Marine partially protected areas: drivers of ecological effectiveness

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The number of marine protected areas (MPAs) has grown exponentially worldwide over the past decade in order to meet international targets. Most of these protected areas allow extraction of resources and are therefore designated as "partially protected areas" (PPAs). However, the effectiveness of PPAs remains unclear due to the high variability of use types permitted. Here, we carried out what we believe to be the first global meta-analysis of PPAs using a regulation-based classification system for MPAs to assess their ecological effectiveness. This novel classification allows for unambiguous differentiation between areas according to allowed use, which is the key feature determining PPA performance. Highly and moderately regulated areas exhibited higher biomass and abundance of commercial fish species, whereas fish abundance and biomass in weakly regulated areas differed little from unprotected areas. Notably, the effectiveness of moderately regulated areas can be enhanced by the presence of an adjacent fully protected area. We concluded that limited and well-regulated uses in PPAs and the presence of an adjacent fully protected area confer ecological benefits, from which socioeconomic advantages are derived.

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Coastal zones around the world are increasingly subjected to human and environmental pressures and are in need of strategic management (Halpern *et al*. 2015). The establishment of marine protected areas (MPAs) is a commonly used tool for improving conservation, food security, and fisheries management (Gaines *et al*. 2010). The ecological effects of fully protected areas (ie no-take areas) are well studied, and the abundance and size of species are usually enhanced within (eg Claudet *et al*. 2008; Edgar *et al.* 2014) and in some cases outside of (eg Caselle *et al*. 2015) these areas. MPAs also support the recovery of populations and communities of fish and other marine taxa and can preserve habitat structure (Sandin *et al.* 2008).

The establishment of fully protected areas has often resulted in conflicts between conservation and socioeconomic objectives, especially in areas with numerous users and types of uses (Fox *et al*. 2011). As such, the implementation of partially protected areas (PPAs), in which some extractive activities may be allowed, has in some cases become a preferable option, given that PPAs can provide a better balance between social and ecological objectives, and may be easier to implement. Simultaneously, in response to international agreements and commitments, more and more MPAs are being established, most of which are PPAs of one type or another (Lubchenco and Grorud-Colvert 2015). It is therefore urgent to identify which forms of partial protection can provide socioeconomic benefits while still protecting biodiversity.

PPAs are context-dependent, and their regulations vary with management objectives; in turn, regulations will likely affect their ecological effectiveness. Only a handful of studies have examined the effects of different levels of partial protection (eg Di Franco *et al*. 2009; Sciberras *et al*. 2013; Ban *et al.* 2014), none of which have been based on a systematic classification for these different levels, leading to variable results that are difficult to generalize. Sciberras *et al.* (2013), for instance, broadly characterized three types of PPAs based on replies to a survey questionnaire that included somewhat subjective questions (eg whether an activity damages the bottom, targets particular species, or affects other species); moreover, the study did not account for such factors as aquaculture, bottom exploitation, and other non-extractive activities (eg anchoring) that may impact the marine habitat.

Ban *et al.* (2014) re-analyzed the dataset used by Sciberras *et al.* (2013) but used the International Union for Conservation of Nature (IUCN) categories of protected areas instead (see Table 1 in Ban *et al*. 2014); however, the current IUCN classification system is based on management objectives that can be mismatched to regulations, resulting in considerable uncertainty when evaluating MPA effectiveness (Horta e Costa *et al.* 2016). In fact, when correlating IUCN categories with the expected impacts of activities, there is a high degree of variability among, and overlap between, categories. There is also no clear trend between the expected cumulative impacts of activities and the IUCN classification scheme, from more restricted (Ia) to less restricted (V or VI) categories (Horta e Costa *et al.* 2016).

A recently published regulation-based classification system for MPAs, that of Horta e Costa *et al.* (2016), presents a new

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way to categorize both MPAs and each type of zone within them according to allowed commercial and recreational uses (WebFigure 1). In this system, PPAs are classified based on the cumulative impacts of allowed activities.

