

1 **Title:** Current and potential contributions of the Gulf of Lion Fisheries Restricted Area to
2 fisheries sustainability in the NW Mediterranean Sea

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21 **Abstract**

22 Many commercial species of the world are overexploited resulting in substantial
23 reductions of biomass and ecological changes. Spatial-temporal restrictions of fishing
24 activities are important measures used for the management of marine stocks. However,
25 evidence of whether fishing bans benefit whole ecosystems is still scant. Here, we
26 developed a food-web model approach using the Ecopath with Ecosim (EwE) model
27 representing the Fisheries Restricted Area (FRA) of the Gulf of Lion ecosystem (CoSEGoL
28 model) prior to the establishment of the fisheries restrictions (2006-2008) to characterize
29 the structure and functioning of the ecosystem before and after its establishment. The
30 constructed food-web model was, then, fitted to available time series of data from 2008 to
31 2016 to verify whether this FRA has contributed to recovery of target demersal species
32 and the demersal community. The fitted model was used to explore alternative future
33 management scenarios to explore feasible management options in order to ensure a full
34 ecosystem recovery under climate change conditions. Both small positive and negative
35 ecosystem changes occurred between prior and after the establishment of the FRA,
36 potentially revealing a lack of protection efficiency and/or enforcement. Scenarios of
37 management options under plausible climate futures revealed possible recovery of
38 targeted species, especially European hake. The study highlighted the importance of
39 considering trophic interactions between predators and prey to identify trade-offs and
40 synergies in fisheries management outcomes and the need to consider both fishing and
41 climate dynamics.

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48 1. Introduction

49

50 Fishing is considered one of the most harmful stressors of marine ecosystems [1],
51 with impacts on habitat [2], biodiversity [3] and ecosystem structure [4]. Overexploitation of
52 marine resources is widely distributed [5], and it has substantially reduced fish biomass
53 and caused significant ecological changes in the global ocean [6,7]. In the Mediterranean
54 Sea, many assessed demersal stocks are either fully exploited or overexploited [8]. This
55 situation is not substantially improving as exploitation rate is increasing [8,9], and
56 selectivity is decreasing [8,10].

57 Spatial-temporal restrictions of fishing activities and the establishment of technical
58 measures are the main management tools used in the Mediterranean Sea for marine
59 exploited stocks [9]. Under the European Union (EU) and the General Fisheries
60 Commission for the Mediterranean (GFCM), legal frameworks concerning the
61 establishment of spatial-temporal restrictions of fishing activities come mostly from two
62 regulations [11,12] and one recommendation [13]. The first regulation indicates the
63 definition for fishing protected areas and spatial-temporal restrictions in the Mediterranean
64 Sea, while the second one establishes the need to advance the spatial-temporal measures
65 for recovering populations of demersal stocks in the Western Mediterranean Sea. The
66 recommendation states that the use of trawl nets in waters deeper than 1000 metres shall
67 be prohibited to protect little-known deep-sea benthic habitats in the Mediterranean.
68 Waters below 1000 meters were officially declared as a Fisheries Restricted Area (FRA)
69 by the EU Commission in 2016 [8]. In addition, since 2006, eight FRAs have been
70 established to ensure the protection of deep-sea sensitive habitats and essential fish
71 habitats in well-defined areas of the Mediterranean Sea. Among these is the continental
72 slope of the Eastern Gulf of Lion (CoSEGoL) FRA, the only FRA located in the Western
73 Mediterranean Sea outside territorial waters. The CoSeGoL FRA was established in 2009,
74 following a Recommendation by GFCM (GFCM/33/2009/1) [14], which froze the fishing
75 effort in the area, pending the delivery of additional information by the Scientific Advisory
76 Committee on Fisheries (SAC). In fact, the SAC had advised “to ban the use of towed and
77 fixed gear and longlines for demersal resource in an area of the continental shelf and
78 slope of the eastern Gulf of Lion” [14].

79 A lack of effective management and/or enforcement in restricted areas to fishing
80 has been identified as a major flaw in the Mediterranean Sea management system [15],

81 and it is likely that the FRAs are not reaching their total effectiveness due to increasing
82 illegal or unreported fishing activities inside these areas or due to insufficient measures.
83 For example, Petza *et al.*, [16] reviewed the effectiveness of several national FRAs in the
84 Aegean sea and found that more than 50% of the studied FRAs (n=516) were slightly
85 effective because of their multi-criteria based on the management of FRAs.

86 By 2020 the 10% of the Mediterranean Sea should be protected [17] to ensure the
87 improvement of the status of fish stocks and fisheries. Well established and effective FRAs
88 could contribute to increase the protected surface in the Mediterranean Sea [18,19].
89 Currently, official spatial protection in the Mediterranean Sea covers more than 10% of its
90 surface [20], although most of these areas are poorly protected or unprotected [21] and the
91 surface of fully protected areas is around 0.04% [22].

92 In such a context, it is important to assess whether the proposed FRAs are effectively
93 delivering the benefits they are expected to. Here, we developed a food-web model to
94 evaluate the effectiveness of the CoSEGoL FRA to rebuild and protect demersal
95 commercial stocks in the North Western Mediterranean Sea and to ensure a resilient
96 structure and functioning of the ecosystems. Specifically, we characterized the structure
97 and functioning of the area; we assessed whether the FRA helped recover targeted
98 demersal species and the demersal community since its establishment; and we explored
99 the viability of alternative management options under climate change. To this end we
100 developed a food web model using the Ecopath with Ecosim (EwE) approach [23,24]
101 representing the CoSEGoL area (2006-2008) prior to the establishment of the FRA. The
102 food-web model was fitted to available time series of data from 2008 to 2016 using the
103 temporal dynamic module Ecosim [24,25] to simulate how the structural and functional
104 traits of the ecosystem changed since the establishment of the FRA, and to verify if its
105 establishment resulted in the recovery of commercially targeted species. The fitted model
106 was then used to explore alternative future management scenarios under climate change
107 conditions (accounting for changes in the water temperature and primary productivity
108 dynamics), following similar approaches applied in other modelling studies [26–28]. This
109 study complements existing modelling studies of protected areas in the Mediterranean Sea
110 [29–32] using the EwE approach, by explicitly representing the FRA in the basin. .

111 **2. Material & Methods**

112 **2.1. Study area**

113 The CoSEGoL FRA is located in the Gulf of Lion in the Northwestern
114 Mediterranean Sea, bounded by the following geographic coordinates: 42°40'N, 4°20' E;
115 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
116 the most productive regions of the Mediterranean Sea because of the inputs from the
117 Rhone river and experiences annual upwelling [33]. The bathymetry of the CoSEGoL FRA
118 ranges from 100 to 1500 meters and covers an area of 2,051 km² [34]. This area has been
119 identified as containing essential fish habitats (nurseries and spawning areas) for
120 European hake (*Merluccius merluccius*) and other commercial species [35]. It is
121 characterized by an intricate network of submarine canyons [36], and important benthonic
122 communities of echinoderms, gorgonians, sponges [37] and deep-sea corals [38,39] occur
123 in the area.

124 The CoSEGoL FRA is historically exploited by Spanish bottom trawlers (BTW),
125 Spanish longliners (LON) and French midwater trawlers (MTW) [14]. French trawlers are
126 the main component of the fleet exploiting the marine resources of the Gulf of Lion, and
127 can be divided in two main components: one directed to the catch of small pelagic fish,
128 and the other exploiting a great diversity of demersal species [37]. The aim of CoSEGoL
129 FRA was to protect very important spawning stocks of several species of fishes of
130 importance in the Northwestern Mediterranean fisheries, the most important one being
131 European hake, and also including anglerfish (*Lophius piscatorius*), Norway lobster
132 (*Nephrops norvegicus*) and the blue and red shrimp (*Aristeus antennatus*), while
133 conserving accompanying species (blue whiting *Micromesistius poutassou* and silver
134 sabbardfish *Lepidopus caudatus*) [37].

135 In the recommendation from which the CoSEGoL FRA was adopted [14], the
136 GFCM called for ensuring that fishing effort for demersal stocks of vessels using towed
137 nets, bottom and mid-water longlines, and bottom-set nets shall not exceed the level of
138 fishing effort applied in 2008. Officially, the fleet operating that area in 2008 was composed
139 by 29 fishing vessels, 70% from France and 30% from Spain [14].

140 **2.2. Ecosystem modelling approach**

141 The CoSEGoL FRA model was developed using the Ecopath with Ecosim
142 ecosystem modelling approach (EwE, version 6.6) and it was built using the best available
143 information to represent the FRA ecosystem just before its establishment. Specifically, the
144 model represented a situation of the CoSEGoL FRA for 2006-2008 time period.

