



HAL
open science

Current and potential contributions of the Gulf of Lion Fisheries Restricted Area to fisheries sustainability in the NW Mediterranean Sea

Daniel Vilas, Marta Coll, Xavier Corrales, Jeroen Steenbeek, Chiara Piroddi, Diego Macias, Alessandro Ligas, Paolo Sartor, Joachim Claudet

► To cite this version:

Daniel Vilas, Marta Coll, Xavier Corrales, Jeroen Steenbeek, Chiara Piroddi, et al.. Current and potential contributions of the Gulf of Lion Fisheries Restricted Area to fisheries sustainability in the NW Mediterranean Sea. *Marine Policy*, 2021, 123, pp.104296. 10.1016/j.marpol.2020.104296 . hal-03025079

HAL Id: hal-03025079

<https://hal.science/hal-03025079v1>

Submitted on 7 Dec 2020

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

1 **Current and potential contributions of the Gulf of Lion Fisheries Restricted**

2 **Area to fisheries sustainability in the NW Mediterranean Sea**

3

4 **Authors**

5 Daniel Vilas*^{1,2,3}, Marta Coll^{1,4}, Xavier Corrales^{1,4,5}, Jeroen Steenbeek⁴, Chiara
6 Piroddi⁶, Diego Macias⁶, Alessandro Ligas⁷, Paolo Sartor⁷ and Joachim Claudet⁸

7 **Affiliations**

8 ¹ Institut de Ciències del Mar (ICM-CSIC), P. Marítim de la Barceloneta, 37-49, 08003
9 Barcelona, Spain.

10 ² Nature Coast Biological Station, Institute of Food and Agricultural Sciences, University of
11 Florida, Cedar Key, FL 32625, United States.

12 ³ Fisheries and Aquatic Sciences Program, School of Forest Resources and Conservation,
13 University of Florida, Gainesville, FL 32611, United States.

14 ⁴ Ecopath International Initiative (EII), Barcelona, Spain.

15 ⁵ AZTI, Marine Research, Txatxarramendi Ugarte a z/g. E-48395, Sukarrieta, Spain.

16 ⁶ European Commission, Joint Research Centre, Institute for Environment and
17 Sustainability, Via Fermi 2749, 21027 Ispra, Italy.

18 ⁷ Consorzio per il Centro Interuniversitario di Biologia Marina ed Ecologia Applicata
19 "G.Bacci", Italy.

20 ⁸ National Center for Scientific Research, PSL Université Paris, CRIOBE, USR 3278
21 CNRS-EPHE-UPVD, Maison des Océans, 195 rue Saint-Jacques 75005 Paris, France.

22

23 **Abstract**

24 Among FAO's Major Fishing Areas, the Mediterranean and the Black Sea had the
25 highest percentage (62.5%) of stocks fished at unsustainable levels, especially demersal
26 stocks. Spatial-temporal restrictions of fishing activities are important measures used for
27 the management of marine stocks. However, sometimes these regulations are not fully

28 implemented due to a lack of effectiveness and compliance, which contributes to their
29 failure. Here, we developed a food-web model approach using the Ecopath with Ecosim
30 (EwE) model representing the Fisheries Restricted Area (FRA) of the Gulf of Lion
31 ecosystem (CoSEGoL model) prior to the establishment of the fisheries restrictions (2006-
32 2008). We characterized the structure and functioning of the ecosystem before and after
33 its establishment. The constructed food-web model was then fitted to the available time
34 series of data from 2008 to 2016 to verify whether this FRA has contributed to the recovery
35 of target demersal species and the demersal community. The fitted model was used to
36 explore alternative future management scenarios to explore feasible management options
37 in order to ensure a full ecosystem recovery under climate change conditions. Our results
38 suggest a failure in the recovery of target species in the restricted area under the current
39 management scenario, potentially revealing a lack of protection efficiency and/or
40 enforcement. Scenarios of management options under plausible climate futures revealed
41 possible recovery of targeted species, especially European hake. The study highlighted
42 the importance of considering trophic interactions between predators and prey to identify
43 trade-offs and synergies in fisheries management outcomes and the need to consider both
44 fishing and climate dynamics.

45

46

47 **Keywords:** Fisheries rebuilding, future management scenarios, Ecopath with Ecosim, Gulf
48 of Lion, food webs, ecological indicators.

49

50

51

52 **1. Introduction**

53

54 Fishing is considered one of the most harmful stressors of marine ecosystems [1]
55 with impacts on habitat [2], biodiversity [3], and ecosystem structure [4]. Overexploitation
56 of marine resources is widely distributed [5], and it has substantially reduced fish biomass
57 and caused significant ecological changes in the global ocean [6,7]. In the Mediterranean
58 Sea, many assessed demersal stocks are either fully exploited or overexploited [8].
59 Despite that the percent of sustainable exploited stocks is improving globally, the

60 Mediterranean Sea is the one among FAOs major fishing areas with the highest
61 percentage (62.5%) of stocks fished at unsustainable levels, several demersal stocks
62 continue to experience high fishing mortality rates, and selectivity is decreasing [8,9].

63 Spatial-temporal restrictions of fishing activities and the establishment of technical
64 measures are the main management tools used in the Mediterranean Sea for marine
65 exploited stocks [10]. A Fisheries Restricted Area (FRA) is a geographically-defined area
66 where all or certain fishing activities are temporally or permanently banned or restricted to
67 protect marine ecosystems and improve the conservation and sustainable exploitation of
68 marine resources [11]. They fall within the category of ABFMs (Area-based Fisheries
69 Management Measures) and specifically OECMs (Other Effective Area-based
70 Conservation Measures) when the FRA is established to protect biodiversity features of
71 concern.

72 In the Mediterranean Sea, fishing activities as well as conserving fish stocks are
73 managed by the European Union (EU) Commission through a set of rules named Common
74 Fisheries Policy (CFP). The CFP sets quotas for which the EU Member States are allowed
75 to catch for some species. These quotas are shared between EU countries and each
76 country distributes national quotas among their fishermen. However, quotas have never
77 been considered useful for highly diverse Mediterranean demersal fisheries [12] and its
78 introduction will create management problems such as an increase in illegal fishing [13].
79 Among CFP rules, there is a regulation to prevent, deter, and eliminate illegal, unreported,
80 and unregulated fishing [14]. To do that, the European Commission established a
81 community control system for ensuring compliance with the rules of the CFP [15]. This
82 system uses information from different sources to improve the quality of fisheries data:
83 electronic recording and reporting system, vessel monitoring system, automatic
84 identification system, and more traditional control and surveillance methods, such as
85 inspection on board. However, despite this, in May 2017, the European Court of Auditors
86 examined the effectiveness of the Control Regulation and found that Member States of the
87 EU do not fully implement the required controls and lack of effectiveness [16].

88 In the Mediterranean Sea, the European Union (EU) and the General Fisheries
89 Commission for the Mediterranean (GFCM) called for advancing the spatial-temporal
90 measures for recovering populations of demersal stocks in the Western Mediterranean
91 Sea [15,16]. Consequently, since 2016 eight Fisheries Restricted Areas (FRAs) have been
92 established to ensure the protection of deep-sea sensitive habitats and essential fish

93 habitats in well-defined areas of the Mediterranean Sea. Additionally, all Mediterranean
94 waters below 1000 meters were officially declared as a FRA by the EU Commission in
95 2016 [11]. Among these FRAs is the continental slope of the Eastern Gulf of Lion
96 (CoSEGoL) FRA, the only FRA located in the Western Mediterranean Sea outside
97 territorial waters. The CoSeGoL FRA was established in 2009, following a
98 Recommendation by GFCM (GFCM/33/2009/1) [17], which froze the fishing effort in the
99 area. In fact, the Scientific Advisory Committee advised “to ban the use of towed and fixed
100 gear and longlines for demersal resource in an area of the continental shelf and slope of
101 the eastern Gulf of Lion” [17]. The CoSEGoL FRA was established for the protection of the
102 spawners that support the demersal fishery of the Gulf of Lions and Spanish coasts in
103 order to help maintain the status quo of the stocks [18].

104 Despite the fact that benefits of regulated and well-enforced marine protected
105 areas (MPAs) and FRAs have been widely demonstrated in the Mediterranean Sea (e.g.
106 [19]), protected areas with the most effective level of protection reach only 0.23% of the
107 basin, while 72% of MPAs lack basic regulation to be effective [20]. As such, a lack of
108 effective management and/or enforcement in restricted areas may hinder ecological
109 benefits [21,22] In addition, the number of studies on the benefits of FRAs on the living
110 resources is scarce in the Mediterranean Sea. For example, Dimarchopoulou *et al.* [23]
111 demonstrated the positive effect of fishing restrictions on commercial demersal species in
112 the Thermaikos Gulf, the Eastern Mediterranean Sea. However, Petza *et al.*, [24] reviewed
113 the effectiveness of several national FRAs in the Aegean Sea and found that more than
114 50% of the studied national FRAs (n=516) were slightly effective based on a multi-criteria
115 analysis (restriction measures, biodiversity and conservation objectives, etc.).

116 By 2020 10% of the Mediterranean Sea should be conserved through effectively
117 managed, ecologically representative and well connected systems of protected areas [25]
118 to ensure the improvement of the status of fish stocks and fisheries. Well established and
119 effective FRAs could contribute to increase the protected surface in the Mediterranean
120 Sea [23,26]. Currently, official spatial protection in the Mediterranean Sea covers more
121 than 10% of its surface [27], although most of these areas are poorly protected or
122 unprotected [28] and the surface of fully protected areas is around 0.04% [29].

123 In such a context, it is important to assess the effectiveness of the proposed FRAs to
124 rebuild and protect demersal commercial stocks in the Northwestern Mediterranean Sea
125 and to ensure a resilient structure and functioning of the ecosystems. Too often, fishing

126 restricted areas are established without time-bound impact assessments and recovery
127 indicators of success. Here, we developed a food-web model using the Ecopath with
128 Ecosim (EwE) approach [30,31] representing the CoSEGoL area (2006-2008) prior to the
129 establishment of the FRA. The food-web model was fitted to available time series of data
130 from 2008 to 2016 using the temporal dynamic module Ecosim [31,32] to simulate how the
131 structural and functional traits of the ecosystem changed since the establishment of the
132 FRA, and to verify if its establishment resulted in the recovery of commercially targeted
133 species. The fitted model was then used to explore the viability of alternative future
134 management scenarios under climate change conditions (accounting for changes in the
135 water temperature and primary productivity dynamics), following similar approaches
136 applied in other modeling studies [33–35]. This study complements existing modeling
137 studies of protected areas in the Mediterranean Sea [e.g. 36–38] using the EwE approach,
138 by explicitly representing the FRA in the basin.

139 To our knowledge, this is the first attempt to build a FRA food-web model in the
140 Western Mediterranean Sea. In the Aegean Sea (the Eastern Mediterranean Sea),
141 Dimarchopoulou *et al.* [39] built an Ecopath and Ecosim model for a FRA and reported
142 higher biomass values when reducing fishing effort and so contributing to rebuilding
143 marine resources. In the Western Mediterranean Sea, despite assessing small-scale
144 fisheries, some previous studies have modeled food-webs in MPAs evaluating the effects
145 of fisheries. For instance, Corrales *et al.* [36] showed slight recoveries of some target
146 species and ecological indicators in three small MPAs and indicated contrasting results
147 related to the effectiveness of the protection and fishing activities allowed in each MPA.

