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## Hybridizing research and decision-making as a path toward sustainability in marine spaces

C. Boemare, E. Mosseri, G. Agin, L. Bramanti, R. Certain, Joachim Claudet, Katell Guizien, C. Jabouin, X. Lagurgue, P. Lenfant, et al.

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1 **Hybridizing research and decision-making as a path toward sustainability in**  
2 **marine spaces**

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4 **Boemare, C., Mosseri, E., Agin, G., Bramanti, L., Certain, R., Claudet, J., Guizien, K., Jabouin,**  
5 **C., Lagurgue, X., Lenfant, P., Levrel, H., Michel, C., Musard, O, Verdoit-Jarraya, M.**

6  
7 **Corresponding author:** Catherine Boemare, [catherine.boemare@ehess.fr](mailto:catherine.boemare@ehess.fr)

8  
9 Catherine Boemare, École des Hautes Études en Sciences Sociales, CIRED, UMR 8568 CNRS-  
10 EHESS-Ecole des Ponts ParisTech-CIRAD-AgroParisTech, Jardin d’Agronomie Tropicale de  
11 la Ville de Paris, 45 bis Avenue de la Belle Gabrielle, F-94736 Nogent-sur-Marne, Cedex  
12 France. <https://orcid.org/0000-0001-5698-8749>

13 Elsa Mosseri, National Center for Scientific Research, CIRED, UMR 8568 CNRS-EHESS-  
14 Ecole des Ponts ParisTech-CIRAD-AgroParisTech, Jardin d’Agronomie Tropicale de la Ville  
15 de Paris, 45 bis Avenue de la Belle Gabrielle, F-94736 Nogent-sur-Marne, Cedex France.  
16 <https://orcid.org/0009-0003-8840-0040>

17 Grégory Agin, Natural Marine Park of the Gulf of Lions, 2 Impasse Charlemagne, F-66 700  
18 Argelès-sur-Mer, France. <https://orcid.org/0000-0003-0878-0235>

19 Lorenzo Bramanti, CNRS-Sorbonne Université, LECOB, Observatoire Océanologique de  
20 Banyuls sur Mer, 1 avenue Pierre Fabre, F-66 650 Banyuls sur Mer, France.  
21 <https://orcid.org/0000-0002-4872-840X>

22 Raphaël Certain, University of Perpignan Via Domitia, CEFREM, UMR 5110 CNRS-UPVD,  
23 F-66860 Perpignan, France. <https://orcid.org/0000-0002-2020-310X>

24 Joachim Claudet, National Center for Scientific Research, PSL Université Paris, CRIOBE,  
25 CNRS-EPHE-UPVD, Maison de l’Océan, 195 rue Saint-Jacques F-75005 Paris, France.  
26 <https://orcid.org/0000-0001-6295-1061>

27 Katell Guizien, CNRS-Sorbonne Université, LECOB, Observatoire Océanologique de Banyuls  
28 sur Mer, 1 avenue Pierre Fabre, F-66 650 Banyuls sur Mer, France. [https://orcid.org/0000-0001-](https://orcid.org/0000-0001-9884-7506)  
29 [9884-7506](https://orcid.org/0000-0001-9884-7506)

30 Coraline Jabouin, Natural Marine Park of the Gulf of Lions, 2 Impasse Charlemagne, F-66 700  
31 Argelès-sur-Mer, France. <https://orcid.org/0009-0006-1578-9288>

32 Xavier Lagurgue, ENSAPVS, CRH-LAVUE, UMR 7218 CNRS-Paris Nanterre-Paris 8-  
33 ENSAPVS, 3 quai Panhard & Levassor, F-75013 Paris, France. [https://orcid.org/0009-](https://orcid.org/0009-0000-5767-9163)  
34 [0000-5767-9163](https://orcid.org/0009-0000-5767-9163)

35 Philippe Lenfant, University of Perpignan Via Domitia, CEFREM, UMR 5110 CNRS-UPVD,  
36 F-66860 Perpignan, France. <https://orcid.org/0000-0001-6664-8342>

37 Harold Levrel, Université de Paris Saclay, AgroParisTech, CIRED, UMR 8568 CNRS-EHESS-  
38 Ecole des Ponts ParisTech-CIRAD-AgroParisTech, Jardin d’Agronomie Tropicale de la Ville  
39 de Paris, 45 bis Avenue de la Belle Gabrielle, F-94736 Nogent-sur-Marne, Cedex France.  
40 <https://orcid.org/0000-0002-4611-3639>

41 Charlotte Michel, Usages et Territoires, MRM Montpellier Research in Management, Montpellier,  
42 France. <https://orcid.org/0009-0005-3577-1504>

43 Olivier Musard, Natural Marine Park of the Gulf of Lions, 2 Impasse Charlemagne, F-66 700  
44 Argelès-sur-Mer, France. <https://orcid.org/0009-0009-8590-0334>

45 Marion Verdoit-Jarraya, University of Perpignan Via Domitia, CEFREM, UMR 5110 CNRS-  
46 UPVD, F-66860 Perpignan, France. <https://orcid.org/0000-0003-1021-1891>

47

## 48 **Abstract**

49 Projecting the combined effect of management options and the evolving climate is necessary to  
50 inform shared sustainable futures for marine activities and biodiversity. However, engaging  
51 multisectoral stakeholders in biodiversity-use scenario analysis remains a challenge. Using a

52 French Mediterranean marine protected area (MPA) as a marine social-ecological case study,  
53 we coupled codesigned visioning narratives at horizon 2050 with an ecosystem-based model.  
54 Our analysis revealed a mismatch between the stated vision endpoints at 2050 and the model  
55 prediction narrative objectives. However, the discussions that arose from the approach opened  
56 the way for previously unidentified transformative pathways. Hybridizing research and  
57 decision-making with iterative collaborative modeling frameworks can enhance adaptive  
58 management policies, leveraging pathways toward sustainability.

59

60

## 61 **Introduction**

62

63 While substantially contributing to human wellbeing, the ocean is increasingly threatened by  
64 local human action and climate change [1]. Marine protected areas (MPAs) are advocated as a  
65 key strategy for simultaneously protecting biodiversity and supporting coastal livelihoods [2,3].  
66 They are now part of the United Nations Convention on Biological Diversity and Sustainable  
67 Development Goals. Their level of protection encompasses fully protected areas where all  
68 activities are prohibited to a range of “partially protected MPA” that allow activities to different  
69 degrees [4, 5]. The former are known to deliver ecological benefits through exclusion of human  
70 activities [6, 7, 8], whereas the latter assume that conservation will be achieved through  
71 cooperation in the social space that leads to sustainable use [9].

72 While scientific evidence shows that most benefits, including biodiversity conservation, food  
73 provisioning and carbon storage, stem from fully or highly protected areas, most established  
74 MPAs are of lower protection levels because of lobbying from current users and political bias  
75 towards creating many, rather than highly protected areas [6, 7, 8, 10]. Also, it has been argued  
76 that excluding people who are dependent on those areas for their livelihood might not be

77 socially equitable [11.], and that cultural and historical assessments should be part of MPA  
78 design. Potential benefits and beneficiaries must also be highlighted and understood at a local  
79 level to discuss trade-offs and address the ecological, social and economic requirements of  
80 sustainability [9.].

