observed. When fishing mortality was doubled for all fisheries, high trophic levels were again the most impacted.

When logbook data were considered, the system at the current state led to closer to the unexploited condition. This was again due to the underestimation of recreational fishing catches (when recreational fishing mortality was set to 0, results were indeed equal to those of the reference model; Appendix S5: Fig. S2).

The analysis of fisheries interactions showed that artisanal fisheries quantitatively impacted the biomass accessible to fisheries more than recreational fisheries (Fig. 9a). Indeed, setting respectively artisanal or recreational fisheries to zero, the accessible biomass would increase about 22 tons$\cdot$km$^{-2}\cdot$yr^{-1} (+47%) and 12 tons$\cdot$km$^{-2}\cdot$yr^{-1} (+25%), respectively.

On the other hand, recreational fishing had a stronger impact on the composition of the fish assemblage, affecting the mean TL of the accessible biomass (Fig. 9b). Forbidding recreational fisheries would, in fact, lead to an increase in the mean TL from approximately 3.15 to 3.35, while a reduction in artisanal fisheries would not modify the mean TL of the accessible biomass.

Quantitative impact of recreational fishing on artisanal fishing catches resulted in a potential increase of 1.2 tons$\cdot$km$^{-2}\cdot$yr^{-1} in the catches of the latter (+23%), if the former was set to 0 (Fig. 9c). Prohibiting recreational fishing moreover would increase the mean TL of the artisanal catches from 2.95 to 3.15 (Fig. 9d).

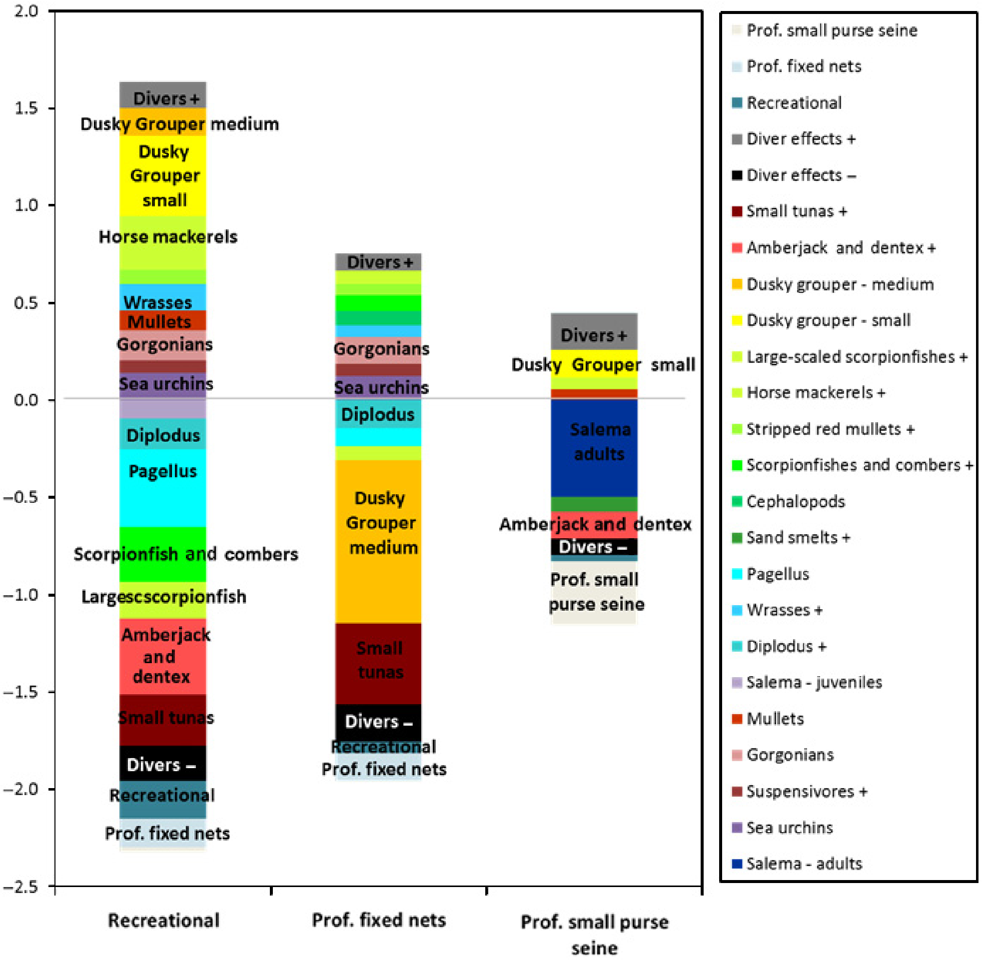

Fig. 6. Cumulative plot of the mixed trophic impact indices of the fishing fleets. Values on the positive axis represent positive impacts of the fishery on the functional groups in the food web, and values on the negative axis represent negative impacts. Impacts <0.05 were grouped together under diverse effects (both negative and positive).