148

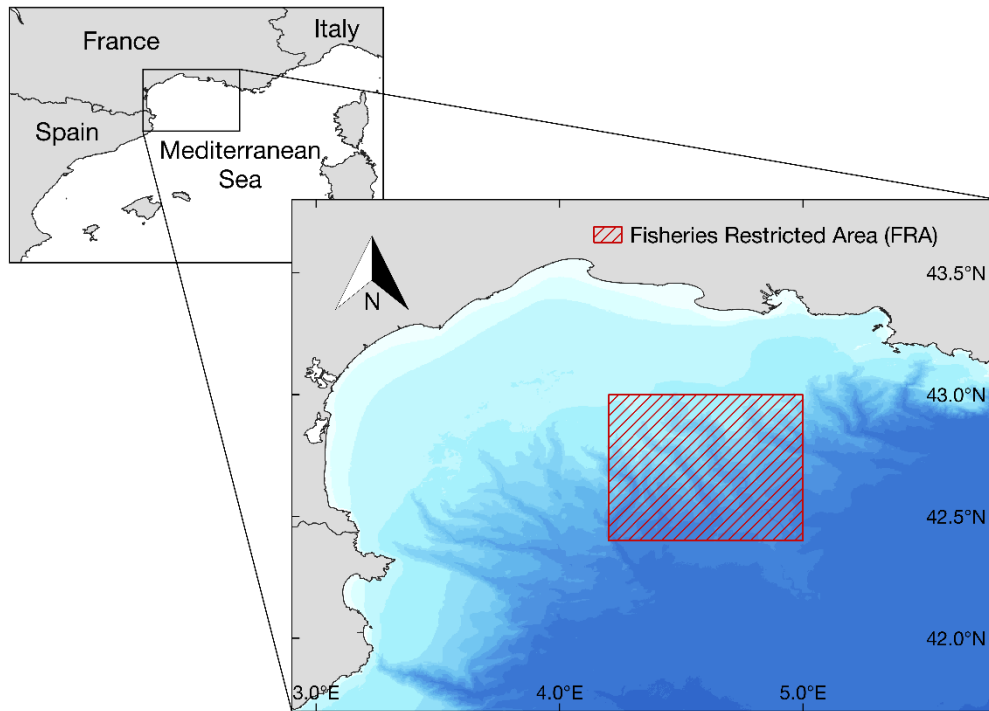
149 **2. Material & Methods**

150 **2.1. Study area**

151 The CoSEGoL FRA is located in the Gulf of Lion of the Northwestern
152 Mediterranean Sea, bounded by the following geographic coordinates: 42°40'N, 4°20' E;
153 42°40'N, 5°00' E; 43°00'N, 4°20' E; 43°00'N, 5°00' E (Figure 1). The Gulf of Lion is one of
154 the most productive regions of the Mediterranean Sea because of the inputs from the
155 Rhone river and experiences annual upwelling [40]. The bathymetry of the CoSEGoL FRA
156 ranges from 100 to 1500 meters and covers an area of 2,051 km² [41]. This area has been
157 identified as containing essential fish habitats (nurseries and spawning areas) for

158 European hake (*Merluccius merluccius*) and other commercial species [42]. It is
159 characterized by an intricate network of submarine canyons [43], and important benthonic
160 communities of echinoderms, gorgonians, sponges [44], and deep-sea corals [45,46]
161 occur in the area.

162



163

164 Figure 1. Location of the continental slope of the Eastern Gulf of Lion Fisheries Restricted
165 Area (Northwestern Mediterranean Sea).

166

167

168 The CoSEGoL FRA has historically been exploited by Spanish bottom trawlers
169 (BTW), Spanish longliners (LON), and French midwater trawlers (MTW) [17]. French
170 trawlers are the main component of the fleet exploiting the marine resources of the Gulf of
171 Lion, and can be divided in two main components: one directed to the catch of small
172 pelagic fish, and the other exploiting a great diversity of demersal species [44]. The aim of
173 CoSEGoL FRA was to protect spawning stocks of several commercially important species

174 in the Northwestern Mediterranean Sea, the most important one being European hake,
175 and also including anglerfish (*Lophius piscatorius*), Norway lobster (*Nephrops*
176 *norvegicus*), and the blue and red shrimp (*Aristeus antennatus*), while conserving
177 accompanying species (blue whiting *Micromesistius poutassou* and silver sabbardfish
178 *Lepidopus caudatus*) [44].

179 In the recommendation from which the CoSEGoL FRA was adopted [17], the
180 GFCM called for ensuring that fishing effort for demersal stocks of vessels using towed
181 nets, bottom and mid-water longlines, and bottom-set nets shall not exceed the level of
182 fishing effort applied in 2008. Officially, the fleet operating that area in 2008 was composed
183 of 29 fishing vessels, 70% from France, and 30% from Spain [17].

184 **2.2. Ecosystem modeling approach**

185 The CoSEGoL FRA model was developed using the Ecopath with Ecosim
186 ecosystem modeling approach (EwE, version 6.6) and it was built using the best available
187 information to represent the FRA ecosystem just before its establishment. Specifically, the
188 model represented a situation of the CoSEGoL FRA for the 2006-2008 time period.
189 Subsequently, an Ecosim model representing the CoSEGoL FRA ecosystem during the
190 2008–2016 period was fitted to time series of historical data (See detailed information
191 about ecosystem modeling approach in Supplementary material Appendix A).

192 **2.3. Model parametrization**

193 The CoSEGoL FRA model represented the state of the ecosystem in 2006-2008,
194 previously to the official establishment of the FRA in 2009. Information about species
195 presence and their biomasses were aggregated into functional groups (FGs) of species or
196 groups of species clustered according to key information about their trophic ecology,
197 commercial value, and abundance in the ecosystem. We used the same meta-web
198 structure as defined for the SafeNet Project¹ Western Mediterranean Sea model [37]. We
199 adapted this meta-web structure to local conditions by removing those FGs that did not
200 occur in the study area. The final food-web structure of the CoSEGoL FRA model contains
201 72 functional groups (five marine mammals, one seabird, one sea turtle, 13 pelagic fishes,
202 24 demersal fishes, four cephalopods, 18 invertebrates, two zooplankton, two
203 phytoplankton, and two detritus groups) (Supplementary material Table B.1).

¹ <http://www.criobe.pf/recherche/safenet/>

204 FGs' biomasses were obtained from different sources from the study area or
205 surrounding areas (see Supplementary Material Table B.1 and C.1. for details on the
206 parameterization of each functional group). Most of the biomasses of demersal and
207 benthic species were calculated from the EU-funded Mediterranean International bottom
208 Trawl Surveys project [47], carried out from spring to early summer (April to June) from
209 1994 to the present. Species biomass was estimated for each haul as the total weight of
210 each species (kg) per km² of trawling. This information was extracted from the MEDITS
211 dataset to account for bathymetric sampling per strata. For pelagic species, we also used
212 the data available from the EU-funded Mediterranean International Acoustic Survey
213 (MEDIAS), which contained information of abundance and biomass per Geographical Sub-
214 Area (GSA).

215 Annual production (P/B) and consumption (Q/B) rates were either estimated using
216 empirical equations [48] or taken from literature or other models developed in the
217 Mediterranean Sea [37] (Supplementary Material Table B.1 and C.1.). The diet information
218 was compiled using published studies (Supplementary Material Table B.1) on stomach
219 content analyses, giving preference to local or surrounding areas (Supplementary Material
220 Table C.2). We used the Diet Calculator (Steenbeek 2018), a custom-built extraction tool
221 that facilitates the process of vetting and incorporating diet data into EwE. Drawing on a
222 large library of published diet studies, the Diet Calculator selects the most likely suitable
223 diet studies for a specific model area, based on a weighted evaluation of diet study
224 characteristics, and generates a diet composition matrix with accompanying pedigree
225 index for each predatory functional group. For migratory species (large pelagic fishes, sea
226 birds, turtles, and dolphins), we set a fraction of the diet composition as import based on
227 the time that these species feed outside the system [30,48].

228 Fisheries data were obtained from different sources (database, literature, and
229 unpublished data) (Supplementary Material Table B.1. and C.1.). Available fishery data
230 were not geolocated, and so we had to scale catches by the fishing area where operates
231 each fleet. We divided fisheries into three commercial fishing fleets for the CoSEGoL FRA
232 model (Spanish Bottom trawlers, Spanish longliners, and French Midwater trawlers). We
233 calculated catches in two different ways: 1) for French fleets, we scaled total catches [49]
234 by FRA area belonging to Gulf of Lion area, and then by the number of vessels working in
235 the study area [17]; and 2) for Spanish fleets, we obtained landings from the official

236 dataset of the Regional Government of Catalonia managed by the Institute of Marine
237 Sciences (ICM-CSIC) [50], and were scaled to the area where these fleet were operating.

238 **2.4. Quality of the model**

239 The quality of the models were evaluated using the EwE pedigree routine, which
240 categorizes the origin of the input parameters (B, P/B, Q/B, diets, and catches) and
241 assigns a measure of confidence and specifies the uncertainty associated with these
242 inputs [30,31]. All pedigree values were manually calculated except for diets, which were
243 obtained from the Diet Calculator algorithm [51]. The algorithm computes a total pedigree
244 value for each diet record as a weighted average of four attributes assigned to each diet
245 study (region and year of collection, data representativeness of the species population,
246 and data collection method). Pedigree values were used to identify parameters with low
247 quality that could be modified during the balancing procedure and were used to calculate
248 the pedigree index of the overall model, which varies between zero (lowest quality) and
249 one (highest quality) [31], for the FRA model. The confidence intervals used to describe
250 the uncertainty of the balanced Ecopath model are described in the Supplementary
251 Material (Supplementary Material Table D.1).

252 **2.5. Fitting to time series procedure**

253 Relative fishing effort data available for the fishing fleets included in the model
254 were used to drive the model. Due to the lack of local fishing effort time series, and to test
255 the hypothesis of compliance and enforcement failure in the CoSEGoL FRA, we tested
256 alternative relative fishing effort time series that considered annual declines (-1%, -5%, -
257 10%), annual increases (+1%, +5%, +10%) or no changes in effort with time. These
258 changes were applied to all fisheries in the model. Available absolute or relative observed
259 biomass time series were incorporated in Ecosim to compare the model outputs to
260 observations.

261 **2.6. Model analyses and ecological indicators**

262 The food web structure of the CoSEGoL FRA ecosystem before and after the
263 establishment of the FRA was visualized using a flow diagram built from the biomass and
264 TL (output) of each FG, and the direct trophic interactions among them. The TL identifies
265 the position of organisms within food webs by tracking the source of energy for each
266 organism, and it is calculated by assigning primary producers and detritus a TL of 1 (e.g.

267 phytoplankton), and consumers to a TL of 1, plus the average TL of their prey weighted by
268 their proportion in weight in the predator's diet [52].

269 With both before and after FRA models, the mixed trophic impact (MTI) analysis
270 was performed to quantify direct and indirect trophic interactions among functional groups
271 [53]. This analysis quantifies the direct and indirect impacts that a hypothetical increase in
272 the biomass of one functional group would have on the biomasses of all the other
273 functional groups in the ecosystem, including the fishing fleets. We also used the Valls
274 keystone index [54] to identify keystone species in both before and after FRA models. A
275 keystone species is a species that may show relatively low biomass but has a relatively
276 important role in the ecosystem [55].

277 Several additional ecological indicators were computed to describe the state and
278 functioning trend of the CoSEGoL FRA before and after the establishment of the fisheries
279 restrictions following [56]:

280 **Biomass-based.** These indicators are calculated from the biomass of components
281 included in the food-web model. We included five biomass-based indicators: biomass of
282 demersal species ($t \cdot km^{-2} \cdot year^{-1}$) biomass of fish species ($t \cdot km^{-2} \cdot year^{-1}$), biomass of
283 commercial species ($t \cdot km^{-2} \cdot year^{-1}$), biomass of predatory species ($t \cdot km^{-2} \cdot year^{-1}$), and
284 biomass of invertebrates species ($t \cdot km^{-2} \cdot year^{-1}$).

285 **Trophic-based.** These indicators reflect the TL position of different groups of the food
286 web. Trophic level indicators may reflect ecosystem “health” because fishing pressure
287 removing predators can cause a decline in the trophic level of the catch and/or the
288 community [52]. We selected four trophic-based indicators: TL of the community (TLc), TL
289 of the community including organisms with $TL \geq 2$ (TL2), TL of the community including
290 organisms with $TL \geq 3.25$ (TL3.25), and TL of the community including organisms with TL
291 ≥ 4 (TL4).

292 **Flows-based.** We used two indicators related to the total flows of the system. The
293 Average Path Length (APL, μ) is defined as the average number of groups that flows
294 passes through and is an indicator of stress [57]. Finn's Cycling Index (FCI, %) is the
295 fraction of the ecosystem's throughput that is recycled [58].

296 **Catch-based.** These indicators are based on catch and discard species data. We included
297 six indicators: total catch ($t \cdot km^{-2} \cdot year^{-1}$), total demersal catch ($t \cdot km^{-2} \cdot year^{-1}$), total fish catch

298 (t·km⁻²·year⁻¹), total invertebrates catch (t·km⁻²·year⁻¹), total discarded catch (t·km⁻²·year⁻¹),
299 and trophic level of the catch.

300 **2.7. Assessment of FRA impact and uncertainty**

301 After fitting the model to time series using Ecosim, we investigated if the establishment
302 of the CoSEGoL FRA resulted in noticeable changes in the structure and functioning of the
303 ecosystem. We compared the ecosystem structure and functioning before and after the
304 establishment of the FRA using the baseline model (2008) and a second FRA model
305 (2016) that was obtained after the fitting procedure. FRA effectiveness and compliance
306 were measured through changes in ecological and keystone species indicators to discern
307 expected biomass increases according to theory [59]. For example, a positive trend in the
308 biomass of a targeted species is to be expected in a FRA after several years of its
309 protection [23]. In addition, changes in mixed trophic impacts (MTI) from the industrial
310 fleets were examined to quantify the direct and indirect impact of each fleet on functional
311 groups, their potential competitions, and trade-offs.

