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1 **Drivers of ecological effectiveness in marine partially protected areas**

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29 **ABSTRACT**

30 The global number of marine protected areas grew exponentially in the last decade to
31 meet international targets. Most of them allow extraction of resources and are called
32 partially protected areas. Their effectiveness remains however unclear due to the high
33 variability of allowed uses. Here, we performed the first global meta-analysis of
34 **partially protected areas** following a new regulation-based classification system, to
35 assess their ecological effectiveness. This classification allows an unambiguous
36 discrimination of **these areas** according to the allowed uses, which are the key feature
37 determining **their** performance. Highly and moderately regulated **areas** provide
38 higher biomass and abundance of commercial fish species, while weakly regulated
39 **ones** do not exhibit differences relative to unprotected areas. Importantly, the
40 effectiveness of moderately regulated **areas** is **sometimes** enhanced by the presence
41 of an adjacent fully protected area. We conclude that limited and well-regulated uses
42 in **partially protected areas** and the presence of an adjacent fully protected area
43 confer ecological benefits, from which socio-economic advantages are derived.

44 **INTRODUCTION**

45 Coastal zones are experiencing increasing human and environmental pressures and
46 they are in need of strategic management decisions (Halpern *et al.* 2015). The
47 implementation of marine protected areas is a commonly used tool for conservation,
48 food security and fisheries management (Gaines *et al.* 2010). The ecological effects of
49 fully protected areas (ie no-take areas) are well studied: they can usually increase
50 abundance and size of species within (eg Claudet *et al.* 2008, Edgar *et al.* 2014) and
51 in some cases outside **these areas** (eg Caselle *et al.* 2015). **They also can support**
52 **the recovery of populations and communities and can preserve habitat structure**
53 (Sandin *et al.* 2014).

54

55 On the downside, the establishment of **fully protected areas** has **resulted in** conflicts
56 between conservation and socio-economic objectives, especially in areas with
57 numerous users and uses (Fox *et al.* 2011). Hence, the implementation of partially
58 protected areas, where some extractive activities may be allowed, **has in some cases**
59 become a preferable option **as it can balance social and ecological objectives and**
60 **may be** easier to implement. Simultaneously, in response to international agreements
61 and commitments, more and more **marine protected areas** are established, most of
62 them being **partially protected areas** of **many different types** (Lubchenco and
63 Grorud-Colvert 2015). Therefore, it is urgent to identify which types of **partial**
64 **protection** can provide socio-economic benefits while still protecting biodiversity.

65

66 **Partially protected areas** are context-dependent, and their regulations vary with the
67 management objectives. In turn, regulations will likely affect their ecological
68 effectiveness. However, only a handful of studies examined the effects of different

69 levels of **partial** protection (eg Di Franco *et al.* 2009; Sciberras *et al.* 2013; Ban *et al.*
70 2014), yet none followed a systematic classification **for these different levels**,
71 leading to variable results which are difficult to generalize. Specifically, Sciberras *et*
72 *al.* (2013) broadly characterized 3 types of **partially protected areas**, based on
73 replies to a questionnaire with somewhat subjective questions (for example whether
74 an activity damages the bottom, target particular species, or impacts other species).
75 **This study** did not account for important activities taking place inside **these areas**,
76 namely aquaculture, bottom exploitation and other non-extractive activities that may
77 impact the marine habitat (eg anchoring).

78

79 Ban *et al.* (2014) reanalysed the dataset used by Sciberras *et al.* (2013) based on the
80 IUCN categories of protected areas (see Table 1 in Ban *et al.* 2014), but the current
81 IUCN categorization is based on management objectives which can have a significant
82 mismatch to regulations, causing strong uncertainty when evaluating the effectiveness
83 of **marine protected areas** (Horta e Costa *et al.* 2016). In fact, when correlating
84 IUCN categories with the expected impacts of activities, there is a high variability
85 among and overlap between categories. Moreover, there is no clear trend between the
86 expected cumulative impacts of activities and the IUCN categories, from more
87 restricted (Ia) to less restricted (V or VI) categories (Horta e Costa *et al.* 2016).