Discussion

Building a trophic model in the context of Mediterranean MPAs

Scientific ecological knowledge on Mediterranean MPAs, when available, is often dispersed among several sources of information, ranging from local or foreign universities or environmental agencies, to local/traditional ecological knowledge, historical archives, and expert opinions. Integration of this wealth of information is essential for a holistic understanding of protection effects on ecosystem functioning and thus a fully informed management of MPAs. The trophic modeling approach adopted here is a useful tool to accomplish such integration, allowing to fit largely scattered data into a coherent picture of ecosystem functioning for the Portofino MPA. In particular, a snapshot of the highly productive area surrounding the southern promontory of the MPA was provided, representing an average year between 2007 and 2014. This model provides a baseline that can be easily updated in the years to come, when more georeferenced data regarding fishing effort and catch become available, together with updated monitoring data on key species biomass.

Similar to most ecosystem models, it was not possible to obtain local data for all functional groups (Pedigree index = 0.46), but model-derived

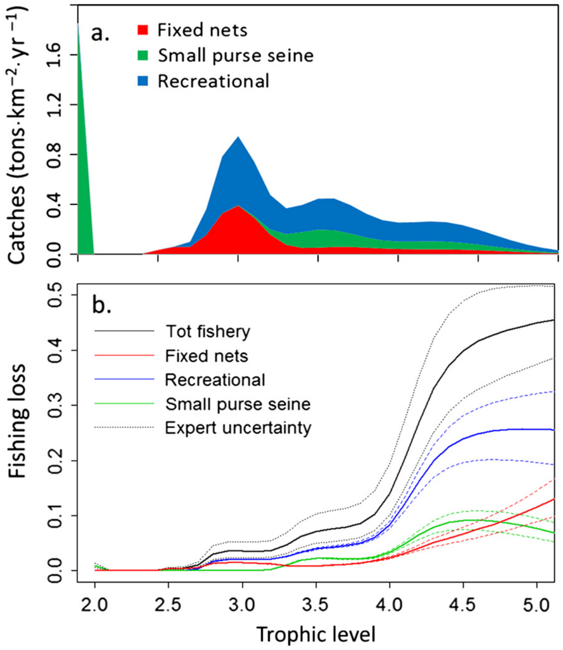

Fig. 7. Trophic spectra of the cumulated fishery's catches (a) and trophic spectra of fishing loss (*Y*/*P*) (b).

estimates were in accordance with ecological knowledge of the area. Biomass ranking of benthic invertebrates was in accordance with expert opinion (C. Cerrano, *personal communication*), and trophic levels computed by the model fell within the range of results for the Mediterranean Sea (Stergiou and Karpouzi 2001).

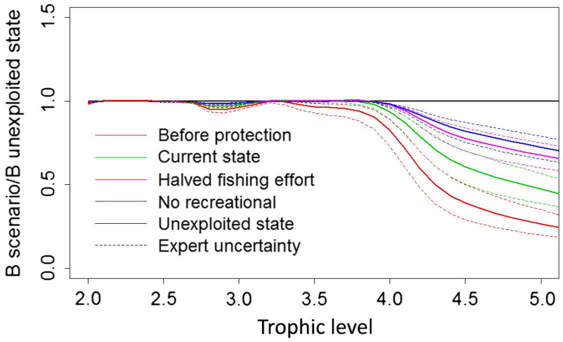

Fig. 8. Trophic spectra of relative biomass (dimensionless) by fishing scenario. Relative biomass was calculated by dividing absolute biomass values of each scenario by the absolute biomass values of the unexploited state. Expert uncertainty relates to the two alternative estimates of catches, according to expert's knowledge (see text).

The analysis of the energy fluxes allowed to unravel a complex food web despite the relatively small area, with a main bentho-pelagic energy path exchanging energy with a more pelagic path through some key groups such as cephalopods, planktonivorous fish, and high trophic level predators. Comparison of relative biomass partitioning among primary producers, benthic invertebrates, and fish with another modeled Mediterranean MPA (Port Cros; Valls et al. 2012) allowed highlighting the peculiarities of Portofino. According to the model, this area supports high benthic community biomass (15% of total biomass) when compared to the Port Cros MPA (3.5%), sustaining high biomass of fish at all trophic levels (2% of total biomass, against 0.65% in Port Cros). The fish biomass observed was particularly high especially for high trophic level predators (10 tons·km^{-2}·yr^{-1}) and sea breams (29 tons·km^{-2}·yr^{-1}). Biomass of sea breams in the MPA was in fact shown to be higher than the accepted threshold of 12 individuals per 125 m^2 necessary to maintain sea-urchin abundance low and avoid rocky reef ecosystem shifts toward barrens (Guidetti and Sala 2007, Guidetti et al. 2008). Indeed, extended sea-urchin barrens are absent in the Portofino MPA (Sala et al. 2012).