312 Pedigree and associated confidence intervals for key input values were used in the
313 EwE Monte Carlo (MC) routine to evaluate input parameter uncertainty over time
314 (Supplementary Material Table D.1) [31,48]. 200 MC simulations were run, and 95% and
315 5% percentile confidence intervals (CIs) were calculated for main target species
316 biomasses and ecological indicators focusing on *M. merluccius*, *L. piscatorius*, *N.*
317 *norvegicus*, *A. antennatus*, *M. poutassou* and *L. caudatus*. The significance and
318 correlation between our suite of ecological indicators and time were measured using the
319 non-parametric Spearman rank correlation coefficient [60]. To evaluate the impact of the
320 CoSEGoL FRA on the fisheries, catch-based indicator trends were examined over time to
321 capture changes of the potential effects of the FRA establishment. This procedure to
322 capture uncertainty was developed to evaluate historical changes (2008-2016) and the
323 forecasting scenarios (see Section 2.8 for more details).

324 **2.8. Future alternative management simulations**

325 After the model was fitted to data from 2008 to 2016, eight future scenarios including
326 fishing regulation and environmental variables (Table 1) were tested in order to evaluate
327 future alternative management scenarios and their potential effects on marine resources
328 and the ecosystem structure and functioning in the 2017-2040 period. The original
329 configuration of the dynamic model was used as a baseline simulation keeping parameters

330 with default values from 2017 to 2040 (Business as usual - BAU). The rest of the scenarios
 331 applied new fishing regulations: for instance, scenario “50” simulated a decreasing 50% of
 332 fishing effort, scenario “100” simulated a decreasing 100% of fishing effort as suggested,
 333 and scenario “ F_{msy} ” simulated fishing at Maximum Sustainable Yield (F_{msy}) in comparison
 334 to fishing at $F_{current}$ (using fishing mortality levels of 2016).

335 For the environmental variables (sea water temperature and primary production)
 336 (Supplementary material, Figures E.1. and E.2), we used projections of the Med-ERGOM
 337 hydro-dynamical biochemical model under two contrasting scenarios of greenhouse
 338 emissions (RCP4.5 and RCP8.5) [61,62] (Table 1). To consider changes in sea water
 339 temperature, we used the environmental response functions of Ecosim, which links the
 340 species or FGs dynamics to the environmental drivers. We first obtained the response
 341 functions from AquaMaps [63], which is a global database on species distribution. These
 342 environmental response functions are given as curves showing the minimum and
 343 maximum tolerance levels and 10th and 90th preferable quintiles to the environmental
 344 parameters (in our case, temperature). The final environmental preferences for each FG
 345 were obtained by weighting the values of the species included in a FG to their relative
 346 biomass. Finally, selected ecological indicators and biomass predictions of targeted
 347 species were extracted in 2025 and 2040 and were used to assess the effects of future
 348 alternative simulations over time.

349

350 Table 1. List of fisheries and Representative Concentration Pathway (RCP) scenarios.

Scenario	Fishing regulation	Temperature	PP
BAU 4.5	Kept at levels 2016	RCP4.5	RCP4.5
BAU 8.5	Kept at levels 2016	RCP8.5	RCP8.5
100 4.5	Reducing 100% fishing effort	RCP4.5	RCP4.5
100 8.5	Reducing 100% fishing effort	RCP8.5	RCP8.5
50 4.5	Reducing 50% fishing effort	RCP4.5	RCP4.5
50 8.5	Reducing 50% fishing effort	RCP8.5	RCP8.5
F_{msy} 4.5	Maximum sustainable yield	RCP4.5	RCP4.5
F_{msy} 8.5	Maximum sustainable yield	RCP8.5	RCP8.5

351

352

353 To obtain the F_{msy} values, we first reviewed fishing mortality values at current levels
 354 ($F_{current}$) and $F_{0.1}$ (defined as the fishing mortality at which the slope of the Yield per
 355 Recruit curve is 10 percent of its slope at the origin) reported by the GFCM and the

356 Scientific, Technical and Economic Committee for Fisheries (STECF) in the last
357 evaluations of Western Mediterranean marine resources (Supplementary material, Table
358 D.2.). Values of F_{current} and F_{msy} for European sardine (*Sardina pilchardus*) and European
359 anchovy (*Engraulis encrasicolus*) were obtained from the EU Tender SPELMED for
360 GSA06 and GSA07 [64]. We estimated the reduction of fishing mortality comparing F_{current}
361 with $F_{0.1}$ for evaluated species, which yielded an average reduction of 64% for the
362 CoSEGoL FRA. This estimate was applied to the rest of the commercial species that were
363 not assessed but also occurred in the model as fisheries targeted or by-catch species.

364

365

366 **3. Results**

367

368 **3.1. Baseline parameterization, model quality, and temporal fitting**

369 The pedigree index of the CoSEGoL FRA model (0.50) revealed that input data
370 was of acceptable quality when compared to the distribution of pedigree values in other
371 existing models [65]. The pedigree value of the CoSEGoL FRA was similar to other
372 published MPAs and FRAs EwE models for the Mediterranean Sea [36,38,39].

373 The best fitted model was obtained for an annual increase in fishing effort of 5%
374 (F_{+5}) (Supplementary material Table F.1.). The parameterization with 30 vulnerabilities
375 (trophic interactions between predators and their prey) and 6 spline points was identified
376 as the best model based on the AIC test criteria (Supplementary material Table F.1).
377 However, the best fitting model did not reproduce observed trends of some target species;
378 these were obtained for a scenario with an increase of 10% in fishing effort. This model
379 was adopted as most likely representative for the ecosystem because of its capability to
380 best reproduce the trends in target species over time (Supplementary material Table F.1)
381 with exception of Norway lobster (SS 11.87) - one of the target groups of the study (Figure
382 2).

383

384

385

386

387

388

389

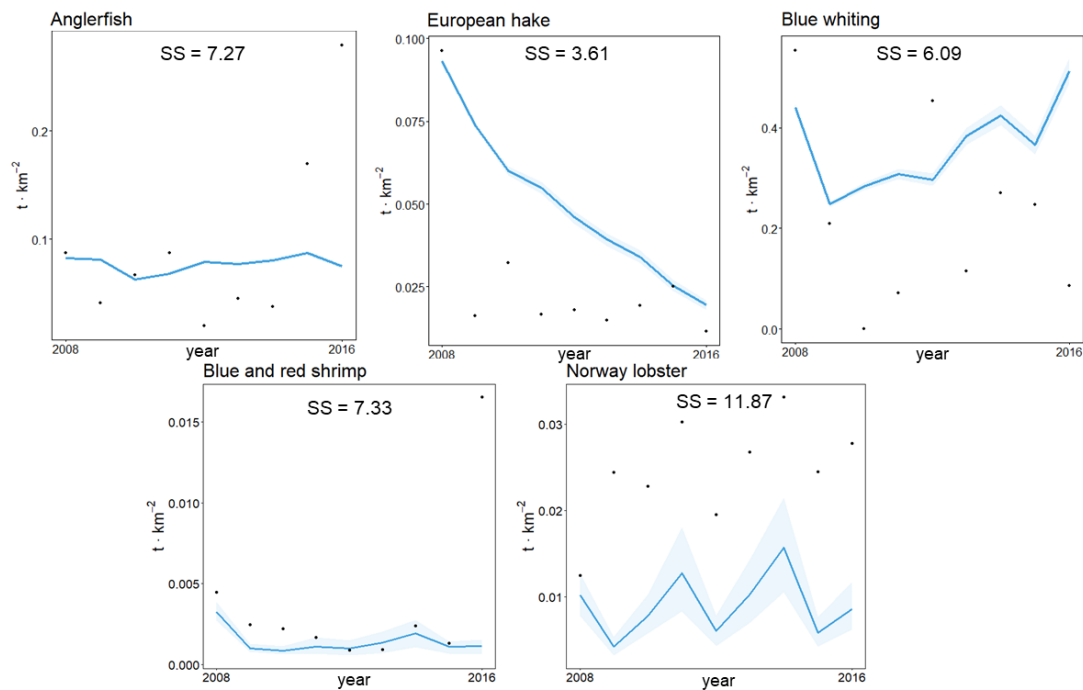
390

391

392

393

394



395

396 Figure 2. Predicted (solid lines) versus observed (dots) biomass (t · km⁻²) for targeted
397 groups in the continental slope of the Eastern Gulf of Lion Fisheries Restricted
398 Areaecosystem model for the period 2008-2016. Blue shadows represent 5% and 95%
399 percentiles obtained using the Monte Carlo routine. Sum of squares (SS) values indicate
400 their contribution to the total SS.

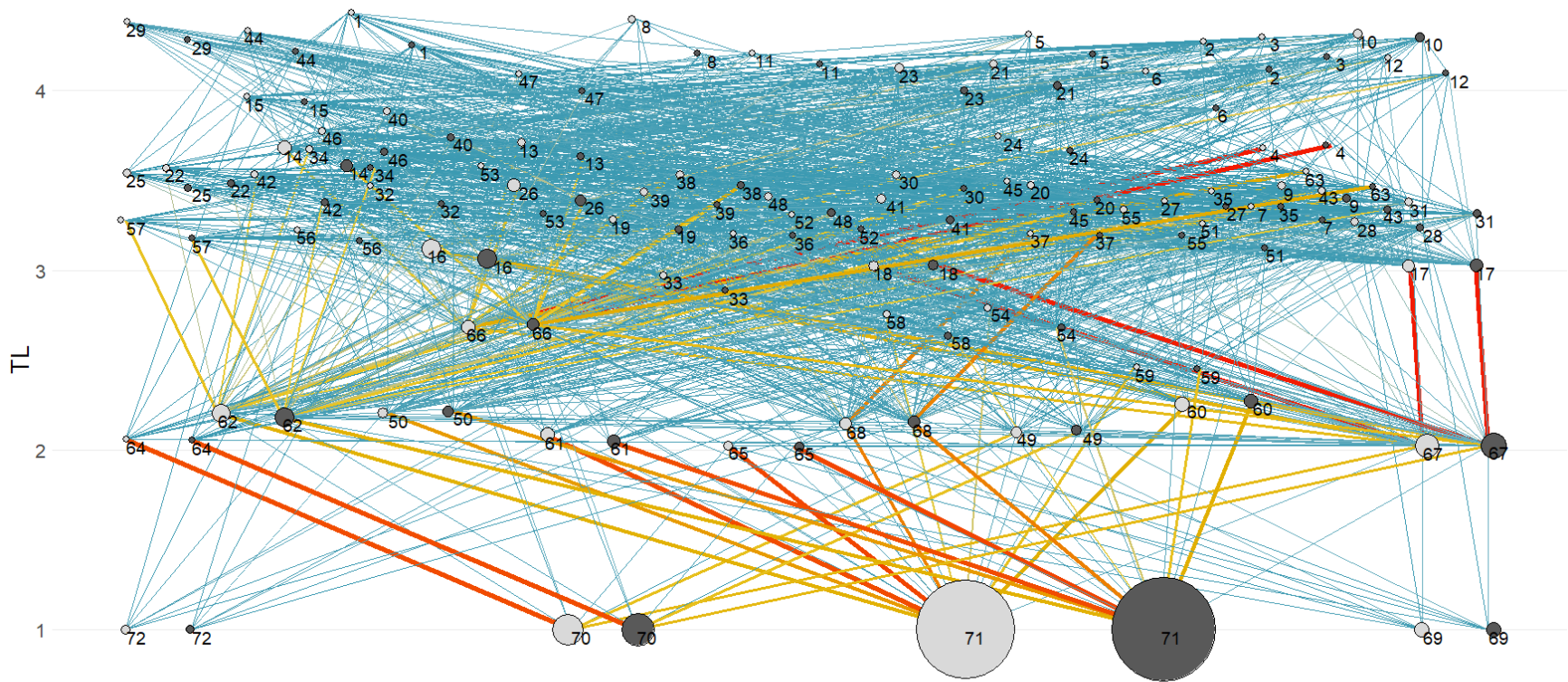
401

402 **3.2. Ecosystem structure and functioning**

403 Ecosystem structure and functioning changes occurred following the establishment
404 of the FRA. The flow diagram showed higher trophic levels for the model prior to the
405 establishment of the FRA (Figure 3). Both models highlighted the same FGs for Valls
406 keystone index (Figure 4), although keystone index values for individual groups differed
407 from one ecosystem state to the other. Ecological indicators showed generally small
408 variation. Of biomass-based indicators, only invertebrates showed noticeable differences
409 (Figure 5), with an increase from 2008 to 2016. The TL community, TL community 2, and
410 APL decreased after the implementation of the FRA (Figure 6 and 7).