Understanding the ecological responses of various types of partial protection is essential, since most MPAs are multiple-use and the ecological effects that each PPA provides are likely linked to different regulatory regimes (Fox *et al.* 2011). In this paper, we present a novel approach to investigate and infer how varying levels of partial protection lead to varying ecological effects through a global meta-analysis. We also examine how design characteristics that are known to influence the effectiveness of no-take areas, such as protected area age and size (Claudet *et al.* 2008), or that are specific to multiple-use MPAs, such as the presence of an adjacent fully protected area, may also mediate the effectiveness of partial protection.

Methods and materials

Data selection: response variables and covariates

We built our database from studies compiled by Sciberras *et al.* (2013) and Horta e Costa *et al.* (2016), updated with recent peer-reviewed literature obtained via a database search following the methods of Sciberras *et al.* (2013). We limited our analyses to studies that reported values for abundance and/or biomass of finfish species targeted by fisheries, as they are directly affected by the protection regimes. In order to qualify, studies must also have included a comparison of these ecological variables between PPAs and surrounding open areas, which we will refer to hereafter as "unprotected areas". We only retained studies that reported ecological responses for a particular PPA when they were compared to unprotected areas, but not in cases where biological responses were aggregated for an entire multiple-use MPA with varied regulations. Studies that reported ecological responses for PPAs with different protection levels within the same MPA were included separately in the database, because they represented different types of partial protection. In cases where more than one study investigated the effects of protection, only the most recent was retained, unless different metrics were used among the studies. Although it would have been important to assess effects on the overall biodiversity of these areas, data for non-target species were not sufficiently available across studies to allow for a detailed analysis.

The studies had to report the mean of the response variable (abundance and/or biomass), sample size (eg number of transects), and an appropriate error measure (eg variance). If the study assessed abundance and biomass of targeted fish species over some other variables (eg depth, habitat types), data were averaged for each variable. When data were collected over time, only the most recent results were extracted, as they represented the longest duration of protection; however, when data were reported several times within a year, results were averaged for that year to minimize seasonal effects associated with sampling period. Similarly, when data were reported for multiple targeted species (k), we calculated the overall mean ($\bar{X}$) and standard deviation (SD) for the study as:

$$\bar{X} = \frac{\sum_{j=1}^{k} n_j \bar{x}_j}{\sum_{j=1}^{k} n_j} \qquad \text{(Eq 1)}$$

and

$$\mathrm{SD} = \sqrt{\frac{1}{k^2} \sum_{j=1}^{k} \mathrm{SD}_j^2} \qquad \text{(Eq 2)},$$

where $\bar{x}$ is the mean biomass or abundance for species j, and SD and n_i are the standard deviation and sample sizes (eg number of transects) associated with $\bar{x}_j$.

As mentioned, we classified each PPA based on the system described by Horta e Costa *et al.* (2016), in which each area type allows different activities. Five classes of PPAs were identified: (1) highly regulated, (2) moderately regulated, (3) weakly regulated, (4) very weakly regulated, and (5) unregulated (WebFigure 1). Highly regulated areas were defined as those allowing only a limited number (five maximum) of low-impact types of fishing gear (eg lines, octopus trap), moderately regulated areas were defined as those that allow more (up to ten) low- to medium-impact fishing gear types (eg gillnets), and weakly regulated areas were defined as those in which higher-impact gear types (eg beach seines, bottom trawling, trammel nets) were permitted.

We recorded the age (years since establishment) and size of each PPA, as well as the presence or absence of an adjacent fully protected area (when side by side with a PPA and part of a multiple-use MPA). We also scored the capacity to implement regulations using an index for fisheries management effectiveness (Mora *et al.* 2009) at the national level as a proxy for enforcement of fishing regulations in MPAs. Values ranged from 0 to 1, with 0 representing low enforcement capacity and 1 representing high enforcement capacity.

The final database consisted of 26 peer-reviewed research articles and 49 case studies worldwide (WebTable 1). Of the PPAs included in the 49 case studies, 24 were characterized as highly regulated, 17 as moderately regulated, seven as weakly regulated, and one as very weakly regulated. We restricted our analysis to the first three classes.

