

Bioeconomic model for a three-zone Marine Protected Area: a case study of Medes Islands (northwest Mediterranean)

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The bioeconomic effects of establishing a three-zone Marine Protected Area (MPA) are investigated. The division of the area into zones, fully protected, partially protected, and a fishing zone, permits a combination of extractive (fishing) and touristic activities. The consequences for species conservation, commercial fishing, and touristic activities are analysed for a set of different area-size distributions and fishing-effort levels. The model parameters are based on Medes Islands MPA in the northwestern Mediterranean. For the case study, the economic analysis includes revenues from scuba diving, glass-bottom boat trips, and commercial fisheries. Our results help to illustrate the benefits of the coexistence of extractive and non-extractive activities in a realistic, three-level MPA.

Keywords: economic analysis, fishing, Medes Islands, multi-user, tourism.

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Introduction

The use of Marine Protected Areas (MPAs) for fishery management has been advocated as a viable strategy for the conservation of living marine resources. MPAs are seen as an effective way of encouraging the recovery of exploited stocks or mitigating overexploitation (Sanchirico and Wilen, 2001; Carter, 2003), although the benefits in terms of fishery management are still being debated (Hannesson, 1998; Anderson, 2000; Holland, 2000; Pipitone *et al.*, 2000; Beattie *et al.*, 2002; Boncoeur *et al.*, 2002; Hannesson, 2002). Moreover, MPAs allow the area to be used simultaneously for multiple purposes other than commercial fishing, thus presenting additional economic opportunities to the local community, most of them derived from non-consumptive (non-extractive) activities, such as scuba diving or wildlife watching. Often, the rent generated by the non-consumptive activities can exceed the rent from commercial fisheries. Recreational fishing is generally considered a non-commercial, consumptive use that has not always been considered as a source of fishing mortality, although it can be significant in some areas (Arlinghaus *et al.*, 2005; Morales-Nin *et al.*, 2005).

Among the expected benefits of an MPA system [including fully protected area (FPA) and partially protected area (PPA)], empirical studies have demonstrated improved fishery indicators within the boundaries of an FPA: increased stock abundance, improved age or size composition, increased spawning-stock biomass or yield-per-recruit (Garcia-Rubies and Zabala, 1990; Polunin and Roberts, 1993; Pipitone *et al.*, 2000). Additionally, ecological indicators (trophic level balance, biodiversity) may improve, indirectly increasing the “quality” of the MPA, as perceived by recreational users, enhancing non-consumptive activities and, perhaps, indirectly benefiting commercial fisheries.

The purpose of the simulation model presented here is to investigate the impacts of the establishment of an MPA on fisheries (catches and revenues) and non-consumptive activities, and to assess the overall revenues generated from different simulation scenarios.

The optimal relative sizes of a three-zone MPA, including consumptive activities (commercial and non-commercial fishing) and a non-extractive use depending on the area's quality, are also investigated.

Material and methods

The design of MPA systems varies among countries, mainly as a function of the original purpose for establishing the MPA and its history. As a compromise between realism and the many different layouts of MPAs for fishery management, the present model deals with a three-zone MPA, comprising an FPA (or no-take zone), where no fishing is allowed; a PPA, where regulated commercial and recreational fishing is allowed (under a scheme of permits or licenses); and a non-protected area (NPA), where all fishing is permitted.

The objective of the FPA is to protect part of the exploited stocks from fishing. It implies that a fraction of the biomass is protected when it is located in the fishing zone and, if no density-dependent biomass transference occurs, the protected population would tend to grow until reaching its carrying capacity. The PPA is a buffer zone, where recreational and commercial fishing is allowed (with special regulation). The NPA is open to fishing, although not necessarily as an open-access fishery. Non-consumptive activities are permitted in the three zones. The structure presented above assumes that fish populations in each zone will increase following a growth function with

species-specific parameters and redistribute in space according to a density-dependent function. The net export of part of the population from a protected zone (high density) to the surrounding waters is modelled using a density-dependent function mimicking spillover (Kellner *et al.*, 2007).

One of the most critical aspects of modelling MPAs is the evaluation of the biomass transfer between the protected and the unprotected areas. Often, the transfer from one area to another is assumed to be density-dependent (Hannesson, 1998; Sanchirico and Wilen, 2001; Boncoeur *et al.*, 2002), although deriving empirical estimates of biomass transfer rates is not simple. In many modelling studies, the choice of the biomass transfer model and spillover rates is very influential.