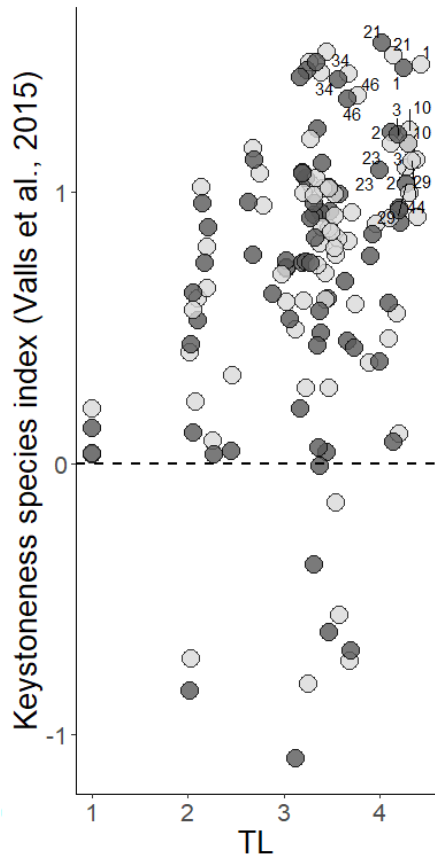
411

412



413

414 Figure 3. Flow diagram of the continental slope of the Eastern Gulf of Lion Fisheries Restricted Areaecosystem before its
 415 establishment (year 2008, light grey) and after (year 2016, dark grey). The size of each circle is proportional to the biomass of the
 416 functional group. The numbers identify the functional groups of both CoSEGoL FRA models (Table A.1). The width and color of
 417 trophic links indicate the magnitude of the trophic flows (low - blue; high - red).



418

419 Figure 4. Keystone Index analysis of the continental slope of the Eastern Gulf of Lion
 420 Fisheries Restricted Area before its establishment (year 2008, light grey) and after (year
 421 2016, dark grey). The numbers identify the functional group of the model (listed in Table
 422 A.1) with a higher keystone index and relative total impact and trophic level (TL).

423

424

425

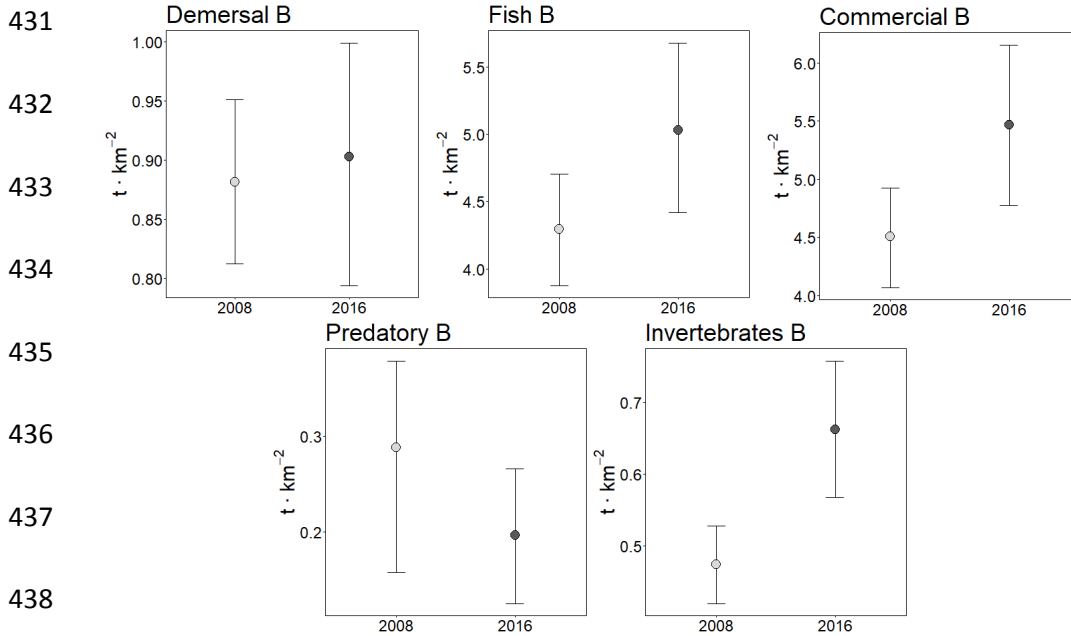
426

427

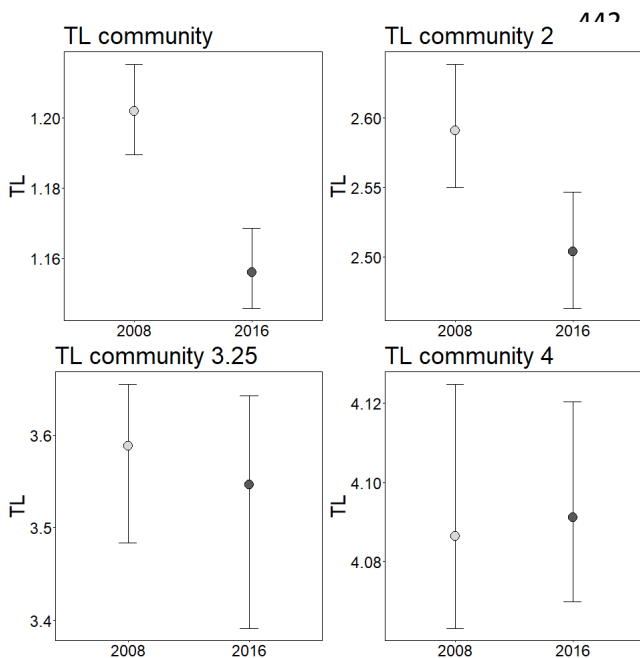
428

429

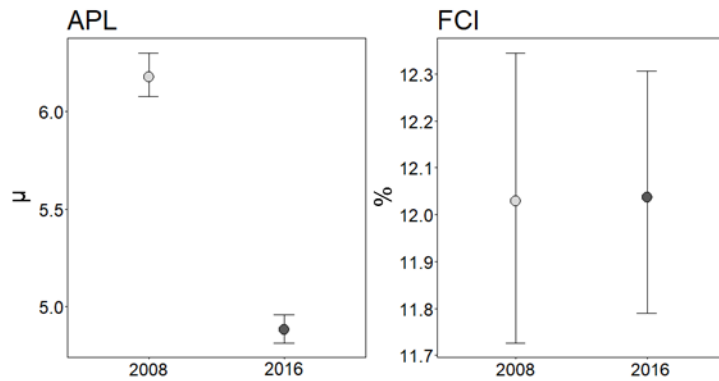
430



439 Figure 5. Biomass-based indicators of the continental slope of the Eastern Gulf of Lion
 440 Fisheries Restricted Area model before its establishment (year 2008, light grey) and after
 441 (year 2016, dark grey). B: Biomass. Error bars represent 95% confidence intervals.



451 Figure 6. Trophic-based indicators of the continental slope of the Eastern Gulf of Lion
 452 Fisheries Restricted Area model before its establishment (year 2008, light grey) and after
 453 (year 2016, dark grey). TL: Trophic Level. Error bars represent 95% confidence intervals.



454

455 Figure 7. Flow-based indicators of the continental slope of the Eastern Gulf of Lion
 456 Fisheries Restricted Area model before its establishment (year 2008, light grey) and after
 457 (year 2016, dark grey). APL: Average Path Length; FCI: Finn's Cycling Index. Error bars
 458 represent 95% confidence intervals.