Meta-analysis

We used a weighted random-effects meta-analysis to assess the ecological effectiveness of PPAs. The effect size R_i for each area i was modeled as a natural logarithm (ln) response ratio of the mean ($\bar{X}_i$) abundance or biomass estimates measured within and outside the PPA (Osenberg *et al.* 1997; Hedges *et al.* 1999):

$$R_i = \ln\left(\frac{\bar{X}_{\mathrm{PPA}_i}}{\bar{X}_{\mathrm{UPA}_i}}\right) \qquad \text{(Eq 3)},$$

where $\bar{X}_{\text{PPA}}$ and $\bar{X}_{\text{UPA}}$ are the mean abundance/biomass within and outside the PPA of study i, respectively. The variance v_i of the effect sizes (ie the within-study variance) was calculated as follows:

$$v_i = \frac{\text{SD}^2_{\text{PPA}_i}}{n_{\text{PPA}_i} * \bar{X}^2_{\text{PPA}_i}} + \frac{\text{SD}^2_{\text{UPA}_i}}{n_{\text{UPA}_i} * \bar{X}^2_{\text{UPA}_i}} \qquad \text{(Eq 4)},$$

where $\bar{X}_{\text{PPA}}$ and $\bar{X}_{\text{UPA}}$ are the mean abundance/biomass within and outside the PPA of study i, respectively; SD_{PPA} and SD_{UPA} are the standard deviations associated with $\bar{X}_{\text{PPA}}$ and $\bar{X}_{\text{UPA}}$ of study i, respectively; and n_{PPA} and n_{UPA} are the sample sizes of study i for the estimation of the mean (eg number of transects). As in traditional random-effects meta-analyses, our weights w_i included both the within- and among-study variances, and were calculated as follows:

$$w_i = \frac{1}{v_i + v_A} \qquad \text{(Eq 5)},$$

where v_i is defined as above and v_A is the among-study variance.

The overall effect of partial protection was calculated as a weighted average of the effect sizes:

$$\bar{R} = \frac{\sum_{i=1}^{n_i} w_i R_i}{\sum_{i=1}^{n_i} w_i} \qquad \text{(Eq 6)},$$

where w_i and R_i are defined above. The overall heterogeneity (Q_t) was calculated as:

$$Q_t = \sum_{i=1}^{n_i} w_i (R_i - \bar{R})^2 \qquad \text{(Eq 7)},$$

and its significance was tested against the χ^2 distribution with n_i − 1 degrees of freedom.

We used weighted general linear (mixed-effects) models to examine how different features impact the ecological effectiveness of PPAs. We first investigated if different types of areas exhibited different levels of ecological responses. For a given class category, weighted cumulative effect sizes were calculated as:

$$\bar{R}_c = \frac{\sum_{i=1}^{n_c} w_i R_i}{\sum_{i=1}^{n_c} w_i} \qquad \text{(Eq 8)},$$

where n_c is the number of PPAs belonging to class c, and R_i and w_i are defined as above. The heterogeneity of the model explained by the class (Q_m) was calculated as follows:

$$Q_m = \sum_{j=1}^{m} \sum_{i=1}^{n_c} w_{ij} (\bar{R}_c - \bar{R})^2 \qquad \text{(Eq 9)},$$

where m is the number of classes $\bar{R}$, and $\bar{R}_c$ is calculated as above. The significance of Q_m was tested against the χ^2 distribution with n_c − 1 degrees of freedom.

In addition, we ran models to assess if different features were mediating the response to protection, namely (1) the age of the protected area, (2) the size of the protected area (measured in square kilometers and log-transformed in the analyses), (3) the capacity to implement regulations, and (4) the presence/absence of an adjacent fully protected area. We ran mixed-effects categorical analyses for categorical variables and applied meta-analytic regression through linear mixed-effects models to the continuous variables. In addition, interaction models between classes and each of the features were also tested (WebTable 2). All statistical analyses were performed with R (R Core Team 2016).

