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Marine protected areas Overall Success Evaluation (MOSE): A novel integrated framework for assessing management performance and social-ecological benefits of MPAs

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Abstract

Characterized by interlinked social, economic, and ecological dynamics, Marine Protected Areas (MPAs) are a management tool for achieving sustainability goals in social-ecological systems. The recent increase in their establishment worldwide, fostered by international policies, highlights the need for comprehensive and integrated assessment frameworks able to address the evaluation of their social-ecological effectiveness and management performance, which is of fundamental importance for their adaptive management and decision making processes. Although several indicators and methodologies exist to assess MPAs ecological or social performances, no comprehensive assessment framework currently captures their broad range of objectives, encompassing the ecological, socio-cultural, and economic spheres. In this study, we present a novel quantitative framework (named MPAs Overall Success Evaluation – MOSE) able to assess the overall effectiveness and management performance of MPAs under the perspective of social-ecological systems. The multicriteria framework includes indicators linked to nature conservation, socio-cultural, socio-economic, and management objectives, integrating the multidisciplinary knowledge on MPAs in a single but comprehensive approach. The proposed framework was applied to the case study of Cerbère-Banyuls Natural Marine Reserve (France), the first MPA included in the IUCN Green List. Results showed that a high level of management effort is applied to the investigated MPA, generating several social-ecological benefits. This study showed the applicability of the MOSE framework and its potential usefulness as a tool to inform managers and decision-makers in charge for developing adaptive management strategies.

Keywords: marine protected areas; management performance; reserve effectiveness; multicriteria assessment framework; social-ecological systems.

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1. Introduction

In the last decades, particular emphasis has been placed upon the sustainable use of the global ocean (Claudet et al., 2020; IOC-UNESCO, 2017; UN, 2015). Close to 40 per cent of the world's population lives in coastal areas and relies on marine and coastal ecosystems for vital services such as food security, coastal protection, and employment in the fishing industry and tourist sector (Barbier, 2017). Nonetheless, ocean benefits to people go far beyond the coastal zone, involving the delivery of ecosystem services at the global scale such as carbon sequestration and climate regulation (Herr and Landis, 2016; Laffoley and Baxter, 2016; Nellemann et al., 2009). Direct and indirect human pressures like overfishing, pollution, urbanization, and climate change are synergically impacting marine natural capital jeopardizing the provisioning of these essential ecosystem services (Buonocore et al., 2018; Pauna et al., 2018; Worm et al., 2006). Considering the vital role of the oceans for human survival and well-being, effective policies and actions aiming at the sustainable use of marine natural capital are imperative.

The 2030 Agenda for Sustainable Development of the United Nations included the Sustainable Development Goal (SDG) 14 “Life below water” to face the challenge of the sustainable use of the ocean (UN, 2015). This Goal aims to “conserve and sustainably use the oceans, seas and marine resources for sustainable development” and shares with the Aichi Biodiversity Target 11 the objective of conserving at least the 10 per cent of coastal and marine areas by 2020 (UN, 2015; CBD, 2011). In this context, Marine Protected Areas (MPAs) are increasingly being established to protect and conserve marine natural capital, ecosystem services, and cultural values from the variety of anthropogenic threats on coastal and offshore marine ecosystems (Claudet, 2011). Characterized by interlinked social, economic, and ecological dynamics (Leenhardt et al., 2015a,b), MPAs represent complex conservation and management tools to support the achievement of sustainability goals in social-ecological systems (SESSs) (López-Angarita et al., 2014; Pollnac et al., 2010; Zupan et al., 2018a). Marine sustainability studies have been showing an increasing interest towards the SESSs approach (e.g., Adger et al., 2005; Berkes, 2011; Leenhardt et al., 2015b; Winter et al., 2018) due to its suitability to integrate natural and social sciences while addressing management issues involving ecosystems, human economy, and governance (Charles, 2012). The growing research on MPAs as sustainability tools has increasingly expanded from the sole ecological domain to also include social, health, cultural, and governance spheres (Bennet et al., 2017; Gill et al., 2017; Hogg et al., 2013; Mascia, 2004). MPAs are indeed expected to deliver social and economic benefits in addition to conserving biodiversity (Leenhardt et al., 2015a, Vihervaara et al., 2019; UNEP-WCMC, IUCN and NGS, 2018).

74 The many ecosystem services provided by MPAs contribute to human well-being in several ways
75 (Ban et al., 2019). MPAs can potentially reduce poverty by creating alternative livelihoods and new
76 jobs, especially in the tourism sector, and by increasing fish catches as a result of fishing spillover
77 from no-take zones (Beukering et al., 2014; Russ et al., 2004). By recovering fish stocks and
78 promoting more productive and sustainable fisheries, MPAs also improve food security of local
79 communities that rely on such food sources (Mascia et al., 2010). In addition, when good
80 governance is in place, MPAs foster equity through community participation to decision-making
81 processes, empowering usually marginalized categories such as women and therefore promoting
82 gender equality (Beukering et al., 2014; Jones et al., 2019). Moreover, by improving ecosystems
83 health and resilience, MPAs play an important part in promoting climate change adaptation and
84 mitigation (Otero et al., 2013; Simard et al., 2016). Finally, MPAs are also tools for scientific
85 research and education. Indeed, they can serve as laboratories to enhance the understanding of the
86 marine environment (Galzin et al., 2004) and can help raising the awareness of the public on marine
87 sustainability issues (Angulo-Valdés and Hatcher, 2010; Brander et al., 2015). It is therefore evident
88 that the well-being of coastal communities is influenced by the overall success of MPAs in the
89 management of marine ecosystems and their resources.

90 The contribution of MPAs to the sustainability of marine SESs follows a hierarchical pattern, in
91 which socio-economic goals can be achieved only after the biophysical ones are met. Considering
92 the abovementioned potential benefits and applying the classification of the United Nations
93 Sustainable Development Goals (SDGs) (UN, 2015), successful MPAs contribute to human well-
94 being supporting not only SDG14 “Life Below Water”, but also SDGs 1 “No Poverty”, 2 “Zero
95 Hunger”, 3 “Good Health and Well-Being”, 4 “Quality Education”, 5 “Gender Equality”, 8 “Decent
96 Work and Economic Growth”, 10 “Reduced Inequalities”, 12 “Responsible Consumption and
97 Production”, and 13 “Climate Action” (Fig.1).

98

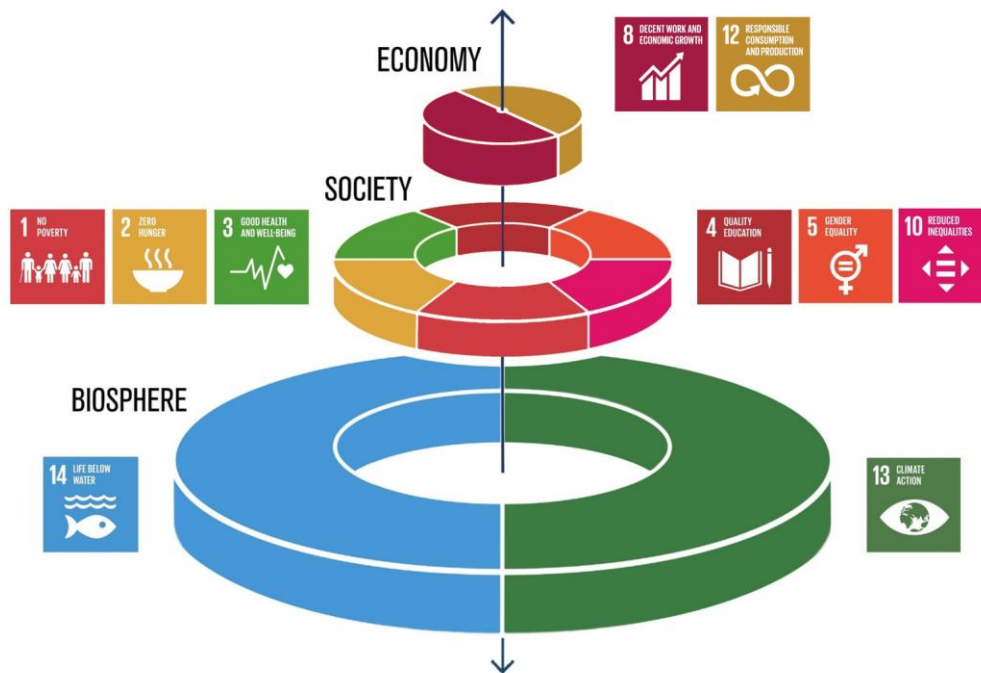


Figure 1. Modified version of the Sustainable Development Goals (SDGs) cake model showing the SDGs supported by MPAs: 1 “No Poverty”, 2 “Zero Hunger”, 3 “Good Health and Well-Being”, 4 “Quality Education”, 5 “Gender Equality”, 8 “Decent Work and Economic Growth”, 10 “Reduced Inequalities”, 12 “Responsible Consumption and Production”, 13 “Climate Action”, 14 “Life Below Water”.

Of course, the implementation of MPAs entails costs besides benefits. Recent findings show that a global expansion of MPAs can generate economic benefits almost three greater than costs (Brander et al., 2020). Nonetheless, the establishment of MPAs should be complemented by cost-benefit analysis to understand the social, economic and environmental implications involved.