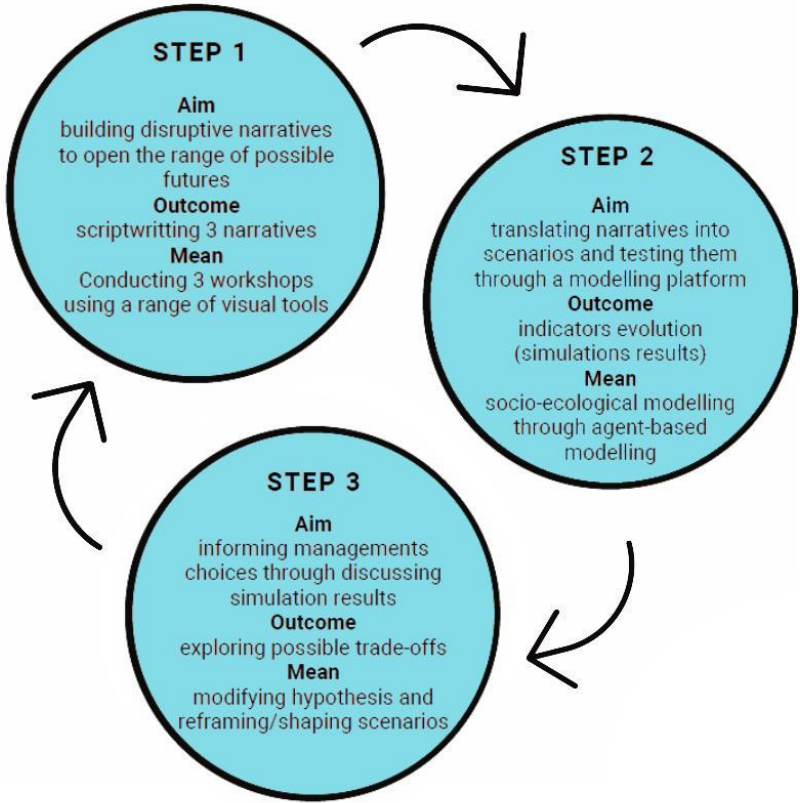
81 However, guiding principles are lacking on how to manage trade-offs in specific social-  
82 ecological systems (SES) [12]. Indeed, while conceptual models of SES have been elaborated  
83 to characterize human-nature interactions and inform decision-making [13, 14, 15, 16, 17, 18,  
84 19], and previous works have been developed [20, 21, 22], effective science-policy interfaces  
85 in marine environments are scant [8]. There is, therefore, room for more effective and inclusive  
86 science-policy frameworks, including dedicated modelling approaches. Each step of  
87 collaborative prospective modeling from elaborating narratives to interpreting simulation  
88 results, including model conception, may help explore the ecological, social and economic  
89 consequences of management alternatives at a local level and in the context of ongoing climate  
90 change.

91 For decision-makers, there is a growing awareness that integrating valuable scientific  
92 knowledge and stakeholders during the management process can offer better outcomes [23, 24,  
93 25, 26, 27, 28, 29, 30] and is less likely to result in resources' collapse [31, 32]. However, such  
94 integration raises three main challenges for science. First, how to collaboratively develop  
95 narratives that break with the usual approach based on ongoing trends – which has failed to  
96 mobilize transformative change [33] – by including stakeholders and scientists from a diversity  
97 of disciplines. Second, how to shift from resources toward ecosystem-based management, and  
98 addressing interactions among scales within SES [34] by using ecosystem-based modeling.  
99 Third, how to better align the modelling practice and illustration of trade-offs with the decision-  
100 making process, ultimately setting management rules [23] by fitting the modeling on MPA  
101 management plans.

102 In this paper, we argue that bridging the gap between what the literature recommends and what  
103 is done on the field requires an innovative science-policy framework that identifies potential  
104 benefits, tackles necessary trade-offs and promotes collective deliberation on management  
105 measures and rules. To test this hypothesis, we hybridized research and decision-making  
106 through collaborative prospective modeling in the case of a French Mediterranean MPA (the  
107 Natural Marine Park of the Gulf of Lions), in the context of climate change. Climate change  
108 impacts on the ocean (e.g., sea level rise, temperature increase, pH decrease, and to a lesser  
109 extent, moisture decrease) are expected to alter marine ecosystems functioning [35.]. In the  
110 semi-closed Mediterranean Sea, climate change effects on ecosystems are already visible, with  
111 most noteworthy impacts reported being oligotrophication and diversity composition change  
112 [37]. Hence, scientists, policymakers and stakeholders involved in the management of such  
113 MPA were involved in the present transdisciplinary and multi-actors' research. We followed a  
114 three-step process (Figure 1) over a three-year period (2015-2019), which entailed: i)  
115 conducting three workshops in stakeholders' groups (see Supplementary Material Note 1); ii)  
116 developing a social-ecological model through an agent-based modelling; iii) collectively  
117 exploring the simulations' results. The study adds novelty from previous work [13, 14, 15, 16,  
118 17, 18, 19, 20, 21, 22] by combining participatory narrative-building with modelling to shape a  
119 deliberation tool in the marine environment. Although an economic analysis would be  
120 necessary to identify potential benefits and beneficiaries of different scenarios, such an analysis  
121 was not developed as it was beyond the scope of our study. Here, we describe how aiming for  
122 sustainability requires a framework for continued work that allows us to i) build contrasting  
123 narratives for the future addressing biodiversity conservation, food provisioning and economic  
124 activity in the context of climate change; ii) explore resulting strategies with a science-based  
125 SES model illustrating trade-offs; iii) deliberate about results in order to adjust strategies.

126

**PRE-REQUISITE**  
**Aim**  
 Agreeing collectively on main issues  
**Outcome**  
 Representing the territory as a SES  
**Mean**  
 Conducting workshop around a chronological matrix which outlines the main features of the territory



127

128 **Figure 1 – Key steps of the framework proposed.**

129 A three-step process over a three-year period which consists in conducting workshops in stakeholders' group for  
 130 building disruptive narratives (step 1), developing a social-ecological model through agent-based modelling for  
 131 implementing narratives translated into scenarios (step 2) and collectively exploring the simulations results  
 132 eventually leading to modifying scenarios hypothesis and re-shaping scenarios (step 3). A pre-requisite to the  
 133 three-step process consists in agreeing collectively on main issues to be addressed.  
 134

135 **Results**

136

137 Building disruptive narratives to open the range of possible futures

138

139 Recent scientific works suggest that we need to move beyond classical scientific studies  
140 depicting future trajectories of decline that have failed to mobilize transformative change [23].  
141 Exploring different futures through narrative scenarios proves to be helpful to address MPA  
142 management issues in a constructive manner [36]. Lubchenco and Gaines notably emphasize  
143 how narratives help in framing our thinking and action [38]. Indeed, as in mythology or  
144 literature, narratives act as a reference framework to which one can refer to making decisions  
145 adapted to unpredicted but pictured contexts. In the present context, the challenge was to extend  
146 or amend our reference scheme by imagining transformative futures.

147 Here, we did so by inviting scientists, stakeholders, and decision-makers to participate in three  
148 workshops led by a specialist in building prospective scenarios (see Methods). Each time,  
149 participants were split into three groups to progressively write a narrative about the Natural  
150 Marine Park of the Gulf of Lions by 2050 (see Supplementary Note 1-2). It led to the writing  
151 of three original and transformative narratives (Table 1). 2050 was considered close enough to  
152 fit with the real political deadline, i.e., the completion of two management plans, and far enough  
153 to deal with some expected effects of climate change, such as the decline of primary production  
154 in marine ecosystems.

155

156

157 **Table 1 – Co-designed visioning narratives for the Natural Marine Park of the Gulf of**  
158 **Lions by 2050 built at the experts' workshops**

**Narrative 1: Protecting the ecological heritage and strengthening the marine food web**

Starting point: it reports the progressive deficiency of top predators and keystone species (e.g., groupers, sharks) and its corollary: the impoverishment of the whole trophic chain [75]. But this scenario considers the uncertainties surrounding the idea of good ecological status [76] and shifting baselines [76, 77, 78]. Hence, specifying an ideal ecological state to achieve didn't make so much sense for the participants, who focused on preserving key habitats, keystone species, and enhancing the actual food chain [79]. This strategy was inspired by the ecological concept: the more diversity there is, the greater the resilience of the system [80, 81].

Management rules: the participants imagined extending full protection up to 30% of the MPA. This ratio was chosen to echo the most ambitious existing target worldwide: the International Union for the Conservation of Nature recommendation that at least 30% of the entire ocean should benefit from strong protection. Participants also proposed stabilizing fishing effort and re-introducing top predators like groupers in the suitable habitats.

<p><u>Climate change</u></p> <p>Decline of primary production in marine ecosystems</p>	<p><u>Fisheries</u></p> <p>Constant fishing effort but no fishing on existing reefs &amp; in fully protected areas</p> <p><u>Diving</u></p> <p>Constant number of divers but no access to fully protected areas</p>	<p><u>Fully protected areas</u></p> <p>Level: most ambitious existing target</p> <p>Location: most important natural areas all over the sea</p>	<p><u>Facilities &amp; ecological engineering</u></p> <p>No development but no removal of artificial reefs</p> <p>Acceptation of a small experimental wind farm to evaluate its impacts</p> <p>Reintroduction of heritage species</p>
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**Narrative 2: Upgrading the artisanal fishery**

Starting point: it is a strong awareness among the members of the group of the climate change expected consequences on marine primary production, being the first level of the food chain [82, 83] : less nutrient availability for plankton development, through a limitation of river inflows and a reduction of coastal upwelling. Coupled with the actual decrease of nutrients flows due to dams on rivers and partial closure of estuaries, this would cause a decline of primary production, then affect the upper compartments of the ecosystems, including fished species. In order to avoid this global decline and to maintain the biomass of commercial species, stakeholders proposed actions to be taken on land, that are likely to restore good nutrient availability for plankton development and so on\*. To create new sources of income, they suggested aquaculture could be developed in the lagoons in the form of multi-trophic farms (fish/oyster/algae or shrimp/oyster/algae). They also got inspired by "slow food" movements and invented a "slow fishing" style, in the sense that fishing should respect life cycles of different species and marine habitats, in terms of harvesting gears and anchoring systems. It would still be profitable enough for fishermen because the products would be eco-labeled and valued as such.