145 Subsequently, an Ecosim model representing the CoSEGoL FRA ecosystem during the
146 2008–2016 period was fitted to time series of historical data. (See detailed information
147 about ecosystem modelling approach in Supplementary material Appendix A).

148

149 **2.3. Model parametrization**

150 The CoSEGoL FRA model represented the state of the ecosystem in 2006-2008,
151 previously to the official establishment of the FRA in 2009. Information about species
152 presence and their biomasses was aggregated into functional groups (FGs) of species or
153 groups of species clustered according to key information about their trophic ecology,
154 commercial value, and abundance in the ecosystem. We used the same meta-web
155 structure as defined for the SafeNet Project¹ Western Mediterranean Sea model [43]. We
156 adapted this meta-web structure to local conditions by removing those FGs that did not
157 occur in the study area. The final food-web structure of the CoSEGoL FRA model contains
158 72 functional groups (five marine mammals, one seabird, one sea turtle, 13 pelagic fishes,
159 24 demersal fishes, four cephalopods, 18 invertebrates, two zooplankton, two
160 phytoplankton and two detritus groups) (Supplementary material Table B.1).

161 FGs' biomasses were obtained from different sources from the study area or
162 surrounding areas (see Supplementary Material Table B.1 and C.1. for details on the
163 parameterization of each functional group). Most of the biomasses of demersal and
164 benthic species were calculated from the EU-funded Mediterranean International bottom
165 Trawl Surveys project [44], carried out from spring to early summer (April to June) from
166 1994 to the present. Species biomass was estimated for each haul as the total weight of
167 each species (kg) per km² of trawling. This information was extracted from the MEDITS
168 dataset to account for bathymetric sampling per strata. For pelagic species, we also used
169 the data available from the EU-funded Mediterranean International Acoustic Survey
170 (MEDIAS), which contained information of abundance and biomass per Geographical Sub-
171 Area (GSA).

172 Annual production (P/B) and consumption (Q/B) rates were either estimated using
173 empirical equations [45], or taken from literature or from other models developed in the
174 Mediterranean Sea [43] (Supplementary Material Table B.1 and C.1.). The diet information
175 was compiled using published studies (Supplementary Material Table B.1) on stomach

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

176 content analyses, giving preference to local or surrounding areas (Supplementary Material
177 Table C.2). We used the Diet Calculator (Steenbeek 2018), a custom-built extraction tool
178 that facilitates the process of vetting and incorporating diet data into EwE. Drawing on a
179 large library of published diet studies, the Diet Calculator selects the most likely suitable
180 diet studies for a specific model area, based on a weighted evaluation of diet study
181 characteristics, and generates a diet composition matrix with accompanying pedigree
182 index for each predatory functional group. For migratory species (large pelagic fishes, sea
183 birds, turtles and dolphins), we set a fraction of the diet composition as import based on
184 the time that these species feed outside the system [23,45].

185 Fisheries data were obtained from different sources (database, literature and
186 unpublished data) (Supplementary Material Table B.1. and C.1.). Available fishery data
187 were not geolocated, and so we had to scale catches by the fishing area where operates
188 each fleet. We divided fisheries in three commercial fishing fleets for the CoSEGoL FRA
189 model (Spanish Bottom trawlers, Spanish longliners and French Midwater trawlers). We
190 calculated catches in two different ways: 1) for French fleets, we scaled total catches [46]
191 by FRA area belonging to Gulf of Lion area, and then by the number of vessels working in
192 the study area [14]; and 2) for Spanish fleets, we obtained landings from official dataset of
193 the Regional Government of Catalonia managed by the Institute of Marine Sciences (ICM-
194 CSIC) [47], and were scaled to the area where these fleet were operating.

195 **2.4. Quality of the model**

196 The quality of the models were evaluated using the EwE pedigree routine, which
197 allows assigning a measure of confidence to key input parameters (B, P/B, Q/B, diets and
198 catches) [23,24]. All pedigree values were manually calculated except for diets, which
199 were obtained from the Diet Calculator algorithm [49]. The algorithm computes a total
200 pedigree value for each diet record as a weighted average of four attributes assigned to
201 each diet study (region and year of collection, data representativeness of the species
202 population, and data collection method). Pedigree values were used to identify parameters
203 with low quality that could be modified during the balancing procedure, and were used to
204 calculate the pedigree index, which varies between zero (lowest quality) and one (highest
205 quality) [24], for the FRA model.

206 **2.5. Fitting to time series procedure**

207 Relative fishing effort data available for the fishing fleets included in the model
208 were used to drive the model. Due to the lack of local fishing effort time series, and to test
209 the hypothesis of compliance and enforcement failure in the CoSEGoL FRA, we tested
210 alternative relative fishing effort time series that considered annual declines (-1%, -5%, -
211 10%), annual increases (+1%, +5%, +10%) or no changes in effort with time. These
212 changes were applied to all fisheries in the model. Available absolute or relative observed
213 biomass time series were incorporated in Ecosim to compare the model outputs to
214 observations.

215 **2.6. Model analyses and ecological indicators**

216 The food web structure of the CoSEGoL FRA ecosystem before and after the
217 establishment of the FRA was visualized using a flow diagram built from the biomass and
218 TL (output) of each FG, and the direct trophic interactions among them. The TL identifies
219 the position of organisms within food webs by tracking the source of energy for each
220 organism, and it is calculated by assigning primary producers and detritus a TL of 1 (e.g.
221 phytoplankton), and consumers to a TL of 1, plus the average TL of their prey weighted by
222 their proportion in weight in the predator's diet [52].

223 With both before and after FRA models, the mixed trophic impact (MTI) analysis
224 was performed to quantify direct and indirect trophic interactions among functional groups
225 [53]. This analysis quantifies the direct and indirect impacts that a hypothetical increase in
226 the biomass of one functional group would have on the biomasses of all the other
227 functional groups in the ecosystem, including the fishing fleets. We also used Valls
228 keystone index [54] to identify keystone species in both before and after FRA models. A
229 keystone species is a predator species that shows relatively low biomass but has a
230 relatively important role in the ecosystem [55].

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

234 **Biomass-based.** These indicators are calculated from the biomass of components
235 included in the food-web model. We included five biomass-based indicators: biomass of
236 demersal species ($\text{t}\cdot\text{km}^{-2}\cdot\text{year}^{-1}$) biomass of fish species ($\text{t}\cdot\text{km}^{-2}\cdot\text{year}^{-1}$), biomass of
237 commercial species ($\text{t}\cdot\text{km}^{-2}\cdot\text{year}^{-1}$), biomass of predatory species ($\text{t}\cdot\text{km}^{-2}\cdot\text{year}^{-1}$) and
238 biomass of invertebrates species ($\text{t}\cdot\text{km}^{-2}\cdot\text{year}^{-1}$).

239 **Trophic-based.** These indicators reflect the TL position of different groups of the food
240 web. Trophic level indicators may reflect ecosystem “health” because fishing pressure
241 removing predators can cause a decline in the trophic level of the catch and/or the
242 community [52]. We selected four trophic-based indicators: TL of the community (TLc), TL
243 of the community including organisms with $TL \geq 2$ (TL2), TL of the community including
244 organisms with $TL \geq 3.25$ (TL3.25) and TL of the community including organisms with $TL \geq$
245 4 (TL4).

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

250 **Catch-based.** These indicators are based on catch and discard species data. We included
251 six indicators: total catch ($t \cdot km^{-2} \cdot year^{-1}$), total demersal catch ($t \cdot km^{-2} \cdot year^{-1}$), total fish catch
252 ($t \cdot km^{-2} \cdot year^{-1}$), total invertebrates catch ($t \cdot km^{-2} \cdot year^{-1}$), total discarded catch ($t \cdot km^{-2} \cdot year^{-1}$)
253 and trophic level of the catch.

254 **2.7. Assessment of FRA impact and uncertainty**

255 After fitting the model to time series using Ecosim, we investigated if the establishment
256 of the CoSEGoL FRA resulted in noticeable changes in the structure and functioning of the
257 ecosystem. We compared the ecosystem structure and functioning before and after the
258 establishment of the FRA using the baseline model (2008) and a second FRA model that
259 was extracted at the end of the fitting time period (2016). FRA effectiveness and
260 compliance was measured through changes in ecological and keystone species indicators
261 to discern expected biomass increases according to theory [59]. For example, a positive
262 trend in the biomass of a targeted species is to be expected in a FRA after several years
263 of its protection [18]. In addition, changes in mixed trophic impacts (MTI) from the industrial
264 fleets were examined to quantify the direct and indirect impact of each fleet on functional
265 groups, their potential competitions and trade-offs.

