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HAL Authorization

An end-to-end model to evaluate the sensitivity of ecosystem indicators to track fishing impacts

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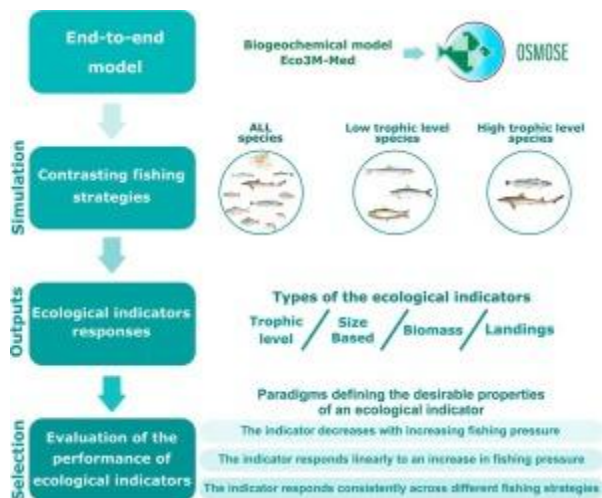
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Abstract :

In order to assist fisheries managers, ecological indicators are needed to evaluate the effects of fishing activities on marine ecosystems and to improve communication of these effects in both public and scientific contexts. Finding appropriate indicators is challenging given the complexity of marine food webs as well as the ecosystem response to fishing pressure. In this study, an end-to-end model developed in the Gulf of Gabes ecosystem (Tunisia) was used to compare the performance of a set of ecosystem indicators in assessing the impact of fishing. This end-to-end model aimed to represent the ecosystem functioning by coupling two existing sub-models, the multispecies individual-based model OSMOSE, representing the dynamics of exploited species and the biogeochemical model Eco3M-Med. The aim of the indicator selection method is to evaluate the sensitivity of a set of ecological indicators regardless the fishing management plan. This method was performed in two major steps. The first step consisted in simulating three simple contrasted fishing strategies in the OSMOSE model exploiting target species (i.e. high trophic level, low trophic level or all species) and then applying a fishing effort multiplier for each fishing strategy to the focus target species. In the second step, three paradigms defining the desirable properties of an ecological indicator have been specified: i/the indicator decreases with increasing fishing pressure, ii/the indicator responds linearly to an increase in fishing pressure and iii/the indicator responds consistently across different fishing strategies. Our results highlighted that the majority of indicators have quite similar performance regarding the trend and the linearity of their responses. However, the size-based indicators seem to be the most robust to track

ecosystem effects of fishing when the fishing strategy changes. A focus on size-based indicators showed that Large Fish Indicators (40 cm) derived from demersal or all surveyed species were the most suitable to reflect a change in the status of the Gulf of Gabes ecosystem due to fishing pressure.

Graphical abstract



Highlights

► An end-to-end model was used to evaluate a set of indicators in the Gulf of Gabes. ► Contrasted fishing strategies were simulated to test the performance of indicators. ► The indicators were compared based on their sensitivity to fishing pressure. ► 3 paradigms defining the desirable properties of an indicator were scrutinized. ► The Large Fish Indicators were the most sensitive to track fishing effects.

Keywords : Ecological indicators, OSMOSE, Ecosystem model, End-to-end model, Marine ecosystem, Fishing impacts, Fishery, Gulf of Gabes

51 **1. Introduction**

52 Fisheries resources are important sources of food, livelihoods and income for millions
53 of people around the world especially in the developing countries which export more
54 than half of fish by value (FAO, 2016). However, the increasing demand for fish
55 products due to human population growth and globalization causes an intense
56 pressure on marine resources. Overfishing combined to other sources of stress (e.g.
57 pollution, habitat degradation, climate change, etc.) is likely to affect the ecosystem
58 integrity and compromise the provision of ecosystem services (Jackson et al., 2001;
59 Worm et al., 2006).

60 Over the past two decades, research organizations have focused on the need for a
61 more holistic management approach to support the Ecosystem Approach to Fisheries
62 (EAF) with the goal of promoting resource sustainability (Garcia, 2003; Plagányi et
63 al., 2007). This approach aims to take into account both ecosystem complexity and
64 the fishing activities in order to limit overfishing and the resulting depletion of fish
65 stocks. To fulfill these objectives there is a need to provide sets of suitable ecological
66 indicators that reflect the status of fisheries and the effects of fishing activities on
67 marine ecosystems. The use of such indicators is essential to implement effective
68 and precautionary fishing management plans (Coll et al., 2016; Shin et al., 2012,
69 2010). Several tools and frameworks have been developed by the scientific
70 community to characterize ecosystem responses to fishing pressure and select a set
71 of measurable indicators over contrasting conditions (Sasaki et al., 2015; Shin et al.,
72 2018; Travers et al., 2006).