Management rules: only this narrative allows increasing the fishing effort while artificial reefs for productive purpose are favored and commercial species are reintroduced. The share of fully protected areas is kept to current level (2% of the MPA). Climate change leads to a decline of primary production in marine ecosystems, that would be counterbalanced by a spatial development improving the circulations between lagoons, rivers and sea.

\*Management measures to be taken upstream: permaculture-type farming would improve soil quality; thus, the water runoff would supply rivers with good nutrients that would be transported to the sea and enhance plankton development. To ensure the good quality of water and nutrients, monitoring at the lagoon level should be performed. To avoid any eutrophication phenomenon, nutrients should not be blocked near the coast by facilities, so the channels of the lagoon should be left open and the undeveloped river mouths should be kept free. Aquaculture in the lagoons would also limit this risk.

<u>Climate change</u>	<u>Fisheries</u>	<u>Fully protected areas</u>	<u>Facilities &amp; ecological engineering</u>
Decline of primary production in marine ecosystems counterbalanced by permaculture-type farming and improved circulation between lagoons, rivers and sea	Increased fishing effort but no fishing on any reefs & in fully protected areas <u>Diving</u> Constant number of divers but no access to fully protected areas	Level: actual MPA's target Location: most important natural areas surrounding the existing marine reserve	Increased density of existing artificial reefs villages and creation of new reefs Development of a commercial wind farm Reintroduction of commercial species

<b>Narrative 3: Fostering a new economy</b>			
<p><u>Starting point:</u> it lies in the climate change expected consequences on the coastline and the consideration of a possible radical transformation in coastal livelihoods due to the loss of biomass of the sea induced by a primary production decrease [83]. Even if the sea level rise consequences exceeded our time frame, participants considered it as a major driver of change. They presumed management would fail to prevent sea level rise and decided to put their efforts in making the best of the new resulting land/sea-scape. They invented a new economic model for the park area, valuing marine underwater seascapes, eco-friendly tourism around artificial reefs and wind turbines, or even an underwater museum around aesthetical artificial reef.</p>		<p><u>Management rules:</u> participants assumed a commercial wind farm would be created allowing for a multifunctional exploitation of the water column, including educational sea trips. Artificial reefs villages would be densified to create a relief zone for the rocky coast diving sites. These reefs would have a cultural function, like an underwater museum. Their design would rely on ecological and aesthetical requirements. An intermediary target for fully protected areas was set after Member States Parties to the Convention on Biological Diversity (CBD) agreement to cover 10% of their coastal and marine areas with MPAs by 2020 (CBD Aichi target 11).</p>	
<p><u>Climate change</u></p> <p>Decline of primary production in marine ecosystems</p>	<p><u>Fisheries</u></p> <p>Constant fishing effort but no fishing in fully protected areas only</p> <p><u>Diving</u></p> <p>No access to fully protected areas but increased number of divers with the creation of new recreational reefs</p>	<p><u>Fully protected areas</u></p> <p>Level: intermediary target</p> <p>Location: most important natural areas but first those surrounding the existing marine reserve</p>	<p><u>Facilities &amp; ecological engineering</u></p> <p>Increased density of existing artificial reefs villages and creation of new recreational reefs</p> <p>Development of a commercial wind farm</p> <p>Sea trips around the farm &amp; diving around recreational reefs</p> <p>No reintroduction of species</p>

162

163 Ecosystem-based modeling to address SES complexity

164 Sustainably managing the ocean requires MPA managers to adopt integrated ecosystem-based  
 165 management (EBM) approaches that consider the entire ecosystem, including humans (Figure  
 166 2). While fishing affects target species, marine food webs and habitats (depending on fishing  
 167 and anchoring gear), climate change is expected to influence the dynamics of all marine  
 168 organisms in terms of growth and spatial distribution (including primary production). EBM

169 focuses on maintaining a healthy, productive, and resilient ecosystem so it provides the  
170 functions humans want and need. It requires a transdisciplinary approach that encompasses both  
171 the natural dimension of ecosystems and the social aspects of drivers, impacts and regulation  
172 [39].

173 Whether “end-to-end models” are recommended by marine scientists to study the combined  
174 effects of fishing and climate change on marine ecosystems, using one of these tools was  
175 beyond the scope of the project (see Methods, *Overview of end-to-end models*). We therefore  
176 looked for alternative approaches and built on knowledge and data from the park management  
177 plan and on past research conducted on the area: ecosystem-based quality indexes (EBQI)  
178 describing the functioning of specific ecosystems and mass-balance models analyzing the  
179 overall ecosystem structure and fishing impacts (Ecopath with Ecosim) (see Methods,  
180 *Ecosystems description*). We mapped four major park habitats (see Figure 3): “sandy & mud”  
181 (31 species), “rock” (18 species), “posidonia” (17 species), and “coralligenous” (15 species).  
182 Here, (group of) species are represented in aggregate form (biomass density) and linked  
183 together with diet ratios (see Supplementary Table 1-4).

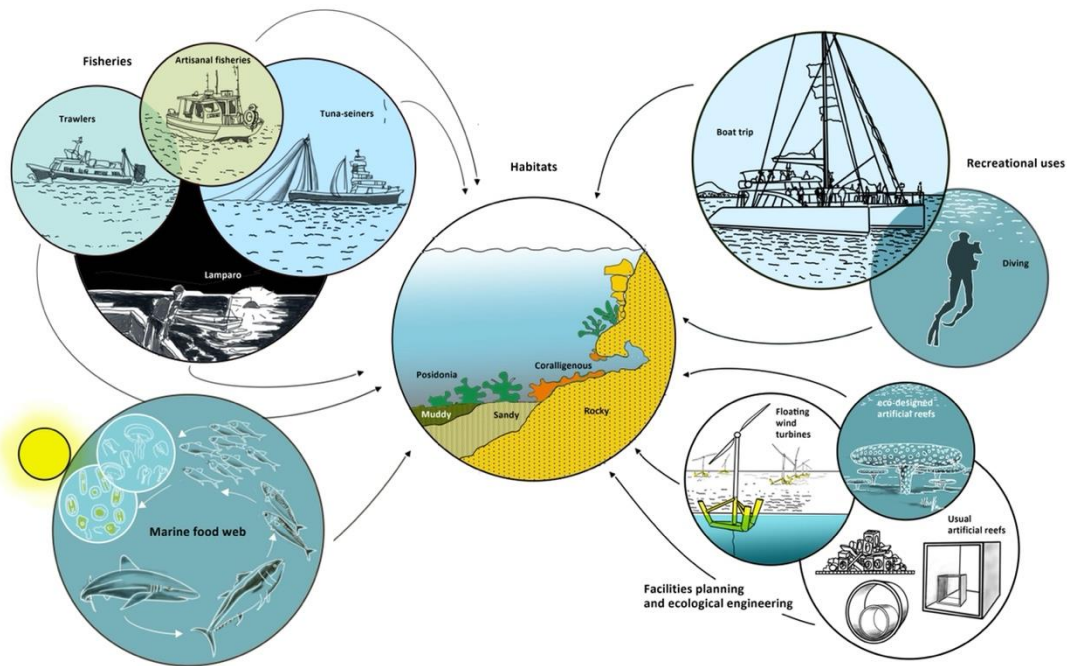
184 This ecosystem-based representation is at the core of our modeling exercise. To simulate  
185 ecosystem dynamics, we used the ecosystem food webs as transmission chains for the type of  
186 controlling factors described in the narratives [40]: bottom-up control (climate, management)  
187 and top-down control (fisheries, management). For each (group of) species, biomass variation  
188 results from the equal combination of two potential drivers on a yearly basis: the abundance of  
189 prey (bottom-up control, positive feedback) and the abundance of predators (top-down control,  
190 negative feedback) (see Methods, *Food-web modelling*). To link this food-web modelling with  
191 the driving factors described in the narratives, we adopted an agent-based modeling framework.  
192 Agent-based models (ABMs) are already used for SES applications and science-policy dialogue  
193 (see Methods, *Rationale for ABM*). We then developed a spatially explicit model for the main

194 dimensions of the MPA described in the narratives. To set up agents and their environments,  
195 we used data from the ecosystem-based representation and geographic information systems  
196 (GIS) layers provided by the MPA team. To model space, we used a regular grid, the size of  
197 each cell being related to the average size of an artificial reef village (0,25 km<sup>2</sup>). In accordance  
198 with our prospective horizon, simulations were run by 2050 with an annual time step.