266 Pedigree and associated confidence intervals for key input values were used in the
267 EwE Monte Carlo (MC) routine to evaluate input parameter uncertainty over time
268 (Supplementary Material Table D.1) [24,45]. 200 MC simulations were run, and 95% and
269 5% percentile confidence intervals (CIs) were calculated for main target species
270 biomasses and ecological indicators focussing on *M. merluccius*, *L. piscatorius*, *N.*

271 *norvergicus*, *A. antennatus*, *M. poutassou* and *L. caudatus*. The significance and
272 correlation between our suite of ecological indicators and time were measured using the
273 non-parametric Spearman rank correlation coefficient [60]. To evaluate the impact of the
274 CoSEGoL FRA on the fisheries, catch-based indicator trends were examined over time to
275 capture changes of the potential effects of the FRA establishment. This procedure to
276 capture uncertainty was developed to evaluate historical changes (2008-2016) and the
277 forecasting scenarios (see section below).

278 **2.8. Future alternative management simulations**

279 After the model was fitted to data from 2008 to 2016, eight future scenarios (Table 1)
280 were tested in order to evaluate future alternative management scenarios and their
281 potential effects on marine resources and the ecosystem structure and functioning in the
282 2017-2040 period. The original configuration of the dynamic model was used as a baseline
283 simulation keeping parameters with default values from 2017 to 2040 (Business as usual -
284 BAU). The rest of the scenarios applied new fishing regulations: for instance, scenario “50”
285 simulated a decreasing 50% of fishing effort, scenario “100” simulated a decreasing 100%
286 of fishing effort, and scenario “ F_{msy} ” simulated fishing at Maximum Sustainable Yield (F_{msy})
287 in comparison to fishing at $F_{current}$ (using fishing mortality levels of 2016). To obtain
288 more realistic predictions, we considered future projections of temperature and primary
289 production change.

290 To obtain the F_{msy} values, we first reviewed fishing mortality values at current levels
291 ($F_{current}$) and $F_{0.1}$ (defined as the fishing mortality at which the slope of the Yield per
292 Recruit curve is 10 percent of its slope at the origin) reported by the GFCM and the
293 Scientific, Technical and Economic Committee for Fisheries (STECF) in the last
294 evaluations of Western Mediterranean marine resources (Supplementary material, Table
295 D.2.). Values of $F_{current}$ and F_{msy} for European sardine (*Sardina pilchardus*) and European
296 anchovy (*Engraulis encrasicolus*) were obtained from EU Tender SPELMED for GSA06
297 and GSA07 [61]. We estimated the reduction of fishing mortality comparing $F_{current}$ with
298 $F_{0.1}$ for evaluated species, which yielded an average reduction of 64% for the CoSEGoL
299 FRA. This estimate was applied to the rest of the commercial species that were not
300 assessed but also occurred in the model as fisheries targeted or by-catch species.

301 For the environmental variables (sea water temperature and primary production)
302 (Supplementary material, Figures E.1. and E.2), we used projections of the Med-ERGOM

303 hydro-dynamical biochemical model under two contrasting scenarios of greenhouse
304 emissions (RCP4.5 and RCP8.5) [62,63] (Table 1). To consider changes in sea water
305 temperature, we used the environmental response functions of Ecosim, which links the
306 species or FGs dynamics to the environmental drivers. We first obtained the response
307 functions from AquaMaps [64], which is a global database on species distribution. These
308 environmental response functions are given as curves showing minimum and maximum
309 tolerance levels and 10th and 90th preferable quintiles to the environmental parameters (in
310 our case, temperature). The final environmental preferences for each FG were obtained by
311 weighting the values of the species included in a FG to their relative biomass. Finally,
312 selected ecological indicators and biomass predictions of targeted species were extracted
313 in 2025 and 2040 and were used to assess the effects of future alternative simulations
314 over time.

315

316 **3. Results**

317 **3.1. Baseline parameterization, model quality and temporal fitting**

318 The pedigree index of the CoSEGoL FRA model (0.50) revealed that input data
319 was of acceptable quality when compared to the distribution of pedigree values in other
320 existing models [65]. However, the pedigree value of the CoSEGoL FRA was lower than
321 other published EwE models for the NW Mediterranean Sea [66,67].

322 The best fitted model was obtained for an annual increase in fishing effort of 5%
323 (F_{+5}) (Supplementary material Table F.1.). The parameterization with 30 vulnerabilities
324 (trophic interactions between predators and their prey) and 6 spline points was identified
325 as the best model based on the AIC test criteria (Supplementary material Table F.1).
326 However, the best fitting model did not reproduce observed trends of some target species;
327 these were obtained for a scenario with an increase of 10% in fishing effort. This model
328 was adopted as most likely representative for the ecosystem because of its capability to
329 best reproduce the trends in target species over time (Supplementary material Table F.1)
330 with exception of Norway lobster (SS 11.87) - one of the target groups of the study (Figure
331 2).

332

333 **3.2. Ecosystem structure and functioning**

334 The structure and functioning of the ecosystem changed between prior and after
335 the FRA establishment. The flow diagram showed higher trophic levels for the model prior
336 the establishment of the FRA (Figure 3). Both models highlighted the same FGs for Valls
337 keystone index (Figure 4), although keystone index values for individual groups differed
338 from one ecosystem state to the other. Ecological indicators showed generally small
339 variation. Of biomass-based indicators, only invertebrates showed noticeable differences
340 (Figure 5), with an increase from 2008 to 2016. The TL community, TL community 2 and
341 APL decreased after the implementation of the FRA (Figure 6 and 7).

342 3.3. The impact of industrial fisheries

343 Total catch, Fish catch, and Discards increased once the FRA was establishment,
344 while the TL of the catch and Demersal catch decreased (Figure 8). The MTI analysis
345 applied to the industrial fisheries showed different patterns among fleets and CoSEGoL
346 FRA states (2008 and 2016) (Figure 9). The highest positive impacting values were mostly
347 found for the mid-water trawlers (MWT) (e.g. FG 12 (other large pelagic fish) or FG 55,
348 (Norway lobster)). The most negative impacting values did not show any pattern among
349 fleets. For example, while longliners (LON) impacted negatively on FG 11, 29 and 43
350 (swordfish, common dentex, and rays and skates, respectively), the bottom trawlers (BTW)
351 impacted on FG 40, 51 and 52 (small-spotted catshark, Deep-water rose shrimp and blue
352 and red shrimp, respectively) and the MTW on FG 10 (bluefin tuna). Although both models
353 highlighted the same impacted FGs, the impact value of industrial fisheries over most FGs
354 was different between both ecosystem states. Several FGs obtained lower positive values
355 or higher negative values after the establishment of the CoSEGoL FRA. For example,
356 other large pelagic fish (FG12) obtained an impacting value of 0.75 by MTW in 2008 while
357 it was reduced to 0.64 in 2016, and blue and red shrimp (FG52) obtained an impacting
358 value of -0.74 by BTW in 2008 while it increased to -0.81 in 2016.

359 3.4. Future scenarios of alternative management

360 Under baseline scenarios considering both RCP projections (BAU RCP4.5 and BAU
361 RCP 8.5), the model predicted that European hake would decrease in both scenarios
362 except in 2025 for scenario BAU RCP 4.5, while blue and red shrimp and Norway lobster
363 showed decreasing biomass for both scenarios except in 2025 for scenario BAU RCP 8.5
364 (Figure 10). On the contrary, results showed an increase of biomass of anglerfish after 10
365 and 25 years of simulation (2025 and 2040, respectively) and blue whiting after 10 years
366 (Figure 10). Within these scenarios, although biomass indicators increased in 2025,

367 invertebrates, fish and commercial biomass indicators decreased in 2040 (Figure 11).
368 Regarding catch-based indicators, invertebrates and demersal catch, and total catch and
369 discards under RCP8.5 increased, while most indicators decreased in 2040 (Figure 12).

370 Applying a reduction of 100% on the fishing effort, both models with different RCP
371 projections (scenarios 100 RCP 4.5 and 100 RCP 8.5) predicted increases on European
372 hake biomass, and on anglerfish except for scenario 100 RCP 4.5 in 2040 (Figure 10), but
373 predicted lower anglerfish biomass compared to scenarios BAU (Figure 10). On the
374 contrary, blue whiting decreased as it did Norway lobster that decreased for both
375 scenarios except for 100 RCP 8.5 in 2025. Blue and red shrimp increased on biomass for
376 both scenarios except for 100 RCP 8.5 in 2040. We note that blue and red shrimp and
377 Norway lobster obtained higher biomass predictions compared to baseline results except
378 for Norway lobster for scenario 100 RCP 8.5 in 2025 (Figure 10).