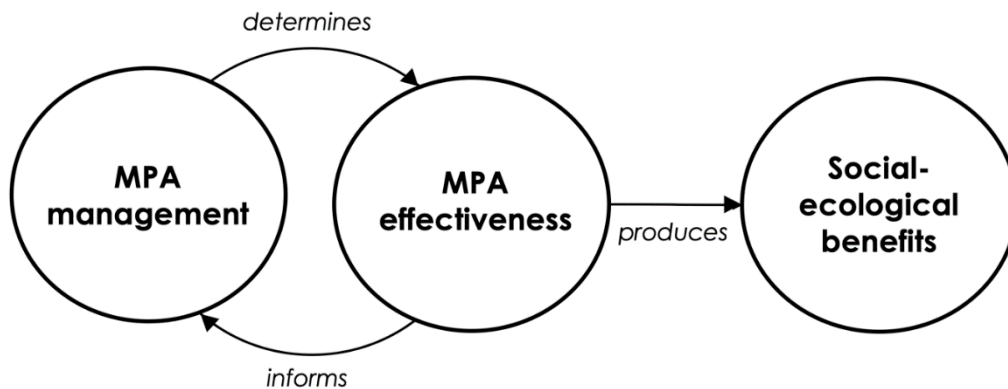
To promote the achievement of MPA sustainability goals and the delivery of the expected benefits to ecosystems and human well-being, the implementation of holistic and integrated social-ecological assessments is much needed (Agardy et al., 2016; Ojeda-Martinez et al., 2009; Rasheed, 2020). Despite the considerable growth of the science of MPAs in the last years, the challenge of how assessing and promoting MPA success still persists (Bennett and Dearden, 2014; Giakoumi et al., 2018). To comprehensively evaluate the effectiveness of MPAs, assessment frameworks need to integrate multiple variables and explore new frontiers of study such as environmental accounting studies (Buonocore et al., 2019; Brander et al., 2020; Franzese et al., 2015, 2017, 2019; Picone et al., 2017; Roncin et al., 2008; Unsworth et al., 2010) and organization science (Scianna et al., 2015, 2018, 2019). Such frameworks require the identification of multidisciplinary success criteria and related measurable indicators suited to the social-ecological context of MPAs (Claudet, 2018; Claudet and Guidetti, 2010). Several indicators and methodologies can be found in the literature to assess their ecological, socio-economic, and management effectiveness (e.g., Bennett and Dearden,

2014; Gallacher et al., 2016; Pelletier et al., 2005; Pomeroy et al., 2005; Rodríguez-Rodríguez et al. 2016). Nonetheless, too often MPAs are only assessed along one dimension of sustainability while the others are neglected, as it has been historically the case of the social domain (Bennet et al., 2017; Claudet and Guidetti, 2010; Pelletier, 2011). This can lead to a false sense of success, for instance when MPAs are an ecological success but a social failure (Christie, 2004). To holistically assess MPA success, biophysical, socio-economic, and governance indicators need to be coherently integrated (Gallacher et al., 2016). In addition to these domains of investigation, fundamental is the evaluation of MPAs management effectiveness, which remains one of the main issues in MPA science (Scianna et al., 2019). Existing frameworks usually focus on just one or few of these domains and fields, providing partial information on MPA outcomes (Tab. 1).

Table 1. Examples of available MPA assessment frameworks. For each one, domain of assessment, authors, and year of release are reported.

Framework name or subject	Domain of assessment	Authors	Year
Rapid Assessment and Prioritization of Protected Area Management (RAPAM)	Management	WWF	2003
MPA Management Effectiveness	Management	Pomeroy	2005
Management Effectiveness Tracking Tool (METT)	Management	WWF	2007
DPSIR framework applied to MPAs	Management	Ojeda-Martínez et al.	2009
MPA Management Effectiveness Assessment Tool (MEAT)	Management	MSN	2010
Integrated MPA Socio-Economic Assessment (IMPASEA)	Socio-economic	Rodríguez-Rodríguez et al.	2015
Protected Area Management Effectiveness (PAME)	Management	Hockings et al.	2015
Marine Protected Area Protection Assessment Framework (MaPAF)	Management	Rodríguez-Rodríguez et al.	2016
Socio-Economic Assessment Tool (SEAT)	Socio-economic	Rosales	2018
Management Performance Index (MPI)	Management	Scianna et al.	2018
IUCN Global Standard for MPAs	Governance; management; socio-economic; biophysical	IUCN	2018
Sustainability Evaluation of Marine Protected Areas Index (SEMPAI)	Biophysical; socio-economic; governance	Avelino et al.	2019

136 Identifying and coherently integrating biophysical, socio-economic, governance, and management
 137 indicators in a single assessment framework is pivotal to support MPA success. By providing
 138 critical information on the main gaps to achieve MPA goals, effectiveness assessments can feed
 139 MPA management and decision-making processes supporting the implementation of *ad hoc*
 140 measures to improve the delivery of the expected social-ecological benefits. When possible, the
 141 information should be quantitative and science-based (Pelletier, 2011). The periodic repetition of
 142 the assessment provides fundamental insights on the system's response to the measures
 143 implemented, feeding back the management process for further decision-making. The negative
 144 feedback loop of the iterated steps “assessment-information-management-countermeasure” acts
 145 then as a single process, forming an adaptive management cycle (Fig. 2).



146
 147 **Figure 2.** Flow diagram showing the relationships among MPA management, effectiveness, and relative social-ecological benefits.

148
 149 In this study, we present a novel quantitative framework (named MPAs Overall Success Evaluation
 150 – MOSE) aimed at assessing the social-ecological effectiveness and management performance of
 151 MPAs under the perspective of SESs. This multicriteria assessment framework includes indicators
 152 linked to nature conservation, socio-economic, governance and management objectives, responding
 153 to the call for a multidisciplinary approach to the study of MPAs. In addition, to verify its
 154 applicability and potential usefulness, the MOSE framework is applied to the case study of Cerbère-
 155 Banyuls Natural Marine Reserve (France), the first MPA included in the IUCN Green List of
 156 Protected and Conserved Areas.

157 158 **2. Materials and methods**

159 **2.1. The MPAs Overall Success Evaluation (MOSE) framework: structure and indicators**

160
 161 The development of the MOSE framework has been inspired by the Ocean Health Index (OHI)
 162 (Halpern et al., 2012). Differently from the OHI, the MOSE framework is articulated in two main

assessment domains and related indices in turn based on two different sets of indicators and sub-indicators, namely the Reserve Effectiveness Assessment (REA) and the Management Performance Assessment (MaPA). With “reserve effectiveness” we refer to the plurality of social-ecological benefits achieved by MPAs. Instead, according to Horigue et al. (2014) and Scianna et al. (2018), with “management performance” we refer to the “level of effort exerted to enhance and sustain the management of MPAs”.

2.1.1 Reserve Effectiveness Assessment (REA)

A number of ecological and social-economic benefits are expected from the establishment of MPAs (Ban et al., 2019; Pelletier et al., 2005). Through conservation, fishing, economic, and cultural indicators, the Reserve Effectiveness Assessment (REA) index addresses the evaluation of the social-ecological reserve effect, which is expected to occur when MPAs are successfully managed. The selected indicators (and sub-indicators) are: 1) *Biodiversity (Habitats and Species)*, 2) *Fishing (Industrial fishing, Artisanal fishing, and Recreational fishing)*, 3) *Local economy (Livelihoods, Tourism and recreation, and Natural products)*, and 4) *Cultural identity (Charismatic species and Traditional activities)* (Tab. 2). The score for each indicator is calculated as the ratio between the value of the measured variable inside the MPA and the value of the same variable in the outside control area. In the case of multi-use (or multiple-use) MPAs (i.e., MPAs where multiple uses are regulated with different restrictions according to the protection zone), REA indicators are evaluated for each protection zone, with the exception of the sub-indicators *Livelihoods* and *Tourism and recreation* that are calculated at the MPA scale. *Biodiversity*, *Fishing*, and *Cultural identity* indicators measure variables that are indeed expected to show differences in the scores across the different zones. Variables such as the biomass of fishes or the catch per unit effort (CPUE) of artisanal fishing are predictably related to the degree of protection (i.e., activities allowed), and therefore the relative indicators are supposed to show different outcomes. On the contrary, the *Livelihoods* and the *Tourism and recreation* sub-indicators target variables that respond to the overall performance of the MPA, and the evaluation of their benefits on local communities could not be unambiguously attributed to single zones where human activities occur. Finally, to calculate the REA score of the MPA, the scores of the protection zones are averaged weighting them by the area occupied by each zone in the MPA.

2.1.2 Management Performance Assessment (MaPA)

197 Besides the Reserve Effectiveness Assessment (REA), to evaluate MPAs not only as SESs but also
 198 as management tools, the MOSE framework includes the Management Performance Assessment
 199 (MaPA) index. The MaPA index targets management objectives that are acknowledged to be
 200 fundamental to the success of MPAs, encompassing financial, social acceptance, information,
 201 organization, and communication aspects. The achievement of such objectives is assessed through
 202 the following indicators: 1) *Level of surveillance*, 2) *Information and awareness of regulations*, 3)
 203 *Stakeholders engagement*, 4) *Monitoring and reporting*, 5) *Financial support*, 6) *Professionalism*
 204 *and competences*, 7) *Personnel stability*, 8) *Cultural heritage*, and 9) *Social media communication*
 205 (Tab. 2). Differently from the approach adopted in the REA, which compares inside vs outside
 206 values, the MaPA index uses a scorecard approach to calculate the scores of its indicators.