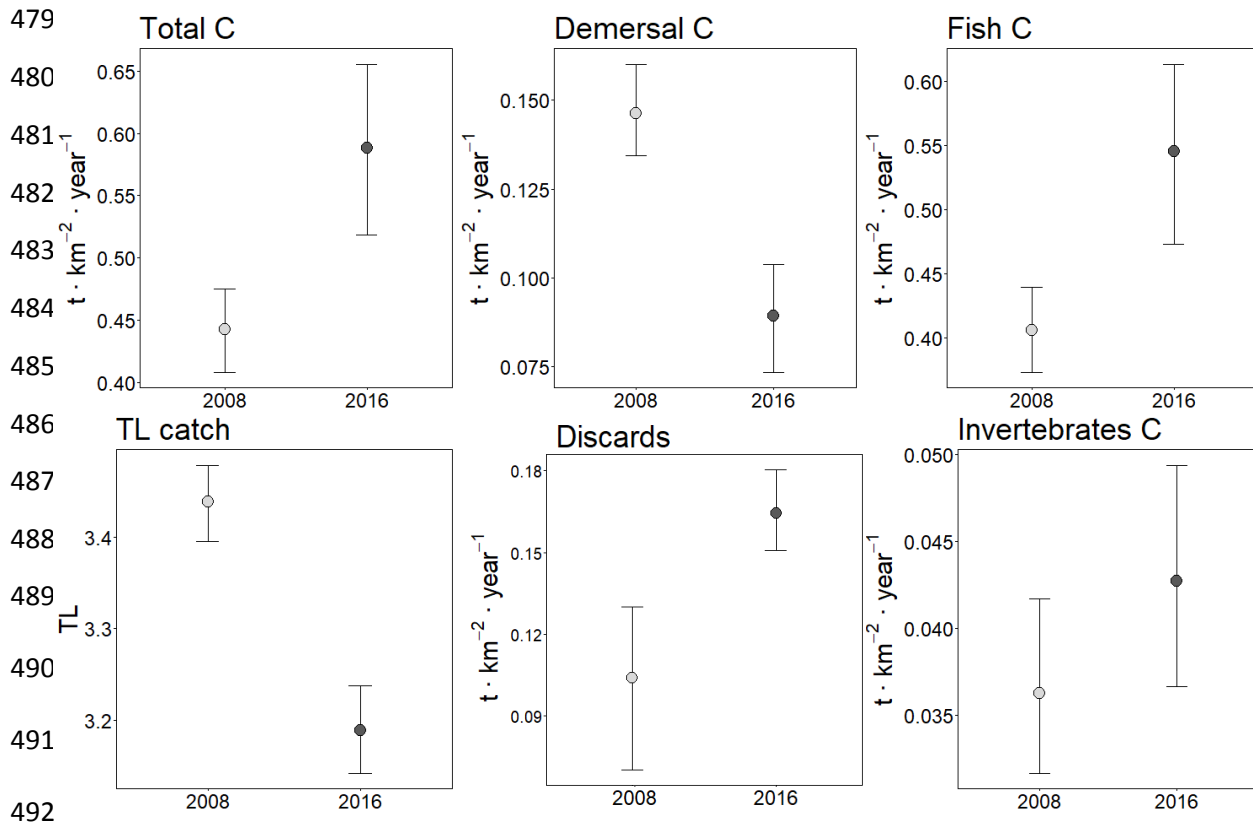
459

460 3.3. The impact of industrial fisheries

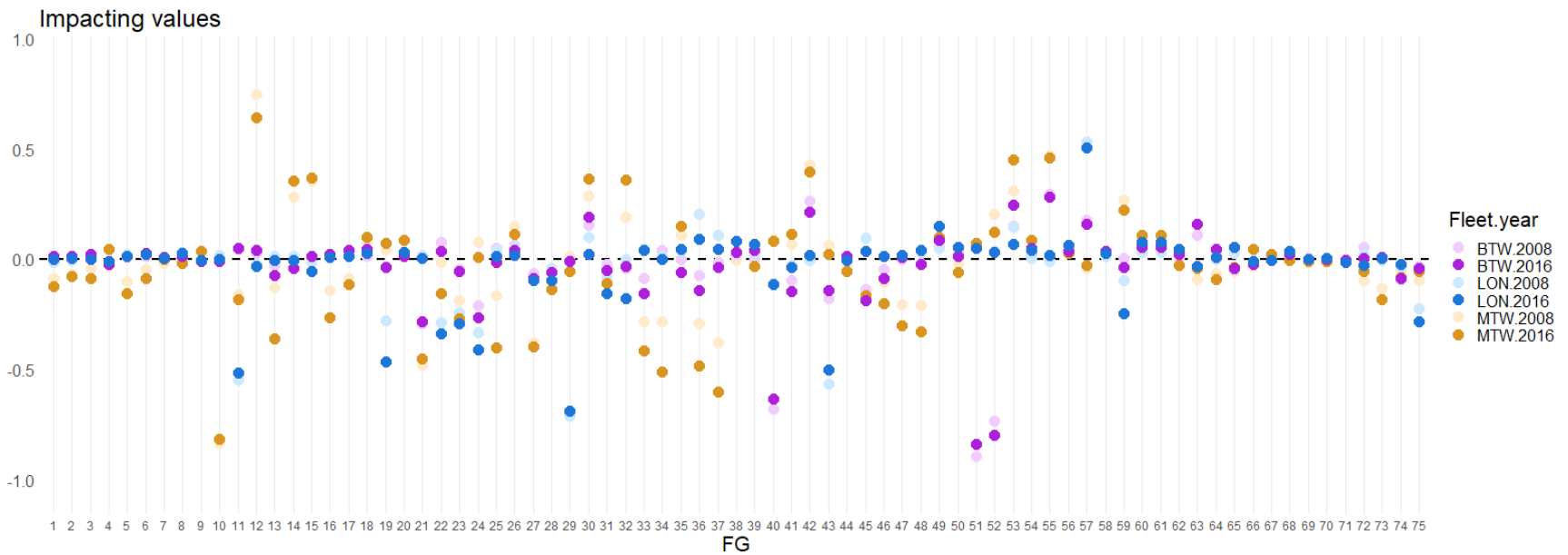
461 The Total catch, Fish catch, and Discards increased once the FRA was
 462 established, while the TL of the catch and Demersal catch decreased (Figure 8). The MTI
 463 analysis applied to the industrial fisheries showed different patterns among fleets and
 464 CoSEGoL FRA states (2008 and 2016) (Figure 9). The highest positive impacting values
 465 were mostly found for the mid-water trawlers (MWT) (e.g. FG 12 (other large pelagic fish)
 466 or FG 55, (Norway lobster)). The most negative impacting values did not show any pattern
 467 among fleets. For example, while longliners (LON) impacted negatively on FG 11, 29, and
 468 43 (swordfish, common dentex, and rays and skates, respectively), the bottom trawlers
 469 (BTW) impacted on FG 40, 51, and 52 (small-spotted catshark, Deep-water rose shrimp
 470 and blue and red shrimp, respectively) and the MTW on FG 10 (bluefin tuna). Although
 471 both models highlighted the same impacted FGs, the impact value of industrial fisheries
 472 over most FGs was different between both ecosystem states. Several FGs obtained lower
 473 positive values or higher negative values after the establishment of the CoSEGoL FRA.
 474 For example, other large pelagic fish (FG12) obtained an impacting value of 0.75 by MTW
 475 in 2008 while it was reduced to 0.64 in 2016, and blue and red shrimp (FG52) obtained an
 476 impacting value of -0.74 by BTW in 2008 while it increased to -0.81 in 2016.

477

478



493 Figure 8. Catch-based indicators of the continental slope of the Eastern Gulf of Lion
 494 Fisheries Restricted Area model before its establishment (year 2008, light grey) and after
 495 (year 2016, dark grey). TL: Trophic Level, C: Catches. Error bars represent 95%
 496 confidence intervals.

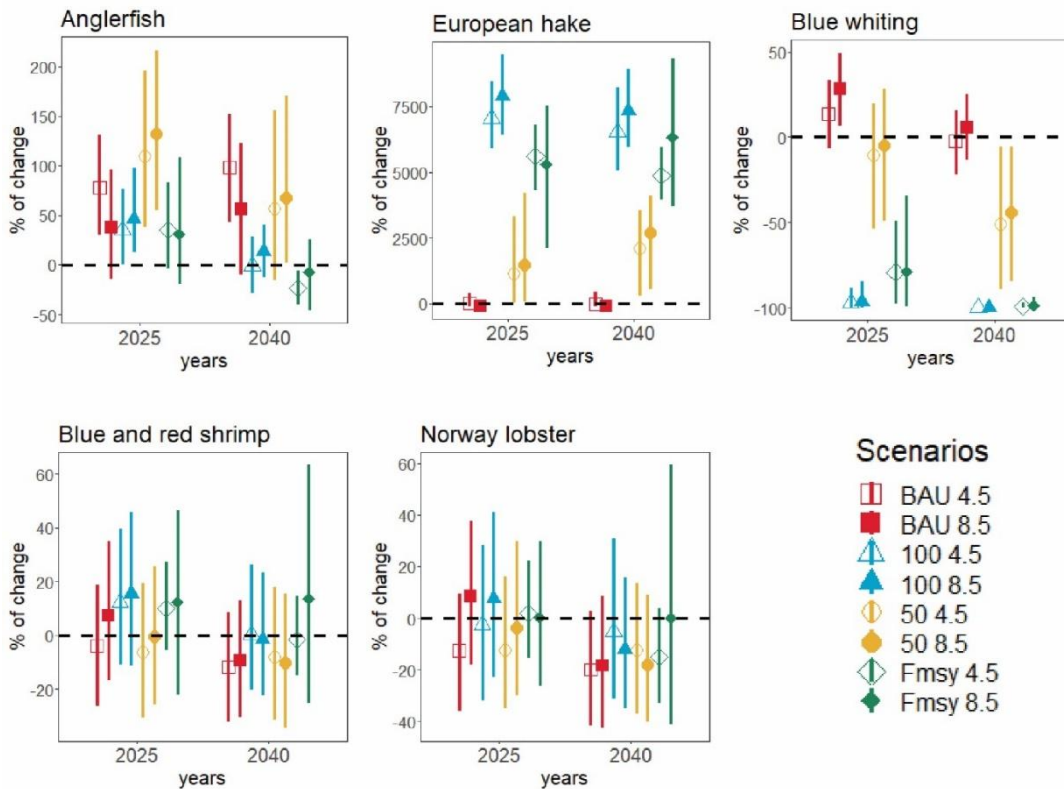


497

498 Figure 9. Industrial fisheries impacting values for each functional group of both ecosystem states of the continental slope of the
 499 Eastern Gulf of Lion Fisheries Restricted Area (2008 and 2016). X-axis identifies the FG number (except for 73, Midwater trawling;
 500 74, Bottom trawling; and 75 Longliner) (MTW – Midwater trawling from France; BTW – bottom trawling from Spain and France; LON –
 501 Longliners from Spain).

502 **3.4. Future scenarios of alternative management**

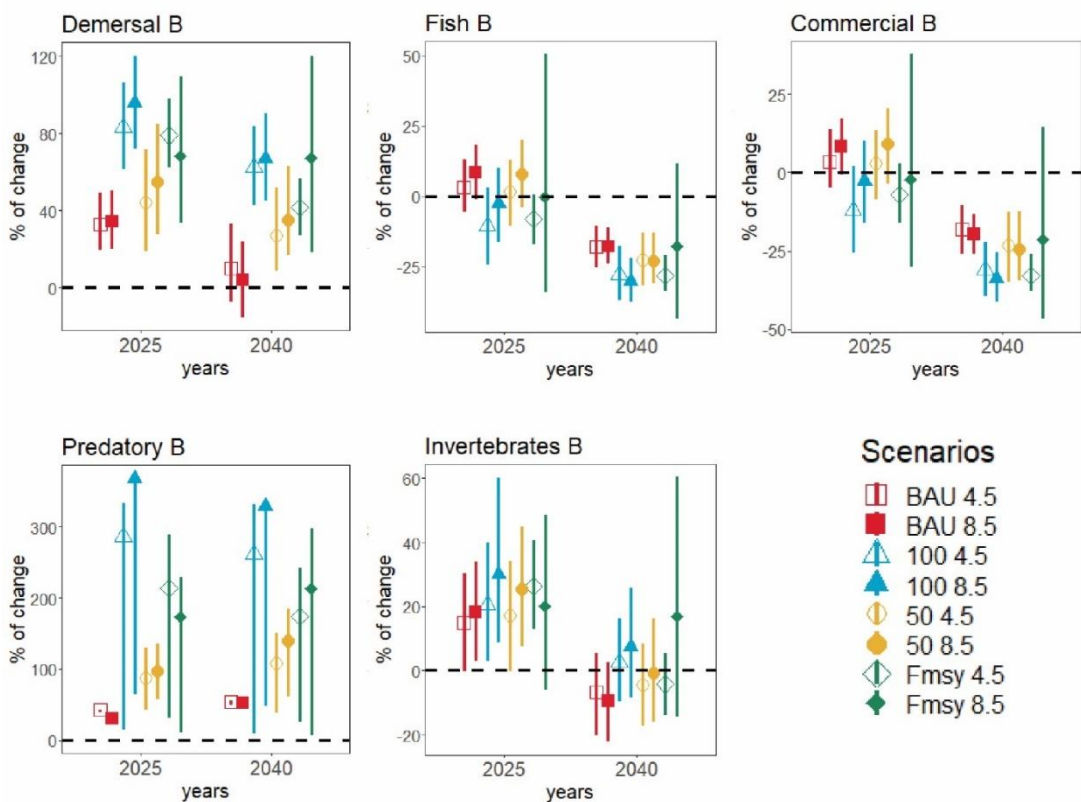
503 Under baseline scenarios considering both RCP projections (BAU RCP4.5 and BAU
 504 RCP 8.5), the model predicted that European hake would decrease in both scenarios
 505 except in 2025 for scenario BAU RCP 4.5, while blue and red shrimp and Norway lobster
 506 showed decreasing biomass for both scenarios except in 2025 for scenario BAU RCP 8.5
 507 (Figure 10). On the contrary, results showed an increase of biomass of anglerfish after 10
 508 and 25 years of simulation (2025 and 2040, respectively) and blue whiting after 10 years
 509 (Figure 10). Within these scenarios, although biomass indicators increased in 2025,
 510 invertebrates, fish and commercial biomass indicators decreased in 2040 (Figure 11).
 511 Regarding catch-based indicators, invertebrates and demersal catch, and total catch and
 512 discards under RCP8.5 increased, while most indicators decreased in 2040 (Figure 12).



513

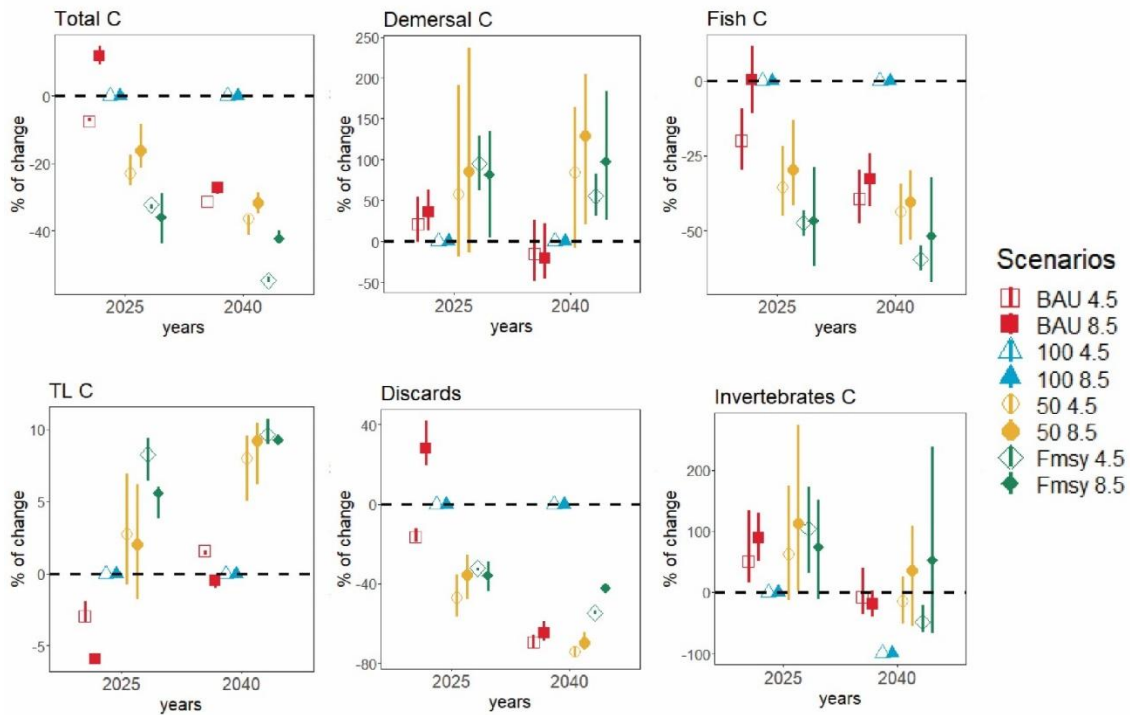
514 Figure 10. Mean percentage of change in biomass for targeted species under eight future
 515 scenarios of management of the continental slope of the Eastern Gulf of Lion Fisheries
 516 Restricted Area in 2025 and 2040. Error bars represent 95% confidence intervals. Hollow

517 points indicate scenarios under RCP4.5 projection, and solid points indicate scenarios
 518 under RCP8.5 projection.