The model

Fish population dynamics are simulated by logistic growth and density-dependent biomass transfer within areas. Fishing mortality in the PPA and NPA is assumed to be proportional to the fishing effort (commercial or recreational), so that the catch per effort unit is proportional to fish density (Hannesson, 1998; Boncoeur *et al.*, 2002) through the catchability coefficient, q (Hilborn and Walters, 1992), defined as the fishing mortality applied by a unit of effort.

The MPA system is divided into three areas,

$$G(B_{i,s}) = r_s B_{i,s} \left(1 - \frac{B_{i,s}}{\alpha_i K_s}\right) + \sum_{i \neq j} T_{ij,s} - Y_{i,s}. \quad (1)$$

For each area i , ($i = \text{FPA, PPA, NPA}$), the growth (G) of s species population depends on the biomass in the area (B_i), the species intrinsic growth rate (r_s), the carrying capacity (K_s), the surface of the area (α), as a fraction of the total area (A), a density-dependent biomass transfer to or from adjacent areas ($T_{ij,s}$), and the total catch ($Y_{i,s}$) by f fleets ($Y_{i,s} = \sum Y_{i,f,s}$). Fishing in the FPA is completely forbidden, but the model allows the estimation of the effect of recreational fishing, poaching, etc.

The species catch ($Y_{i,f,s}$) in each area i for the operating fleet (f) is, maintaining the proportions, a function of the catchability coefficient of the fishing gears ($q_{i,f,s}$), the fishing effort applied ($E_{i,f}$) to the area, and the species density ($D_{i,s}$), expressed as the biomass present in area fractions (α_i) of the total study area (A),

$$\frac{Y_{i,f,s}}{E_{i,f}} = q_{i,f,s} D_{i,s} \leftrightarrow Y_{i,f,s} = q_{i,f,s} E_{i,f} \frac{B_{i,s}}{\alpha_i A}. \quad (2)$$

One of the most difficult aspects of modelling MPAs is estimating biomass transfer. In our model, the density gradient within areas determined the total biomass transfer (following Boncoeur *et al.*, 2002), using a δ parameter describing species spatial mobility,

$$T_{ij,s} = \delta_s \left(\frac{B_{i,s}}{A \times \alpha_i} - \frac{B_{j,s}}{A \times \alpha_j} \right). \quad (3)$$

The economic analysis of the area includes the extractive and non-extractive activities; gross revenue from the sale of fish produced by fishers, and revenues from non-extractive activities related to tourism.

Revenues from fishing are calculated from the sale of the catch ($Y_{i,f,s}$) of each species ($s = 1, 2, \dots, S$) by each fleet at price $p_{i,f,s}$,

$$R = \sum_{i=1}^I \sum_{s=1}^S \sum_{f=1}^F p_{i,f,s} Y_{i,f,s}. \quad (4)$$

Revenues from tourism include a finite number of non-extractive activities ($u = 1, 2, \dots, U$) and are described as a function of the number of tourists attracted to the marine reserve ($YT = \sum YT_u$), based on a Cobb–Douglas production function, depending on the protected-area size, the effort invested in marketing aimed at attracting tourists (for instance, by the public administration and measured in monetary terms; ET), and inversely, on the fishing effort applied. The inverse relationship between fishing effort and tourists (or frequentation) is based on the assumption that fishing activity around a protected area negatively impacts fish diversity and subjectively diminishes the appeal of touristic activities. The positive proportionality parameter (λ) is a tourism-use quality parameter: high for areas with interesting ecosystems (less affected by commercial fishing, and with high biodiversity) or strong possibilities for non-extractive activities, and low for ecologically poor, degraded, or uninteresting areas. Cobb–Douglas functions are used with elasticity parameters ($\eta > 0$, $\mu > 0$, and $\nu < 0$). Revenues from touristic activities RT are estimated using the price paid for a non-extractive activity in the MPA (scuba diving, mammal-watching tours, sailing trips, etc.) and the number of tourists (YT),

$$YT = \sum_{u=1}^U \lambda_u [(\alpha + \beta)A]^{\eta_u} ET_u^{\mu_u} \left(\sum_{i=1}^I \sum_{f=1}^F E_{i,f} \right)^{\nu_u}, \quad (5)$$

$$RT = \sum_{u=1}^U p_u YT_u. \quad (6)$$

The simulations were programmed in R (R Core Development Team, 2005) and the asymptotic situations were compared for different fishing-effort regimes and protected-area combinations for equilibrium biomass situations, $G(B_{i,s}) = 0$.

The effects of modifying protected surface and fishing intensity are analysed with the present model, based on theoretical and realistic parameterizations of the Medes Islands MPA.

The case study: Medes Islands MPA

The data used for a realistic parameterization of the model come mainly from provisional results of the EMPAFISH (Marine Protected Areas for Fisheries Management and Conservation) European project and, to a lesser extent, from published literature.