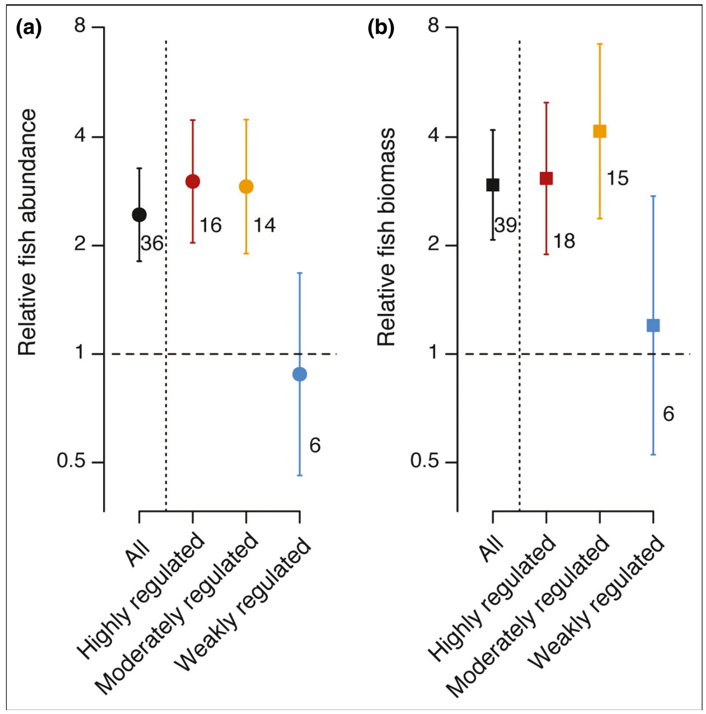

Figure 1. Ecological effectiveness of partially protected areas (PPAs) for (a) abundance and (b) biomass of targeted fish species for all PPAs combined and for PPAs grouped by class (sensu Horta e Costa *et al.* 2016). The horizontal dotted line at 1 represents equal fish abundance or biomass within and outside the PPA; values greater than 1 indicate more fish (or more biomass) within the PPA; values below 1 indicate fewer fish (or less biomass) within the PPA. The bars represent 95% confidence intervals. Sample sizes for each group are shown.

Results

Abundance and biomass of targeted fish species were significantly higher overall within PPAs than in unprotected areas (on average 2.4 and 2.9 times higher, respectively; Figure 1). PPA effectiveness was, however, variable across studies, both in terms of abundance (R_i = 0.89, Q_t = 961, df [degrees of freedom] = 35, P < 0.001) and biomass (R_i = 1.08, Q_t = 2197, df = 38, P < 0.001), with different classes exhibiting different levels of effectiveness (abundance Q_m = 11.35, P = 0.0034; biomass Q_m = 6.6636, P = 0.048). When compared to unprotected areas, highly regulated PPAs supported 2.9 times higher fish abundance (R_k = 1.1) and 3 times higher fish biomass (R_k = 1.12), and moderately regulated PPAs supported 2.9 times higher fish abundance (R_k