Keystone species impacted by fishing

The presented modeling approach not only allowed identifying species that play important keystone roles in the food web (the high trophic level predators Amberjack&dentex+ and Dusky grouper and the Large-scaled scorpionfishes+), but also highlighted that some of these species are also subject to strong fishing impact. In Portofino indeed, species included in the Amberjack&dentex+ and Large-scaled scorpionfishes+ groups can be considered as "sentinels" of the condition of the food web, and their monitoring should therefore be regarded as a priority within the MPA. Monitoring such species should take place both by assessing their biomass state in the ecosystem and by evaluating their exploitation status through the survey of artisanal and recreational fishing catches. Keystone species highly impacted by fishing could also be a reference for the definition of management actions (for instance, calculating the reduction of fishing mortality needed to attain predefined conservation objectives) and for the assessment of their efficiency.

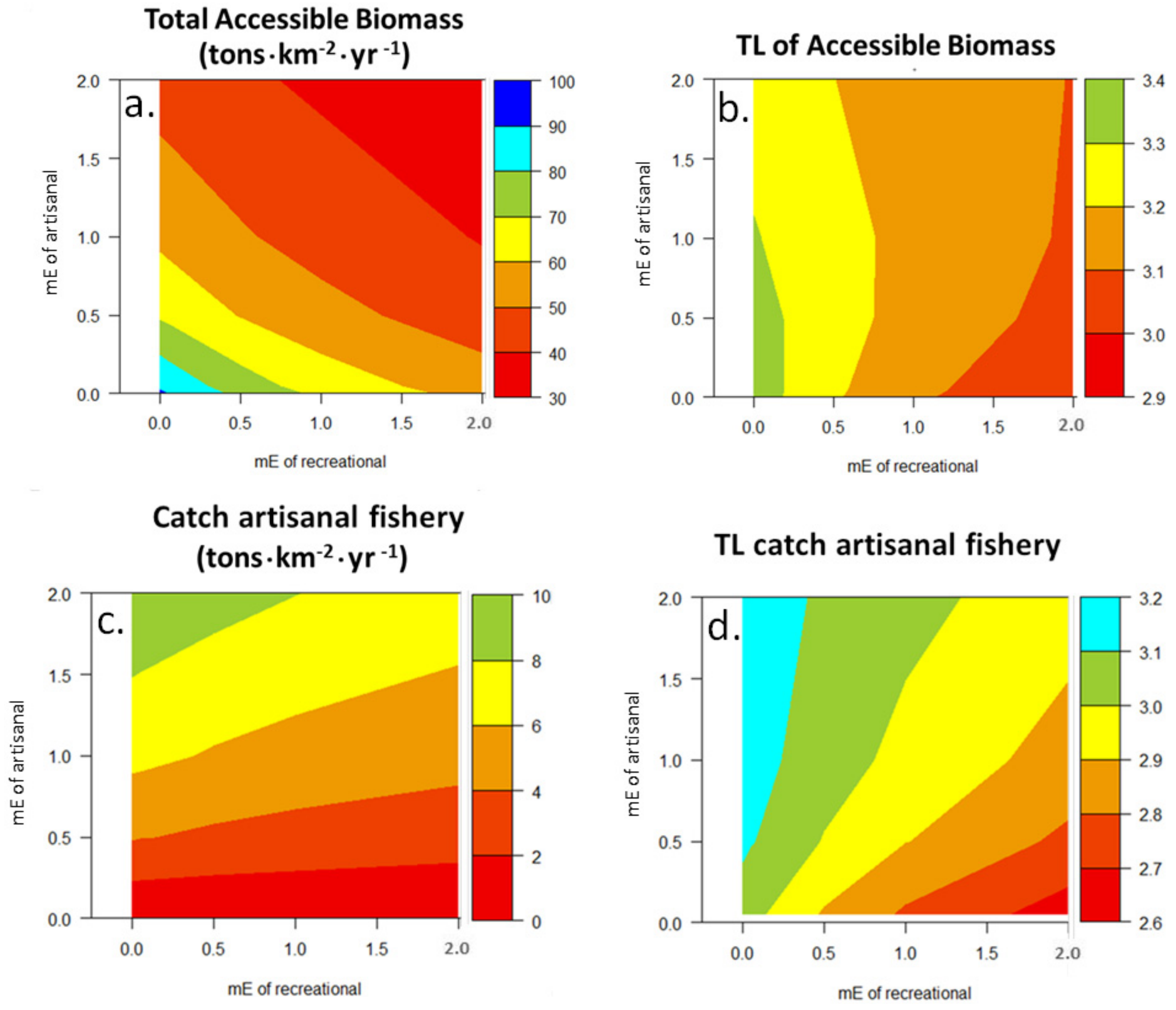

Fig. 9. Isopleths of scenarios showing the effects of a variation in fishing effort on (a) the total accessible biomass of the system, (b) the mean trophic level of the accessible biomass, (c) the artisanal fishery catches, and (d) the mean trophic level of the artisanal fishery catches. mE, multiplier of the fishing effort. Artisanal fishery includes fixed nets and small purse seine.

It is noteworthy that cephalopods have also shown a high keystonness index in the Portofino MPA, similar to the Port Cros model (Valls et al. 2012, Prato et al. 2014). Being both a preferred prey for many high trophic level predators and predators acting on a wide range of trophic levels, cephalopods occupy an important functional role in both coastal and pelagic ecosystems (Piatkowski et al. 2001, Coll et al. 2013); large variations in their biomass can thus lead to strong effects on the marine food webs, through both bottom-up and top-down impacts. In the Portofino MPA, they are subject to some artisanal and recreational fishing pressure, which is likely underestimated due to the presence of illegal fishing in the MPA. This issue is common to most Mediterranean coastal areas, but is generally difficult to address. If the exploitation state of cephalopods is not controlled, their biomass could become a limiting food item for their predators, especially for the protected Dusky grouper. Cephalopods should thus be regarded as an important monitoring target in the context of Mediterranean MPAs.

Cumulated fishing impacts on the food web