88

89 A recently published regulation-based classification system for **marine protected**
90 **areas** (Horta e Costa *et al.* 2016) presents a new way to classify both **marine**
91 **protected areas** and each **type of zones** within them, according to allowed
92 commercial and recreational uses (WebFigure 1). **Partially protected areas** are
93 therefore classified based on the cumulative impacts of activities.

94

95 Understanding the ecological responses of various types of **partial protection** is
96 essential, since most **marine protected areas** are multiple-use and the ecological
97 effects each **partially protected area** provides are likely linked to different
98 regulatory regimes (Fox *et al.* 2011).

99

100 We present a novel approach to investigate and infer how varying levels of partial
101 protection lead to varying ecological effects through a global meta-analysis. We also
102 examine how design characteristics that are known to affect the effectiveness of no-
103 take areas, such as age and size (Claudet *et al.* 2008), or that are specific to multiple-
104 use **marine protected areas**, such as the presence of an adjacent fully protected area,
105 may also mediate the effectiveness of **partial protection**.

106

107 **METHODS**

108 Data selection: response variables and covariates

109 We built our database based on studies compiled by Sciberras *et al.* (2013) and Horta
110 e Costa *et al.* (2016), updated with recent peer reviewed literature resulting from a
111 database search following the methods of Sciberras *et al.* (2013). We limited our
112 analyses to studies that reported values for abundance and/or biomass of finfish
113 species targeted by fisheries, as they are directly affected by the protection regimes.

114 **Studies would also need to** compared these ecological variables between **partially**
115 **protected areas** and the surrounding open areas outside, which in this study we will
116 refer to as unprotected areas. We only retained studies that reported ecological
117 responses for a particular **partially protected area** when compared to **unprotected**
118 **areas**, but not cases where biological responses were aggregated for an entire

119 multiple-use **marine protected area** with varied regulations. When studies reported
120 ecological responses for **partially protected areas** with different protection levels
121 within the same **marine protected area**, we included them separately in the database,
122 since they represent different types of **partial protection**. In cases where more than
123 one study investigated the effects of protection, only the most recent one was retained,
124 unless different metrics were used. Although it would have been important to assess
125 effects on the overall biodiversity of these areas, data for non-targeted species were
126 not available across studies to allow a detailed analysis.

127

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

138
$$(1) \bar{X} = \frac{\sum_{j=1}^k n_j \bar{x}_j}{\sum_{j=1}^k n_j} \quad \text{and} \quad (2) \text{sd} = \sqrt{\frac{1}{k^2} \sum_{j=1}^k n_j \text{sd}_j^2}$$

139 where \bar{x} is the mean biomass or abundance for species j ; sd and n_j are the standard
140 deviation and sample sizes (eg number of transects) associated with \bar{x}_j .

141

142 We classified each **partially protected area** based on Horta e Costa *et al.* (2016)
143 where each **area** type allows different activities, resulting in five classes: i) highly

144 regulated, ii) moderately regulated, iii) weakly regulated, iv) very weakly regulated,
145 and v) unregulated (WebFigure 1). Highly regulated **areas** allow a limited number
146 (max 5) of low impact fishing gears (eg lines, octopus trap), whereas weakly
147 regulated **ones** allow higher impacting fishing gear (eg beach seines, bottom trawling,
148 trammel nets).

149

150 Moreover, we recorded the age (years since establishment), size, and the presence or
151 absence of an adjacent **fully protected area** (when side by side with a **partially**
152 **protected area** and part of a multiple-use **marine protected area**). We also scored
153 the capacity to implement regulations using an index for fisheries management
154 effectiveness (Mora *et al.* 2009) at national level, as a proxy for enforcement
155 regarding fishing regulations in **marine protected areas**. Values range from 0 to 1,
156 with 0 representing low capacity and 1 representing high capacity for enforcement.

157

158 The final database resulted in 26 peer-reviewed research articles and 49 case studies
159 worldwide (WebTable 1). Out of the 49 **partially protected areas**, 24 were
160 characterized as highly regulated, 17 as moderately regulated, 7 as weakly regulated
161 and 1 as very weakly regulated. We restricted our analysis to the first three classes.