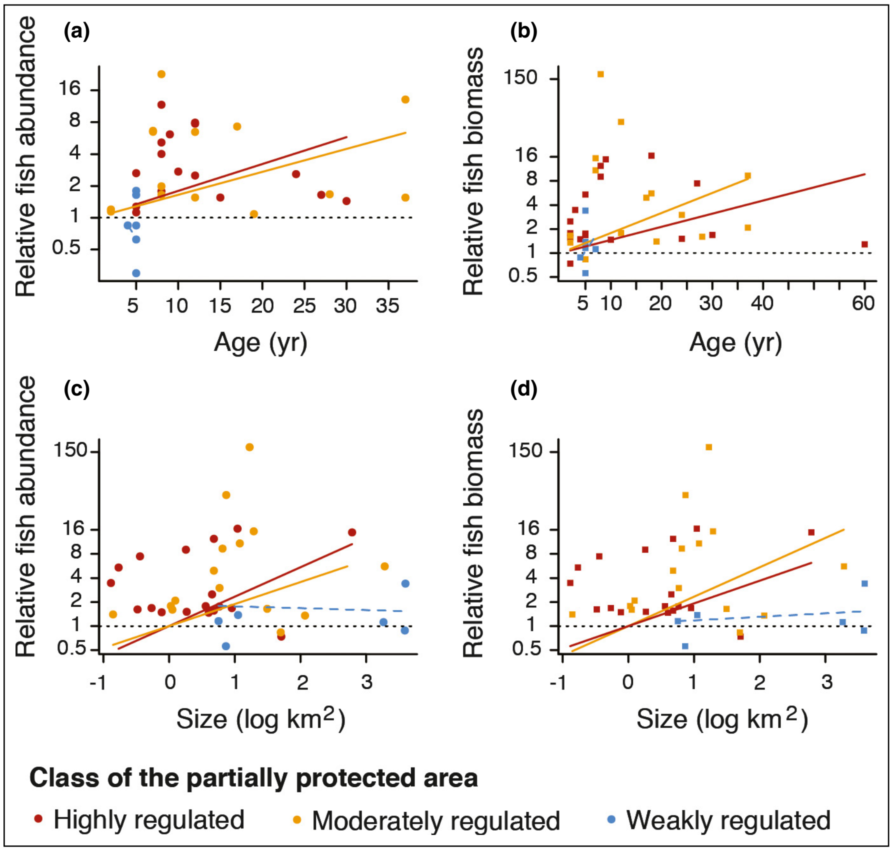

Figure 2. Ecological effectiveness of the classes of PPAs as mediated by PPA age (a and b) and size (c and d) for abundance (top panel) and biomass (bottom panel) of targeted fish species. The horizontal dotted line at 1 represents equal fish abundance or biomass inside and outside the PPA; values greater than 1 indicate more fish (or more biomass) within the PPA; values below 1 indicate fewer fish (or less biomass) within the PPA. The fitted lines are regressions of each PPA class and the corresponding feature (solid line: significant regression, $P <$ 0.05; dashed line: non-significant regression, $P >$ 0.05).

= 1.07) and 4.2 times higher fish biomass (R_k = 1.42). However, fish abundance (R_k = –0.13) and biomass (R_k = 0.18) in weakly regulated PPAs did not differ from that in surrounding unprotected areas (Figure 1).

Ecological effectiveness increased with both the age and size of PPAs, and with the capacity to implement regulations (Figure 2; WebFigure 2; WebTable 2a). Abundance and biomass of targeted fish species increased on average by 5.1% and 4.6% annually, respectively, in protected areas relative to unprotected areas following implementation. For every tenfold increase in the size of a PPA, fish abundance and biomass increased by 37% and 46%, respectively. Furthermore, increasing the implementation capacity by 10% resulted in 4.3- and 6.4-fold higher abundance and biomass of targeted fish species, respectively. The effect of age, size, and capacity to implement regulations varied across the three PPA classes, yet these interactions were significant only for targeted fish species abundance and not biomass (WebTable 2b). Targeted species within moderately and highly regulated areas were positively affected by age, size, and the capacity to implement regulations, whereas no significant effect was detected for targeted species within weakly regulated areas (Figure 2; WebFigure 2).

Interestingly, the presence of a fully protected area adjacent to a PPA played a role in enhancing the ecological effectiveness of partial protection (abundance Q_m = 2.05, P = 0.15; biomass Q_m = 5.47, P = 0.082). Fish abundance and biomass were on average 1.6 and 2.1 times higher, respectively, within PPAs that were adjacent to a fully protected area (Figure 3). This effect varied across the three classes (abundance Q_m = 22.07, P = 0.0005; biomass Q_m = 12.59, P = 0.096), with some moderately regulated areas showing positive ecological benefits only when adjacent to a fully protected area (Figure 3; WebTable 2b) and weakly regulated areas not showing any benefit.

Discussion

We provide what is, to our knowledge, the first global assessment of the performance of marine PPAs based on a regulation-based MPA classification system (Horta e Costa *et al.* 2016). We show that the ecological effectiveness of partial protection depends on specific components: (1) their type (classified according to allowed uses; WebFigure 1), (2) the presence of an adjacent fully protected area that might influence their effectiveness, (3) the capacity to enforce regulations, and their (4) age and (5) size. These results help to clarify the previously reported mixed responses to protection in PPAs (eg Lester and Halpern 2008; Di Franco *et al.* 2009; Sciberras *et al.* 2013).