The Medes Islands MPA, located in the northwestern Mediterranean (Figure 1), is a three-zone MPA. First, there is a 51 ha no-take FPA, where daytime diving, restricted anchoring, and navigation are the only activities permitted. No commercial or recreational fishing is authorized in the FPA. Second, there is a 460 ha PPA, where diving, navigating, and recreational and restricted commercial fishing by local artisanal vessels are permitted. The number of licensed fishing boats is 21, but only seven fish regularly in the PPA. Delimitation of the NPA was based on a spatial analysis by Stelzenmüller *et al.* (2007) and was estimated to be 3329 ha. The total surface of the three-zone

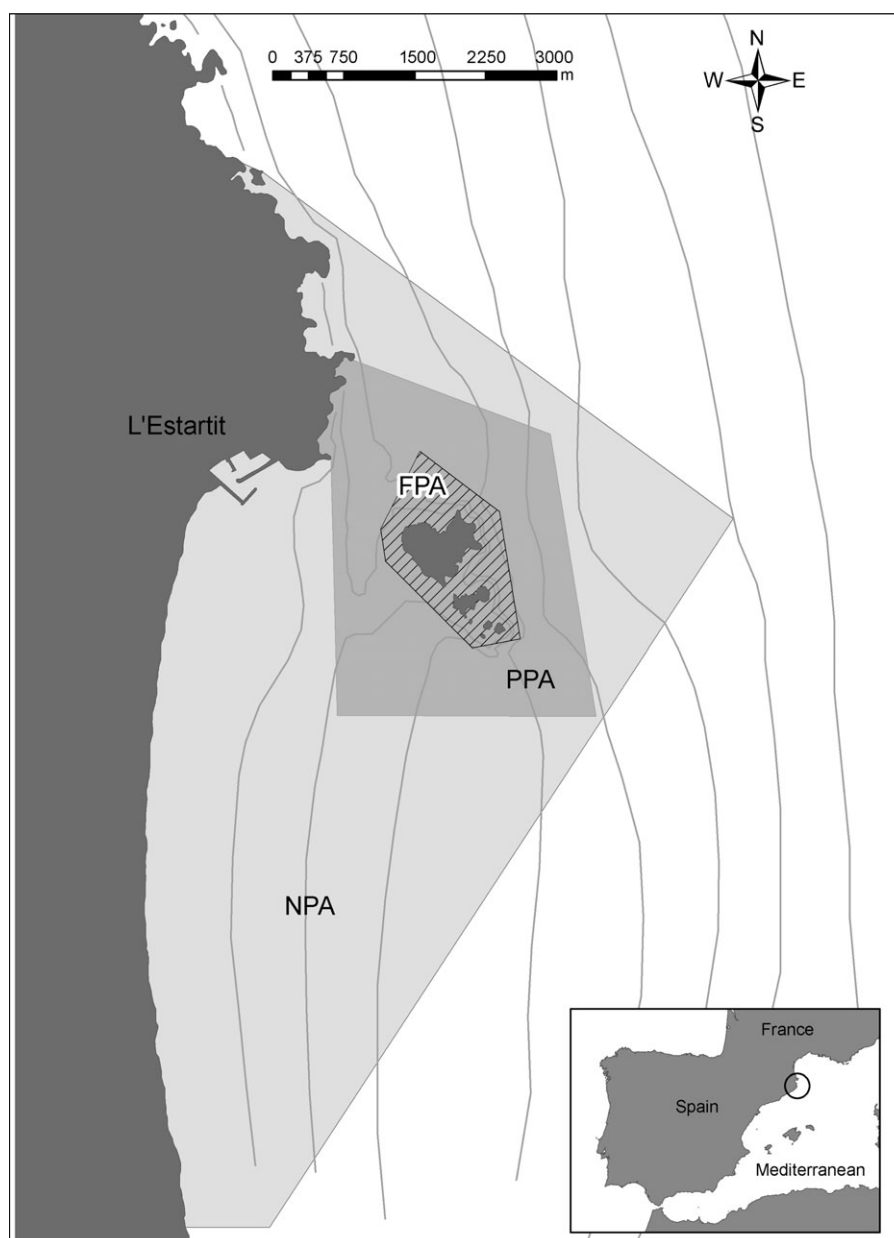


Figure 1. Study area with the Medes Islands integral reserve (FPA), buffer zone (PPA), estimated fishing area (NPA), and the port of L'Estartit.

MPA is 3840 ha (1.34% FPA, 12% PPA, and 86.6% NPA). The FPA is fairly small, which is typical of Mediterranean MPAs, but this bioeconomic model structure is general and can be applied to other situations. Table 1 provides a summary of the activities in the Medes Islands.