199 The food-web model is located at the cell level with the previous year's outputs as input data  
200 for each new year. Other human and non-human agents are also represented at the cell level. At  
201 this stage, we modelled temporal dynamics but lacked important spatial dynamics, such as  
202 adaptive behaviors of human and nonhuman agents relocating their activities as a result of  
203 management measures. For now, interactions between agents are mostly made of spatial-  
204 temporal co-occurrence with restricted mobility.

205 Despite this, we were able to simulate the variation in any group of species in terms of biomass  
206 density in the case of a change in primary production, fishing effort, artificial reef planning or  
207 reintroduction of species. To disentangle the efficacy of the MPA's management measures from  
208 climate change impacts, we ran each scenario with and without climate change (see Figure 4).  
209 Indeed, the variation in primary production is the only difference among scenarios that does not  
210 depend on management choices at the MPA level. We could capture some of their propagation  
211 and final effects on indicators similar to those of the park management plan and the ecosystem  
212 function and natural resources targeted by the narratives: total biomass, harvested biomass, and  
213 diving sites access (see Methods, *Modelling of drivers and indicators of ecosystem status*). For  
214 now, all indicators are expressed in biomass quantity and number/share of accessible diving  
215 sites (physical units), not in economic value (monetary units). This would require an accurate  
216 economic analysis, which is to be developed in a future experiment.

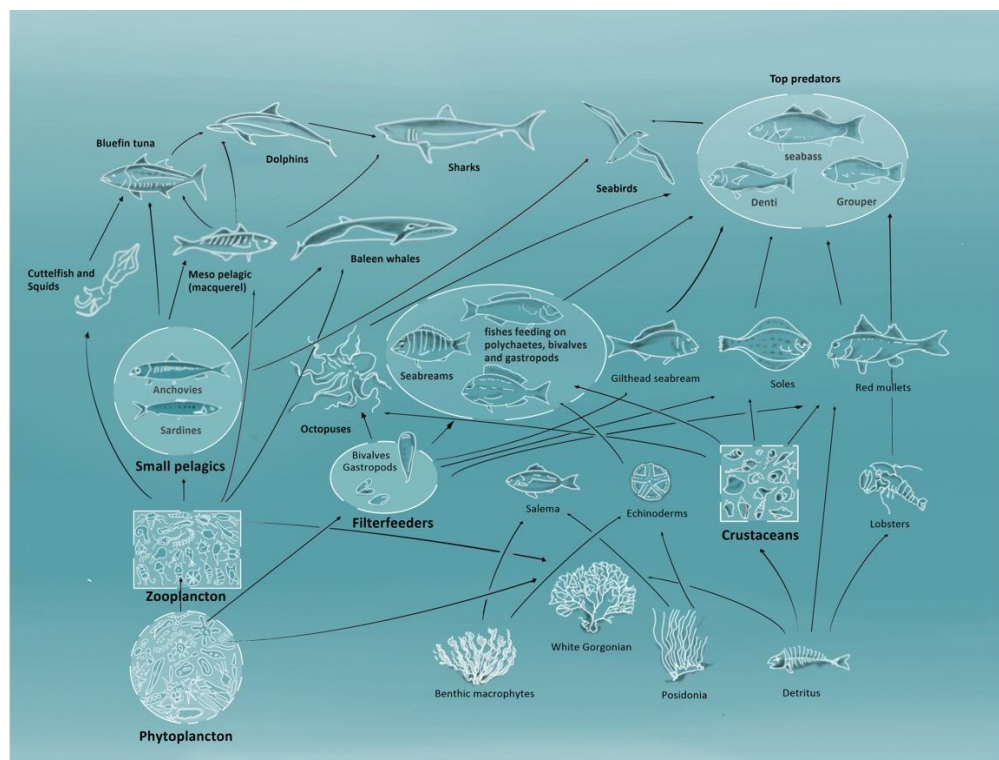
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219

220 **Figure 2 - The social-ecological system (SES) of the Gulf of Lions marine protected area.**

221 Representing the Natural Marine Park of the Gulf of Lions as a social-ecological system outlining the main  
 222 interactions on the territory to be addressed when talking about managing economic activities and environment  
 223 protection. This representation has been issued through conducting a workshop held around a chronological matrix  
 224 summarizing the mean features of the territory.  
 225



226

227

228

229 **Figure 3 – The Gulf of Lions marine protected area food web.**

230 A snapshot of the trophic flows in the ecosystem during a given period describing the ecological functioning of  
231 the Natural Marine Park of the Gulf of Lions.

232

233 Informing management choices based on simulation results

234 No scenario perfectly reached the objectives it was designed for (Figure 4). However, they all  
235 draw interesting perspectives, such as the occurrence of unexpected co-benefits. In effect, the  
236 developed framework allows us to look at the building blocks of the scenarios and the  
237 combination of variables to explain the obtained results, as well as proposing explanations and  
238 suggesting new hypotheses for enhancing the efficacy of each scenario. Table 2 summarizes  
239 the major assumptions of the three scenarios developed by the project team based on the  
240 narratives.

241

242 **Table 2 - Overview of the three scenarios**

243

Topic	Element	Scenario 1 – enhancing total biomass	Scenario 2 – enhancing harvested biomass	Scenario 3 – enhancing diving site access
Climate change - impact on primary production	Phytoplankton biomass density	steady decrease up to -4% by 2050	stable	steady decrease up to -4% by 2050
Sea-users - fisheries	Fishing effort	stable	5% increase from 2019	stable
	Practice area	artisanal fisheries: 0 to -200 meters; 0 to 6 miles trawls: prohibited between 0 to 3 miles		
	Access rights to Full Protected Area (FPA)	no fishing in FPA no transfer to others areas		
Sea-users - diving	Number of divers	stable		
	Practice area	most popular diving sites (from Geographical Information System -GIS-layer)		
	Access rights to FPA	no diving in FPA no transfer to others areas		
Management - FPA	Share of FPA in the Marine Protected Area (MPA)	30% by 2050 after extensions in 2020/2025/2030	2% by 2050 after extensions in 2020/2025/2030	10% by 2050 after extensions in 2020/2025/2030
	Location	1 existing marine reserve (GIS) new FPA: GIS layer scaling important natural areas		
	Allocation rule	overall extension after the level of natural value	extension around the existing reserve	2020: scenario 1 2025/2030: scenarios 1 & 2
Management - artificial reefs	Density of existing artificial reefs villages	stable	steady increase from 12% to 50% between 2019 and 2050	
	New recreational reefs in new villages	no	from sandy habitat to rocky habitat with a density of 50% colonization by marine organisms following three steps between 2019 and 2024	
Management - floating wind turbines	Type of farm	experimental farm of 4 turbines	commercial farm of 80 turbines	
	Location	map of feasible and acceptable areas		
	Allocation rule	development every five years between 2020 and 2045 around more or less acceptable areas		
Management - multi-purpose facilities	Sea trips around the commercial farm	no	no	visitor attendance follows from the development of the farm
	Diving around recreational reefs	no	no	visitor attendance follows from the development of recreational reefs
Management - ecological engineering	Reintroduction of species in existing artificial reefs villages	2020-2025: annual release of 1 heritage specie (grouper)	2020-2025: annual release of 2 commercial species (seabass, dentex)	no