Our most notable finding is that regulations are the key feature determining the ecological effectiveness of PPAs. Moderately and highly regulated areas are effective at harboring greater abundances and biomass of targeted fish species as compared to unprotected areas, whereas no ecological benefits were detected in weakly regulated areas. Highly and moderately regulated PPAs permit some extractive uses (maximum of five and 10 fishing gears, respectively) that have low (eg lines and traps) or moderate (eg gillnets) impacts on ecosystems. Weakly regulated areas permit more types of fishing gear and/or types that have greater negative environmental impacts (eg trawling; Horta e Costa *et al.* 2016). Fernández-Chacón *et al.* (2015) demonstrated empirically that the exclusion of several fishing gears within PPAs resulted in fish species targeted by those gears benefiting from protection as compared to populations in unprotected areas.

In addition, we show that combining a fully protected area with moderately regulated ones confers positive benefits (Figure 3), with the full range of response always above 1 (non-significant differences between partial protection and open areas are shown when response overlaps 1). As this class (ie moderately regulated) is a common choice of MPA design, placing these areas adjacent to fully protected areas is an important option to consider, since doing so can enhance their ecological benefits. Highly and weakly regulated PPAs may be less sensitive to the presence of an adjacent fully protected area for different reasons. For highly regulated areas, this is likely due to the limited amount of extractive activities permitted within them, which already confers high conservation benefits, whereas weakly regulated areas may be less influenced by an adjacent fully protected area due to the large number of activities with substantial impacts that occur in these areas. In moderately regulated areas, regulations alone may be insufficient to greatly enhance populations of targeted fish species; moreover, spillover effects from an adjacent no-take area may increase their ecological effectiveness (eg Hackradt *et al.* 2014). Spillover effects from highly regulated PPAs may benefit adjacent areas with weaker regulations, but more research is needed to test this. Future studies should assess how designing MPAs with different combinations of protection levels affects ecological responses.

We also show that the effectiveness of protection is positively correlated with both age and size, demonstrating that these variables matter not only for no-take areas but also for PPAs (Claudet *et al.* 2008; Edgar *et al.* 2014). Moreover, we found that the higher the capacity to implement regulations, the greater the ecological effectiveness, confirming that investment in control and enforcement mechanisms should be a high priority when establishing and managing MPAs (Guidetti *et al.* 2008; Mora *et al.* 2009; Edgar *et al.* 2014). The positive ecological effects associated with larger, older, and better-enforced PPAs decline, however, with the number of extractive activities allowed.

Our findings suggest that well-regulated, well-enforced, large, and longer-established PPAs can provide substantial ecological benefits, which are enhanced in some cases by the presence of an adjacent fully protected area (Figure 4). Enforcement, age, and size are key components of success (Edgar *et al.* 2014). Several studies have compared the effects of full and partial protection to unprotected areas, demonstrating that, overall, full protection provides more ecological benefits than partial protection (eg Lester and Halpern 2008; Sciberras *et al.* 2013; Giakoumi *et al.* 2017). Here, however, we demonstrate that MPAs do not have to be strictly no-take (Edgar *et al.* 2014) to provide ecological benefits. Highly regulated PPAs can be effective and sometimes a preferable option in complex socioecological systems where full protection is difficult to implement, or as a complement to full protection in multiple-use MPAs. Moderately regulated areas can be combined with adjacent fully protected areas to further enhance ecological benefits. However, the overall ecological benefits of highly regulated PPAs, when compared to full protection, are much lower; there is 300% more fish biomass and density within those PPAs than in unprotected areas, but Sala and Giakoumi (2018) reported 670% higher fish biomass within fully protected areas than in unprotected areas; Sciberras *et al.* (2013) reported 92% higher biomass in no-take areas than in PPAs; and Gill *et al.* (2017) found a twofold difference in biomass between no-take areas and PPAs.