The FPA is surrounded by the buffer zone (Figure 1). In the NPA, 14 vessels from a local artisanal fleet operate regularly. We estimated that annual catches in the PPA and NPA in 2005 were 5.8 and 14.6 t, respectively. Red mullet (*Mullus surmuletus*) and common pandora (*Pagellus erythrinus*) are the main target species in this MPA, although they represent only ~5% of catches and total revenues for the local fishing fleet (García-Rubies and Zabala, 1990; Stelzenmüller *et al.*, 2007). The L'Estartit artisanal fleet alternates three fishing gears (gillnet, longline, and trammelnet) and also targets other species, such as

Table 1. Summary of the activities permitted in the Medes Island marine reserve.

Activity	FPA, 51 ha	PPA, 460 ha	NPA, 3 329 ha
Fishing	None permitted	Seven artisanal vessels	Fourteen artisanal vessels
Tourism	Daytime diving, restricted anchoring, and navigation	Diving, recreational fishing, anchoring, and navigation	No restrictions

hake (*Merluccius merluccius*), gilthead sea bream (*Sparus aurata*), European sea bass (*Dicentrarchus labrax*), striped sea bream (*Lithognathus mormyrus*), and common sole (*Solea solea*). The total revenues from commercial fishing were estimated to be €0.37 million (Sunyer, 2001).

The MPA generates €5.9 million from non-extractive activities (tourism). Scuba diving (including dives organized through clubs and the resulting revenue generated for accommodations) and glass-bottom boats represent €2.71 million and €2.55 million, respectively, or 88.7% of the total revenues from tourism. Other activities (e.g. snorkelling, excursions) generate around €0.67 million (Sunyer, 2001; Oliveira, 2006).

Scuba divers pay €3.50 per dive to the Park Authority. A 2005 internal report of the Park Authority states that different administrations (Autonomous Government of Catalonia, L'Estartit local corporation) invest around €0.44 million annually for MPA management (personnel, maintenance, meetings, publications, monitoring, etc.).

In 2005, 60 800 dives took place in the marine reserve (corresponding to an average of five dives for 12 000 visitors). In 2001, glass-bottom boats carried 200 000 visitors around the Medes Island reserve (Sunyer, 2001).

In the application of the model, we considered two main activities: fishing for red mullet and common pandora by 7 vessels in the PPA and 14 vessels in NPA, and tourism, including scuba diving and glass-bottom boats in the FPA and PPA. The set of parameters (r, K, q, p) was estimated for population dynamics, using unpublished catch and effort data. Density transfer rate parameters (δ) and tourist production parameters (λ, η, μ, v) are impossible to estimate from the existing literature or our own data, but we used realistic assumptions to illustrate the interaction of the two activities and the influence of MPA characteristics on the economic results. The parameters are given in Tables 2 and 3.

Results

The benefit of an MPA is evaluated in terms of the effects on commercial fishing and tourism. Theoretical and realistic results are presented to contextualize the Medes Islands MPA in the general model.

Figure 2 shows different equilibrium situations reached under different effort levels and area combinations. The consequences of the creation of a three-zone MPA demonstrate the combined objectives of conservation, maximizing fisheries, and overall revenues.

One of the aims of MPA establishment is the conservation of fisheries resources. As the fishing effort in the NPA increases (Figure 2a, b, and c), there are different effects on stock biomass. Biomass decline in the NPA is partially offset by the transfer from both the FPA and the PPA.

Table 2. Estimated population dynamics parameters (r, K, q, δ) and price (p) of red mullet (*M. surmuletus*) and common pandora (*P. erythrinus*).

Species	r (year ⁻¹)	K (t)	q_{fleet} (boat ⁻¹)	δ	p (€ kg ⁻¹)
Red mullet	0.35	24.921	0.003	1	9.97
Common pandora	0.2	59.774	0.00125	1	9.72

Table 3. Parameters of the main touristic activities on the Medes Island marine reserve.

Tourism activity	λ (tourists area ⁻¹ € ⁻¹ boats ⁻¹)	η	μ	v	p (€ activity ⁻¹)
Scuba diving	1.2	0.2	1	-1.1	44.6
Glass-bottom boats	1	1.17	0.5	-0.5	12.8

Cobb–Douglas production function equation parameters (λ, η, μ, v) and prices (p).

The model forces the system to distribute biomass homogeneously as a response to the density gradient between areas. Biomass is transferred from high-density areas to lower density areas. As shown in Figure 2c, transfer from the FPA to the PPA tends to decrease slightly as the transfer from the FPA and PPA to the NPA increases. Figure 2d shows catch and effort equilibrium curves for different area distributions and fishing-effort levels in the NPA.