208 **Table 2.** Indicators of Reserve Effectiveness Assessment (REA) and Management Performance Assessment (MaPA)
 209 composing the MOSE framework.

Index	Indicator (and sub-indicators)	Description
REA	Biodiversity	Habitats (HAB) Ecological status of the main habitats Species (SPP) Biomass of fish species
	Fishing	Industrial fishing (IF) Catch Per Unit Effort (CPUE) of industrial fishing Artisanal fishing (AF) CPUE of artisanal fishing Recreational fishing (RF) CPUE of recreational fishing
	Local economy	Livelihoods (LIV) Number of allowed diving clubs Tourism and recreation (TR) Number of tourists Natural products (NP) Harvest Per Unit Effort (HPUE) of non-food resources
	Cultural identity	Charismatic species (CSPP) Biomass of charismatic species Traditional activities (TA) Number of traditional activities practitioners
	Level of surveillance (LS)	Effort and diversity of surveillance activities
	Information and awareness of regulations (IAR)	Communication of regulations to the public
	Stakeholder engagement (SE)	Degree of involvement of stakeholders
	Monitoring and reporting (MR)	Monitoring campaigns and reporting activity on main ecological features and threats
MaPA	Financial support (FS)	Sufficiency and diversity of financial support
	Professionalism and competences (PC)	Coverage of the main fields of expertise needed for management
	Personnel stability (PS)	Permanent staff working full time
	Cultural heritage (CH)	Conservation and valorisation of cultural heritage
	Social media communication (SMC)	Engagement rate of social media

211 A detailed description of the abovementioned indicators, including the rationale behind their choice
212 and the full calculation method, is provided in section 2.4.

213 214 **2.2. Score calculation**

215
216 The overall scores of REA and MaPA are calculated as the average of the scores of their indicators:

$$\text{REA, MaPA} = \sum_{i=1}^N \frac{I_i}{N}$$

217 where I_i is the score of the i -th indicator and N is the number of indicators evaluated (Table 2).
218 Each indicator (I_i) is valued on a dimensionless scale from 0 to 100. When indicators score more
219 than 100, the value of 100 is assigned.

220 221 **2.3. Complementary indicators**

222
223 The two proposed indices REA and MaPA included in the MOSE framework synthetically integrate
224 information pertaining to different domains. To better interpret their results, two complementary
225 indicators are proposed, the *Protection level* and the *Degree of reliability*.

226 The *Protection level (PL)* indicator supports the interpretation of REA results. Multi-use MPAs
227 have different regulations in their protection zones and therefore differences in the social-ecological
228 outcomes are to be expected. Based on regulations of uses and relative potential impacts on
229 biodiversity, Horta e Costa et al. (2016) developed a classification system that unambiguously
230 scores MPAs as well as each MPA zone individually. The protection level is expressed in a range
231 from 1 (i.e., highest protection) to 8 (i.e., lowest protection) classified into 5 protection levels:
232 *unprotected, poorly protected, moderately protected, highly protected, and fully protected*. Such
233 classification method has been applied to a number of MPAs worldwide (Horta e Costa et al.,
234 2016), then used to carry a global meta-analysis of the ecological effectiveness of partially
235 protected areas (PPAs) of MPAs (Zupan et al., 2018b), and also suggested as a tool to support the
236 assessment of protection levels in the context of international marine conservation targets (Claudet,
237 2019; Devillers et al., 2019).

238 The *Degree of reliability (DR)* indicator is included in the MOSE framework to allow for
239 applications even when data are partially lacking and not all indicators can be assessed. It is
240 unlikely that MPA management bodies collect all the ecological, organizational, and management
241 data needed to perform integrated analyses (Guidetti et al., 2014). Therefore, a reliability indicator
242 of such assessments would provide useful information. The DR indicator is calculated for both the
243 REA and MaPA indices as the number of indicators assessed over the total of the assessable ones.

244 This information expresses the consistency of the overall indices scores, suggesting the
245 comprehensiveness level of the assessments.

246

247 **2.4. Rationale behind indicators and calculation methods**

248

249 **2.4.1. Biodiversity**

250 Historically, MPAs have been established with the main goal of conserving marine biodiversity,
251 anticipating positive ecological effects on species and habitats. Assessing and keeping track of the
252 extent to which biodiversity goals are achieved are crucial steps to inform the adaptive management
253 process. The *Biodiversity* indicator is composed by two sub-indicators: Habitats and Species.

254

255 *Sub-indicator: Habitats (HAB)*

256 The establishment of MPAs is expected to have positive impacts on the status of marine and coastal
257 habitats (Ban et al., 2019; Pelletier et al., 2005). As a general rule, habitats in good status are more
258 likely to harbor higher biodiversity than disturbed habitats, maintain their ecological functions, and
259 support the delivery of ecosystem services (Cardinale et al., 2012; Vihervaara et al. 2019). Habitats
260 are valuable not only from an ecological perspective, but also for recreational, aesthetic, sanitary,
261 and existence reasons.

262 Fostered by European policies such as the Water Framework Directive (WFD - 2000/60/EC) and
263 the Marine Strategy Framework Directive (MSFD - 2008/56/EC), the interest in the development of
264 indexes of habitat quality has been increasing in the last years. Such indexes are built to represent
265 an ecological quality target for selected habitats and are often used as proxy of environmental
266 status, thus supporting monitoring and managing coastal environments (Borja et al., 2009). Biotic
267 indexes can integrate information at species or community levels, assessing parameters such as
268 abundance and diversity of sensitive and tolerant taxa. Most assessments classify habitat quality in
269 five Ecological Status Classes (ESCs): High, Good, Moderate, Poor, and Bad.

270 The *Habitats (HAB)* sub-indicator assesses the reserve effect on MPA habitats by comparing the
271 ESCs evaluated in the different protection zones versus the ESCs outside the MPA according to the
272 following formula:

$$\text{Hab} = \frac{1}{N} \sum_{j=1}^N \left(\frac{C_{ji}}{C_{jo}} - 1 \right) \times 100$$

273 where, C_{ji} and C_{jo} are the values associated to the ESC of the j -th habitat, inside (i) the investigated
274 protection zones and outside (o) the MPA, and N is the number of habitats assessed.

275

276 *Sub-Indicator: Species (SPP)*

277 When full protection measures are actually enforced, an increase in abundance, size, and biomass of
278 previously fished assemblages is expected to occur (Guidetti, 2002; Claudet et al., 2008). The
279 increase in size and density of fishes at upper trophic levels, mainly targeted by fishing activities,
280 leads to cascading effects bringing community-wide ecological benefits (Claudet et al., 2011;
281 Filbee-Dexter, 2014; Guidetti, 2006; Prato et al., 2013). In the case of partially protected zones
282 where fishing occurs with restrictions, such benefits are significantly lower or even absent, showing
283 more similarities to open access fished areas (Di Franco et al., 2009). For the *Species (SPP)* sub-
284 indicator, the biomass of fish assemblages in the protection zones versus outside the MPA is
285 compared, as it is commonly considered the most responsive indicator of the effect of protection on
286 fish assemblages (Guidetti et al., 2014). Biomass is calculated based on abundance and size data of
287 fish assemblages collected by means of visual census sampling techniques (Harmelin-Vivien et al.,
288 1985).

289 The sub-indicator is then calculated as follows:

$$SPP = \frac{1}{N} \sum_{j=1}^N \left(\frac{B_i}{B_o} - 1 \right) \times 100$$

290 where, B_i and B_o are the average biomasses per unit area of the j -th species, inside (i) the evaluated
291 protection zone and outside (o) the MPA, and N is the total number of species assessed.

292

293 **2.4.2. Fishing**

294 *Sub-indicators: Industrial fishing (IF), artisanal fishing (AF), and recreational fishing (RF)*

295 Fisheries are an important source of food, livelihoods and incomes for hundreds of millions of
296 people globally (FAO, 2016). Recent estimations on the world's fish stocks state that about 30% of
297 them are fished at a biologically unsustainable rate (i.e., overfished) and almost 60% are fully
298 exploited (i.e., fished close to their maximum sustainable yield) (FAO, 2016). Consequences of
299 overfishing are vast, including the ecological, social, and economic spheres. The need for moving
300 towards a sustainable use of fish resources has led to the Ecosystem Approach to Fisheries (EAF),
301 which identifies principles and guidelines for the sustainability of fisheries management, explicitly
302 linking human and ecosystem health (Garcia et al., 2003 Coll et al. 2013). This approach recognizes
303 the important role that MPAs have in the sustainable management of the linked fisheries-marine
304 resources system through the restrictions of fishing activities inside their boundaries. MPAs
305 regulations aim at protecting and conserving marine biodiversity and, at the same time, enhance
306 local fisheries by promoting a sustainable use of fish resources (Di Franco et al., 2016).
307 Theoretically, the reserve effect on fish assemblages (i.e., increase in size, abundance, and biomass)

should lead to spillover phenomena from no-take to buffer zones when the carrying capacity of fish populations is reached. Similarly to the assessment of the reserve effect on fished species, the benefits of MPAs on fisheries could be evaluated by comparing values of catch per unit efforts (CPUEs) in fished protected zones versus outside unprotected areas. According to this approach, the reserve effect on industrial, artisanal, and recreational fishing activities is assessed through the following formula:

$$IF, AF, RF = \frac{1}{N} \sum_{j=1}^N \left(\frac{CPUE_i}{CPUE_o} - 1 \right) \times 100$$

where $CPUE_i$ and $CPUE_o$ are the catches per unit effort of the j -th fishing techniques inside (i) and outside (o) the MPA, and N is the total number of fishing techniques assessed.