162

163 Meta- analysis

164 To assess the ecological effectiveness of **partially protected areas** we used a
165 weighted random-effect meta-analysis. The effect size R_i for each **area** i was
166 modelled as a natural logarithm (Ln) response ratio of the mean (\bar{X}_i) abundance or
167 biomass estimates measured inside and outside the **partially protected area**
168 (Osenberg *et al.* 1997; Hedges *et al.* 1999):

169

$$(3) R_i = \text{Ln} \left(\frac{\bar{X}_{\text{PPA}_i}}{\bar{X}_{\text{UPA}_i}} \right)$$

170 where \bar{X}_{PPA} and \bar{X}_{UPA} are the mean abundance or biomass inside and outside the
171 **partially protected area** of the study i . The variance v_i of the effect sizes, the within
172 study variance, was calculated as follows:

173

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

174

175 where \bar{X}_{PPA} and \bar{X}_{UPA} are the mean abundance or biomass inside and outside the
176 **partially protected area** of the study i , sd_{PPA} , sd_{UPA} , are the standard deviations
177 associated with \bar{X}_{PPA} and \bar{X}_{UPA} of study i , and n_{PPA} and n_{UPA} are the sample sizes
178 of study i for the estimation of the mean (e.g. number of transects). As in traditional
179 random-effects meta-analysis, our weights w_i included both the within- and among-
180 study variances as follows:

181

$$(5) w_i = \frac{1}{v_i + v_A}$$

182

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

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

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

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

187

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

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

190

191 We used weighted general linear (mixed-effects) models to examine how different
192 features impact the ecological effectiveness of **partially protected areas**. We first
193 investigated if different types of **areas** show different levels of ecological responses.
194 For a given class category, weighted cumulative effect sizes were computed as:

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

195 where n_c is the number of **partially protected areas** belonging to class c and R_i and
196 w_i are defined as above. The heterogeneity of the model explained by the class (Q_m)
197 was calculated as follows:

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

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

200

201 In addition, we ran models to assess if different features were mediating the response
202 to protection, namely: i) age, ii) size (measured in km^2 and log-transformed in the
203 analyses), iii) the capacity to implement regulations, and iv) the presence/absence of
204 an adjacent **fully protected area**. We ran mixed-effects categorical analyses for
205 categorical variables and did meta-analytic regression through linear mixed-effects
206 models for the continuous variables. In addition, interaction models between classes

207 and each of the features were also tested (WebTable 2). All analyses were conducted
208 with the statistical software environment R (R Development Core Team 2016).

209

210 **RESULTS**

211 Both abundance and biomass of targeted fish species were significantly higher,
212 overall, inside **partially protected areas** compared to open areas: on average 2.4 and
213 2.9 times higher, respectively (Figure 1). **Their** effectiveness was however variable
214 across studies, both when considering abundance ($R_i=0.89$, $Q_i = 961$, $df=35$, $p<0.001$)
215 or biomass ($R_i=1.08$, $Q_i = 2197$, $df=38$, $p<0.001$), with different classes showing
216 different levels of effectiveness (abundance $Q_m=11.35$, $p=0.0034$; biomass
217 $Q_m=6.6636$, $p=0.048$). When compared to unprotected areas, highly regulated
218 **partially protected areas** exhibited 2.9 times higher fish abundance ($R_k=1.1$) and 3
219 times higher biomass ($R_k=1.12$), and moderately regulated **ones** exhibited 2.9 times
220 higher fish abundance ($R_k=1.07$) and 4.2 times higher biomass ($R_k=1.42$). However, in
221 weakly regulated **partially protected areas**, abundance ($R_k=-0.13$) and biomass
222 ($R_k=0.18$) did not differ from the surrounding open areas (Figure 1).