The establishment of an MPA supports the sustainability of a fishery, even for high levels of effort in the NPA area. As the protected area (FPA + PPA) expands, overexploitation is avoided. The yield in the NPA area depends on fishing pressure. In a fishery at maximum sustainable yield (MSY), the protected areas imply lower equilibrium yield. In contrast, at high levels of exploitation, where the system tends to the bioeconomic equilibrium (Hannesson, 1998), the establishment of an MPA increases the total yield when fishing effort exceeds optimum levels. For fishing pressure above the optimum, higher levels of yield are guaranteed by the MPA's establishment. For high levels of fishing effort, the most appropriate area distribution, shown in Figure 2d, seems to be 30% FPA, 20% PPA, 50% NPA, and 40% FPA, 30% PPA, 30% NPA, where catches are higher than the highest effort level situation with NPAs, and stock collapse is avoided.

Economic analysis of MPAs is shown in Figure 2e and f. Revenues from commercial fishing and tourism are displayed for different protected-area sizes and fishing effort. The optimal protection level is found for 60% of protection (FPA + PPA) for the idealized MPA. Figures 2e and f show the economic outcome of the coexistence of extractive and non-extractive activities. When tourism and fishing generate similar revenues, the design of the MPA and fishing-effort management should attend to both activities. As shown in Figure 2f, fishing activity affects the results of fisheries and touristic activities.

The application of the model to the Medes Islands MPA is shown in Figure 3, demonstrating the results based on realistic area-size distributions and fishing-effort ranges. Red mullet and common pandora biomass density in the FPA and PPA is stable across a wide range of fishing effort applied in the NPA (Figure 3a). The expected density reduction in NPA will have almost no effect on the MPA's fish density. Fishing effort can significantly exceed the current 14 vessels operating in the NPA with no effect on the red mullet and common pandora populations. Total biomass, therefore, only varies slightly as a result of changes in fishing effort in the NPA (Figure 3b), for a variety of MPA distributions. The model used was the actual current distribution (1.34% FPA, 12% PPA, 86.66% NPA) to simulate realistic changes in MPA design and other possible designs. There is no biomass transfer from the FPA to NPA because there is no contact surface between the two areas. Transfer from the PPA to the fishing zone compensates for the increased fishing effort in the NPA. Transfer from the FPA to PPA compensates for biomass lost to regulated fishing in the PPA and the transfer from the PPA to NPA.