244

245

246 Scenario 1, “Enhancing total biomass”, aimed at increasing biodiversity. Simulation results  
247 showed that undersea biomass varied little (-0.11%) despite the primary production decrease  
248 under climate change (see Supplementary Table 5). However, the trophic chain structure  
249 changed with a large increase in important species to local fisheries (see biomass variation of  
250 each group in Supplementary Table 6-10). For example, mackerel, whiting, hake, tuna,  
251 octopuses, and soles notably increased in muddy and sandy ecosystems; octopuses, seabass,  
252 echinoderms, bivalves, and gastropods in the coralligenous ecosystem; echinoderms, octopuses,  
253 and conger in the rocky ecosystem; suprabenthos, echinoderms, octopuses, conger, and  
254 scorpion fish in the Posidonia ecosystem. The increase in the above listed species is balanced  
255 due to the double prey/predator constraint by a decrease in the biomass of other existing species:  
256 benthic invertebrates and fish feeding on benthic crustaceans in muddy and sandy ecosystems;  
257 benthic macrophytes, scorpion fish, suprabenthos, and lobsters in the coralligenous ecosystem;  
258 suprabenthos, salema, seabass, and scorpion fish in the rocky ecosystem; and, worse, Posidonia  
259 itself, salema, and crabs in the Posidonia ecosystem. Simulation results also showed that fished  
260 biomass drops by 36%, which is consistent with the high share of fully protected areas (FPAs)  
261 in the absence of spatial dynamics and fishing effort relocation. Also, most diving sites that are  
262 currently appealing will no longer be accessible (-98%), which is expected to support habitat  
263 and species biomass regeneration but would mark the end of an attractive activity.

264 Hence, scenario 1 proposed an extension of FPA up to 30% and localized it on the richest areas  
265 in terms of biodiversity, which leads to a sharp drop in the potential fished biomass indicator.  
266 While this strong protection may not be sufficient to trigger system recovery as a whole, it  
267 greatly changes the trophic chain structure, improving the biomass of some very important  
268 targeted fishing species (see Supplementary Table 6-10). This improvement could be seen as a  
269 co-benefit aligned with the analysis by Sala et al. [10]. It opens avenues to move forward in

270 searching for “win-win” strategies and opens a perspective of co-benefits for local fisheries in  
271 case spillovers occur and adequate fisheries management rules are to be defined.  
272 Moreover, if coupled with the same kind of measures that allow us to cancel the negative effect  
273 of climate change on primary production (as in scenario 2), scenario 1 would exhibit the best  
274 results in terms of total and undersea biomass variation, although these two indicators are  
275 insufficient to assess the quality of the ecosystem. Two hypotheses could be further tested: (i)  
276 the time horizon may not be sufficient, and/or (ii) the intensity of the reintroduction of grouper  
277 as a keystone species is insufficient given its low reproduction rate and longevity. Nevertheless,  
278 it would be interesting to review this scenario searching co-benefits strategies. A new version  
279 of the model could test pairing spatial use rights and different levels of protection within  
280 strategic zoning and a connected MPA network. It could also consider the spillover of marine  
281 organisms and the relocation of human activities due to FPA. In this case, it would be important  
282 to determine if the spillover of marine species would be enough so that the relocation of the  
283 fishing effort would not significantly affect ecosystem functioning of unprotected areas. In a  
284 timely manner, additional measures regulating the fishing effort from a strategic  
285 planning/zoning perspective should complement the framework.

286

287 Scenario 2, “Enhancing harvested biomass”, aimed at increasing food provisioning. Simulation  
288 results showed that total fished biomass increases by 2% with or without considering climate  
289 change impacts on primary production, which matches the guideline of the narrative. However,  
290 fished biomass increases only in the muddy habitat, by more than 3%, while it decreases by  
291 between -3 and -32% in the other habitats, as a result of the counterbalancing effect of keeping  
292 the 2% share of FPA. Interestingly, the total biomass in the rocky habitat decreases less (with  
293 climate change) or even increases (without climate change) in scenario 2 compared to scenario  
294 1.

295 At the same time, while undersea biomass seems stable when climate change is not included (-  
296 0.03%), it will decrease with primary production (-0.89%) in contrast with scenario 1. Indeed,  
297 when compared to scenario 1, few species showed significant downward variation, except crabs  
298 in the Posidonia ecosystem. Also, even with the smallest FPA's share, currently appealing  
299 diving sites are reduced by 63%, which confirms that most existing diving spots are  
300 concentrated in areas of high natural value in or around the existing MPA.

301 Scenario 2 favors fishing by increasing fishing effort (5%) and limiting FPA (2%). It also  
302 supports fishing with the reintroduction of target species and the densification of the species'  
303 habitats. This scenario notably avoids the negative effects of climate change on primary  
304 production due to ecological measures taken at the watershed level. However, comparative  
305 simulation results illustrate that marine park management measures alone would not generate  
306 such an effect. In view of the results, the fishing effort may have been increased too early,  
307 thereby cancelling out the efforts made elsewhere. Moreover, catches might have been higher  
308 if the model had considered a shift of fishing activities from FPA to areas where fishing is  
309 allowed. Here, FPAs are located on rocky, Posidonia, and coralligenous habitats, which are  
310 areas of greatest natural value (GIS layer). Even if the share of FPA is the lowest in this  
311 scenario, almost all of the rocky habitat (excluding artificial reefs) is considered, which is one  
312 reason explaining the biomass increase in this habitat. This shows the importance of precise  
313 and strategic zoning in determining access rules in MPAs. This is also due to the densification  
314 of existing villages of artificial reefs and the creation of new villages in the rocky habitat. Three  
315 new hypotheses could be further tested: (i) maintaining the fishing effort at its 2018 level, (ii)  
316 increasing the introduction of target species, and (iii) enhancing the functioning of the trophic  
317 chain by reintroducing keystone species rather than target species of fishing?

318

319

320 Finally, scenario 3, “Enhancing diving site access”, aimed at increasing eco-tourism.  
321 Simulation results indicated that the main objective of the scenario is not achieved since diving  
322 access is restricted by 100% and 91% respectively in the coralligenous and rocky habitats, that  
323 host most currently appealing diving sites. At the same time, undersea biomass (and total  
324 biomass) decreases more than in scenario 1 (-0.6%) and less than in scenario 2 in the same  
325 climatic context of primary production reduction, reflecting the difference in FPA cover of the  
326 different scenarios. Interestingly, despite taking for granted the loss of historical ecosystems  
327 and traditional economic activities, and including primary production reduction, the total  
328 biomass increases by 0.12% in the rocky habitat, which is again a better score than what  
329 scenario 1 reached. Finally, fished biomass lowers by 14%, due to a 10% FPA’s share, which  
330 is in accordance with a narrative that promotes the creation of alternative economic activities.  
331 Scenario 3 is the scenario that produces the most impressive results since diving site access was  
332 in sharp decrease, whereas the scenario was supposed to favor it. These results’ explanation lies  
333 in a contradiction between the assumptions of the narrative. In fact, by placing 10% of the  
334 territory under full protection and locating these areas on sites of high biodiversity, FPAs are  
335 located on the very sites favored by divers. This contradiction between the goal of this narrative  
336 and the restricted access to FPA proves to be a determining factor in the success of the scenario.  
337 Retrospectively, this may seem obvious, but the exact delimitation of access rules to protected  
338 areas remains a hot topic. This scenario is of high interest because it illustrates an actual  
339 dilemma and confirms scenario 2’s analysis that access rules need to be aligned and defined  
340 with precise and strategic zoning. Other hypotheses to be tested include allowing recreational  
341 diving access to FPA, while extractive activities remain prohibited.

342



343  
344

345 **Figure 4 - Simulation results for the scenario 1 (S1), scenario 2 (S2), scenario 3 (S3) in**  
346 **each ecosystem.**

347 Those three scenarios correspond to the narratives that emerged from stakeholders' groups (SG) (see table 1).  
348 Scenarios 1 and 3 make no special provision for the effects of climate change and therefore include an  
349 assumption about the effects of climate change (CC) in the form of reduced primary production. They are rated  
350 "+ CC". On the other hand, narrative 2 and thus scenario 2 provides for combating climate change, therefore it  
351 does not include an assumption regarding the impacts of climate change and is scored "no CC".  
352 S1 + CC: enhancing total biomass with primary production decreasing due to climate change  
353 S2 no CC: enhancing harvested biomass without decreasing primary production  
354 S3 + CC: enhancing diving sites access with primary production decreasing due to climate change.  
355 **a** evolution of the total biomass representing the evolution of the sum of biomass of all species in each ecosystem  
356 between 2018 and 2050. **b** evolution of the undersea biomass representing the evolution of the difference between  
357 the total biomass and the fished species biomass in each ecosystem between 2018 and 2050. **c** evolution of the  
358 fished biomass representing the evolution of the sum of biomass of all fished species in each ecosystem between  
359 2018 and 2050. **d** evolution of the diving sites access in each ecosystem between 2018 and 2050. **e** evolution of  
360 the share of fully protected areas in each ecosystem between 2018 and 2050.