223

224 Ecological effectiveness increased with **partially protected areas'** age, size and the
225 capacity to implement regulations (Figure 3, WebFigure 2, WebTable 2.1). Each year
226 after implementation, abundance and biomass of targeted fish species increased on
227 average by 5.1 and 4.6%, respectively, relative to unprotected areas. For every 10-fold
228 increase in the size of a **partially protected area**, fish abundance and biomass
229 increased by 37 and 46%, respectively. Further, increasing the implementation
230 capacity by 10% resulted in a 4.3 and 6.4-fold increase in, respectively, the abundance
231 and biomass of targeted fish species. The effect of age, size and capacity to implement

232 regulations did vary with classes, yet these interactions were significant only for the
233 abundance of targeted fish species and not for biomass (see WebTable 2.2). The
234 response of target species inside moderately and highly regulated **areas** was
235 positively affected by age, size and the capacity to implement regulations, whereas no
236 significant effect was detected on weakly regulated **ones** (Figure 2, WebFigure 2).

237

238 Interestingly, the presence of a fully protected area adjacent to a **partially protected**
239 **area** played a role in making **partial protection** more ecologically effective
240 (abundance $Q_m=2.05$, $p=0.15$; biomass $Q_m=5.47$, $p=0.082$). Fish abundance and
241 biomass were on average 1.6 and 2.1 times higher, respectively, within **partially**
242 **protected areas** which are adjacent to a **fully protected area** (Figure 3). This effect
243 varied across the three classes (abundance $Q_m=22.07$, $p=0.0005$; biomass $Q_m=12.59$,
244 $p=0.096$), with **some** moderately regulated **areas** showing positive ecological benefits
245 only when adjacent to a **fully protected area** (Figure 3, WebTable 2.2) and weakly
246 regulated **areas** not showing any benefit.

247

248 **DISCUSSION**

249 We provide here the first global assessment of the performance of marine partially
250 protected areas based on the regulation-based classification system of **marine**
251 **protected areas** (Horta e Costa *et al.* 2016). We show that the ecological effectiveness
252 of **partial protection** depends on specific key features: i) their type (classified
253 accordingly to allowed uses, see WebFigure 1), ii) the presence of an adjacent fully
254 protected area that **might in some cases** influence their effectiveness, iii) the capacity
255 to enforce regulations, iv) age and v) size. These results clarified the previously

256 reported mixed responses to protection in partially protected areas (e.g. Lester and
257 Halpern 2008; Di Franco *et al.* 2009; Sciberras *et al.* 2013).

258

259 Our most important finding is that the regulations are the key feature determining
260 ecological effectiveness of **partially protected areas**. Moderately and highly
261 regulated **areas** are effective at harbouring greater abundance and biomass of target
262 fish when compared to unprotected areas, whereas weakly regulated **ones** do not show
263 ecological benefits. Highly and moderately regulated **partially protected areas** allow
264 **a few** extractive uses (maximum of five and ten gears, respectively) that have low (eg
265 lines and traps) or moderate (eg gillnets) impact on the ecosystems. Weakly regulated
266 **areas have** more gears and/or with greater negative environmental impacts (eg
267 trawling) (Horta e Costa *et al.* 2016). Fernández-Chacón *et al.* (2015) demonstrated
268 empirically that by excluding a number of fishing gears inside **partially protected**
269 **areas**, fish species targeted by those gears benefit from protection when compared to
270 unprotected areas.

271

272 Additionally, we show that combining a fully protected area with moderately regulated
273 **ones** confers positive benefits (Figure 3), with the full range of response always above
274 1 (non-significant differences between **partial protection** and **open areas** are shown
275 when response overlaps 1). This class is commonly used and therefore placing these
276 areas adjacent to a **fully protected area** is an important option to consider, since it **can**
277 increase **their** ecological benefits. Highly and weakly regulated **partially protected**
278 **areas** may be less sensitive to a presence of an adjacent **fully protected area** for
279 different reasons. For **highly regulated areas this is** likely due to the limited amount
280 of extractive activities permitted within them, which already confers high conservation

281 benefits. **Weakly regulated ones may be less influenced by an adjacent fully**
282 **protected area** due to the large number of activities with significant impacts occurring
283 within them. **In moderately regulated areas, regulations alone may be insufficient**
284 **to significantly enhance populations of targeted fish species. Further, spill-over**
285 **effects from an adjacent no-take area may increase their ecological effectiveness**
286 **(eg Hackradt *et al.* 2014). Spill-over effects from highly regulated partially**
287 **protected areas may benefit adjacent areas with weaker regulations, yet more**
288 **data are needed to test this. Future research should assess how designing marine**
289 **protected areas with different combinations of levels of protection affects**
290 **ecological responses.**