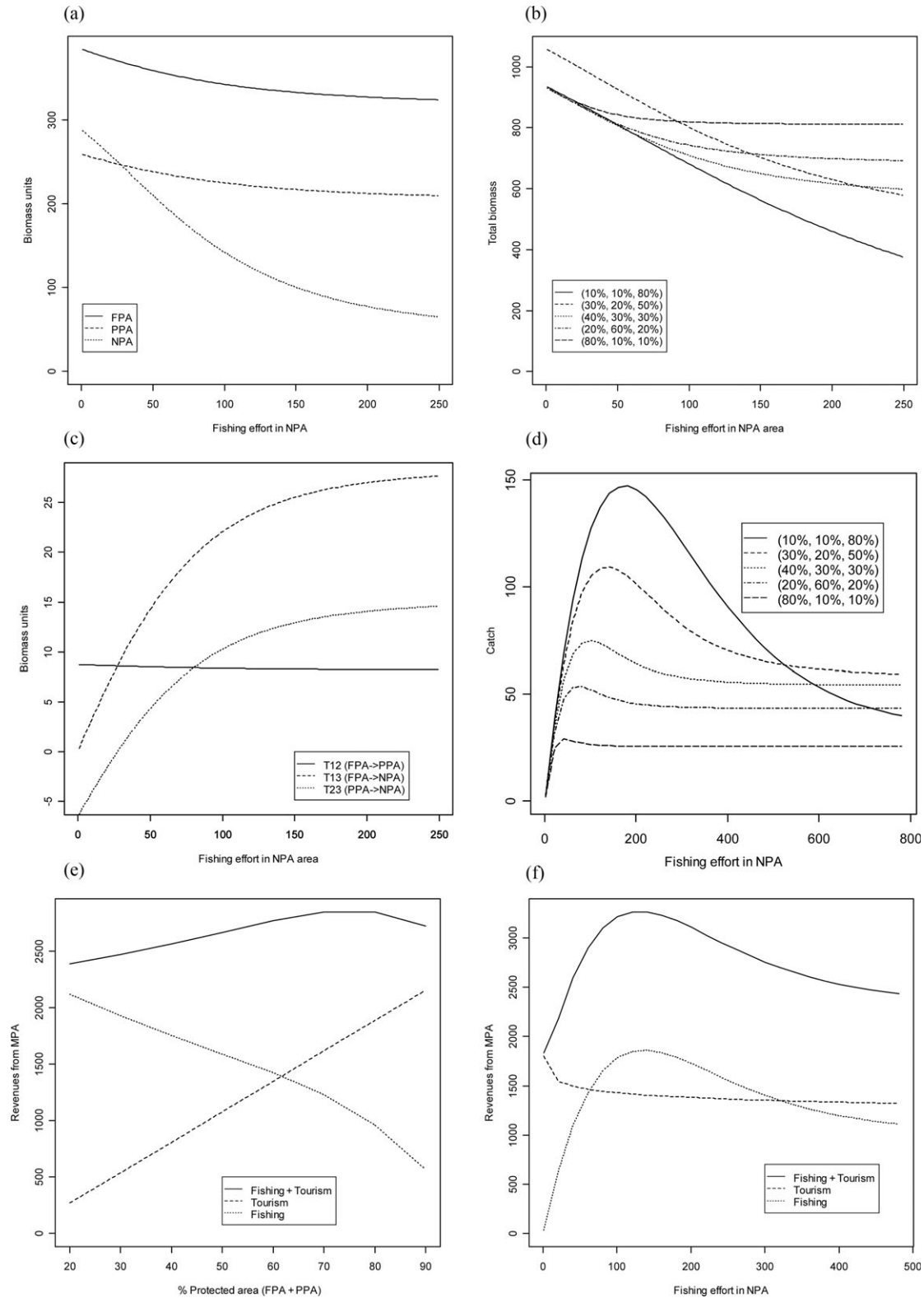


Figure 2. Theoretical bioeconomic indicators of a three-zone MPA for different fishing-effort levels and protected area sizes. (a) Biomass (t) in each zone for different effort levels; (b) total biomass (t) in the MPA system (NPA + PPA + FPA) for different fishing-effort levels and area designs; (c) net biomass (t) transfer between zones; (d) fish production (t) curve; (e) extractive, non-extractive activities, and total revenues (€) from the MPA for different levels of protection; and (f) extractive, non-extractive activities, and total revenues (€) from the MPA for different levels of fishing effort. The parameters for the idealized graphs were: $r = 0.4$, $K = 1000$ t, $A = 1$, $\delta = 0.3$; $q_{NPA} = 0.002$, $q_{PPA} = 0.005$, $p_{fish} = 17$, $p_{tour} = 1000$, $\lambda = 300$ (e), $\lambda = 3$ (f), $\mu = 1$, $\eta = 1$, $\nu = -0.05$. For particular cases, (a, c, and f) $\alpha_{FPA} = 40\%$, $\alpha_{PPA} = 30\%$, $\alpha_{NPA} = 30\%$, (a and c) $E_{PPA} = 60$, (b, d, e, and f) $E_{PPA} = 0$.