361

362

## 363 **Discussion**

364 Our analysis highlights the usefulness of using a three-step (plus one) framework, hybridizing  
365 a collaborative modeling approach and a decision-making process (Figure 1) as a way to  
366 identify both the future desired for an MPA and the pathways to get there. Similar collaborative  
367 approaches have been developed by the Commod community [19]. A Commod-type project  
368 can focus on the production of knowledge to improve understanding of the actual SES, or it can  
369 go further and be part of a concerted effort to transform interaction practices with the resource  
370 or forms of socio-economic interactions [19]. Ours is original as it aims not only to share a  
371 common understanding of the SES at present and help solve current challenges, but also to  
372 anticipate and create a shared future. Indeed, the proposed framework allows discussion of  
373 hypotheses concerning the future of the management area, which enables the reshaping of our  
374 thinking and the potential framing of new strategies. The framework acts as a dialogue space  
375 for people concerned with SES and willing to support the implementation of management plans.  
376 This dialogue space offers the possibility to realize that there is a difference between  
377 expectations or likely effects of management options and the complexity of reality. Indeed, the  
378 simulation results only sometimes illustrated the expected effects of the narratives. In this  
379 respect, our method paves the way for questioning beliefs, which did not occur in previous  
380 similar studies [10]. It contributes to moving to informed-based strategies, as recommended by

381 Cvitamovic et al. [41]. The science-policy future experiments we conducted considered place-  
382 based issues, participants knowledge, and imaginaries. Scientists coming from ecology and  
383 social sciences, decision-makers, and other MPA stakeholders all found the approach to be  
384 groundbreaking; by opening the box of scriptwriting, involved stakeholders experienced a way  
385 to construct new narratives and broaden solutions for ocean use, as advocated by Lubchenco  
386 and Gaines [38]. However, such an approach must be taken cautiously, as it is time-consuming  
387 for all participants. At the beginning of the project, participants shared concerns about the  
388 usefulness of a prospective approach not connected to a real political agenda. The mobilization  
389 of tools during the workshops (see Methods, *Prospective workshops*) was beneficial to show  
390 how much the approach was anchored in reality, and allowed for creating a common ground.  
391 In the end, most participants underlined how instructive it was to meet with each other and  
392 exchange viewpoints on challenges concerning the future of the MPA rather than being  
393 consulted separately as it usually happens.

394 Another interesting point is that the proposed framework fosters anticipatory governance  
395 capacity by testing assumptions, understanding interdependencies, and sparking discussions. It  
396 avoids policymakers acting in their own jurisdiction generating spillovers that modify the  
397 evolutionary pathways of related SESs or constraining the adaptive capacity of other  
398 policymakers [42]. Lack of coordination between policy actors across jurisdictions and  
399 incomplete analysis of potential cascading effects in complex policy contexts can lead to  
400 maladaptation [42]. In this regard, our framework can contribute to understanding the marine  
401 space as a "commons" [43.] and to resolving issues facing an MPA as a decentralized  
402 governance institution. Marine parks are social constructs that must build on historical legacy  
403 and be invested with new commonalities to become legitimate and formulate acceptable,  
404 sustainable policies (see Supplementary Note 1).

405 The framework also allowed to collaboratively explore the impacts of alternative management  
406 scenarios on marine SESs considering climate change, identifying benefits and beneficiaries,  
407 and resulting trade-offs among ecological functions supporting them. This experience led to  
408 interesting conclusions from the simulation results themselves. The latter showed that co-  
409 benefits may arise and be favored by a precise and coherent system of rules of access and uses  
410 complementing a more physical, biological, and ecological set of measures. Our findings  
411 showed that some trade-offs might satisfy several objectives, even if not those targeted first,  
412 opening the way to potential co-benefits, as shown by [10]. For instance, the strong protection  
413 extension in scenario 1 changed each species' biomass distribution within each ecosystem,  
414 improving the biomass of some important fished species and opening avenues to search for  
415 "win-win" strategies. Similarly, measures allowing us to cancel the negative effect of climate  
416 change on primary production proposed in scenario 2 would increase the total biomass together  
417 with maintaining biodiversity in scenario 1.

418 More generally, this research developed a companion modeling framework that would enable  
419 us to move forward in the search for win-win strategies by pairing strategic zoning of high  
420 protection and access rules. As far as we know, the co-designed model we developed is the only  
421 agent-based model combining collaborative and ecosystem-based modelling that can be used  
422 as a lab experiment to identify co-benefiting strategies in marine spaces. Nevertheless, some  
423 improvements are needed. There are avenues insofar as the model suffers from shortcomings.

424 The first difficulty faced in the modelling exercise was the mismatch between spatial scales of  
425 ecological and climate modelling. While the former operates at the habitat scale (1 km<sup>2</sup>), the  
426 latter provides smoothed environmental variables at a resolution larger than 50 km<sup>2</sup>,  
427 unresolving taking into account thresholds leading to life cycle bottlenecks for instance. The  
428 latter points to the need to downscale climate projections at relevant scales for ecosystem  
429 functioning. Other concern relies on improving the modeling tool by describing spatiotemporal

430 dynamics arising from the spillover of marine organisms [44], the resilience brought by  
431 population connectivity [45], and the relocation of human activities [46]. Proceeding to a  
432 sensitivity analysis, or building alternative outputs indicators, allows disentangling and clarifies  
433 the different modelled effects inside each scenario. There is a tension here between re-writing  
434 scenarios and pertaining their collaborative scriptwriting which led to the scenarios  
435 implemented, very meaningful about the richness of the stakeholder's engagement.

436 Finally, marine management should be an inclusive, iterative process, where modeling acts as  
437 an ongoing exploratory experiment to identify the conditions under which co-benefits and win-  
438 win strategies can be realized. Hence, the modeling process facilitates interactions between  
439 participants in a transparent and open process. One can thus imagine working sequentially until  
440 satisfactory results are obtained for any stakeholder involved. This search for a hybridized  
441 collaboration framework in the construction of policies proves particularly fruitful in creating  
442 a shared future and looking for sustainability.

443

444

445

## 446 **Methods**

447

### 448 **Prospective workshops**

449 Each of the three groups focused on fostering one of the three ecosystems' functions considered:  
450 production of total biomass, fish stock level for fishing activities or potential access to diving sites. They  
451 allow us to work on interactions between biodiversity conservation and economic development. Proxys  
452 used and related to these ecosystem functions are also aligned with the ones used in the park  
453 management plan, which helps for science-policy dialogue.

454 To reach the objectives of the narratives, participants were especially requested to give indications about  
455 considering climate change impact or not, fishing effort evolution, spatial sea-users' rights (FPA),  
456 facilities planning (artificial reefs, floating wind turbines, harbors and breakwaters, multipurpose  
457 facilities) and ecological engineering (reintroduction of species), the main features of the social-  
458 ecological representation on which we all agreed (see Figure 2). In order to help envisioning disruptive  
459 changes, we decided to draw on possible future land/sea-scapes of the MPA. Here land/sea-scapes are  
460 understood in several aspects: coastal viewpoint, marine natural or artificial habitats, above/undersea  
461 marine space occupation by humans and non-humans. To do so, we introduced visual tools during the  
462 prospective workshops (see Supplementary Note 1):

463 i) an archetypal map of the MPA including typical features to recall main territorial issues without being  
464 trapped in too specific considerations: a city by the sea, the mouth of a river, an estuary, a rocky coast,  
465 a sandy coast;

466 ii) tokens related to the available means to reach the narratives' objectives: ecosystem status (primary  
467 production), fisheries evolution (fishing effort), facilities planning & ecological engineering (esthetical  
468 artificial reefs, floating wind turbines, harbors and break walls, reintroduction of species), sea-users'  
469 access and regulation (recreational uses and fully protected areas). Tokens were used to inform  
470 participants about the localization and intensity of each item, which helped shape the participant's vision  
471 of the future and link with the simulation model.