This study was the first attempt to assess the cumulated impact of both recreational and artisanal fisheries on a Mediterranean MPA food web, starting from available although limited local logbook data. Estimates of artisanal fishing catches within the MPA zones surrounding the southern promontory front (3.35 $\text{tons}\cdot\text{km}^{-2}\cdot\text{yr}^{-1}$) were much higher than catches in the Port Cros MPA (0.3 $\text{tons}\cdot\text{km}^{-2}\cdot\text{yr}^{-1}$) and Bonifacio Straits Natural Reserve (0.09 $\text{tons}\cdot\text{km}^{-2}\cdot\text{yr}^{-1}$) for which similar Ecopath models had been built (Valls et al. 2012, Albouy et al. 2010). Estimates of recreational fishing (3.56 $\text{tons}\cdot\text{km}^{-2}\cdot\text{yr}^{-1}$) were also markedly higher when compared to Bonifacio (0.1 $\text{tons}\cdot\text{km}^{-2}\cdot\text{yr}^{-1}$), although in Bonifacio these were indirectly derived by applying a percentage to artisanal fishing catches (Albouy et al. 2010). Total estimates were instead similar to those from the Côte Bleue Marine Park (SW France), comparable to Portofino in terms of number of fishing boats and metiers, with 4.6 $\text{tons}\cdot\text{km}^{-2}\cdot\text{yr}^{-1}$ landed by coastal artisanal fisheries operating with fixed nets, and approximately 3.6 $\text{tons}\cdot\text{km}^{-2}\cdot\text{yr}^{-1}$ of recreational fishing catches (from boat and shore) (Charbonnel et al. 2014, Leleu et al. 2014). The overlap of catches among artisanal and recreational fisheries in the Portofino MPA led to strong fishing losses on high trophic level predators, due to the lower turnover rates of these groups. Although the Portofino MPA was demonstrated to be effective in sustaining a recovery of fish biomass within its borders (Guidetti et al. 2008), as also shown by the high biomass levels within it, fishing losses on high trophic level predators are still high within the MPA. Recreational fishing, in particular, contributed for approximately half of these fishing losses, leading to the largest impact on the whole food web, as shown by the MTI analysis. Indeed, fisheries primarily targeting high trophic level predators often lead to wide impacts on the ecosystem, as demonstrated in the whole Ligurian Sea (Britten et al. 2014). The analysis of 25 years of landings (1950–1974) from the tuna trap ("*tonnarella*") situated in the zone C of the Portofino MPA, just outside our modeled area, revealed a strong depletion of top predators associated with this coastal area, which were gradually replaced by lower trophic levels with variable life history (mainly herbivores, cephalopods, and planktonivores) (Britten et al. 2014). Such trophic downgrading ultimately led to a decrease in the stability of the fish community. Our analysis suggests that similar intermediate trophic level groups could benefit from an increase in recreational fishing effort in the Portofino MPA, due to a release from top-down control.