379 Simulating a reduction of 50% of the fishing effort, the model predicted increases in
380 the biomass of European hake, too. The percentage of change in biomass under
381 scenarios 50 were higher than BAU scenarios but lower than scenarios 100. Results
382 showed higher increase on anglerfish biomass than scenarios 100 and BAU, except in
383 2040 under RCP4.5 (Figure 10). In contrast, scenarios 50 RCP 4.5 and 50 RCP 8.5
384 predicted a decrease in biomass trends for blue whiting as scenario 100 but this reduction
385 was smaller. Scenarios 50 RCP 4.5 and 50 RCP 8.5 also predicted a decreasing biomass
386 trend for blue and red shrimp and Norway lobster. This pattern was similar to their baseline
387 scenario predictions except for BAU RCP 8.5 in 2025 (Figure 10).

388 Under fishing at Maximum Sustainable Yield scenarios, both models (F_{msy} RCP 4.5
389 and F_{msy} RCP 8.5) predicted an increase in biomass trends for European hake, which was
390 higher than baseline predictions. Scenarios F_{msy} RCP 4.5 and F_{msy} RCP 8.5 predicted an
391 increase in 2025 and a decrease in 2040 for anglerfish biomass, respectively (Figure 10).
392 These anglerfish predictions were lower than baseline predictions. Oppositely, scenario
393 F_{msy} predicted a decreasing biomass trend for blue whiting, which was much lower than
394 baseline projections (Figure 10). For blue and red shrimp and Norway lobster, these two
395 models predicted an increase in biomass trends except for F_{msy} RCP 4.5 in 2040. Blue and
396 red shrimp and Norway lobster predictions under scenario F_{msy} were higher than the
397 baseline ones except for Norway lobster under RCP 8.5 in 2025 (Figure 10).

398 Under fishing scenarios, biomass-based indicators increased in 2025 except for the
399 commercial and fish biomass indicators which decreased for scenario 100 and F_{msy} (Figure
400 11). In 2040, these indicators decreased except for demersal, predatory and invertebrates'
401 biomass. Scenarios 100 obtained higher biomass values than scenarios 50, except for fish
402 and commercial biomass. Generally, most biomass-based scenarios showed higher mean
403 values under RCP 8.5. Catch-based indicators showed decreasing trends for total and fish
404 catch and discards, while invertebrates catch, demersal catch and trophic level of the
405 catch increased (Figure 12). Most catch-based indicators obtained higher mean values
406 under RCP8.5.

407

408 **4. Discussion**

409 Too often, fishing restricted areas are established without time-bound impact
410 assessments and recovery indicators of success. Here, we presented a first attempt, to
411 our knowledge, to develop a time dynamic ecosystem model of a fisheries restricted area
412 in the Mediterranean Sea accounting for the effect of its establishment.

413 Overall, according to our results the CoSEGoL FRA failed at improving the condition
414 of the ecosystem over time. Most ecological indicators showed higher values prior to the
415 establishment of the FRA compared to after. The biomass-based indicators did not show
416 positive effects of the establishment of the FRA on biomass of commercial, fish, predatory
417 neither demersal community after eight years of protection in the study area. Trophic-
418 based indicators showed a reduction in TL community and TL community 2 from 2008 to
419 2016, which could evidence an ecosystem degradation with time [4]. After the
420 implementation of the CoSEGoL FRA, the APL decreased which could suggest higher
421 stress, less maturity, and lower resilience of the ecosystem [57]. These results could show
422 that the measure to freeze the fishing effort to 2008 levels established by GFCM was
423 insufficient to allow the rebuilding and protection of demersal commercial stocks. This
424 difference could also be due to a failure on the enforcement of the FRA and the
425 consecutive degradation of the system over time due to higher impacts of fishing. In
426 accordance to our results, a recent report developed in European waters [68] pointed out
427 that the fleet operating in the Gulf of Lion is the one with the highest non-compliance rate
428 regarding relative fishing power of the vessels. In addition, the Automatic Identification
429 System (AIS) data provided by Global Fishing Watch [69] were recently used to

430 demonstrate the illegal fishing activities inside several Mediterranean FRAs including the
431 CoSEGoL FRA [70], documenting the lack of enforcement in these areas.

432 Our study showed that most FGs were highly impacted by industrial fisheries after the
433 implementation of the FRA, and this impact was higher compared to the pre-establishment
434 of the FRA. This pattern reinforces previous results and it is likely highlighting an increase
435 in the impact of fisheries after the establishment of the FRA [12]. In accordance with this,
436 most catch-based indicators increased in their values. The low effectiveness of the FRA
437 was also identified through the fitting procedure of the ecosystem model to historical time
438 series of data, which showed that the best model configuration was achieved when an
439 annual increase of 10% on the fishing effort was included in the initial parameterization.

440 Our study also illustrates that future management simulations are useful to explore
441 trade-offs on species' recovery as well as potential effects at the ecosystem level. In
442 general, baseline scenarios showed different biomass historical trends for target species,
443 such as an increase in anglerfish and blue whiting with a decrease in European hake, blue
444 and red shrimp and Norway lobster. These contrasting biomass trends suggested direct
445 and indirect impacts of fisheries on the food-web, as seen in the MTI analysis. For
446 instance, European hake is targeted by all fleets operating in the CoSEGoL FRA,
447 especially by longliners, and a high negative impact is expected. Other negative biomass
448 trends can be explained by the profound impacts of just one fleet, such as Norway lobster
449 by bottom trawlers. Increasing biomass trends are due to multiple trophic effects triggered
450 by decreases of various predators and competitors. Since baseline historical scenarios
451 showed a lack of positive biomass trends for key target species (including European
452 hake), these results are likely suggesting that fishing regulations established in 2008 have
453 not been effective, in accordance with previous results and reports [68,70] and that
454 management was not enough to achieve the CoSEGoL FRA objectives [14].

455 Alternative fishing management scenarios showed different biomass trends for
456 target species. In general, none of these scenarios showed simultaneous biomass
457 increases for all five target species. Even scenario 100, where all fishing activities were
458 banned, failed to show recovery effects for all target species. This suggests an important
459 role of trophic interactions between some of the targeted species in the demersal
460 community. For instance, blue whiting is an important source of food for European hake
461 [71] and as such when hake recovers it has a negative effect on its prey. Food-web
462 models can represent a useful tool for MPA assessment that can help to identify ecological

463 trade-offs and synergies [72]. Results also show that trade-offs must be considered
464 between fisheries management and climate change [73] and emphasize the need to
465 include other stressors than fisheries to appropriately assess the future of marine
466 ecosystems [26,27].

467 Despite these trade-offs, overall, demersal and invertebrates' biomass showed
468 increasing trends with recovery scenarios, which indicates that the improvement on the
469 status of demersal community may be possible under alternative management. In
470 accordance with biomass-based indicators, catch-based indicators showed positive values
471 for demersal and invertebrates catches. Additionally, although total catch and discards
472 decreased, more substantial decreases in discards may indicate a move towards
473 sustainable fishing under alternative future management scenarios. Our results also
474 showed that the establishment of specific objectives should be the main aspect of
475 implementing a restricted area to fisheries [74,75] and managers should focus on
476 indicators related to the overall objective of this protection [76]. The CoSEGoL FRA was
477 focused on demersal species [37], and our study showed that reducing fishing effort in the
478 CoSEGoL FRA could benefit demersal species, in accordance to findings by other studies
479 [18]. Regarding target species, biomass and catch-based indicators changed under
480 different RCP scenarios in 2040, and thus climate change predictions under multiple
481 scenarios should be considered for management purposes in the future [77].

482 During the study we dealt with several limitations. One was the lack of spatial-
483 temporal series of catches and fleet distribution data, which could improve the analysis on
484 the effect of the FRA potential benefits on the industrial fisheries. Although biomass data
485 came from MEDITS survey database and are characterized spatially and temporally,
486 catches within the FRA were assumed to be proportional to catches in the Geographical
487 Sub-Area 7 (Gulf of Lion), scaled to fishing vessel presence at fishable velocities in the
488 FRA. These assumptions increased the uncertainty in catch estimates. Additionally, the
489 organization in charge to regulate the CoSEGoL FRA, the GFCM, reported the list of
490 vessels operating in this area², which differs from AIS data available at Global Fishing
491 Watch [70]. Considering that enforcement has demonstrated to be an important feature to
492 achieve ecological benefits in an MPA [78], this calls for a better understanding of the
493 catch data inside the FRA and probably an improvement in the surveillance. Collecting

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

494 time series of fishing activities inside the CoSEGoL FRA should be a monitoring priority, as
495 previously highlighted for other marine protected areas [31,32,79]. In addition, response
496 functions to sea temperature were included from a global database [64] because we
497 lacked specific response functions in the study area. Specific sea temperature response
498 function could improve the predictions under different RCP projections (e.g. [80]).