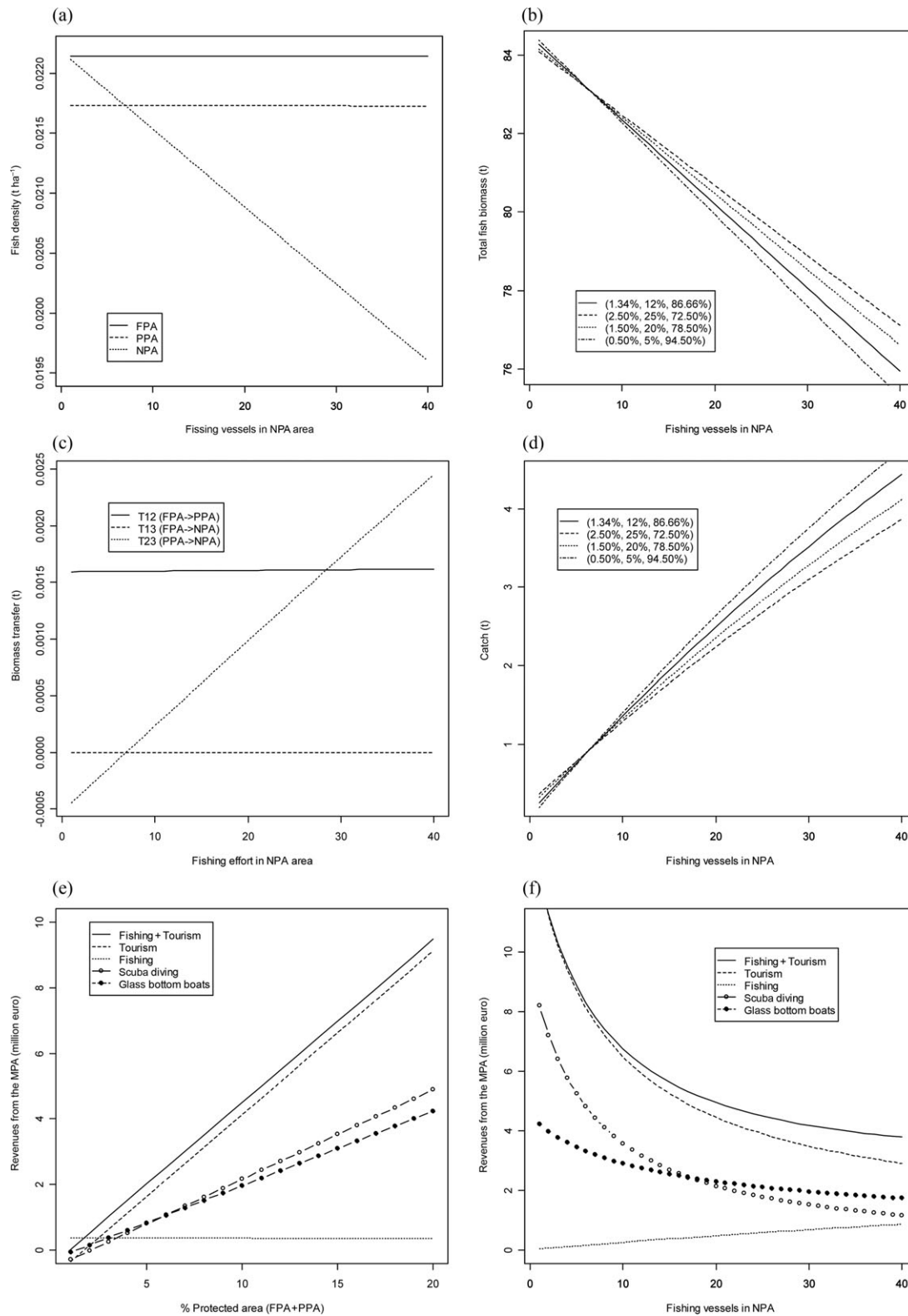


Figure 3. Medes Islands MPA's bioeconomic indicators for realistic ranges of fishing-effort (vessels) and area distributions. (a) Red mullet and common pandora fish density in each zone for different effort levels; (b) total red mullet and common pandora biomass in the MPA system (NPA + PPA + FPA) for different fishing-effort levels and area designs; (c) net red mullet and common pandora biomass transfer between zones (note that there is no transfer from FPA to NPA); (d) fish production curve (including red mullet and common pandora); (e) extractive (artisanal fishing) and non-extractive (scuba diving and glass-bottom boats tourism) activities and total revenues from the MPA for different levels of protection; (f) extractive, non-extractive activities, and total revenues from the MPA for different levels of fishing effort. (a, c, and f) Current $\alpha_{FPA} = 1.34\%$, $\alpha_{PPA} = 12\%$, $\alpha_{NPA} = 86.6\%$. See Tables 2 and 3 for the remaining parameters.

Another salient aspect of the analysis is the evaluation of the area size and the effect of changing the level of protection.

According to previous unpublished assessments, red mullet and common pandora are far from either their MSY or overexploitation risk. The two species are underexploited, and increasing the fishing effort in the fishing zone would bring a significant production increase. The MSY effort level is significantly higher than the current one (Figure 3d).

The economic analysis of MPA also includes non-extractive activities. Figure 3e shows the slight reduction of fisheries revenues and the significant improvement of non-extractive activities as the protected area increases. Increasing fishing intensity (fishing effort) affects the results of use by fisheries and tourists (Figure 3f). As observed, in our case, the increase in fishing effort allows an increase in the income from fisheries (as expected, the result of current underexploitation), while reducing revenue from tourism. Within the parameter space explored here, fishing vessels in the NPA disturb glass-bottom boat trips more than scuba diving. Scuba diving occurs close to rocks and coral reefs, where fishing is forbidden, so the interaction is minimal. Moreover, glass-bottom boat excursions take place not only in the protected ecosystem but in the surrounding areas. The chosen parameters reflect this difference on the impact of fishing on the two non-extractive activities.

Model estimates for revenues from fishing and for the two main touristic activities are shown in Figure 4, with the current structure (2005) of the Medes Islands MPA. As described earlier, scuba diving and glass-bottom boat trips generate €5.26 million in revenues, which represent 83.6% of the revenues from the marine reserve and 88% of the non-extractive activities.