73 This study represents an application of an end-to-end model to perform a
74 comparative analysis of ecological indicators in the Gulf of Gabes using the
75 OSMOSE model (Object-oriented Simulator of Marine ecOSystem Exploitation)

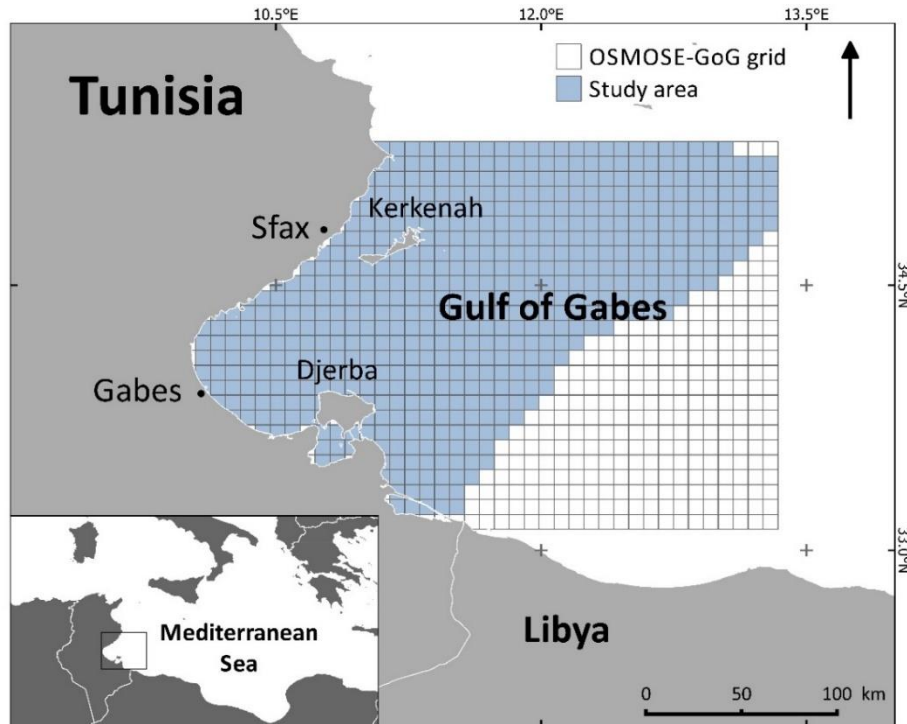
76 coupled to the biogeochemical model Eco3M-Med. The main objective of this work is
77 to evaluate the response of a set of ecological indicators to different fishing
78 mortalities and assess their sensitivity to track fishing pressure under different fishing
79 strategies. The OSMOSE model was chosen because of its ability to consider the
80 complexity and the high stochasticity of marine ecosystems, as well as the possibility
81 to provide a great variety of ecological indicators in output, e.g., size-based, species-
82 based, trophic indicators (Shin and Cury, 2004, 2001). The multispecies model
83 OSMOSE is a spatial, age- and size-structured individual-based model (IBM). It
84 explicitly accounts for ecological and biological processes at the individual level,
85 considering whole-life cycle dynamics of marine organisms to simulate the
86 functioning of marine food webs. Given the complexity of ecosystem attributes, this
87 model can be used as a virtual laboratory to investigate fishing impacts at different
88 biological organization levels.

89 The OSMOSE model has been applied in different marine ecosystems to model
90 trophic structure/dynamics and to address several ecological and management
91 questions. This study is based on the OSMOSE model OSMOSE-GoG developed in
92 the coastal ecosystem of the Gulf of Gabes (Halouani et al., 2016). This ecosystem
93 was historically managed with the objective of maximizing the landings of commercial
94 species. However, given the expansion of the fishery and the increase of fishing
95 effort, the first signs of overfishing appeared in the early 1990s. Hence, there is an
96 interest from local policy-makers to track fishing impacts on the Gulf of Gabes
97 ecosystem.