499 To our knowledge, this study represents the first attempt to develop a food-web
500 model in an FRA and provides an assessment on the current management and potential
501 outcomes of alternative fishing management scenarios. Our results suggest a failure on
502 the recovery of target species in the restricted area under current management scenario.
503 Results on future scenarios highlight the need to undertake important reductions in fishing
504 effort in the FRA area, with highest benefits for marine resources and the ecosystem if the
505 area would be closed to fishing. The CoSEGoL FRA could act as an important refuge of
506 large spawners of commercial species which can contribute to rebuild demersal stocks in
507 the Northwestern Mediterranean Sea [37]. However, the lack of enforcement and/or
508 effectiveness of the FRA is contributing to its failure. The study also highlights the
509 importance of considering trophic interactions when assessing the impacts of fishing
510 management options, especially when target species are trophically related and include
511 both predators and prey.

512

513

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518

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765 **Tables**

766 Table 1. List of fisheries and 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

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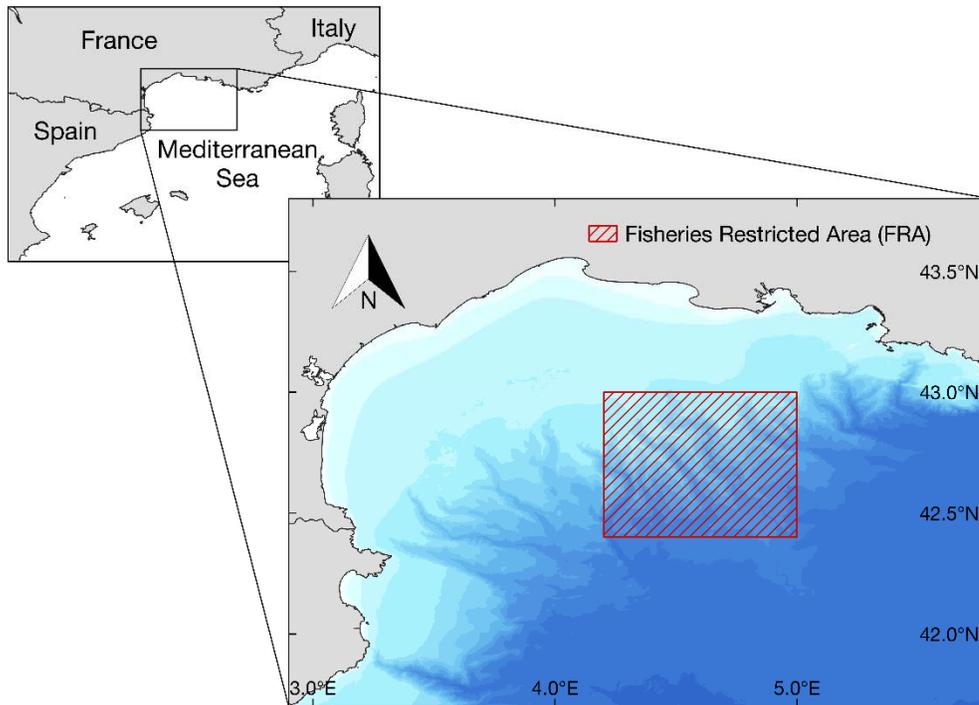
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784 **Figures**



785

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

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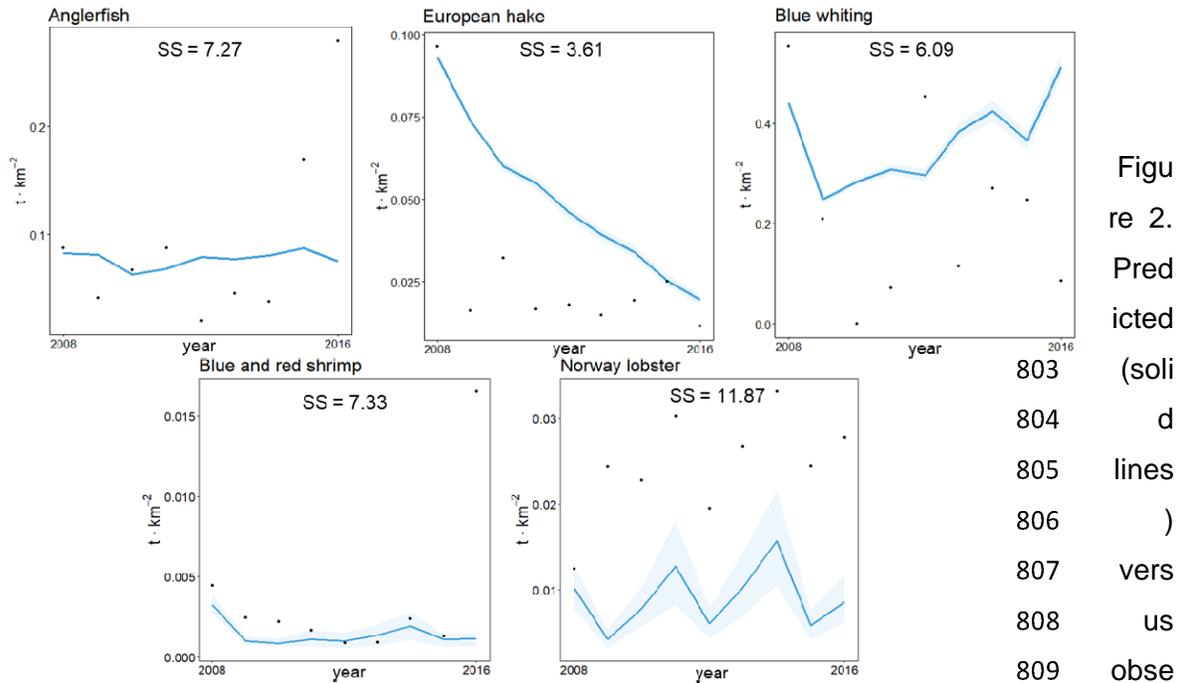
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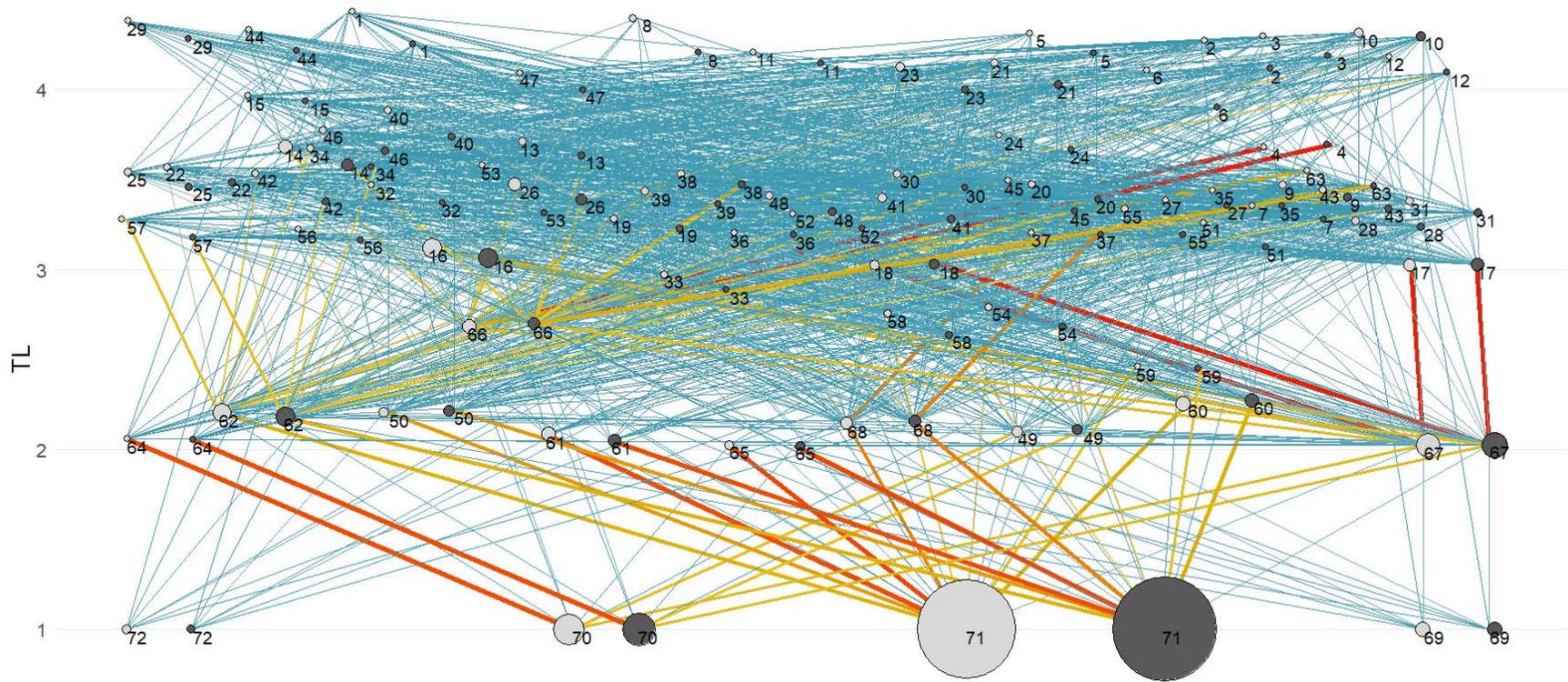
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Figure 2. Predicted (solid lines) versus observed biomass (dots) for targeted groups in the continental slope of the Eastern Gulf of Lion Fisheries Restricted Areaecosystem model for the period 2008-2016. Blue shadows represent the 5% and 95% percentiles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