291

292 We also show that the effectiveness of protection is positively correlated with age and
293 size, demonstrating that these variables matter not only for no-take areas but also for
294 partial protection (Claudet *et al.* 2008; Edgar *et al.* 2014). Moreover, the higher the
295 capacity to implement regulations the greater the ecological effectiveness, confirming
296 that investment in control and surveillance mechanisms should be a high priority when
297 establishing and managing **marine protected areas** (Guidetti *et al.* 2008; Mora *et al.*
298 2009; Edgar *et al.* 2014). The positive ecological effects associated with larger, older
299 and better-enforced **partially protected areas decrease, however**, with the number of
300 extractive activities allowed.

301

302 Our findings suggest that well-regulated, well-enforced, large and old **partially**
303 **protected areas**, can provide high ecological benefits, which are enhanced **in some**
304 **cases** by the presence of an adjacent **fully protected area** (Figure 4). Enforcement,
305 age and size are key features for success (Edgar *et al.* 2014). Several studies have

306 compared the effects of **fully and partial protection** to unprotected areas, showing
307 that, overall, full protection provides stronger ecological benefits than partial
308 protection (eg Lester and Halpern 2008; Sciberras *et al.* 2013; Giakoumi *et al.* 2017).
309 Here, we show that **marine protected areas** do not have to be strictly no-take (Edgar
310 et al 2014) to provide benefits. Highly regulated **partially protected areas** can be
311 successful and sometimes an acceptable option in complex socio-ecological systems
312 where **full protection is** harder to implement, or as a complement to **full protection** in
313 multiple-use **marine protected areas**. Moderately regulated **areas** can be combined
314 with an adjacent **fully protected area** to increase ecological benefits. However, the
315 overall ecological benefits of highly regulated **partially protected areas**, when
316 compared to **full protection**, are much lower. We show that in those **partially**
317 **protected areas** there are 300% more fish biomass and density inside than in open
318 areas. Sala and Giakoumi (in press) report 670% higher fish biomass inside **fully**
319 **protected areas** when compared to unprotected areas. **Sciberras *et al.* (2013) report**
320 **92% higher biomass in no-take areas than in partially protected areas and Gill *et***
321 ***al.* (2017) a twofold difference between no-take areas and partial protection.**

322

323 Our case studies **are global**, with most fish biomass and density data being measured
324 on relatively shallow (less than 30m) reefs. Previous studies of Mora *et al.* (2011) and
325 Cinner *et al.* (2013) have shown that social factors can influence the biomass of reef
326 fishes in coastal areas. Factors such as coastal development and land use, human
327 population density (Mora *et al.* 2011), distance to market and economic development
328 (Cinner *et al.* 2013) can have a strong explanatory role in the structure of reef fish
329 biomass globally. Future studies could incorporate these correlates when enough
330 information is available for the different classes of **partially protected areas**.

331

332 Most of the studies included in this analysis were for **partial protection** classes where
333 extraction is limited (highly and moderately regulated **areas**) and, therefore, stronger
334 responses are to be expected, whereas only a handful of studies reported results for
335 **areas with** lower levels of protection (weakly and very weakly regulated **areas**).

336 Publication bias (ie scientists tend to sample where it is likely to record an effect and
337 journals tend to favour the publication of positive results) can explain why we were
338 only able to find detailed information for 47 case studies while there are more than
339 11,000 MPAs listed globally (MPA Atlas: www.mpatlas.org). **Therefore, it is**
340 **important to note that it is very likely that we have captured the most effective**
341 **partially protected areas, potentially leading to an overestimation of the average**
342 **effects.**