519

520 Figure 11. Mean percentage of change in biomass-based indicators under eight future
 521 scenarios of management of the continental slope of the Eastern Gulf of Lion Fisheries
 522 Restricted Area in 2025 and 2040. B: Biomass. Error bars represent 95% confidence
 523 intervals. Hollow points indicate scenarios under RCP4.5 projection, and solid points
 524 indicate scenarios under RCP8.5 projection.



525

526 Figure 12. Mean percentage of change in catch-based indicators under eight future
 527 scenarios of management of the continental slope of the Eastern Gulf of Lion Fisheries
 528 Restricted Area in 2025 and 2040. TL: Trophic Level, C: Catches. Error bars represent
 529 95% confidence intervals. Hollow points indicate scenarios under RCP4.5 projection, and
 530 solid points indicate scenarios under RCP8.5 projection.

531

532 Applying a reduction of 100% on the fishing effort, both models with different RCP
 533 projections (scenarios 100 RCP 4.5 and 100 RCP 8.5) predicted increases on European
 534 hake biomass, and on anglerfish except for scenario 100 RCP 4.5 in 2040 (Figure 10), but
 535 predicted lower anglerfish biomass compared to scenarios BAU (Figure 10). On the
 536 contrary, blue whiting decreased as it did Norway lobster that decreased for both
 537 scenarios except for 100 RCP 8.5 in 2025. Blue and red shrimp increased on biomass for
 538 both scenarios except for 100 RCP 8.5 in 2040. We note that blue and red shrimp and
 539 Norway lobster obtained higher biomass predictions compared to baseline results except
 540 for Norway lobster for scenario 100 RCP 8.5 in 2025 (Figure 10).

541 Simulating a reduction of 50% of the fishing effort, the model predicted increases in
 542 the biomass of European hake, too. The percentages of change in biomass under

543 scenarios 50 were higher than BAU scenarios but lower than scenarios 100. Results
544 showed a higher increase in anglerfish biomass than scenarios 100 and BAU, except in
545 2040 under RCP4.5 (Figure 10). In contrast, scenarios 50 RCP 4.5 and 50 RCP 8.5
546 predicted a decrease in biomass trends for blue whiting as scenario 100 but this reduction
547 was smaller. Scenarios 50 RCP 4.5 and 50 RCP 8.5 also predicted a decreasing biomass
548 trend for blue and red shrimp and Norway lobster. This pattern was similar to their baseline
549 scenario predictions except for BAU RCP 8.5 in 2025 (Figure 10).

550 Under fishing at Maximum Sustainable Yield scenarios, both models (F_{msy} RCP 4.5
551 and F_{msy} RCP 8.5) predicted an increase in biomass trends for European hake, which was
552 higher than baseline predictions. Scenarios F_{msy} RCP 4.5 and F_{msy} RCP 8.5 predicted an
553 increase in 2025 and a decrease in 2040 for anglerfish biomass, respectively (Figure 10).
554 These anglerfish predictions were lower than baseline predictions. Conversely, scenario
555 F_{msy} predicted a decreasing biomass trend for blue whiting, which was much lower than
556 baseline projections (Figure 10). For blue and red shrimp and Norway lobster, these two
557 models predicted an increase in biomass trends except for F_{msy} RCP 4.5 in 2040. Blue and
558 red shrimp and Norway lobster predictions under scenario F_{msy} were higher than the
559 baseline ones except for Norway lobster under RCP 8.5 in 2025 (Figure 10).

560 Under fishing scenarios, biomass-based indicators increased in 2025 except for the
561 commercial and fish biomass indicators which decreased for scenario 100 and F_{msy} (Figure
562 11). In 2040, these indicators decreased except for demersal, predatory, and
563 invertebrates' biomass. Scenarios 100 obtained higher biomass values than scenarios 50,
564 except for fish and commercial biomass. Generally, most biomass-based scenarios
565 showed higher mean values under RCP 8.5. Catch-based indicators showed decreasing
566 trends for total and fish catch and discards, while invertebrates catch, demersal catch, and
567 trophic level of the catch increased (Figure 12). Most catch-based indicators obtained
568 higher mean values under RCP8.5.

569

570 **4. Discussion**

571

572 Overall, according to our results, the CoSEGoL FRA failed at improving the condition
573 of the ecosystem over time. Most ecological indicators showed higher values prior to the

574 establishment of the FRA compared to after. The biomass-based indicators did not show
575 positive effects of the establishment of the FRA on commercial, fish, and predatory
576 biomass neither demersal community biomass after eight years of protection in the study
577 area. Trophic-based indicators showed a reduction in TL community and TL community 2
578 from 2008 to 2016, which could evidence an ecosystem degradation with time [4]. After the
579 implementation of the CoSEGoL FRA, the APL decreased which could suggest higher
580 stress, less maturity, and lower resilience of the ecosystem [57]. These results may show
581 that the measure to freeze the fishing effort to 2008 levels established by GFCM was
582 insufficient to allow the rebuilding and protection of demersal commercial stocks. This
583 difference could also be due to a failure on the enforcement of the FRA and the
584 consecutive degradation of the system over time due to the higher impacts of fishing.

585 In accordance with our results, a recent report developed in European waters [66]
586 pointed out that the fleet operating in the Gulf of Lion is the one with the highest non-
587 compliance rate regarding the relative fishing power of the vessels. In addition, the
588 Automatic Identification System (AIS) data provided by Global Fishing Watch [67] were
589 recently used to demonstrate the illegal fishing activities inside several Mediterranean
590 FRAs including the CoSEGoL FRA [68], documenting the lack of enforcement in these
591 areas.

592 Our study shows that most FGs were highly impacted by industrial fisheries after the
593 implementation of the FRA, and this impact was higher compared to the pre-establishment
594 of the FRA. This pattern reinforces our ecological indicators results and it is likely
595 highlighting an increase in the impact of fisheries after the establishment of the FRA [69].
596 In accordance with this, most catch-based indicators increased in their values, which may
597 suggest illegal fishing activities in the FRA. Even though the lack of enforcement can not
598 be a major conclusion from the fitting procedure, we acknowledge that catch-based
599 indicators were consistent with the possibility of illegal fishing, and hence a lack of
600 effective enforcement follows by implication. The low effectiveness of the FRA was also
601 suggested through the fitting procedure of the ecosystem model to historical time series of
602 data, which showed that the best model configuration was achieved when an annual
603 increase of 10% on the fishing effort was included in the initial parameterization. Using
604 food-web models, previous simulations on other FRAs in the Mediterranean Sea
605 demonstrated a declining trend for exploitation species when the fishing effort was kept
606 constant with time [39]. Additionally, Corrales *et al.* [36] identified low effectiveness on one

607 MPA in the Northwestern Mediterranean Sea through ecological indicators, which may be
608 due to the level of enforcement and the nature of the fishing activities allowed.

609 Our study also illustrates that future management simulations are useful to explore
610 trade-offs on species' recovery as well as potential effects at the ecosystem level. In
611 general, baseline scenarios showed different biomass historical trends for target species,
612 such as an increase in anglerfish and blue whiting with a decrease in European hake, blue
613 and red shrimp, and Norway lobster. These contrasting biomass trends suggested direct
614 and indirect impacts of fisheries on the food-web, as seen in the MTI analysis. For
615 instance, European hake is targeted by all fleets operating in the CoSEGoL FRA,
616 especially by longliners, and a high negative impact is expected. Other negative biomass
617 trends can be explained by the profound impacts of just one fleet, such as Norway lobster
618 targeted by bottom trawlers as highlighted in previous studies and assessments in the
619 Northwestern Mediterranean Sea [70,71]. This may be due to high fishing mortality rates
620 [71] and/or high discarding rate [72]. Increasing biomass trends are due to multiple trophic
621 effects triggered by decreases of various predators and competitors. Since baseline
622 historical scenarios showed a lack of positive biomass trends for key target species
623 (including European hake), these results are likely suggesting that fishing regulations
624 established in 2008 have not been effective, in accordance with previous results and
625 reports [66,68] and that management was not enough to achieve the CoSEGoL FRA
626 objectives [17].

627 Alternative fishing management scenarios showed different biomass trends for
628 target species. In general, none of these scenarios showed simultaneous biomass
629 increases for all five target species. Even scenario 100, where all fishing activities were
630 banned, failed to show recovery effects for all target species. This suggests an important
631 role of trophic interactions between some of the currently targeted species in the demersal
632 community. For instance, blue whiting is an important prey of European hake [73] and as
633 such when hake recovers it has a negative effect on its prey. Food-web models can
634 represent a useful tool for MPA assessment that can help to identify ecological trade-offs
635 and synergies [74]. Results also show that trade-offs must be considered between
636 fisheries management and climate change [75] and emphasize the need to include other
637 stressors than fisheries to appropriately assess the future of marine ecosystems [33,34].

638 Despite these trade-offs, overall, demersal and invertebrates' biomass showed
639 increasing trends with recovery scenarios, which indicates that the improvement on the

640 status of the demersal community may be possible under alternative management. In
641 accordance with biomass-based indicators, catch-based indicators showed positive values
642 for demersal and invertebrates catches. Additionally, although total catch and discards
643 decreased, more substantial decreases in discards may indicate a move towards
644 sustainable fishing due to the reduction of unwanted catch under alternative future
645 management scenarios. These results are in line with a previous study [39], which
646 confirmed that targeted species biomass increased under fishing pressure reduction
647 scenarios in the Pagasitikos Gulf, the Eastern Mediterranean Sea. Our results also
648 showed that the establishment of specific objectives should be the main aspect of
649 implementing a restricted area to fisheries [76,77] and managers should focus on
650 indicators related to the overall objective of this protection [78]. The CoSEGoL FRA was
651 focused on demersal species [44], and our study showed that reducing fishing effort in the
652 CoSEGoL FRA could benefit demersal species, in accordance with findings by other
653 studies [23]. Regarding target species, biomass and catch-based indicators changed
654 under different RCP scenarios in 2040, and thus climate change predictions under multiple
655 scenarios should be considered for management purposes in the future [79].

656 During the study, we dealt with several limitations. One was the lack of spatial-
657 temporal series of catches and fleet distribution data, which could improve the analysis on
658 the effect of the FRA potential benefits on the industrial fisheries. Although biomass data
659 came from MEDITS survey database and are characterized spatially and temporally,
660 catches within the FRA were assumed to be proportional to catches in the Geographical
661 Sub-Area 7 (Gulf of Lion), scaled to fishing vessel presence at fishable velocities in the
662 FRA. These assumptions decreased the pedigree value of the model and increased the
663 uncertainty in catch estimates as well as catch indicators results. Consequently, possible
664 negative effects identified in the CoSEGoL FRA could be the result of high fishing pressure
665 in adjacent areas and they call for additional assessments on the spatio-temporal fisheries
666 and biological dynamics from the area. Additionally, the organization in charge to regulate
667 the CoSEGoL FRA, the GFCM, reported the list of vessels operating in this area², which
668 differs from AIS data available at Global Fishing Watch [68]. Considering that enforcement
669 has demonstrated to be an important feature to achieve ecological benefits in an MPA
670 [80], this calls for a better understanding of the catch data inside the FRA and probably an
671 improvement in the surveillance. Collecting time series of fishing activities inside the

² <https://gfcmsitestorage.blob.core.windows.net/contents/DB/GoL/Html> and
<http://www.fao.org/gfcm/data/fleet/fras>

672 CoSEGoL FRA should be a monitoring priority, as previously highlighted for other MPAs
673 [36,38,81]. In addition, response functions to sea temperature were included from a global
674 database [63] because we lacked specific response functions in the study area. Specific
675 sea temperature response function could improve the predictions under different RCP
676 projections (e.g. [82]).

677 To our knowledge, this study represents the first attempt to develop a FRA food-
678 web model in the Western Mediterranean Sea and provides an assessment of the current
679 management and potential outcomes of alternative fishing management scenarios. Our
680 results suggest a failure in the recovery of target species in the restricted area under the
681 current management scenario. Results on future scenarios highlight the need to undertake
682 important reductions in fishing effort in the FRA area, with the highest benefits for marine
683 resources and the ecosystem if the area were to be closed to fishing. The CoSEGoL FRA
684 could act as an important refuge of large spawners of commercial species which can
685 contribute to rebuilding demersal stocks in the Northwestern Mediterranean Sea [44].
686 However, the lack of enforcement and/or effectiveness of the FRA is contributing to its
687 failure. The study also highlights the importance of considering trophic interactions when
688 assessing the impacts of fishing management options, especially when target species are
689 trophically related and include both predators and prey.