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

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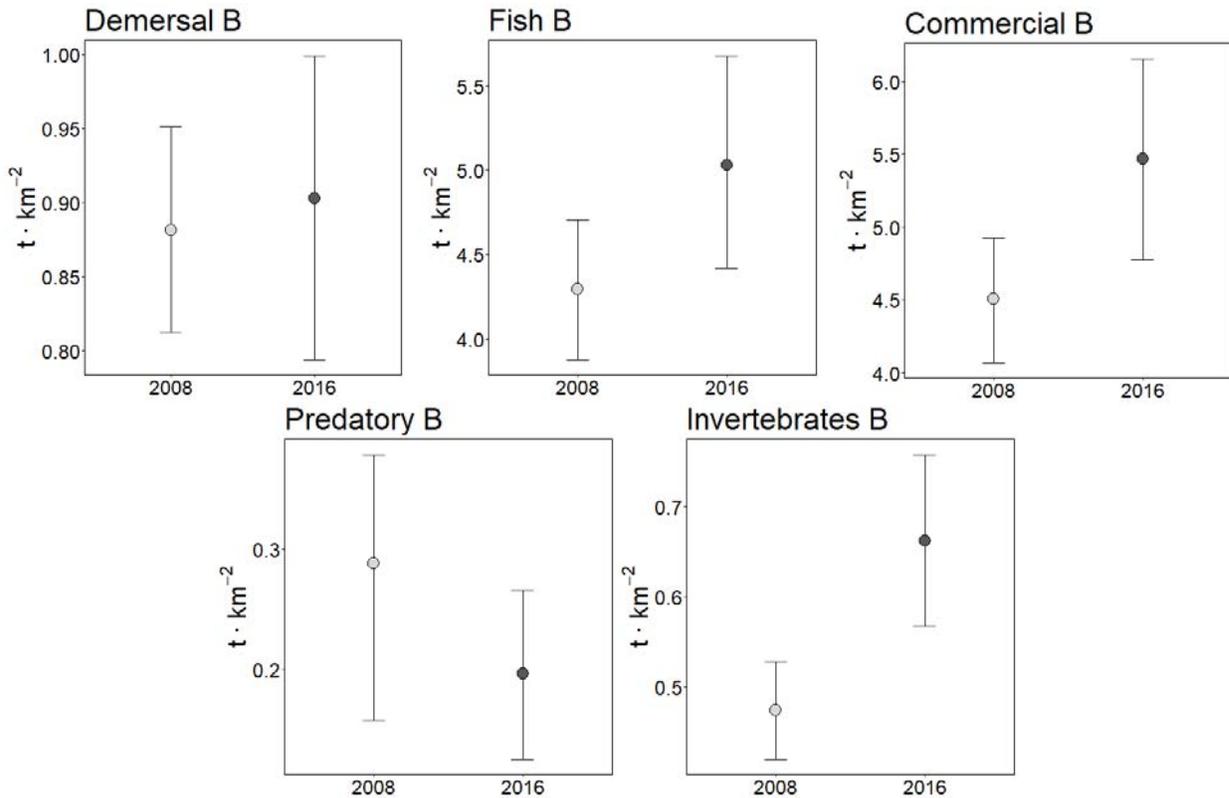
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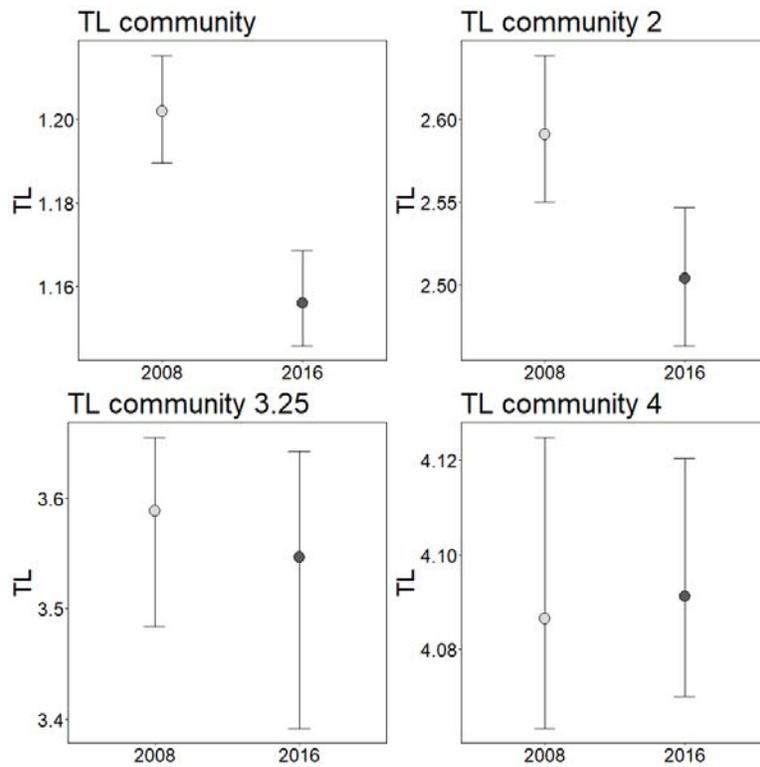
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842 Figure 5. Biomass-based indicators of the continental slope of the Eastern Gulf of Lion
843 Fisheries Restricted Area model before its establishment (year 2008, light grey) and after
844 (year 2016, dark grey). B: Biomass. Error bars represent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



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

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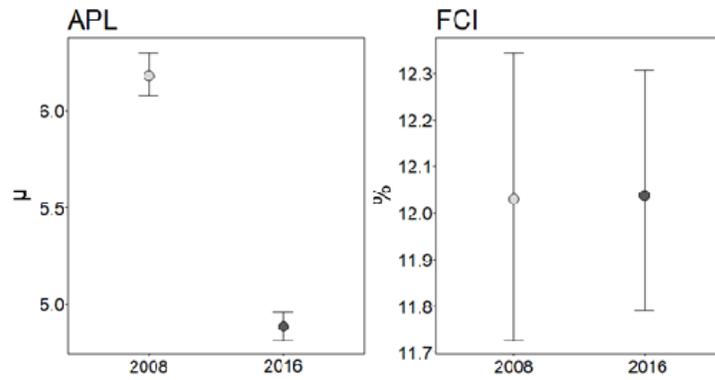
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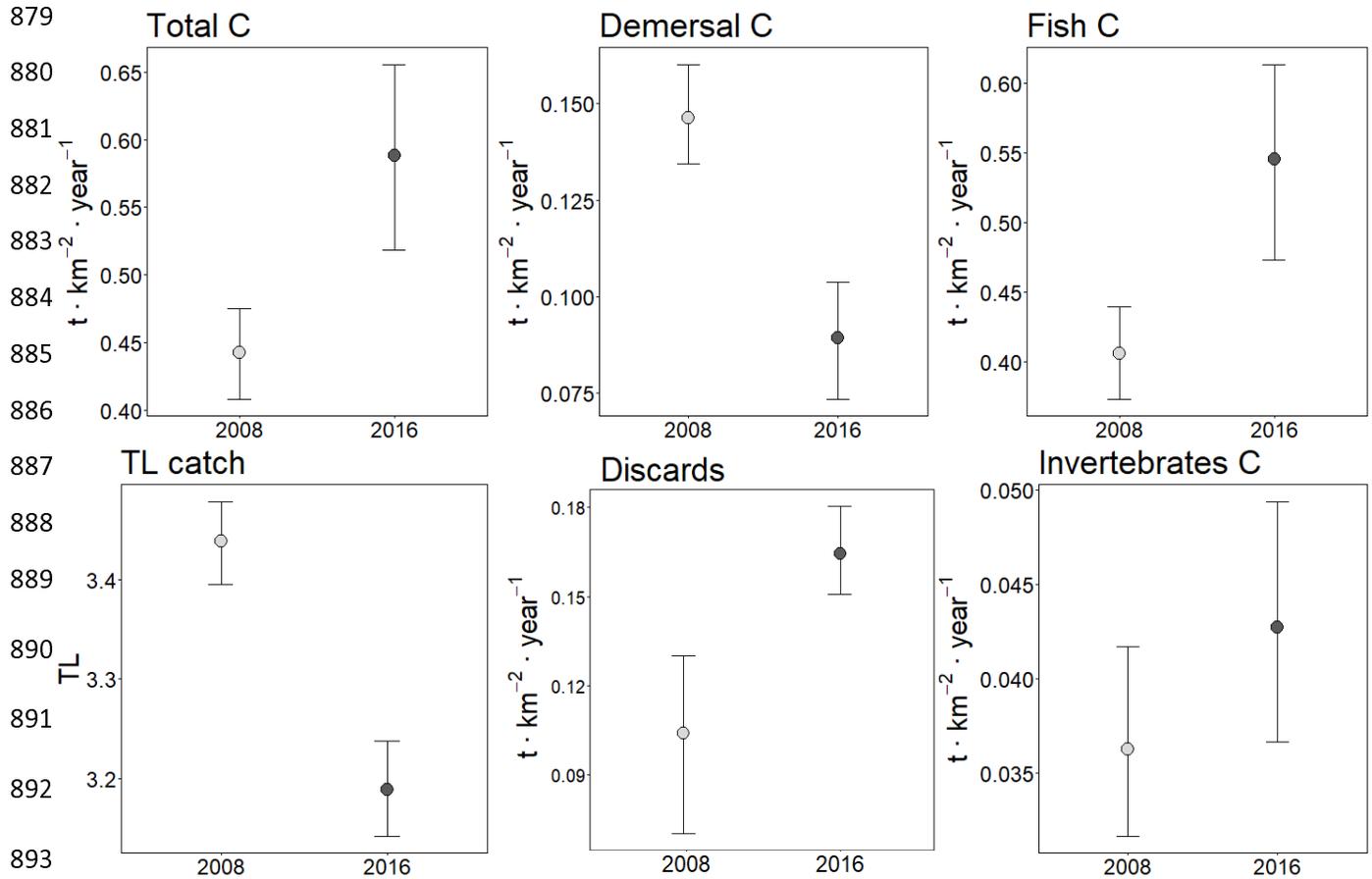