472 iii) cards describing real-world examples of what tokens stand for. They were used to broaden the  
473 participants' thinking scope by introducing stories in foreign places and at different times. Here, they  
474 helped illustrate alternative options among scenarios.

475

#### 476 **Overview of end-to-end models**

477 End-to-end models represent the different ecosystem components from primary producers to top  
478 predators, linked through trophic interactions and affected by the abiotic environment [47]. They allow  
479 the study of the combined effects of fishing and climate change on marine ecosystems by coupling  
480 hydrodynamic, biogeochemical, biological and fisheries models. Some are suited to explore the impact  
481 of management measures on fisheries dynamics with an explicit description of fishing stocks' spatial  
482 and seasonal dynamics, fishing activities and access rights (ISIS-Fish) [48, 49, 50] but they do not  
483 represent environmental conditions or trophic interactions, so their capacity to simulate the impact of  
484 fisheries management on ecosystem dynamics and possible feedbacks is limited.

485 Others explicitly model trophic interactions between uniform ecological groups with biomass flows  
486 based on diet matrixes (Ecopath with Ecosim [51], Atlantis). They rely on the assumption that major  
487 features of marine ecosystems depend on their trophic structure; thus, there is no need to detail each  
488 species to describe the state and dynamics of the ecosystem. They can be used to explore the evolution  
489 of the system under variations in biological or fishery conditions but may lack flexibility to simulate  
490 regime shifts due to radical variations in such conditions.

491 Some others do not set a priori trophic interactions, which are considered too rigid to explore the  
492 nonlinear effects of both fishing and change in primary production. They describe predation as an  
493 opportunistic process that depends on spatial co-occurrence and size adequacy between a predator and  
494 its prey (OSMOSE). Due to the simulation of emergent trophic interactions, it is particularly relevant to  
495 explore the single or combined effects of fishing, management and climate change on ecosystem  
496 dynamics. However, they do not properly describe fisheries dynamics (fixed fishing mortality) and must  
497 be coupled with fleet dynamics models (dynamic effort allocation) [52].

498

499

## 500 **Ecosystems description**

501 First, we selected three publications describing the specific ecosystem functioning associated with  
502 marine park habitats: the Mediterranean seagrass ecosystem [53], the coralligenous ecosystem [54] and  
503 the algae-dominated rocky reef ecosystem [55].

504 Second, we selected two publications using the same mass-balance model (EwE) to analyze the overall  
505 ecosystem structure and fishing impacts in the Gulf of Lion [56] and the northwestern Mediterranean  
506 Sea [57]. They both provide a snapshot of the trophic flows in the ecosystem during a given period,  
507 which is based on a consistent set of detailed data for each group of species: biomass density, food  
508 requirements (diet matrix), mortality by predation and mortality by fishing. The former focuses on the  
509 Gulf of Lion but depicts a larger area than that of the park in terms of distance to the shore and especially  
510 depth (-2500 m against -1200 m). Thus, the rocky reef ecosystem that exists within the park is “masked”  
511 by the prevalence of sandy/muddy habitats. The latter depicts a wider part of the Mediterranean Sea but  
512 is comparable to the park in terms of depth (- 1000 m against -1200 m) and provides useful information  
513 on the rocky reef ecosystem.

514 Each ecosystem represents the following proportion of the whole system: muddy = 85.57%, sandy =  
515 12.23%, rocky = 1.75, posidonia = 0.23 and coralligenous = 0.22%. For “rocky”, “posidonia” and  
516 “coralligenous”, we selected corresponding ecological groups and associated data (Ewe) from functional  
517 compartments (EBQI). For “sandy&muddy”, we created an ad hoc conceptual model of the ecosystem  
518 functioning from the Gulf of Lion trophic chain (Ewe).

519

## 520 **Food-web modeling**

521 For each related group of species, the variation in the average density results from the equal combination  
522 of two potential drivers on a yearly basis: the abundance of prey (bottom-up control, positive feedback)  
523 and the abundance of predators (top-down control, negative feedback). To do so, we use data from the  
524 EwE publications listed above: biomass density, food requirements (diet matrix), mortality by predation  
525 and by fishing (see Supplementary Table 11-14). For one species, the White gorgonian (*Eunicella*  
526 *Singularis*), we use site-specific data produced during the RocConnect project [58].

527 To model the effect of prey abundance on their predators, the biomass of each group of species is  
528 described as the sum of its annual food requirements, detailing each prey (see Supplementary Table 1-  
529 4). While nothing happens to a prey species, there is no change in prey abundance, and the biomass of  
530 each predator species remains the same. If anything happens to a prey species, this translates into that  
531 species density, which then reflects its availability for feeding predators and eventually affects the  
532 biomass of predator species. The effect on the biomass of predator species is proportional to the change  
533 in prey species density and to the specific weight of prey species in each predator's diet. In other words,  
534 the more prey there is at the beginning of the period, the more of its predators there could be at the end.  
535 To model the effect of predator abundance on their prey, we follow the reciprocal reasoning of the above  
536 mechanism. Here, the biomass of each group of species is described as the sum of its annual catches by  
537 each other species (see Supplementary Table 1-4). Here again, while nothing happens to a predator's  
538 species, there is no change in predator abundance, and the biomass of each prey species remains the  
539 same. If anything happens to a predator's species, this translates into that species density, which is then  
540 reflected in its food requirements and eventually affects the biomass of prey species. However, this time,  
541 the effect on the biomass of prey species is inversely proportional to the change in predator species  
542 density and to the specific weight of predator species in each prey's mortality. In other words, the more  
543 predators there are at the beginning of the period, the less prey there could be at the end.  
544 There are only two exceptions to this rule: phytoplankton and detritus. The production of phytoplankton  
545 relies on photosynthesis, which requires water, light, carbon dioxide and mineral nutrients. These  
546 elements are beyond our representation, so we impose the value of the phytoplankton biomass density  
547 at each time step. Additionally, the value of phytoplankton biomass density is the variable used to  
548 represent the expected effect of climate change on primary production. The production of detritus comes  
549 from three sources: natural detritus, discards and bycatch of sea turtles, seabirds and cetaceans. In other  
550 words, the amount of detritus depends on the activity of other marine organisms. Here, we model the  
551 amount of detritus as a constant share of the total annual biomass.

552

553

554

## 555 **Rationale for ABM**

556 Most studies on MPA analyze how they succeed from an ecological point of view [56]. Few others  
557 argue about the conditions under which they succeed from a socio-economical or cultural point of view  
558 ([3], [59, 60, 61, 62, 63, 64]). Little work embraces both aspects of MPA [65, 66, 67]. Currently, agent-  
559 based models (ABMs) are convenient methods to integrate ecological and socioeconomic dynamics and  
560 are already used by researchers in ecology or economics for ecosystem management [68, 69, 70]. ABMs  
561 allow the consideration of any kind of agent with different functioning and organization levels [70, 71],  
562 including human activities, marine food webs and facilities planning. ABMs are also usually spatially  
563 explicit, which favors connecting with narratives that are spatially explicit too. Basically, an agent is a  
564 computer system that is located in an environment and that acts autonomously to meet its objectives.  
565 Here, environment means any natural and/or social phenomena that potentially have an impact on the  
566 agent.

567 For these reasons, ABMs are convenient methods to deal with SESs. The possibility of providing each  
568 kind of agent with a representation of the environment, according to specific perception criteria, is  
569 particularly interesting for applications in the field of renewable resource management [19]. The ABM  
570 developed for SES management usually integrates an explicit representation of space: a grid with each  
571 cell corresponding to a homogeneous portion of space. Time is generally segmented into regular time  
572 steps. The simulation horizon (total time steps) corresponds to the prospective horizon.

573

## 574 **Modelling of drivers and indicators of ecosystem status**

575 In the Mediterranean Sea, current scientific consensus outlines a reduction of the primary production  
576 and changes in species composition in the ecosystems as an effect of climate change. However, trophic  
577 network re-organization linked to these species' composition changes is still an open debate. Hence, to  
578 model the expected effect of climate change on the ecosystems Natural Marine Park of the Gulf of Lions,  
579 we build on IPCC projections that consider a 10% to 20% decrease in net primary production under low  
580 latitudes by 2100 due to reduced vertical nutrient supply [72, 73]. Indeed, combined consequences of  
581 climate change like water temperature increase and hydric stress act synergistically to reduce primary  
582 production. The former reinforces stratification of surface waters resulting in a reduction in the supply

583 of nutrients which leads to a decrease in primary production. The second also leads to a decrease in  
584 nutrients from the rivers to the sea impacting primary production Applied to our simulation horizon, this  
585 can be translated into an annual steady decrease of up to -4% in phytoplankton biomass density between  
586 2018 and 2050.