The case studies included in our analysis are global in scope, with most fish biomass and density data being measured on relatively shallow (less than 30 m) reefs. Mora *et al.* (2011) and Cinner *et al.* (2013) have shown that social factors can influence the biomass of reef fishes in coastal areas; coastal development and land use, human population density (Mora *et al.* 2011), distance to market, and economic development (Cinner *et al.* 2013) can all greatly influence the structure of reef fish biomass. Future studies should incorporate these correlates when enough information is available for the different classes of PPAs. Most of the studies included in our analysis were for partial protection classes where extraction is limited (highly

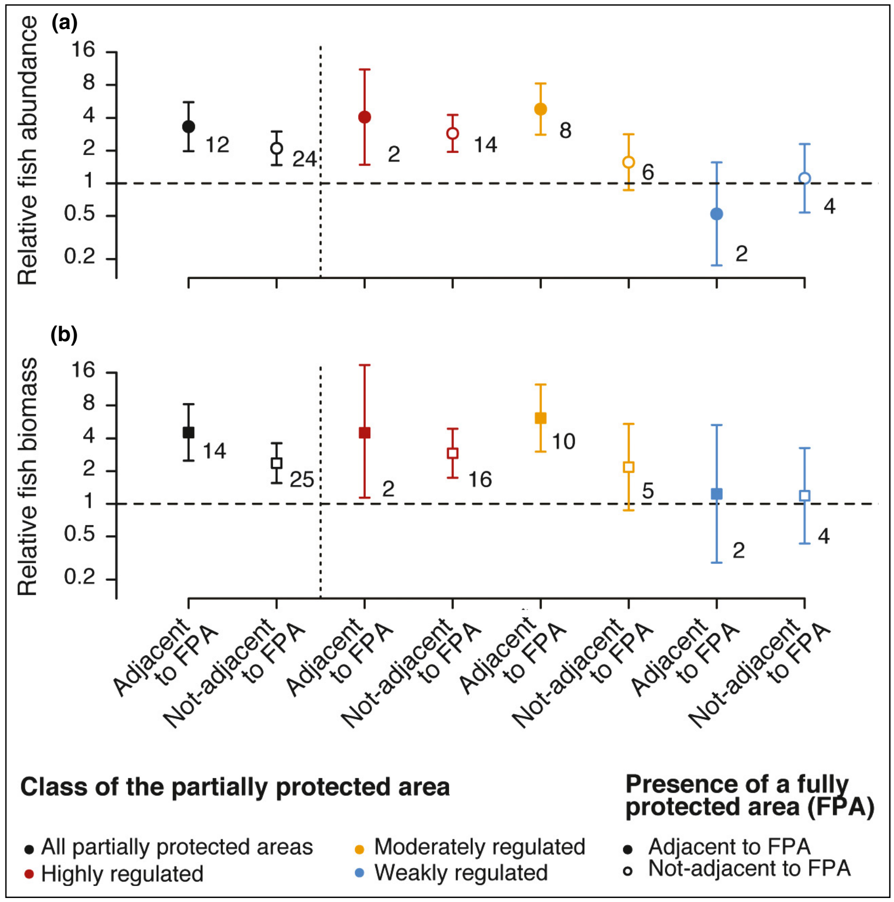

Figure 3. Ecological effectiveness of classes of PPAs for the (a) abundance and (b) biomass of targeted fish species as affected by the presence of an adjacent fully protected area (open symbols). The horizontal dotted line at 1 represents equal fish abundance inside and outside of the PPA; values greater than 1 indicate more fish (or more biomass) within the PPA; values below 1 indicate fewer fish (or less biomass) within the PPA. The bars represent 95% confidence intervals. Sample sizes for each group are shown.