2.4.3. Local Economy

Extractive activities (i.e., fishing and harvest of non-food resources) and tourism are sectors driving the local economy of coastal communities, representing important sources of economic growth and jobs (European Commission, 2018; FAO, 2016). Through the regulations of human activities, MPAs influence local coastal economies that rely on ecosystem services generated by marine and coastal environments. Although less investigated in the literature compared to the ecological ones, impacts of the establishment of MPAs on the local economy are well-known and deserving of as much attention, especially under a SES perspective (Ojea et al., 2017). Economic benefits result from increasing tourist visits leading to higher revenues, increased jobs, and additional livelihood opportunities (European Commission, 2018). The *Local economy* indicator is composed of three sub-indicators: *Livelihoods*, *Tourism and recreation*, and *Natural products*.

Sub-indicator: Livelihoods (LIV)

The establishment of MPAs is generally linked to increases in jobs and/or incomes in commercial and tourism sectors, driven by those activities that benefit from the positive ecological impacts of protection on marine ecosystems, e.g. commercial fishing and recreational scuba diving (Alban et al. 2011; Pascual et al., 2016; Roncin et al., 2008). The most direct way to approach an evaluation of the economic impacts of MPAs on local coastal communities would be to collect and analyze data on net income of their activities. Nonetheless, this process could be challenging as entrepreneurs of these activities may be reluctant to share such sensitive data. The employment rate in the diving sector is suggested as one of the potential measures of the impacts of MPAs on local economy, as a consequence of the increase of diver visits (Ojea et al., 2017). For the *Livelihoods* (*LIV*) sub-indicator, we used the number of diving clubs in a 10 km² radius as a proxy of the

employment rate in the sector. This buffer area was calculated considering dive boats speed limits and usual length of dives. To assess the score, the number of diving clubs is divided by the considered coast length and then compared to the outside value, according to the formula:

$$LIV = \frac{d_i}{d_o} \times 100$$

where d_i is the number of diving clubs per unit of coast length in the buffer area or authorized by the MPA (if MPA regulations foreseen a maximum number of authorizations) and d_o is the number of diving clubs per unit of coast length outside the MPA. Except from the number of authorized diving clubs, data to calculate the indicator are not supposed to be in possession of the MPA and are therefore collected independently.

Sub-indicator: Tourism and recreation (TR)

Nature-based tourism and recreational activities constitute the main attractions of MPAs (Leenhardt et al., 2015; Roncin et al., 2008) and their establishment is expected to have a positive impact on tourist visits (Pascual et al., 2016). Tourism and recreation affect the overall economy of coastal communities, including hotels and restaurants sectors and non-tourism aspects such as the increase of the local real estate values and the improvement of community infrastructure (European Commission, 2018). To account for the increase in the number of tourists in the MPA, different indicators can be used, e.g., tourist arrivals and accommodation capacities, depending on available data. The *Tourism and recreation (TR)* sub-indicator compares data on the number of beds between the MPA area of influence and reference comparable areas. Its score is calculated as follows:

$$TR = \frac{T_i}{T_o} \times 100$$

where T_i and T_o are the number of beds in the MPA area of influence and in the control area placed outside the MPA. Data to calculate the indicator are not supposed to be in possession of the MPA and are therefore collected independently.

Sub-indicator: Natural products (NP)

MPAs can have an important role in the provisioning of natural products, i.e., non-food marine resources for manufactured products (sensu Halpern et al., 2012), which can be relevant components of the economies of coastal communities. The *Natural products (NP)* sub-indicator evaluates the artisanal and/or industrial Harvest Per Unit Effort (HPUE) of resources such as coral, marine plants, shells, and sponges, according to the formula:

$$NP = \frac{1}{N} \sum_{j=1}^N \left(\frac{HPUE_i}{HPUE_o} - 1 \right) \times 100$$

where, $HPUE_i$ and $HPUE_o$ are the harvests per unit effort of the j -th product inside and outside the MPA, and N is the total number of products assessed.

2.4.4. Cultural identity

The local human component of MPAs is significantly connected to its territory, traditions and history. Communities place a high value to activities passed through generations (e.g., artisanal fishing), local species and culturally important places, being evidence of their cultural identity and heritage. MPAs could represent a shelter for such cultural features, whose existence and protection may be valued also by non-local people. According to definitions in Gee et al. (2017), MPAs can be considered culturally significant areas, as they “contain several culturally significant features to which one or more community have a significant connection”. From this perspective, besides the traditional function of protecting and conserving their ecological features, MPAs may play an important role in the preservation of the cultural identity of local coastal communities.

The *Cultural identity* indicator is composed by two sub-indicators: *Charismatic Species* and *Traditional activities*.

Sub-indicator: Charismatic species (CSPP)

The concept of charismatic species is frequently used in conservation biology, even if it is poorly defined compared to other categories of focal species (Ducarme et al., 2012). Here, we refer to charismatic species as the ones that hold existence, aesthetic, or tradition-related values for the local coastal culture, inspiring a sense of belonging and identity in the local communities (Ducarme et al., 2012). The *Charismatic species (CSPP)* sub-indicator is calculated as the reserve effect on the biomass of charismatic species (or density in case of species more appropriately assessed through the number of individuals rather than biomass, e.g. in the case of marine mammals or sea turtles), according to the following formula:

$$CSPP = \frac{1}{N} \sum_{j=1}^N \left(\frac{B_i}{B_o} - 1 \right) \times 100$$

where, B_i and B_o are the average biomasses (or number of individuals) per unit area of the j -th species inside (i) the evaluated protection zone and outside (o) the MPA, and N is the total number of species assessed.

Sub-indicator: Traditional activities (TA)

398 Traditional activities are important cultural features of local communities. The knowledge of the
399 environment embedded in such practices and its passing down across generations give them both
400 ecological and cultural relevance. In marine environments, anthropization of the coasts, decrease in
401 fish stocks, and competition with large-scale fishing are endangering the sustainability of artisanal
402 or small-scale fisheries (Kolding et al., 2014). Artisanal fishing is a relevant traditional activity of
403 coastal communities, being an important source of employment, food security, and income (FAO,
404 2016).

405 Through the regulations of extractive uses, MPAs represent a form of spatial management that can
406 be a suitable tool to preserve the viability of artisanal fisheries, providing an environment in which
407 they can thrive in accordance to sustainability goals, potentially creating “win-win” situations
408 (Dalton, 2010; Di Franco et al., 2016). To assess the support MPAs provide to small-scale fisheries,
409 the *Traditional activities (TA)* sub-indicator measures the number of artisanal fishers authorized by
410 the MPA, compared to outside values (e.g., regional or national scales). The score is calculated
411 according to the following formula:

$$TA = \frac{1}{N} \sum_{j=1}^N \left(\frac{A_i}{A_o} - 1 \right) \times 100$$

412 where, A_i and A_o are the average number of people per unit of coast length practicing the j -th
413 traditional activity inside (i) the evaluated protection zone of the MPA and at a regional or national
414 scale (o), and N is the total number of traditional activities assessed.

415 The sub-indicator can be adapted to local peculiarities, accounting for traditional activities
416 occurring in the MPA other than artisanal fishing. Data to calculate the indicator may not be in
417 possession of the MPA. In this case, missing data are collected independently.

418

419 **2.4.5. Level of surveillance (LS)**

420 The enforcement of regulations is one of the main social drivers determining the success of MPAs
421 (Giakoumi et al., 2018). Where the level of enforcement is low, compliance of users and
422 stakeholders with regulations can be easily undermined as rulebreakers are unlikely punished (Rife
423 et al., 2013). In these cases, no positive ecological effects on marine ecosystems should be expected
424 (Guidetti et al., 2008; Edgar et al., 2014). Enforcement represents more than just surveillance or
425 patrolling activities. It can be depicted as a chain composed by technical/operative, social,
426 legislative, and financial links (Arias et al., 2015, 2016). Nonetheless, surveillance is a key aspect of
427 enforcement as it increases the probability of detecting offenses and its lacking can lead to poaching
428 and social distrust about the MPA (López Ornat and Vignes, 2015).