587

588 To model fisheries, we use the same rule as to model the effect of predator abundance on their prey, but  
589 here, this represents the effect of fishing effort on harvested species. As our entry point is traditional  
590 small-scale multispecies fisheries, we do not directly modify fishing effort by species but rather by  
591 fishing gear [56]. A change in the fishing effort of a given fishing gear first affects the total biomass of  
592 its harvested species and then is allocated between each species after the fishing ratio from the base year.

593 Thanks to the EwE publication on the Gulf of Lion and included data on landings by gear and by species  
594 [56], we were able to distinguish 4 fishing gear: trawls, tuna seiners, lamparos (traditional kind of night-  
595 time fishing using light to attract small pelagics), and other artisanal fishing gear. It does not include  
596 recreational fishing. To spatialize fisheries, we do not associate each fishing gear with specific locations  
597 or habitats: fishing effort by fishing gear is the same all over the area, with two exceptions. The former  
598 refers to FPA areas where any kind of fishing is forbidden (Cerbère-Banyuls Natural Marine Reserve).

599 The latter refers to trawls and artisanal fisheries whose activity is constrained by practical or legal  
600 concerns. First, it is known that artisanal fisheries work mostly near the coast up to a maximum distance  
601 of 6 nautical miles and a maximum depth of -200 meters. Second, trawls are prohibited between 0 and  
602 3 nautical miles (2013 Trawl Management Plan). Here, we do not model transfer effects between sites  
603 or towards new sites.

604

605 To model diving, we use a GIS layer indicating the most popular diving sites in the park. With each  
606 diving site, we associate an annual number of visitors that fits known trends. Here, changes in diver  
607 attendance depend on the extent of fully protected areas prohibiting this practice. Here, again, we do not  
608 model transfer effects between sites or towards new sites.

609

610 To model FPA and access rights, we use a GIS layer indicating the boundaries of the existing FPA  
611 (Cerbère-Banyuls Natural Marine Reserve). There fishing is prohibited. To model the creation of the  
612 new FPA, we target important natural areas. To do so, we use a GIS layer corresponding to a map from  
613 the park management plan that indicates important natural areas (see Supplementary Figure 1a-b). More  
614 precisely, the map scales areas after their natural value using a “heat gradient” (see management plan  
615 for details). To reach the level of protection expected in each scenario, we downgraded the level of  
616 natural value required to be designated an FPA every five years between 2020 and 2030. Here, these  
617 levels of natural value are chosen to get closer to the expected level of protection. Areas to be protected  
618 are designated after their natural value, but the rules of attribution slightly change among scenarios.  
619 When protecting a large portion of the MPA (scenario 1, Supplementary Figure 2), there is no need to  
620 first target a specific area: one is sure that all areas of great natural value will be included in the protected  
621 perimeter. Here, we seek to make progress on the overall MPA, and the only criterion to be designated  
622 a protected area refers to the level of natural value. When protecting a small portion of the MPA  
623 (scenario 2), one may want to make sure to protect consistent areas of great natural value rather than  
624 sparse micro hot points. To do so, we target the existing Marine Reserve and let new protected areas  
625 develop in its surroundings. When protecting a medium portion of the MPA (scenario 3), we use a  
626 combination of the two previous rules: in 2020, we target the surroundings of the Marine Reserve to be  
627 sure to protect this area of greatest natural value, while in 2025 and 2030, we also let protected areas  
628 develop elsewhere, after the local level of natural value. Concerning access rights, fully protected areas  
629 were intended as “no go, no take” zones/integral reserves during the workshops. Thus, we prohibit  
630 fishing and diving in the corresponding perimeters.

631

632 To model facilities planning, we select artificial reefs and floating wind turbines. We do not represent  
633 harbors and break walls, as they were much likely associated with sea level rise during the workshops.  
634 This is a major issue but beyond the scope of this ecosystem-based modeling.

635

636 To model ecological engineering and artificial reefs implementation, we use a GIS layer indicating their  
637 location, and we assume that they are comparable to natural rocky reefs [74]. Thus, existing artificial

638 reefs are associated with the same food web as the Rock ecosystem cited above. According to expert  
639 opinion, the occupancy rate of existing artificial reef villages inside the park is approximately 12%. To  
640 model their densification, we impose a steady annual increase in the biomass of each species until it  
641 reaches the equivalent of a 50% occupancy rate by 2050. To model the installation of new reefs in new  
642 villages, we replace a portion of sandy habitat with rocky habitat corresponding to an occupancy rate of  
643 50%. Then, we describe a three-step colonization by marine organisms: (i) a pioneer phase of 1 year  
644 with the development of phytoplankton, zooplankton, detritus, macroalgae and worms; (ii) a maturation  
645 phase of 2 to 5 years with the development of supra-benthos, gorgonians, benthic invertebrates, sea  
646 urchins, octopuses and bivalve gastropods; (iii) a completion phase after 5 years, with the development  
647 of salema, sparidae, seabream, conger, seabass, scorpion fish, and picarel [74].

648

649 To model floating wind turbines, we create a GIS layer from a map used by the management team of  
650 the park to initiate debates with stakeholders on possible locations of already approved experimental  
651 turbines and possible new commercial ones. During the workshops and the project team meetings, two  
652 possible adverse effects of floating turbines on the ecosystem were discussed. Some determined that the  
653 floating base and the anchorages would have a sort of “fish aggregating device” effect, while the location  
654 area would be prohibited from fishing. Other thought antifouling paint would prevent such an effect,  
655 while ultrasounds due to the functioning of turbines would trouble cetaceans. Here, we do not model  
656 these alternative effects because of time constraints and lack of scientific evidence and data to our  
657 knowledge. We model their possible progressive development every five years between 2020 and 2045  
658 around the “overall” and “most acceptable” areas designated by the map using a propagation rule in the  
659 surroundings of already approved experimental turbines.

660

661 To model multipurpose facilities, we add attendance indicators to artificial reefs and floating turbines in  
662 some cases. In scenarios 2 and 3, the development of a commercial wind farm is associated with the  
663 development of a touristic dedicated activity consisting of sea-visiting the area, explaining its purpose  
664 and possible effects on ecosystems. With each turbine, we associate an annual number of visitors  
665 deduced from assumptions on the number of opening days by year, number of visits by day, and number

666 of passengers by visit. Here, visitor attendance follows from the development of a commercial wind  
667 farm. In scenario 3, a few artificial reefs are developed with both ecological and aesthetic concerns and  
668 are associated with the development of a dedicated diving activity. With each reef, we associate an  
669 annual number of divers deduced from assumptions on the number of opening days by year, number of  
670 visits by day, and number of divers by visit. Here, visitors' attendance follows from recreational reef  
671 development. Two aesthetic artificial reef villages are being developed in 2025 and 2035.

672

673 To model the reintroduction of species, we focus on one heritage species in scenario 1 (grouper) and on  
674 two commercial species in scenario 2 (seabass and dentex). Concerning sites of reintroduction, we  
675 targeted rocky ecosystems and specifically existing artificial reef villages. Each year between 2020 and  
676 2025, we repopulate from juveniles and adult individuals expressed in biomass equivalents. Here,  
677 priority is given to meeting the food needs of reintroduced species, corresponding to their estimated  
678 biomass levels, even if at the expense of the already established species. As biomass levels of  
679 reintroduced species are of the same order as those of top predators already represented in the rock  
680 ecosystem, this hypothetical situation calls for a later more complex representation of their competition  
681 for food.

682

683 **Contributions**

684 All authors wrote and reviewed the main text. Catherine Boemare, Arancha Sanchez and  
685 Xavier Lagurgue designed Figure 1. Elsa Mosseri and Xavier Lagurgue designed Figures 2  
686 and 3. Elsa Mosseri and Catherine Boemare designed Figure 4. Elsa Mosseri coded the agent-  
687 based model.

688

689 **Competing interests**

690 The authors declare no competing financial or non-financial Interests

691

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696

697 **Data availability**

698 The data that support the findings of this study are available in the Supplementary Materials.

699

700 **Code availability**

701 The code that supports the findings of this study is available on GitHub at:

702 <https://github.com/elsamosseri/SAFRAN>

703

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