690

691

692 **Acknowledgments**

693 This work was funded by the EU Research Project SAFENET project (“Sustainable
694 Fisheries in EU Mediterranean Waters through Network of MPAs.” Call for proposals
695 MARE/2014/41, Grant Agreement n. 721708).

696

697 **5. References**

698 [1] S. Diaz, J. Settele, E. Brondízio, Intergovernmental Science-Policy Platform on Biodiversity
699 and Ecosystem Services. Summary for policymakers of the global assessment report on
700 biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on
701 Biodiversity and Ecosystem Services, (2019).

- 702 [2] M.R. Clark, F. Althaus, T.A. Schlacher, A. Williams, D.A. Bowden, A.A. Rowden, The impacts of
703 deep-sea fisheries on benthic communities: A review, *ICES J. Mar. Sci.* (2016).
704 <https://doi.org/10.1093/icesjms/fsv123>.
- 705 [3] S.F. Thrush, K.E. Ellingsen, K. Davis, Implications of fisheries impacts to seabed biodiversity
706 and ecosystem-based management, *ICES J. Mar. Sci.* (2016).
707 <https://doi.org/10.1093/icesjms/fsv114>.
- 708 [4] D. Pauly, V. Christensen, J. Dalsgaard, R. Froese, F. Torres, Fishing down marine food webs,
709 *Science*. 279 (1998) 860–863.
- 710 [5] R.A. Watson, W.W.L. Cheung, J.A. Anticamara, R.U. Sumaila, D. Zeller, D. Pauly, Global
711 marine yield halved as fishing intensity redoubles, *Fish Fish.* 14 (2013) 493–503.
- 712 [6] V. Christensen, M. Coll, C. Piroddi, J. Steenbeek, J. Buszowski, D. Pauly, A century of fish
713 biomass decline in the ocean, *Mar. Ecol. Prog. Ser.* (2014).
714 <https://doi.org/10.3354/meps10946>.
- 715 [7] D. Pauly, D. Zeller, Catch reconstructions reveal that global marine fisheries catches are
716 higher than reported and declining, *Nat. Commun.* 7 (2016) ncomms10244.
- 717 [8] FAO, *The State of World Fisheries and Aquaculture 2020. Sustainability in action*, Rome,
718 2020.
- 719 [9] P. Vasilakopoulos, C.D. Maravelias, G. Tserpes, The alarming decline of Mediterranean fish
720 stocks, *Curr. Biol.* 24 (2014) 1643–1648.
- 721 [10] F. Colloca, M. Cardinale, F. Maynou, M. Giannoulaki, G. Scarcella, K. Jenko, J.M. Bellido, F.
722 Fiorentino, Rebuilding Mediterranean fisheries: a new paradigm for ecological sustainability,
723 *Fish Fish.* 14 (2013) 89–109. <https://doi.org/10.1111/j.1467-2979.2011.00453.x>.
- 724 [11] FAO, *The State of World Fisheries and Aquaculture 2018 - Meeting the sustainable*
725 *development goals*. Rome. Licence: CC BY-NC-SA 3.0 IGO., (2018).
- 726 [12] J.L. Sánchez Lizaso, I. Sola, E. Guijarro-García, J.M. Bellido, R. Franquesa, A new management
727 framework for western Mediterranean demersal fisheries, *Mar. Policy*. 112 (2020) 103772.
728 <https://doi.org/10.1016/j.marpol.2019.103772>.
- 729 [13] S. Villasante, M. do Carme García-Negro, F. González-Laxe, G.R. Rodríguez, Overfishing and
730 the Common Fisheries Policy:(un) successful results from TAC regulation?, *Fish Fish.* 12
731 (2011) 34–50.
- 732 [14] European Council, Council Regulation (EC) No 1288/2009 of 27 November 2009 establishing
733 transitional technical measures from 1 January 2010 to 30 June 2011, 2009.
- 734 [15] EU Council Regulation, Commission Implementing Regulation (EU) No 404/2011 of 8 April
735 2011 laying down detailed rules for the implementation of Council Regulation (EC) No
736 1224/2009 establishing a Community control system for ensuring compliance with the rules
737 of the Common Fisheries Policy, 2011.
- 738 [16] European Union, Special Report No 08/2017: EU fisheries controls: more efforts needed,
739 2017.
- 740 [17] GFCM, Recommendation CM-GFCM/33/2009/1. On the Establishment of a Fisheries
741 Restricted Area in the Gulf of Lions to Protect Spawning Aggregations and Deep Sea Sensitive
742 Habitats, (2009).
- 743 [18] GFCM, Report of the ninth session of the sub-committee on marine environment and
744 ecosystems., Antalya, Turkey, 2008.
- 745 [19] A. Di Franco, S. Bussotti, A. Navone, P. Panzalis, P. Guidetti, Evaluating effects of total and
746 partial restrictions to fishing on Mediterranean rocky-reef fish assemblages, *Mar. Ecol. Prog.*
747 *Ser.* 387 (2009) 275–285.
- 748 [20] J. Claudet, C. Loiseau, M. Sostres, M. Zupan, Underprotected Marine Protected Areas in a
749 Global Biodiversity Hotspot, *One Earth*. 2 (2020) 380–384.

- 750 [21] A. Di Franco, P. Thiriet, G. Di Carlo, C. Dimitriadis, P. Francour, N.L. Gutiérrez, A.J. De Grissac,
751 D. Koutsoubas, M. Milazzo, M. del Mar Otero, Five key attributes can increase marine
752 protected areas performance for small-scale fisheries management, *Sci. Rep.* 6 (2016) 38135.
- 753 [22] S. Giakoumi, C. Scianna, J. Plass-Johnson, F. Micheli, K. Grorud-Colvert, P. Thiriet, J. Claudet,
754 G. Di Carlo, A. Di Franco, S.D. Gaines, Ecological effects of full and partial protection in the
755 crowded Mediterranean Sea: a regional meta-analysis, *Sci. Rep.* 7 (2017) 8940.
- 756 [23] D. Dimarchopoulou, A. Dogrammatzi, P.K. Karachle, A.C. Tsikliras, Spatial fishing restrictions
757 benefit demersal stocks in the northeastern Mediterranean Sea, *Sci. Rep.* (2018).
758 <https://doi.org/10.1038/s41598-018-24468-y>.
- 759 [24] D. Petza, C. Chalkias, N. Koukourouvli, M. Coll, V. Vassilopoulou, P.K. Karachle, V.
760 Markantonatou, A.C. Tsikliras, S. Katsanevakis, An operational framework to assess the value
761 of fisheries restricted areas for marine conservation, *Mar. Policy.* (2019).
- 762 [25] CBD, Convention on Biological Diversity, Strategic Plan 2011-2020, Aichi Biodiversity Targets,
763 (2010).
- 764 [26] D. Petza, I. Maina, N. Koukourouvli, D. Dimarchopoulou, D. Akrivos, S. Kavadas, A.C. Tsikliras,
765 P.K. Karachle, S. Katsanevakis, Where not to fish - Reviewing and mapping fisheries restricted
766 areas in the Aegean Sea, *Mediterr. Mar. Sci.* (2017). <https://doi.org/10.12681/mms.2081>.
- 767 [27] European Environment Agency, Marine protected areas conserve life, 2018.
768 <https://doi.org/10.2800/405185>.
- 769 [28] B. Horta e Costa, J. Claudet, G. Franco, K. Erzini, A. Caro, E.J. Gonçalves, A regulation-based
770 classification system for Marine Protected Areas (MPAs), *Mar. Policy.* 72 (2016) 192–198.
- 771 [29] MedPAN, SPA/RAC, The 2016 status of Marine Protected Areas in the Mediterranean, Tunis,
772 2019.
- 773 [30] V. Christensen, C.J. Walters, D. Pauly, R. Forrest, *Ecopath with Ecosim version 6: user guide.*
774 November 2008, *Fish. Cent. Univ. Br. Columbia Vanc. Can.* 235 (2008).
- 775 [31] V. Christensen, C.J. Walters, *Ecopath with Ecosim: methods, capabilities and limitations, Ecol.*
776 *Model.* 172 (2004) 109–139. <https://doi.org/10.1016/j.ecolmodel.2003.09.003>.
- 777 [32] C. Walters, V. Christensen, D. Pauly, Structuring dynamic models of exploited ecosystems
778 from trophic mass-balance assessments, *Rev. Fish Biol. Fish.* 7 (1997) 139–172.
- 779 [33] X. Corrales, M. Coll, E. Ofir, J.J. Heymans, J. Steenbeek, M. Goren, D. Edelist, G. Gal, Future
780 scenarios of marine resources and ecosystem conditions in the Eastern Mediterranean under
781 the impacts of fishing, alien species and sea warming, *Sci. Rep.* 8 (2018).
- 782 [34] N. Serpetti, A.R. Baudron, M.T. Burrows, B.L. Payne, P. Helaouet, P.G. Fernandes, J.J.
783 Heymans, Impact of ocean warming on sustainable fisheries management informs the
784 Ecosystem Approach to Fisheries, *Sci. Rep.* 7 (2017) 13438.
- 785 [35] D. Vilas, M. Coll, T. Pedersen, X. Corrales, K. Filbee-Dexter, M.F. Pedersen, K.M. Norderhaug,
786 S. Fredriksen, T. Wernberg, E. Ramírez-Llodra, Kelp-carbon uptake by Arctic deep-sea food
787 webs plays a noticeable role in maintaining ecosystem structural and functional traits, *J. Mar.*
788 *Syst.* 203 (2020) 103268.
- 789 [36] X. Corrales, D. Vilas, C. Piroddi, J. Steenbeek, J. Claudet, J. Lloret, A. Calò, A. Di Franco, T.
790 Font, A. Ligas, G. Prato, R. Sahyoun, P. Sartor, P. Guidetti, M. Coll, Multi-zone marine
791 protected areas: Assessment of ecosystem and fisheries benefits using multiple ecosystem
792 models, *Ocean Coast. Manag.* 193 (2020) 105232.
793 <https://doi.org/10.1016/j.ocecoaman.2020.105232>.
- 794 [37] M. Coll, D. Vilas, X. Corrales, C. Piroddi, J. Steenbeek, Report describing the quantitative
795 models. Sustainable Fisheries in EU Mediterranean waters through network of MPAs -
796 Safenet MARE/2014/41 Deliverable 4.2.:17, 2019.