This result and the economic data illustrate that Medes Island MPA is a tourism-income generator that directly (through diving taxes) generates €0.21 million for the local economy.

Finally, a fishery-optimization exercise allows assessment of the potential use of the area exclusively as a fishing ground. If the fishery were increased to its MSY, the boats operating in the area would number 67, reducing the red mullet and common pandora total biomass to a 45 t equilibrium, significantly lower than the current 82 t (Figure 3b). The total revenues for the L'Estartit fishing fleet from the two analysed species in the MSY were found to reach €0.5 million, which would represent a significant improvement over the current €0.2 million. In contrast, these numbers are significantly lower than the current revenues from touristic activities (€5.26 million).

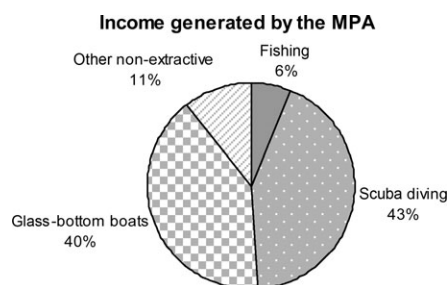


Figure 4. Estimated revenues from extractive and non-extractive activities in the Medes Islands MPA in 2005 (Sunyer, 2001; Oliveira, 2006).

Discussion

The model presented here describes the consequences of creating a three-zone protected area formed by an FPA, a PPA, and a fishing area. The steady state for the different area size and effort demonstrates the benefit of this management strategy. The benefits of MPA creation are discussed with a case study where the economic relevance of fisheries is significantly less than non-extractive activities.

The model accommodates the coexistence of the two activities, which is a common characteristic of Mediterranean MPA systems.

Focusing on resource conservation, the performance of an MPA system depends on each species' biologic characteristics (growth and mobility patterns). Red mullet and common pandora, exploited by the L'Estartit small-scale fleet, are far from being overexploited, and the MPA's objectives have more to do with the preservation of a high-diversity ecosystem, where scuba diving and glass-bottom boats generate a significant income. Species mobility parameters are difficult to estimate and, following Kellner *et al.* (2007), a moderate mobility coefficient ($\delta = 1$) was used for red mullet and common pandora. However, the implications of the MPA creation on the conservation of the two analysed species for fisheries would be negligible for the Medes Island marine reserve, according to the results of our model. On the contrary, some other species, such as dusky groupers (*Epinephelus marginatus*) and brown meagre (*Sciaena umbra*), were heavily exploited in the 1980s, mainly by spearfishers, before the establishment of the reserve; since then, the trend has reversed (García-Rubies and Zabala, 1990).

The model is useful for the areas where the objective is preserving stocks suffering a high fishing intensity and where spillover effect is demonstrable.

The touristic possibilities of MPAs have been analysed in different ways by many authors (Agardy, 1993; Boncoeur *et al.*, 2002). The most attractive touristic activities include scuba diving, recreational fishing, and marine wildlife watching (Boncoeur *et al.*, 2002). The model presented permits the partial evaluation of the area as an alternative economic generator, as a function of a quality parameter (λ). The idealized system in Figure 2 shows comparable revenues from extractive and non-extractive activities. The non-extractive activities increase their revenues because the protected area is wider. On the other hand, the model does not account for congestion or touristic overcapacity that may reduce the appeal of a marine reserve (Alban and Boncoeur, 2006). In contrast, in the realistic analysis of the Medes Island MPA, revenues from tourism greatly exceed fisheries revenues.

Medes Islands represent an example of the joint use of extractive and non-extractive activities. In the co-occurrence zones, the interaction between fishing and tourism is negative for touristic interests. The benefit for artisanal fisheries and the importance of non-extractive activities as income and employment generators make Medes Islands an interesting opportunity for the restructuring of declining fishing communities along the Mediterranean coast.

The effects on tourism of both regulating fishing effort and designing the marine reserve are crucial in the Medes Islands marine reserve.

The fishery-optimization calculations revealed the potential revenues to the Medes Islands from fishing (€0.5 million) to be one order of magnitude lower than revenues from touristic activities. As a consequence, the potential income generator of the area

is expected to be maximized, promoting its touristic activities. On one hand, the number of fishing units in L'Estartit harbour has been decreasing in the past decades, and the activity should be valued more from a socio-economic point of view than from a strictly economic one. On the other hand, landings of vessels provide valuable species for fresh consumption in the local restaurants.

For simulation purposes, catchability and effort dynamics and multi-agent analysis appear as the next challenges to be incorporated in MPA analysis, including the relationships or feedback among different user types.

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