343

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

352

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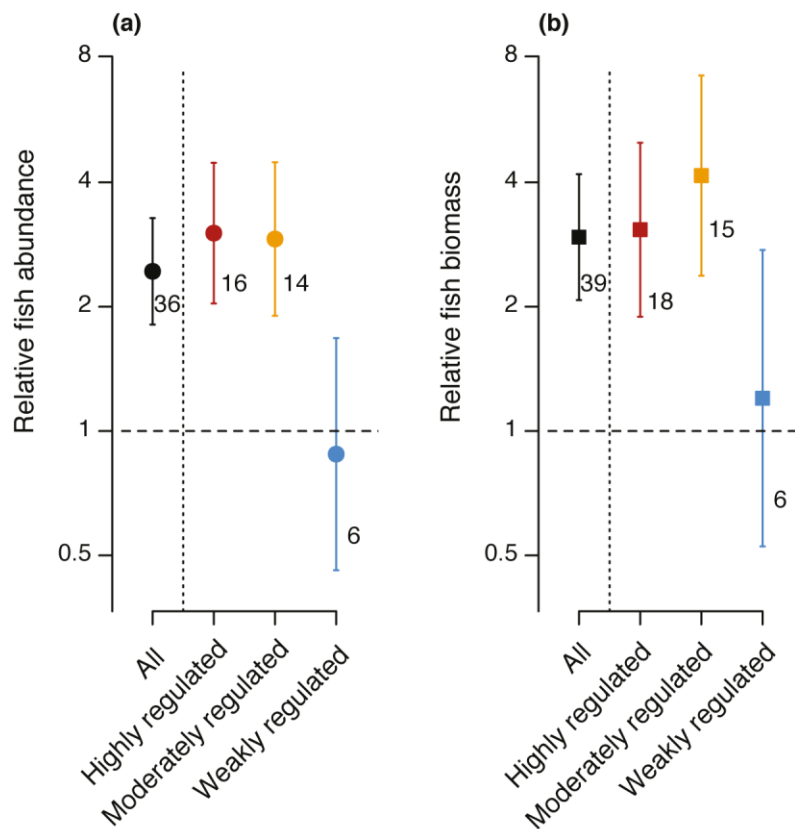
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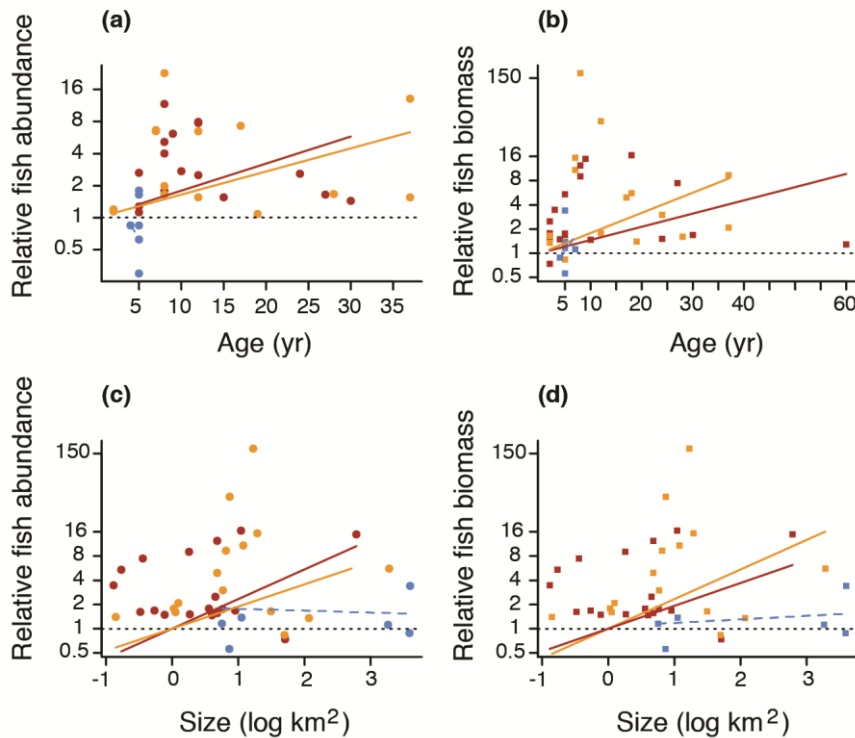
449 **FIGURE CAPTIONS**



450

451 **Figure 1:** Ecological effectiveness of partially protected areas (PPAs) for abundance
 452 (a) and biomass (b) of targeted fish species for all PPAs combined and for PPAs
 453 grouped by classes (sensu Horta e Costa *et al.* 2016). The horizontal dotted line at 1
 454 represents equal fish abundance or biomass inside and outside the PPA. Values higher
 455 than 1 mean more fish (or biomass) inside the PPA and values below 1 mean fewer
 456 fish (or biomass) inside the PPA. The bars represent 95% confidence intervals. The
 457 sample size of each group is indicated.