429 The *Level of surveillance (LS)* indicator focuses on the evaluation of the main aspects affecting the
430 effort deployed in the surveillance activity. It is based on Scianna et al. (2018) approach and the
431 score is calculated according to the following formula:

$$LS = \left(\frac{AC + M + A}{3} \right) \times T \times 100$$

432 where, *AC* stands for “authority and cooperation”, *M* for “methods”, *A* for “area”, and *T* for “time”.
433 *AC* assesses the legal powers of the MPA staff enforcement and the cooperation with police bodies.
434 The presence of these features is valued 1, and the absence 0. The score of *AC* is calculated as the
435 mean of the two. *M* refers to the methods used to perform surveillance. A set of available methods
436 and technologies was identified according to López Ornat and Vignes (2015) and Scianna et al.
437 (2018), and is composed by *controls* “at sea”, “from land”, “during daytime”, and “at night”, and
438 through *technologies* such as “video camera”, “radar”, “vessel monitoring system”, “night vision
439 binocular”, “camera with georeferenced position”, “laser”, and “drones”. These methods are valued
440 1 if present and 0 if absent. Finally, the *M* score is calculated as the average of *controls* and
441 *technologies* values. *A* is calculated as the area under surveillance over the total area of the MPA.
442 Different importance (i.e., weights) can be given to different zones, depending on their protection
443 levels. The average of *AC*, *M*, and *A* is then multiplied by *T*. *T* refers to the time of surveillance,
444 accounting for the type of surveillance body and the season. Surveillance bodies are of three types,
445 i.e. “staff without legal power”, “police”, and “staff with legal power or staff cooperating with
446 police”, to which 1, 1.2, and 1.5 weights are given, respectively, to value more the active
447 cooperation of legally powered staff and police bodies. Each surveillance body, if active, is then
448 multiplied by the time ratio between the days of surveillance and the days in the two seasons, i.e.
449 “summer” and “winter”.

450

451 **2.4.6. Information and awareness of regulation (IAR)**

452 The enforcement of regulations does not depend merely on surveillance activity. An important part
453 is played by the extent to which information on regulations is conveyed to the users and visitors.
454 Ignorance and misinformation are indeed the main cause of offences inside MPAs (López Ornat
455 and Vignes, 2015) as compliance can be expected only to rules people are aware of and understand.
456 According to López Ornat and Vignes (2015), different practices are recommended to inform users
457 and visitors. These practices are used to calculate the *Information and awareness of regulations*
458 (*IAR*) indicator as follows:

$$IAR = \frac{S + AI}{2} \times 100$$

where, *S* and *AI* are the signage and active information scores. Each score is calculated averaging the presence (value = 1) or absence (value = 0) of three factors. The calculation of the *signage* score takes into account the presence of: 1) information panels on land, 2) buoys delimiting the “no-take zones”, 3) internet website with explained zonation and rules. The *active information* considers if: 1) MPA staff distributes brochures with detailed regulation information, 2) MPA staff, in summer, meets the leisure boats on arrival and informs them about boating activity rules, 3) tourist operators inform visitors they bring in the MPA.

2.4.7. Stakeholder engagement (SE)

The involvement of stakeholders is recognized as a major factor affecting the success of MPAs (Claudet and Guidetti, 2010; Giakoumi et al., 2018; Guidetti et al., 2010). Well-managed engagement can facilitate learning and trust among stakeholders (Durham et al., 2014) as it helps mediating conflicts and favoring social compliance. This is particularly true in the case of certain stakeholders such as small-scale fisheries and local government for which well-managed engagement is crucial for MPA effectiveness (Beger et al., 2004; Di Franco et al., 2016). For these stakeholders, the need for assessing and monitoring the effectiveness of their engagement is essential.

Different levels of engagement with stakeholders can be identified, based on the influence they have on the success of the MPA, and corresponding to different levels and methods of interaction (Durham et al., 2014; Sterling et al., 2017). For the *Stakeholder engagement (SE)* indicator, we identify three levels, namely “inform”, “consult”, and “collaborate” (Durham et al., 2014):

- 1) “inform” defines a low level of engagement, in which stakeholders are adequately updated with tailored information;
- 2) “consult” defines an intermediate level of engagement, in which stakeholders are more engaged with a higher level of interaction resulting in feedback information;
- 3) “collaborate” defines a high level of engagement, in which the involvement of stakeholders can include decision-making.

Appropriate methods of interaction can be associated to the three levels of engagement (Durham et al., 2014). The appropriateness of the method to the target level of engagement for a given stakeholder category can be classified in: H = high, M = medium, L = low, NA = not appropriate. If different methods of engagement are adopted for a stakeholder, the most appropriate one is used for the evaluation. Examples of engagement methods and their level of appropriateness are shown in Table 3.

493 **Table 3.** Modified from Durham et al. (2014). The table shows the appropriateness of the engagement method. H =
494 high; M = medium; L = low; NA = not appropriate.

	Inform	Consult	Collaborate
Website	H	M	L
Social media	H	L	L
Lectures	H	L	L
Multi-stakeholder forums	NA	M	H
One-to-one meeting and interviews	NA	M	H
Town Hall meeting	NA	M	H
Workshops	NA	L	H
Questionnaires/surveys	NA	H	L
Practical demonstration	NA	NA	H
Steering group	NA	NA	H

495

496 The *Stakeholder engagement (SE)* indicator is calculated according to the following formula:

$$SE = \sum_{i=1}^N \beta_i \frac{St_i}{N} \times 100$$

497 where, β_i is the engagement appropriateness factor of the *i-th* category (not appropriate = 0; low =
498 0.3; medium = 0.6; high = 1); St_i is the representativeness score of stakeholder category *i*, calculated
499 as the number of stakeholders engaged on the total of category *I*; *N* is the total number of
500 stakeholder categories assessed.

501

502 **2.4.8. Monitoring and reporting (MR)**

503 The adaptive management approach requires that decisions are taken based on the most updated
504 evaluations on the status of social and ecological features. To make these data available, it is crucial
505 that well-designed and long-term scientific monitoring programs are in place and carried out
506 consistently. This would allow to readily respond to pressures, state changes, and impacts on the
507 components of the social-ecological systems, providing effectiveness and legitimacy of
508 implemented regulations and management measures (López Ornat and Vignes, 2015).

509 The *Monitoring and reporting (MR)* indicator jointly addresses the evaluation of: 1) the effort put in
510 the collection of data on the most context-important ecological features and threats through
511 monitoring activities, and 2) the use of these data to produce public reports/scientific publications.
512 The monitoring assessment takes into account the continuity of monitoring campaigns, while the
513 reporting assessment considers both a measure of the quality of the product (i.e., type of report),
514 according to Scianna et al. (2018), and the continuity of the reporting activity.

515 The indicator is calculated according to the following formula:

$$MR = \frac{1}{2} \left(\sum_{i=1}^M \frac{m_i \alpha_i}{M} + \sum_{i=1}^R \frac{r_i \beta_i \gamma_i}{R} \right) \times 100$$

516 where, m_i is the presence of monitoring campaigns on the i -th feature (presence = 1; absence = 0);
 517 α_i is the “*continuity factor*” of monitoring campaigns on the i -th feature; M is the total number of
 518 ecological features and threats to be monitored; r_i is the presence of reports on data collected
 519 through monitoring campaigns on the i -th feature; β_i is the “*continuity factor*” of reports produced
 520 on collected data on the i -th feature; γ_i is the “*communication impact factor*” of these reports; and
 521 R is the number of features monitored. The way α , β , and γ are calculated is showed in table 4.

522

523 **Table 4.** The table shows the calculation method of the three factors α , β , and γ of the *Monitoring and reporting*
 524 indicator. For each factor, quantities or categories are converted to values from 0 to 1.1.

Factor	Unit	Quantity or category	Value
α	Number of monitoring campaigns in the last 5 years	0	0
		1	0.6
		2	0.7
		3	0.8
		4	0.9
β	Number of reports in the last 5 years	5	1
		> 5	1.1
γ	Communication method	not reported	0
		internal reports	0.6
		communications and outreach	0.8
		scientific papers without impact factors and scientific reports	1
		scientific papers with impact factor	1.1

525

526

527 2.4.9. Financial support (FS)

528 Effective management requires that sufficient financial resources are available to the MPA to cover
 529 overall costs to support management teams and actions (Binet et al., 2015). Given financial
 530 constraints, the capacity of management to achieve MPA goals and objectives is threatened as basic
 531 management costs (such as staff hiring, monitoring, and research) cannot be carried out.

532 The *Financial support (FS)* indicator aims to assess the availability of financial resources and the
 533 evenness of their distribution among their sources. The financial availability is calculated as the gap
 534 between the total amount of financial resources available to the MPA in the assessed year and the

sum of the costs faced in the same year. Costs are here intended as the financial needs to operate in a basic management scenario, as defined by Binet et al. (2015). Such scenario takes into account four components: 1) administrative organization and planning; 2) administrative support for stakeholder engagement; 3) knowledge acquisition and environment monitoring; 4) control, regulation, and supervisory.

The diversity of financial sources is also an important factor that can affect the financial stability of MPAs. In case the main source is lacking or fails, other sources can help compensating. Several funding sources can be identified for MPAs: local, regional, and national governments, international donors and NGOs, private sector, and self-financing.

The *Financial support (FS)* indicator is then calculated according to the following formula:

$$FS = \frac{F_t}{C} \times J \times 100$$

where F_t is the total amount of financial resources, C is the overall costs expected for the basic management, and J is the evenness of distribution of F_t among the financial sources calculated using the Shannon-Wiener diversity index.