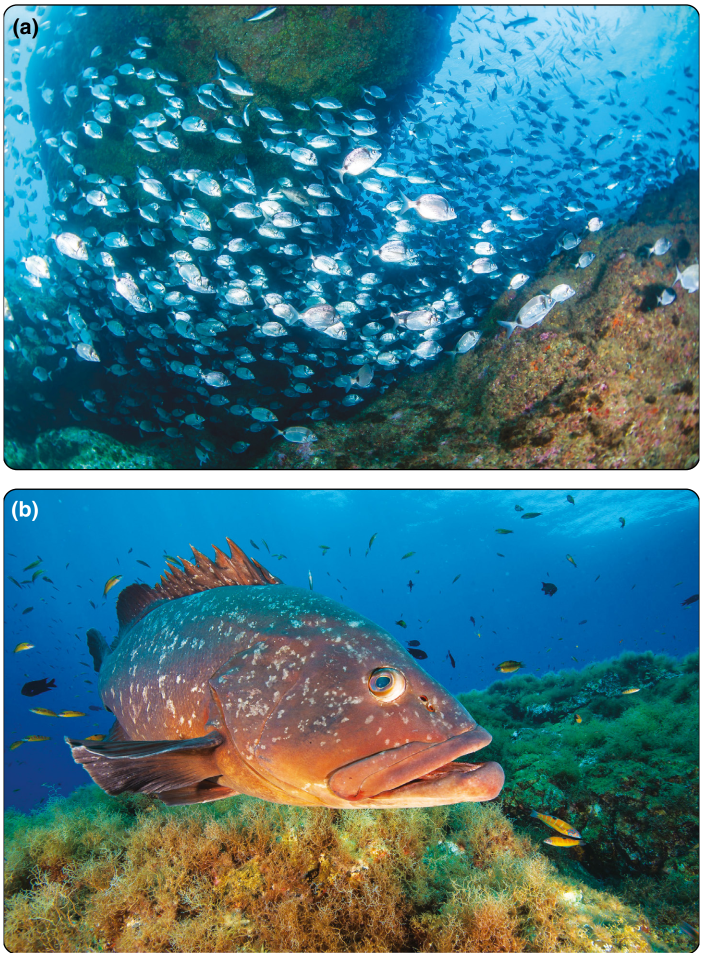

Figure 4. Ecological effectiveness of highly regulated PPAs can be high, as shown in these two photographs. (a) Seabreams (*Diplodus sargus* and *Diplodus vulgaris*) respond strongly to protection, increasing in both abundance and size in areas with high levels of protection, thereby boosting tourism operations such as diving (here, in Arrábida Marine Park, Portugal); (b) the endangered dusky grouper (*Epinephelus marginatus*) is a long-lived hermaphroditic fish that is highly vulnerable to both recreational and commercial fishing, but this species thrives in areas with strong protection (here, in the Formigas Islets, a nature reserve in the Azores).

and moderately regulated areas) and therefore stronger responses are to be expected, whereas only a handful of studies reported results for areas with lower levels of protection (weakly and very weakly regulated areas). Publication bias (ie scientists tend to sample where an effect is likely to be detected and journals tend to favor the publication of positive results) can partially explain why we were only able to locate detailed information for 47 case studies despite there being more than 11,000 MPAs listed globally (MPA Atlas; www.mpatlas.org). Therefore, we have very likely captured the most effective PPAs, potentially leading to an overestimation of the average effects.

The implementation of MPAs requires the integration of conservation, social, economic, and political goals, and MPA design should be driven by the particular management objectives. A regulation-based classification system such as the one used in this study (Horta e Costa *et al.* 2016) provides an adequate tool to test not only aspirational goals, based on objectives, but also concrete impacts as predicted by regulations of uses. Our results can assist policy makers and managers in determining the appropriate levels of protection to reach specific goals by accounting for the type of regulations adopted in each MPA.

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Supporting Information

Additional, web-only material may be found in the online version of this article at http://onlinelibrary.wiley.com/doi/10.1002/fee.1934/suppinfo

FrontiersEcoPics

Opportunistic fishing buddy

A common kingfisher (*Alcedo atthis*) patiently waits for its catch by Saheb Bandh Lake in Purulia, West Bengal, India, near a fishing spot that is popular with the local people. Although kingfishers are usually very sensitive to the presence of humans and do not commonly perch so near to them, and despite the occurrence of many large trees near the lake's edge, a few of these birds choose to sit close to the fishermen. To help entice the fish to their lures, the anglers throw bait into the water, leading to large aggregations of fish; at this point, the kingfisher will dive into the water, sometimes emerging with a fish in its beak. Even though several other species of birds – including herons, little grebes, and cormorants – live around the lake, only the kingfisher exhibits this behavioral modification, joining humans in the hunt!

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