458



Class of the partially protected area

- Highly regulated
- Moderately regulated
- Weakly regulated

459

460 **Figure 2:** Ecological effectiveness of the classes of partially protected areas (PPAs) as

461 mediated by PPA age (a-b) and size (c-d) for abundance (top panel) and biomass

462 (bottom panel) of target fish species. The horizontal dotted line at 1 represents equal

463 fish abundance or biomass inside and outside the PPA. Values higher than 1 mean

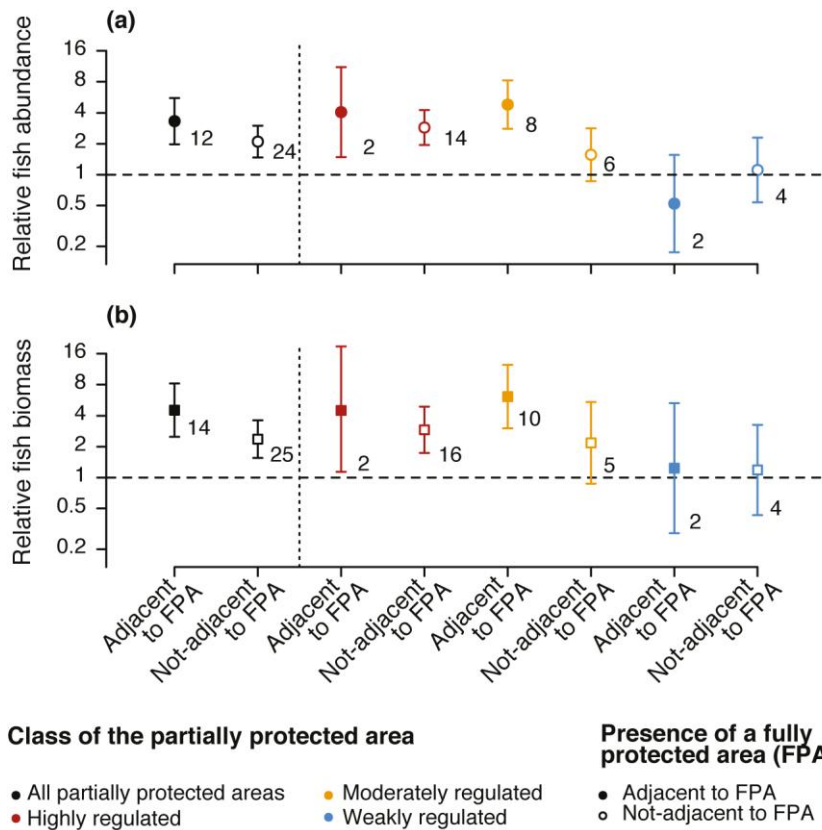
464 more fish (or biomass) inside the PPA and values below 1 mean fewer fish (or

465 biomass) inside the PPA. The fitted lines are regressions of each PPA class and the

466 corresponding feature (solid line: significant regression, $p < 0.05$; dashed line: non-

467 significant regression, $p > 0.05$).

468



469

470 **Figure 3:** Ecological effectiveness of classes of partially protected areas (PPAs) for
 471 the abundance (a) and biomass (b) of targeted fish species as affected by the presence
 472 of an adjacent fully protected area (open symbols). The horizontal dotted line at 1
 473 represents equal fish abundance inside and outside of the PPA. Values higher than 1
 474 mean more fish (or biomass) inside the PPA and values below 1 mean fewer fish (or
 475 biomass) inside the PPA. The bars represent 95% confidence intervals. The sample
 476 size of each group is indicated.

477

478