2.4.10. Professionalism and competences (PC)

MPA management requires a multidisciplinary approach and cross-sectors expertise. Considering social-ecological targets and management needs of MPAs, an efficient staff would need to include experts in the fields of reserve management, natural sciences, fisheries science, communication, accounting, and technical support. The *Professionalism and competences (PC)* indicator takes into account the presence of specialized staff in the main identified fields as well as their level of expertise. The indicator is calculated according to the following formula:

$$PC = \sum_{i=1}^N \frac{F_i + E_i}{N} \times 100$$

where, F_i is the presence of a staff member expert in the i -th field (presence = 0.5; absence = 0); E_i is the expertise score, calculated as the education, training, and working years of the most experienced staff member of the i -th field multiplied by 0.1; N is the total number of fields of expertise considered.

2.4.11. Personnel stability (PS)

The stability of MPA personnel over time is an important factor affecting the effectiveness of management actions. Among other benefits, such as improvements in efficiency of working relationships and management continuity, stability helps meeting social-ecological targets, usually

565 characterized by long-term responses to protection. Such long-term responses need continuity and
566 consistency of management actions (Scianna et al., 2018). Following Scianna et al. (2018), the
567 *Personnel stability (PS)* indicator is calculated as follows:

$$PS = \frac{PE}{FTE} \times 100$$

568 where, *PE* is the number of full-time permanent employees, and *FTE* is the total number of full-
569 time employees.

570

571 **2.4.12. Cultural heritage (CH)**

572 As already stated for the *Cultural identity* indicator of the REA, cultural features may represent
573 important elements of the identity of local coastal communities, carrying historical and traditional
574 values and therefore heritage to pass through generations. Cultural heritage is considered the
575 “cultural capital” of contemporary societies, “essential for promoting peace and sustainable societal,
576 environmental, and economic development” (UNESCO, 2014).

577 Following UNESCO (2014), the *Cultural heritage (CH)* indicator aims at assessing: 1) the adoption
578 of “conservation and valorization” measures and 2) the promotion of activities to “raise awareness
579 and education” on the cultural heritage of MPAs. Cultural heritage elements are identified through
580 sites in the seascape that can be defined as “works of men, or the combined works of nature and
581 man, and areas including archeological sites, which are of outstanding value from the historical,
582 aesthetic, ethnological or anthropological point of view” (UNESCO, 2014). Examples can be
583 natural monuments (e.g., caves, peculiar geological formations), and historical or archeological
584 sites (e.g., prehistorical settlements, harbors, underwater shipwrecks, fish establishments).

585 The score of the indicator is calculated as follows:

$$CH = \sum_{i=1}^N \frac{CV_i + AE_i}{2N} \times 100$$

586 where, CV_i and AE_i represent the presence of “conservation and valorization” measures and of
587 activities aimed at “raising awareness and education” on the i -th cultural element, and N is the total
588 number of cultural elements considered. “Conservation and valorization” covers the adoption of
589 specific legislation and concrete measures or the establishment of infrastructures intended to
590 safeguard, protect and enhance heritage assets (UNESCO, 2014). “Raising awareness and
591 education” covers measures and programmes intended to promote the educational potential of
592 heritage and its transmission as well as informational and media programmes and facilities
593 addressed to the general public and to key social agents in order to foster understanding,
594 recognition, respect and enhancement of heritage in society (UNESCO, 2014).

595

596 **2.4.13. Social media communication (SMC)**

597 Communication is an important tool for building support for protected areas, bringing
598 environmental awareness to the public and thus helping the achievement of conservation targets
599 (Hamú et al., 2004). In the case of MPAs, the media coverage of the activities performed and the
600 relative social-ecological benefits help connecting people to nature and promote the establishment
601 of trust, thus favouring compliance to MPA rules by users and stakeholders (López Ornat and
602 Vignes, 2015). Even if the MPA is not covered in TV, local radio, or other media, communicating
603 to the public is today possible by means of social networks (e.g., Facebook, Twitter), which provide
604 powerful and easily accessible global communication platforms. Through such channels, awareness
605 and education on environmental topics and conservation issues are not only desirable but probably
606 necessary.

607 The *Social media communication (SMC)* indicator assesses the ability of the MPA to engage users
608 in social networks. It is calculated as follows:

$$SMC = \sum_{i=1}^N \beta \frac{ER_i}{N} \times 100$$

609 where ER_i is the engagement rate of the i -th social network, calculated as the ratio between the total
610 engaged users (i.e., users that engaged with a post by clicking on, reacting to, commenting on, or
611 sharing it) and the total reach (i.e., the number of users that found that post in the news feed); β is
612 the ER target, set to 1% (i.e., 1 user out of 100 that found a MPA post on the news feed engaged
613 with it); N is the total number of social media considered.

614

615 **2.5. Graphic output**

616

617 Results of the MOSE framework are presented through an adapted version of the OHI flower plots
618 (Halpern et al., 2012). R scripts to generate flower plots were downloaded from the GitHub
619 platform (https://github.com/OHI-Science/arc/blob/master/circle2016/plot_flower_local.R) and then
620 modified to display REA and MaPA results. REA sub-indicators and MaPA indicators are
621 represented as petals of the flower. Each petal area is filled according to its score and coloured in a
622 traffic light gradient.

623

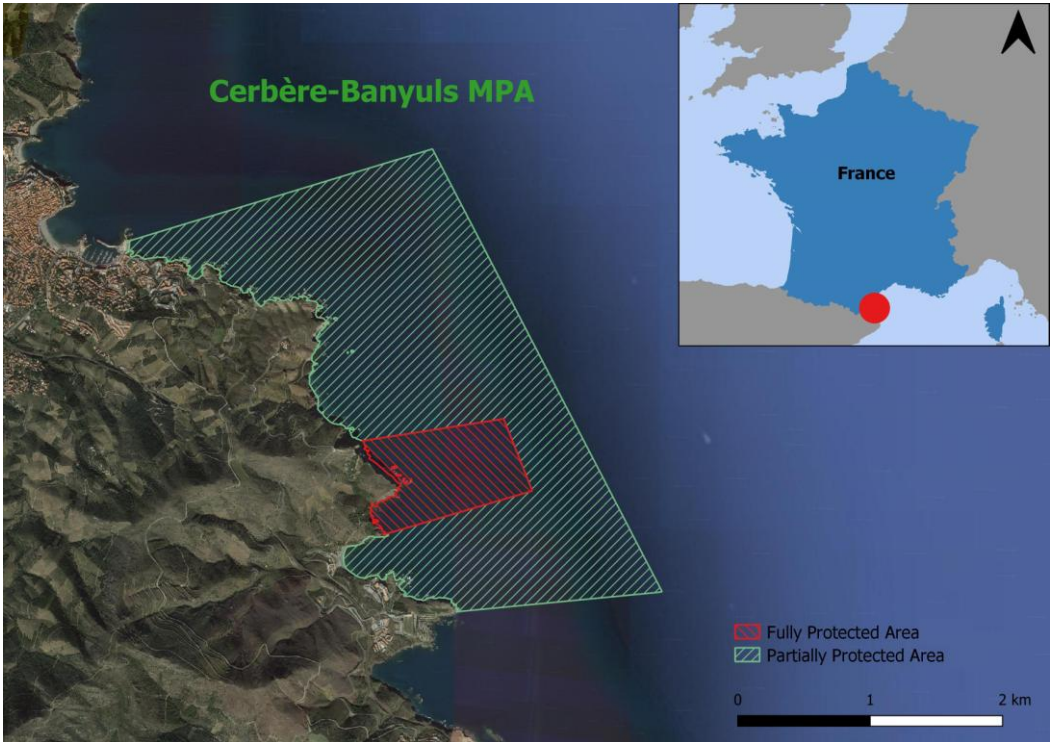
624 **2.6. Case study**

625

626 Located on the Catalan coast of Southern France, the Cerbère-Banyuls Natural Marine Reserve is
627 one of the oldest MPAs of the Mediterranean. It was established in 1974 to protect the seabed and

628 marine species and to sustainably manage human activities and development (Payrot et al., 2014).
629 The MPA aims at protecting local biodiversity and rare and threatened ecosystems as well as areas
630 valuable for geological or other natural features (www.blueparks.org). With an overall area of 6.5
631 km² and a 6 km coast length, the MPA is divided in two distinct protection zones, namely the fully
632 protected area (0.65 km²) and the partially protected area (5.85 km²), where different human uses
633 are allowed (Claudet et al. 2011) (Fig. 3). In the fully protected area, no human activity can occur
634 except from authorized scientific research. Instead, the partially protected area allows human
635 activities such as artisanal and recreational fishing, bathing, and scuba-diving, while others such as
636 spearfishing are prohibited. Scientific monitoring activities are routinely carried out throughout the
637 year, both inside and outside the MPA, also in collaboration with research laboratories
638 (www.blueparks.com).

639 The MPA was chosen as case study to test the applicability and potential usefulness of the MOSE
640 framework because of its management and remarkable conservation results, for which the MPA
641 was awarded with the Green List IUCN label in 2015 and the Global Ocean Refuge System status
642 in 2018 (recently renamed Blue Parks Awards). For these reasons, the MPA represented a suited
643 first application to try out the response of the MOSE framework against the social-ecological
644 effectiveness and management performance of a successful MPA.