- 797 [38] G. Prato, C. Barrier, P. Francour, V. Cappanera, V. Markantonatou, P. Guidetti, L. Mangialajo,
798 R. Cattaneo-Vietti, D. Gascuel, Assessing interacting impacts of artisanal and recreational
799 fisheries in a small Marine Protected Area (Portofino, NW Mediterranean Sea), *Ecosphere*. 7
800 (2016).
- 801 [39] D. Dimarchopoulou, I. Keramidas, K. Tsagarakis, A.C. Tsikliras, Ecosystem Models and Effort
802 Simulations of an Untrawled Gulf in the Central Aegean Sea, *Front. Mar. Sci.* 6 (2019) 648.
803 <https://doi.org/10.3389/fmars.2019.00648>.
- 804 [40] P. Raimbault, X. de Madron, Research activities in the Gulf of Lion (NW Mediterranean)
805 within the 1997–2001 PNEC project, *Oceanol. Acta.* 26 (2003) 291–298.
806 [https://doi.org/10.1016/S0399-1784\(03\)00030-6](https://doi.org/10.1016/S0399-1784(03)00030-6).
- 807 [41] E. Massutí, F. Ordinas, N. González, A. Pérez, B. Guijarro, U. Fernández, Informe del
808 seguimiento científico de la acción piloto RAI/AP-26/2007: Pesca experimental de arrastre de
809 fondo en el Golfo de León (Mediterráneo Noroccidental), (2008) 112.
- 810 [42] M. Giannoulaki, A. Belluscio, F. Colloca, S. Fraschetti, M. Scardi, C. Smith, P. Panayotidis, V.
811 Valavanis, M.T. Spedicato, Mediterranean Sensitive Habitats. DG MARE Specific Contract
812 SI2.600741, Final Report, 557 p., 2013.
- 813 [43] M. Canals, J.L. Casamor, G. Lastras, A. Monaco, J. Acosta, S. Berne, B. Loubrieu, P. Weaver, A.
814 Grehan, B. Dennielou, The role of canyons on strata formation, *Oceanography*. 17 (2004) 80–
815 91.
- 816 [44] UNEP-MAP-RAC/SPA, Description of the ecology of the Gulf of Lions shelf and slope area and
817 identification of the areas that may deserve to be protected. By Sardà, J.M.G. and
818 Domínguez-Carrió, C. Ed. RAC/SPA, Tunis. 64pp., (2013).
- 819 [45] G. Chimienti, M. Bo, M. Taviani, F. Mastrototaro, 19 Occurrence and Biogeography of
820 Mediterranean Cold-Water Corals, in: *Mediterr. Cold-Water Corals Past Present Future*,
821 Springer, 2019: pp. 213–243.
- 822 [46] G. Chimienti, M. Bo, F. Mastrototaro, Know the distribution to assess the changes:
823 Mediterranean cold-water coral bioconstructions, *Rendiconti Lincei*. (2018).
824 <https://doi.org/10.1007/s12210-018-0718-3>.
- 825 [47] J.A. Bertrand, L.G. de Sola, C. Papaconstantinou, G. Relini, A. Souplet, The general
826 specifications of the MEDITS surveys, *Sci. Mar.* 66 (2002) 9–17.
- 827 [48] J.J. Heymans, M. Coll, J.S. Link, S. Mackinson, J. Steenbeek, C. Walters, V. Christensen, Best
828 practice in Ecopath with Ecosim food-web models for ecosystem-based management, *Ecol.*
829 *Model.* 331 (2016) 173–184. <https://doi.org/10.1016/j.ecolmodel.2015.12.007>.
- 830 [49] S. Demaneche, C. Merrien, P. Berthou, P. Lespagnol, Rapport R3, Méditerranée continentale,
831 échantillonnage des marées au débarquement, Méthode D'élévation Éval. Captures L'effort
832 Pêche Flot. Façade Méditerranée Cont. Sur Période. 2008 (2007) 217.
- 833 [50] P. Tudó, Unpubl. Data. Directorate of Fishing and Maritime Affairs, Government of Catalonia,
834 Avinguda Diagonal 523-525, 08029 Barcelona, Spain, (2017).
- 835 [51] J. Steenbeek, Diet Calculator - Quick Reference Guide. Version 0.8.5, 11 June 2018. Safenet
836 project - EU-DGMARE (MARE/2014/41), Barcelona, (2018).
- 837 [52] V. Christensen, Managing fisheries involving predator and prey species, *Rev. Fish Biol. Fish.* 6
838 (1996) 417–442.
- 839 [53] R.E. Ulanowicz, C.J. Puccia, Mixed trophic impacts in ecosystems, *Coenoses*. (1990) 7–16.
- 840 [54] A. Valls, M. Coll, V. Christensen, Keystone species: toward an operational concept for marine
841 biodiversity conservation, *Ecol. Monogr.* 85 (2015) 29–47.
- 842 [55] M.E. Power, D. Tilman, J.A. Estes, B.A. Menge, W.J. Bond, L.S. Mills, G. Daily, J.C. Castilla, J.
843 Lubchenco, R.T. Paine, Challenges in the quest for keystones, *BioScience*. 46 (1996) 609–620.

- 844 [56] M. Coll, J. Steenbeek, Standardized ecological indicators to assess aquatic food webs: The
845 ECOIND software plug-in for Ecopath with Ecosim models, *Environ. Model. Softw.* 89 (2017)
846 120–130.
- 847 [57] V. Christensen, Ecosystem maturity - towards quantification, *Ecol. Model.* (1995).
848 [https://doi.org/10.1016/0304-3800\(93\)E0073-C](https://doi.org/10.1016/0304-3800(93)E0073-C).
- 849 [58] J.T. Finn, Measures of ecosystem structure and function derived from analysis of flows, *J.*
850 *Theor. Biol.* 56 (1976) 363–380.
- 851 [59] J. Claudet, P. Guidetti, D. Mouillot, N.T. Shears, F. Micheli, Ecology–Ecological effects of
852 marine protected areas: conservation, restoration, and functioning, *Mar. Prot. Areas*
853 *Multidiscip. Approach Camb. Univ. Press Camb.* (2011) 37–71.
- 854 [60] C. Spearman, The proof and measurement of association between two things, *Am. J. Psychol.*
855 15 (1904) 72–101.
- 856 [61] D. Macias, E. Garcia-Gorriz, C. Piroddi, A. Stips, Biogeochemical control of marine
857 productivity in the Mediterranean Sea during the last 50 years, *Glob. Biogeochem Cycles.* 28
858 (2014) 897–907. <https://doi.org/10.1002/2014GB004846>.
- 859 [62] D.M. Macias, E. Garcia-Gorriz, A. Stips, Productivity changes in the Mediterranean Sea for the
860 twenty-first century in response to changes in the regional atmospheric forcing, *Front. Mar.*
861 *Sci.* (2015). <https://doi.org/10.3389/fmars.2015.00079>.
- 862 [63] K. Kaschner, K. Kesner-Reyes, C. Garilao, J. Rius-Barile, T. Rees, R. Froese, AquaMaps:
863 Predicted range maps for aquatic species. World wide web electronic publication,
864 www.aquamaps.org, Version 08/2016., (2016).
- 865 [64] J.G. Ramirez, A. Giráldez, J.M. Bellido, M. Coll, F. Maynou, Report on stock status and
866 reference points. SC NR 02 - TENDER EASME/EMFF/2016/32 – SPELMED: Evaluation of the
867 population status and specific management alternatives for the small pelagic fish stocks in
868 the Northwestern Mediterranean Sea:119No Title, 2018.
- 869 [65] L. Morissette, Complexity, cost and quality of ecosystem models and their impact on
870 resilience: a comparative analysis, with emphasis on marine mammals and the Gulf of St.
871 Lawrence, University of British Columbia, 2007.
- 872 [66] European Commision, Study on engine power verification by Member States, 2019.
873 <https://doi.org/10.2771/945320>.
- 874 [67] D.A. Kroodsmā, J. Mayorga, T. Hochberg, N.A. Miller, K. Boerder, F. Ferretti, A. Wilson, B.
875 Bergman, T.D. White, B.A. Block, P. Woods, B. Sullivan, C. Costello, B. Worm, Tracking the
876 global footprint of fisheries, *Science.* (2018). <https://doi.org/10.1126/science.aao5646>.
- 877 [68] Oceana, Building a GFCM framework to combat IUU fishing. Oceana case studies and
878 recommendations (Oceana submission to the Working Group on IUU Fishing Beirut, Lebanon
879 24-27 April, 2018), 2018.
- 880 [69] EU Council Regulation, No 1967/2006 of 21 December 2006, concerning management
881 measures for the sustainable exploitation of fishery resources in the Mediterranean Sea,
882 amending Regulation (EEC) No 2847/93 and repealing Regulation, *Off. J. Eur. Union.* L
883 409(30.1 (2006).
- 884 [70] D. Bănanu, C. Mellon-Duval, D. Roos, J.L. Bigot, A. Souplet, A. Jadaud, P. Beaubrun, J.M.
885 Fromentin, Trophic structure in the Gulf of Lions marine ecosystem (north-western
886 Mediterranean Sea) and fishing impacts, *J. Mar. Syst.* 111–112 (2013) 45–68.
887 <https://doi.org/10.1016/j.jmarsys.2012.09.010>.
- 888 [71] E.J. Simmonds, I. Bitetto, G. Daskalov, B. Guijarro, A. Ligas, A. Mannini, D. Mantopoulou
889 Palouka, C. Musumeci, P. Martin, J.L. Perez, P. Pesci, C. Pinto, G. Romagnoni, M. Sbrana, V.
890 Ticina, Scientific, Technical and Economic Committee for Fisheries (STECF) – Stock

- 891 Assessments: demersal stocks in the western Mediterranean Sea (STECF-19-10)., 2019.
892 doi:10.2760/5399, JRC119055.
- 893 [72] J. Moranta, E. Massutí, B. Morales-Nin, Fish catch composition of the deep-sea decapod
894 crustacean fisheries in the Balearic Islands (western Mediterranean), *Fish. Res.* 45 (2000)
895 253–264.
- 896 [73] C. Mellon-Duval, M. Harmelin-Vivien, L. Métral, V. Loizeau, S. Mortreux, D. Roos, J.M.
897 Fromentin, Trophic ecology of the European hake in the Gulf of Lions, northwestern
898 Mediterranean Sea, *Sci. Mar.* 81 (2017) 7–18.
- 899 [74] E.A. Fulton, N.J. Bax, R.H. Bustamante, J.M. Dambacher, C. Dichmont, P.K. Dunstan, K.R.
900 Hayes, A.J. Hobday, R. Pitcher, É.E. Plagányi, Modelling marine protected areas: insights and
901 hurdles, *Philos. Trans. R. Soc. B Biol. Sci.* 370 (2015) 20140278.
- 902 [75] M. Barange, T. Bahri, M.C. Beveridge, K.L. Cochrane, S. Funge-Smith, F. Poulain, Impacts of
903 climate change on fisheries and aquaculture, *Synth. Curr. Knowl. Adapt. Mitig. Options Rome*
904 *Food Agric. Organ. U. N.* (2018).
- 905 [76] J. Day, N. Dudley, M. Hockings, G. Holmes, D. d’A Laffoley, S. Stolton, S.M. Wells, Guidelines
906 for applying the IUCN protected area management categories to marine protected areas,
907 IUCN, 2012.
- 908 [77] J. Claudet, D. Pelletier, Marine protected areas and artificial reefs: A review of the
909 interactions between management and scientific studies, *Aquat. Living Resour.* 17 (2004)
910 129–138.
- 911 [78] D. Pelletier, J. Claudet, J. Ferraris, L. Benedetti-Cecchi, J.A. García-Charton, Models and
912 indicators for assessing conservation and fisheries-related effects of marine protected areas,
913 *Can. J. Fish. Aquat. Sci.* 65 (2008) 765–779.
- 914 [79] J.F. Bruno, A.E. Bates, C. Cacciapaglia, E.P. Pike, S.C. Amstrup, R. Van Hooidonk, S.A. Henson,
915 R.B. Aronson, Climate change threatens the world’s marine protected areas, *Nat. Clim.*
916 *Change.* (2018). <https://doi.org/10.1038/s41558-018-0149-2>.
- 917 [80] G.J. Edgar, R.D. Stuart-Smith, T.J. Willis, S. Kininmonth, S.C. Baker, S. Banks, N.S. Barrett, M.A.
918 Becerro, A.T.F. Bernard, J. Berkhout, C.D. Buxton, S.J. Campbell, A.T. Cooper, M. Davey, S.C.
919 Edgar, G. Försterra, D.E. Galván, A.J. Irigoyen, D.J. Kushner, R. Moura, P.E. Parnell, N.T.
920 Shears, G. Soler, E.M.A. Strain, R.J. Thomson, Global conservation outcomes depend on
921 marine protected areas with five key features, *Nature.* (2014).
922 <https://doi.org/10.1038/nature13022>.
- 923 [81] J. Claudet, P. Guidetti, Improving assessments of marine protected areas, *Aquat. Conserv.*
924 *Mar. Freshw. Ecosyst.* 20 (2010) 239–242.
- 925 [82] M. Coll, M.G. Pennino, J. Steenbeek, J. Solé, J.M. Bellido, Predicting marine species
926 distributions: Complementarity of food-web and Bayesian hierarchical modelling
927 approaches, *Ecol. Model.* 405 (2019) 86–101.

928

929

930

931

932

933

934

935

936

937

938

939

940

941

942 Additional Supplementary material may be found in the online version of this article:

943 **Appendix A.** Supplementary information about the ecosystem modeling approach.

944 **Appendix B.** Supplementary table: The CoSEGoL FRA FGs species composition and
945 methods and references used to estimate the basic input parameters (Table B.1).

946 **Appendix C.** Supplementary table: Input parameters and outputs estimate for the
947 CoSEGoL FRA model (Table C.1). Diet composition matrix for the CoSEGoL FRA model
948 (Table C.2).

949 **Appendix D.** Supplementary tables: Confidence intervals used to describe the uncertainty
950 for each functional group (FG) and each input parameter of the balanced Ecopath model
951 (Table D.1). Reference points used to develop the F_{msy} simulations for CoSEGoL FRA
952 (Table D.2).

953 **Appendix E.** Supplementary figures: Historic and future trends under the two scenarios of
954 IPCC projections of environmental variables considered in the CoSEGoL FRA model: sea
955 water temperature (Figure E.1) and primary production (Figure E.2)

956 **Appendix F.** Supplementary table: Results of the fitting procedure of the CoSEGoL FRA
957 ecosystem fitted to time series of data from 2008 to 2016 (Table F.1).

958