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873 Figure 7. Flow-based indicators of the continental slope of the Eastern Gulf of Lion
874 Fisheries Restricted Area model before its establishment (year 2008, light grey) and after
875 (year 2016, dark grey). APL: The Average Path Length; FCI: The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

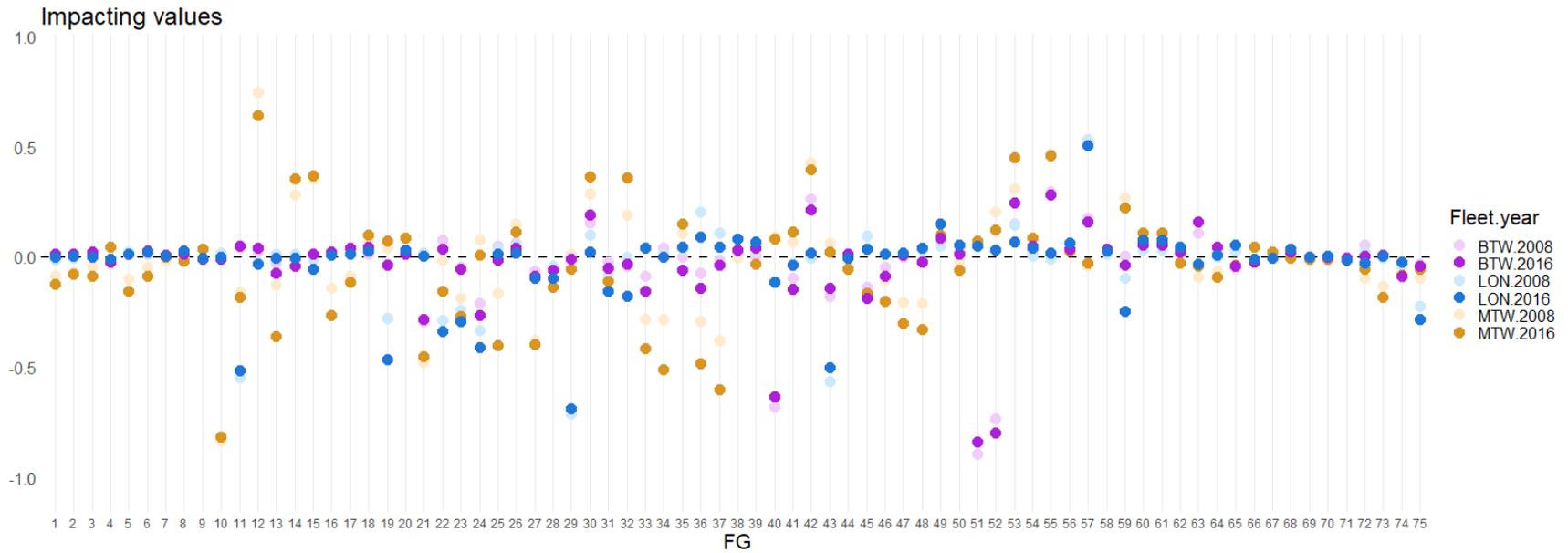
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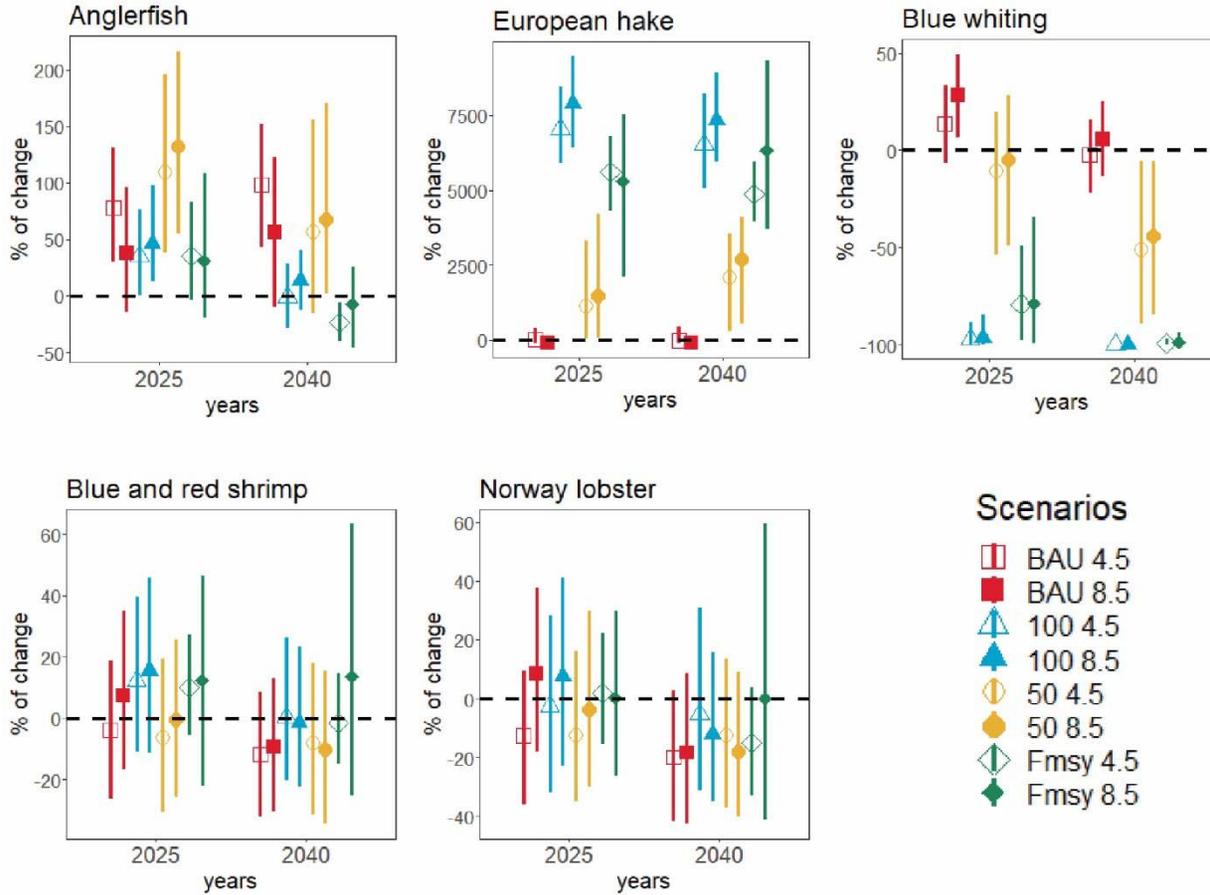
894 Figure 8. Catch-based indicators of the continental slope of the Eastern Gulf of Lion
895 Fisheries Restricted Area model before its establishment (year 2008, light grey) and after
896 (year 2016, dark grey). TL: Trophic Level, C: Catches. Error bars represent 95% confident
897 intervals.