646
647 **Figure 3.** Cerbère-Banyuls Natural Marine Reserve. In the figure, the two protection zones of the MPA are shown: the
648 fully protected area (red grid) and the partially protected area (green grid).

649

2.7. Data collection

Data for calculating the REA and MaPA indices were collected through semi-structured surveys submitted to the reserve management body. These surveys allowed for the collection of management data, scientific literature, and reports produced over the last five years. The survey forms can be found in the Supplementary Information on-line material.

3. Results

The REA index calculated for the zone with the highest level of protection (i.e., the fully protected area) resulted in a score of 100 out of 100, with all indicators assessed (DR = 100) and a level of protection corresponding to the *fully protected* class (PL = 2) (Fig. 4). The *Fishing* and the *Local economy* indicators as well as the *Traditional activities* sub-indicator were not assessed since they referred to activities that are not allowed in the investigated zone (not applicable = NA). The assessed indicators *Habitats*, *Species*, and *Charismatic species* scored more than 100 (Fig. 4).

The partially protected area scored lower than the fully protected one, with an overall score of 83 and also a lower degree of reliability (DR = 87.5) (Fig. 4). The *Protection Level (PL)* indicator scored 5, corresponding to the *highly protected* class. *Industrial fishing* and *Natural products* sub-indicators were not assessed because the relative activities are not allowed (NA), while *Artisanal fishing* lacked data (no data = ND). Among the four REA indicators, *Biodiversity* showed the highest score (100), followed by *Cultural identity* (85), *Local economy* (84), and *Fishing* (64), whose score was exclusively due to the *Recreational fishing* sub-indicator. The value of *Habitats*, *Species*, *Livelihoods* and *Charismatic species* sub-indicators resulted higher than 100, while *Traditional activities* and *Tourism and recreation* sub-indicators scored 70 and 69, respectively.

The REA index score for the whole MPA was calculated as the average of the REA scores of the two protection zones weighted by the area occupied by each zone in the MPA (Fig. 5). Overall, the MPA scored 85 with a higher reliability score (DR = 92.3) than the partially protected area and a level of protection corresponding to the *highly protected* class (PL = 4.7).

The MaPA index scored 90 out of 100 with a DR of 100 (Fig. 5). All indicators scored more than 60, and 3 of them (i.e., *Information and awareness of regulations*, *Professionalism and competences*, and *Personnel stability*) reached 100. *Cultural heritage* and *Social media communication* could not be assessed (NA) and therefore were not accounted for in the calculation of the DR. *Professionalism and competences* was the only MaPA indicator that scored more than 100.

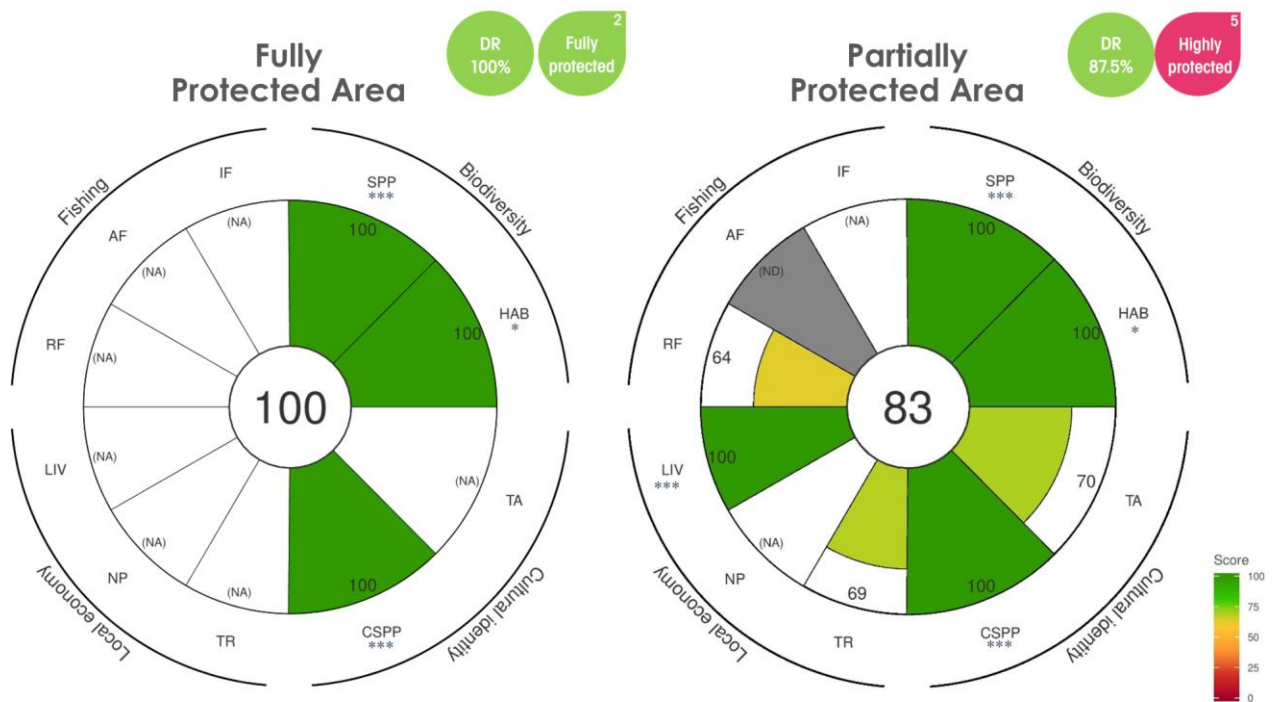


Figure 4. Reserve Effectiveness Assessment (REA) index calculated for the fully protected area (left panel) and the partially protected area (right panel). Each indicator is scored from 0 to 100 following a red-yellow-green colour gradient. On the top right of each plot, the scores of the Degree of reliability (DR) and Protection level (PL) indicators are also shown. Indicators scoring more than 100 are marked with the * symbol (*, $100 < \text{score} < 200$; **, $200 \leq \text{score} < 300$; ***, $\text{score} \geq 300$).

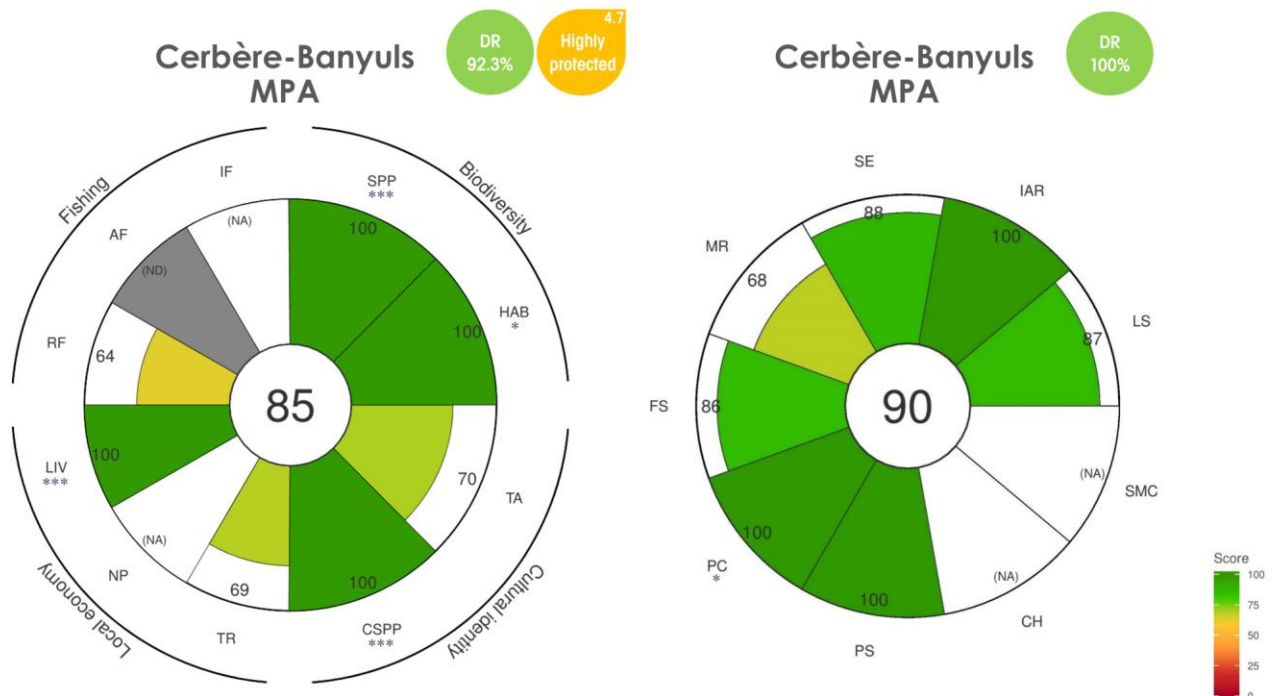


Figure 5. Reserve Effectiveness Assessment (REA) (left panel) and Management Performance Assessment (MaPA) (right panel) indices calculated for the Cerbère-Banyuls Natural Marine Reserve. Each indicator is scored from 0 to 100 following a red-yellow-green colour gradient. On the top right of each plot, the scores of the Degree of reliability (DR) and Protection level (PL) indicators are also shown. Indicators scoring more than 100 are marked with the * symbol (*, $100 < \text{score} < 200$; **, $200 \leq \text{score} < 300$; ***, $\text{score} \geq 300$).