At the current exploitation status, the ecosystem is likely far away from its carrying capacity (assumed to be equal to our simulated condition of no fishing) for high trophic level predators. An eventual interdiction of recreational fishing alone would lead to a significant increase in the biomass of this group (TL > 4), up to 24%, and increase higher than that obtained by halving the effort of both recreational and artisanal fisheries (19%). A similar analysis performed on the Port Cros MPA showed that the ecosystem was instead very near to its simulated unexploited state (Valls et al. 2012). The habitat and ecological differences among the two areas, but also the older age of the Port Cros MPA (more than 50 yr), and the lower fishing pressure within this area are probably explaining this difference. Marine Protected Area carrying capacity for high trophic level predators, for instance, generally needs between 13 and 30 yr depending on the species (Garcia-Rubies et al. 2013). According to our results, the potential carrying capacity for high trophic level predators in the Portofino MPA is likely to be high, but the current level of fishing within the MPA borders should be reduced to pursue the MPA conservation objectives.

Interaction between recreational fishing and artisanal fishing

The competition for target fish among recreational and artisanal fishing is a growing issue in many Mediterranean coastal areas, but few MPAs assess such impact. In the Côte Bleue Marine Park, the long-term assessment of both fisheries highlighted a strong competition of resources, where over 36 species were highly targeted by artisanal fishermen, 25 were also a spearfishing target, and 17 were targeted by recreational fishing from boat. Moreover, recreational fishing was less selective, targeting both the prey of species normally targeted by artisanal fishermen and the large carnivores (Charbonnel et al. 2014, Leleu et al. 2014). Such trend was also highlighted in our study, with competition affecting mainly artisanal fishing with fixed nets, and is likely to be more intense given the probable underestimation of recreational fishing catches. Illegal spearfishing is in fact likely occurring in the MPA, and monitoring recreational fishermen is further complicated by the common custom of providing lower estimates of catches to the MPA board, as revealed by the mismatch among logbooks and local expert's estimates in our study.

Artisanal fishery is a conservation target for many Mediterranean MPAs, which often promote a sustainable socio-economic development and the conservation of traditional activities, when carried on in a sustainable way, and of local identities/cultures (Di Franco et al. 2014). Our results suggest that the artisanal fishery alone would have moderate impact on the food web, reducing by less than 15% of the biomass of top predators (TL > 4.0), with almost no effect on the total biomass of lower trophic levels. Limiting recreational fishing effort could therefore allow the MPA to pursue both its conservation and socio-economic development targets, by (1) reducing the impact on high trophic level predators and thus benefiting the whole ecosystem; and (2) increasing the availability of catches at higher trophic levels for artisanal fishing. This type of catch is generally more valuable on the market, thus providing economic benefits to the naturally declining artisanal fishing activity.

CONCLUSIONS

This study highlighted that the trophic modeling approach with Ecopath and EcoTroph can provide some useful outcomes for the management of MPAs, such as the Portofino MPA. First, it allowed identifying sentinel species that play important keystone roles in the food web, but are at the same time subject to strong fishing impact due to both artisanal and recreational fisheries, and should thus be considered as a priority reference for management actions. Secondly, the interacting impacts of artisanal and recreational fishing on the food web have been unraveled, highlighting the strong coupled pressure on the trophic levels for which the two fisheries compete.

Accounting for uncertainty is essential in any modeling approach, and when possible alternative modeling tools should be used. Our case study was constrained by limits in input data availability, a common concern for most Mediterranean MPAs. However, the application of pre-balancing rules (Link 2010) and Data-Reli tool box (Lassalle et al. 2014) and the comparisons of four different models based on alternative catch estimates provided consistent trends in our results.

The potential of the Ecopath and EcoTroph modeling approach is thus high, not only to assess large-scale ecosystem impacts such as those of industrial fisheries and climate change (Fouzai et al. 2012, Albouy et al. 2014, Coll et al. 2015), but also at a more local scale to address crucial issues such as those of multiple users impacts, common to most coastal ecosystems and MPAs.

In this perspective, it is essential that coastal Mediterranean MPAs develop long-term monitoring programs on key species and on extractive artisanal and recreational activities. Only by increasing ecological and fisheries data availability and integration, it will be possible to develop more robust food web models and enhance their potential as management tools, by integrating dynamic simulations and bridging them with spatial modeling approaches.

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