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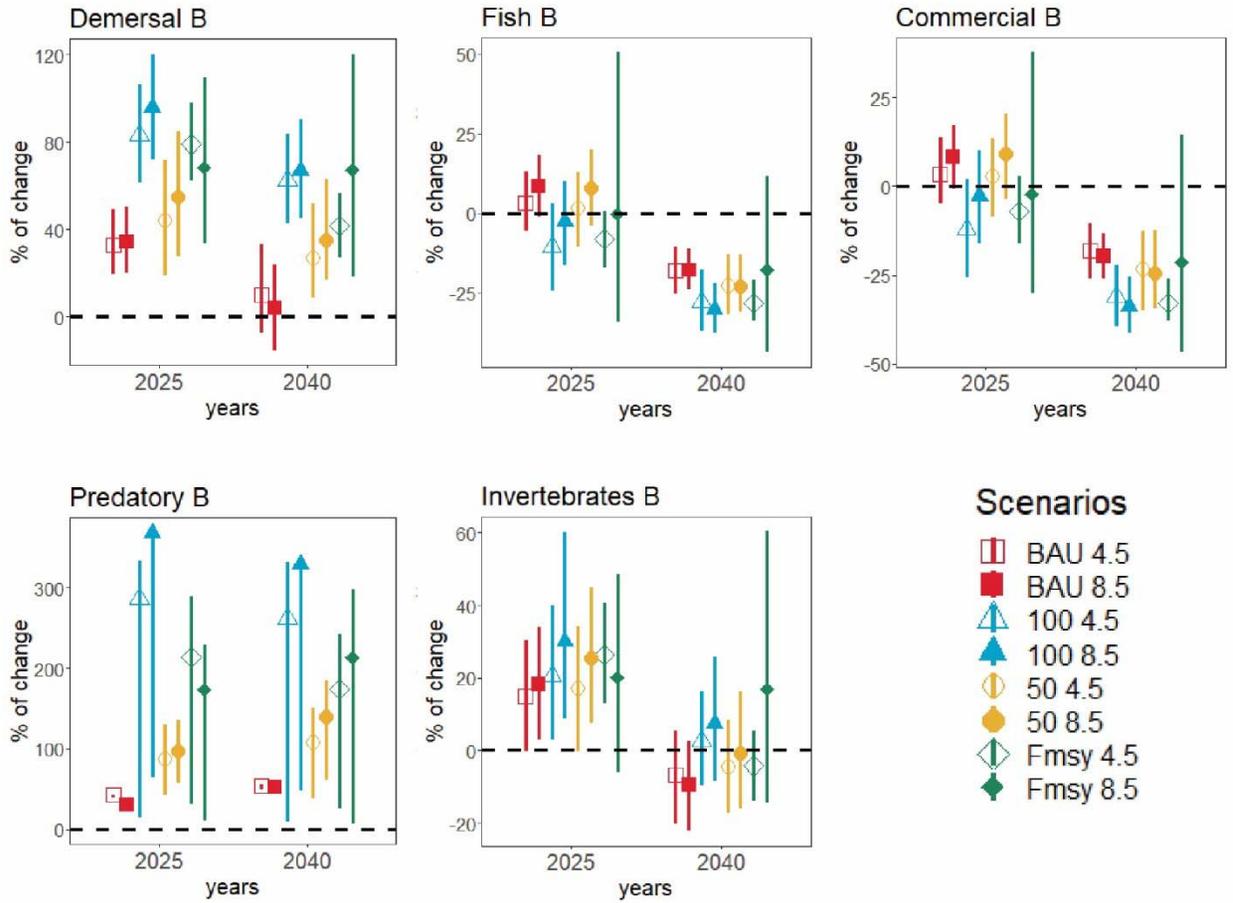
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900 Figure 9. Industrial fisheries impacting values for each functional group of both ecosystem states of the continental slope of the
901 Eastern Gulf of Lion Fisheries Restricted Area (2008 and 2016). X-axis identifies the FG number (except for 73, Midwater trawling;
902 74, Bottom trawling; and 75 Longliner) (MTW – Midwater trawling from France; BTW – bottom trawling from Spain and France; LON –
903 Longliners from Spain).



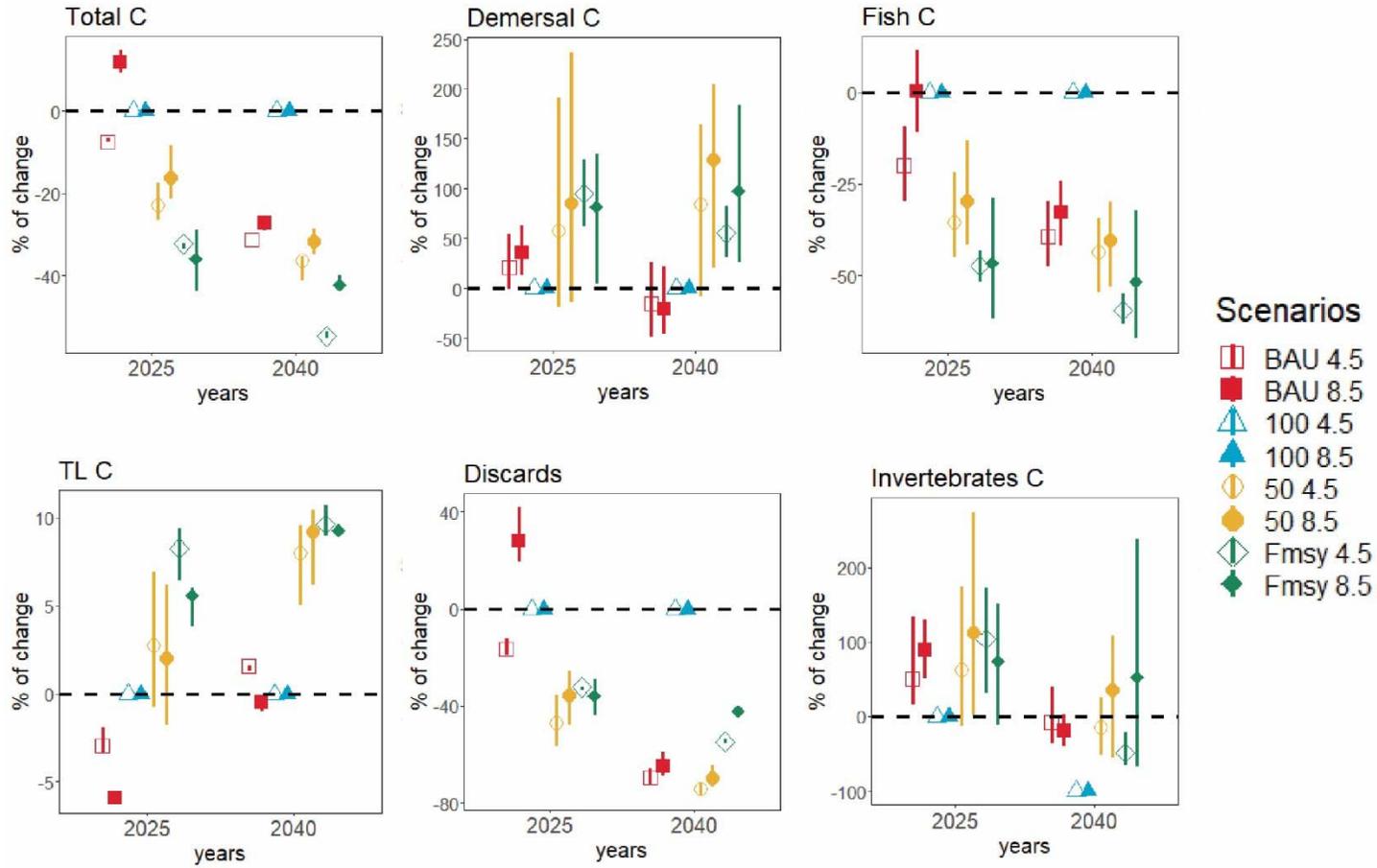
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905 Figure 10. Mean percentage of change in biomass for targeted species under eight future scenarios of management of the continental
 906 slope of the Eastern Gulf of Lion Fisheries Restricted Area in 2025 and 2040. Error bars represent 95% confident intervals. Hollow
 907 points indicate scenarios under RCP4.5 projection, and solid points indicate scenarios under RCP8.5 projection.



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



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913 Figure 12. Mean percentage of change in catch-based indicators under eight future scenarios of management of the continental slope
 914 of the Eastern Gulf of Lion Fisheries Restricted Area in 2025 and 2040. TL: Tropic Level, C: Catches. Error bars represent 95%

915 confident intervals. Hollow points indicate scenarios under RCP4.5 projection, and solid points indicate scenarios under RCP8.5
916 projection.

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

928 **Appendix A.** Supplementary information about the ecosystem modelling approach.

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

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

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

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

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

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