698

699 5. Discussion

700

701 The application of the MOSE framework showed that a high level of management effort is applied
702 to the Cerbère-Banyuls Natural Marine Reserve, generating several social-ecological benefits.
703 Almost all of the data required to implement the MOSE framework were available ($DR_{max}=100$ and
704 $DR_{min}=87.5$), with only the *Artisanal fishing* indicator lacking data. The REA results showed high
705 scores for all the assessed indicators in both protection zones (min = 64; max = 100; average = 83),
706 in accordance to their *Level of protection* (i.e., *fully* and *highly protected*). Remarkable are the
707 *Biodiversity*, *Charismatic species*, and *Livelihoods* scores, reflecting the positive ecological effects
708 of the long-lasting conservation effort on habitats and species of the MPA and its consequent
709 attractiveness for divers. Such positive effects are not as evident for the *Tourism and recreation*
710 indicator, since tourism is highly developed in the whole region (www.cdt66-observatoire.com).

711 The MaPA index scored higher than REA (min = 68; max = 100; average = 90), with all applicable
712 indicators assessed ($DR=100$). *Cultural heritage* and *Social media communication* indicators
713 could not be assessed (NA). Indeed, the reserve is not officially committed to the preservation of
714 local cultural aspects according to its mission. Moreover, it does not manage any social network,
715 which are instead managed by the Department of the Pyrénées-Orientales. Nevertheless, the reserve
716 is regularly requested by press and television but such media were not taken into account in the
717 *Social media communication* indicator. *Professionalism and competences* and *Personnel stability*
718 indicators scored both 100, highlighting the importance of a competent and stable staff. Such results
719 point to professionalism and working stability of the management body as two main drivers of
720 MPA success, allowing quality and continuity of conservation actions.

721 The choice of developing and applying a comprehensive but synthetic assessment framework was
722 taken to provide an overview of the overall level of success of MPAs. Although this first
723 application of the MOSE framework was able to highlight the overall success of the Cerbère-
724 Banyuls Reserve, further applications are needed to test its effectiveness and sensitivity. Such
725 applications should target a larger number and variety of MPAs, including differences in age of
726 establishment, size, geography (i.e., coastal vs island MPA), type (i.e., single- vs multi-use MPA),
727 and configuration (i.e., single MPA vs MPA network).

728 After this first application, strengths of the MOSE framework can be highlighted. Compared to
729 other assessment frameworks for MPAs (Tab. 1), the MOSE framework shows distinctive features.
730 As previously showed, most frameworks focus on one or few domains of assessment. The MOSE
731 framework instead integrates indicators referring to the ecological, social, economic, governance,
732 and management domains, covering all main areas of investigation for the assessment of MPAs

effectiveness and performance. In addition, unlike other frameworks, it is able to provide quantitative results, which are synthetically displayed through an intuitive graphical output that simplifies their communication. Graphical representations of results (Fig. 4 and 5) carry indeed remarkable communicative power as they are able to easily provide a quantitatively comparable measure of the degree to which MPAs meet their goals. Flower plots show results at index score level (synthetic information) and indicators score level (detailed information). Such feature is especially useful when conveying information on effectiveness and performance to politicians, decision-makers, and other stakeholders. In addition, the communication of results is strengthened by the information on the reliability of the overall scores of the two indices. Its inclusion gives a measure of their consistency while providing itself an evaluation on the data gap to implement adaptive management strategies. Another strength of the MOSE framework is represented by the fact that the investigation scale matches the scale at which decisions are made. MPAs are legally empowered to regulate human activities inside their borders, which makes system-level assessments - such as the MOSE framework - particularly effective in informing management actions through feedback adaptive loops to meet marine conservation and sustainability goals. Finally, the development of the MOSE framework is timely. MPAs are playing an important role in international strategies for ocean sustainability. Currently, these strategies focus mainly on increasing the coverage of MPAs worldwide without paying enough attention to their actual effectiveness, which is a fundamental point to achieve the pursued sustainability objectives. Science-based and quantitative informative tools to support the adaptive management process of MPAs are needed to fill this gap. The MOSE framework makes an attempt towards this direction, providing a tool to support managers of MPAs all over the world in targeting and assessing local social-ecological benefits and management efforts. Indeed, like in the case of the Ocean Health Index (Halpern et al., 2012), MOSE is a flexible assessment framework allowing for adaptability towards context-related necessities and peculiarities. New indicators can be added and changes can be applied to the existing ones, depending for instance on the MPA mission and objectives. Nonetheless, consistency is one of the main strengths of system scale assessment frameworks and major modifications could compromise the comparability of results among different MPAs and for the same MPA over time. Finally, as previously stated, REA indicators measure the social-ecological benefits that MPAs provide to local communities. Defining such effects as benefits provided by marine natural capital matches the notion of “ecosystem services” internationally recognized and fostered by several initiatives such as the Millennium Ecosystem Assessment (MA), The Economics of Ecosystems and Biodiversity (TEEB), and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). REA indicators can be also linked to the

United Nations SDGs supported by MPAs, providing a quantitative measure of their local support to global sustainability goals (Fig. 6).

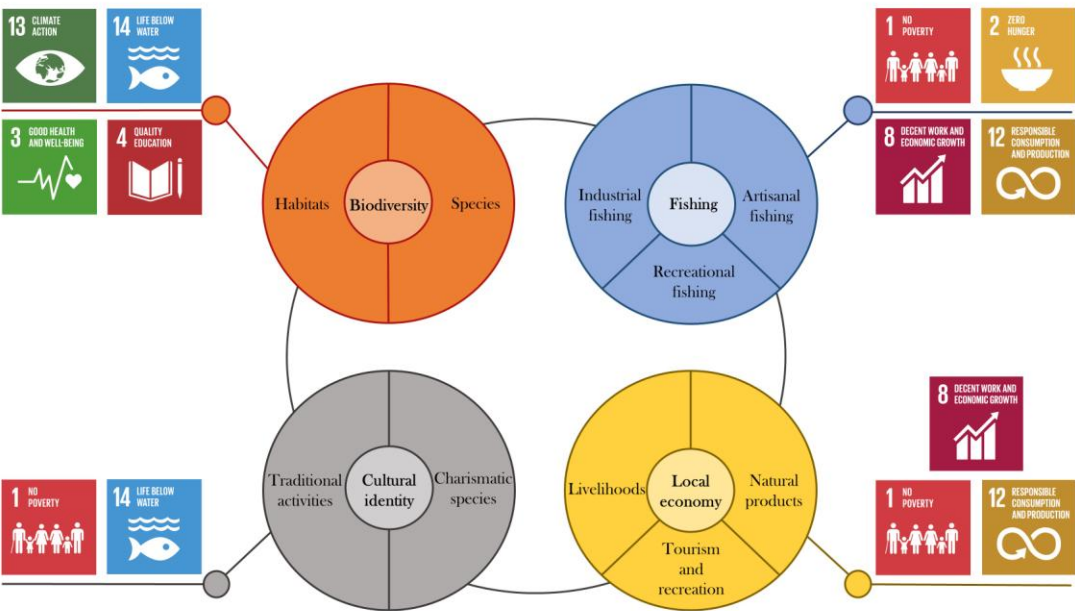


Figure 6. Links between the REA indicators of the MOSE framework and UN-SDGs.

Along with the strengths of the MOSE framework, the following aspects should be carefully considered. The use of a 0-100 scale is well suited in the case of target values which represent the full achievement of the objective that is measured. This is the case of the MaPA indicators, whose scores indicate the degree to which their targets are met. On the contrary, the calculation method of the REA index uses values of measured variables from control areas as reference points for the absence of protection. Hence, the reference points of REA indicators do not represent target values, but rather the threshold beyond which measuring the reserve effect. This difference between REA and MaPA approaches needs to be taken into account when interpreting the results of the two indices. Another aspect to be considered is that the high amount of data required to implement the MOSE framework could represent an obstacle to its applicability. Despite the presence of the *Degree of reliability (DR)* indicator (which can cope with the lack of data addressing the level of assessment comprehensiveness), missing substantial information could compromise the application of the framework and the meaningfulness of the overall REA and MaPA scores. Nevertheless, the verified lack of data represents a result itself as it can inform the adaptive management process and provide useful directions on data to be collected and studies to be carried out. Finally, the

788 multicriteria feature of the MOSE framework requires the capability of dealing with a multitude of
789 socio-economic and ecological data to be managed and interpreted.

790 791 **6. Concluding remarks**

792
793 In this study, a novel integrated framework measuring the overall success of MPAs was presented.
794 The case study of the Cerbère-Banyuls Natural Marine Reserve was implemented to test its
795 applicability and potential usefulness as a tool to support managers and decision-makers in charge
796 for developing nature conservation strategies. These strategies should be based on the application of
797 adaptive management processes requiring multicriteria assessment frameworks and synthetic
798 indices able to capture the complexity of marine social-ecological systems. Future applications of
799 the MOSE framework will allow improving its applicability while contributing to establish a
800 comparative assessment among MPAs at local, national, and larger scales.

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