98 **2. Material and methods**

99 2.1. Study area

100 The Gulf of Gabes is located off southern Tunisia in the South-central Mediterranean
101 Sea and encompasses a total area of approximately 36,000 km² (Fig. 1). Recognized
102 as one of the most important fishing areas in Tunisia, the fishery is multispecies and
103 multigears, landing up to more than 80 different species. This region has a large
104 continental shelf, exclusively composed of soft sediment resulting in the prevalence
105 of bottom trawling activities. Despite the oligotrophic conditions of the Mediterranean
106 Sea, the Gulf of Gabes is one of the most productive ecosystems in the region
107 (Papaconstantinou and Farrugio, 2000). The high level of productivity is partly due to
108 the presence of the ecologically important endemic Mediterranean seagrass
109 *Posidonia Oceanica* (Ben Mustapha and Afli, 2007; Zucchetta et al., 2016). The
110 seagrass meadows provide an important nursery, feeding, and breeding ground for
111 many exploited marine species (Hattour and Ben Mustapha, 2013). Furthermore, the
112 ecosystem is under multiple anthropogenic threats and is subject to important
113 changes on its biodiversity and functioning (Drira et al., 2016; Hattab et al., 2014;
114 Lasram et al., 2015).



115

116 Fig. 1. Map of the Gulf of Gabes ecosystem model showing the spatial grid of
 117 OSMOSE-GoG model (blue cells).

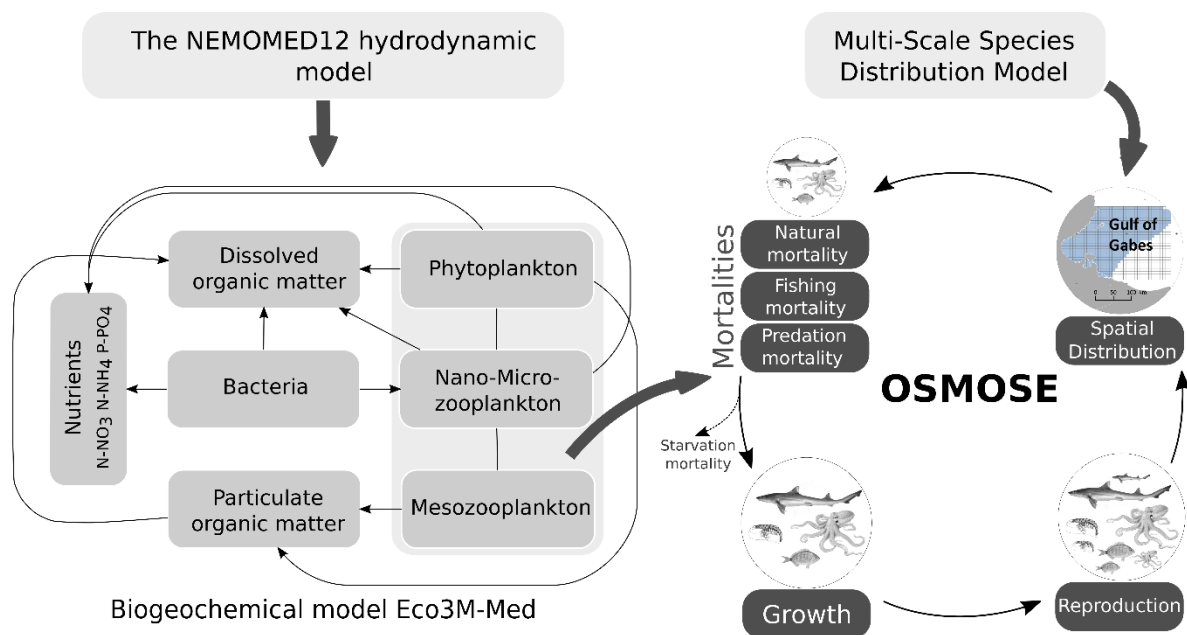
118

119 2.2. The end-to-end modelling approach

120 An end-to-end model has been developed in the Gulf of Gabes to represent the
 121 dynamics of 11 high trophic level species, from climate forcing to fishing, by
 122 integrating physical, biogeochemical and biological processes. This modelling
 123 approach consisted in forcing the individual-based model "OSMOSE" (Halouani et
 124 al., 2016; Shin and Cury, 2004) focused on high trophic levels species (HTL) by a
 125 biogeochemical model "ECO3M-Med" (Alekseenko et al., 2014; Guyennon et al.,
 126 2015) representing the low trophic level organism dynamics (LTL). The two sub-
 127 models were linked through trophic interactions to characterize the food web
 128 structure of the ecosystem from plankton up to top predators for the 2000s period.
 129 This link was established through opportunistic predation based on prey size

130 selection and spatio-temporal co-occurrence between predators and their prey over
 131 space and time. The biomass fields of four planktonic groups (phytoplankton,
 132 nanozooplankton, microzooplankton, and mesozooplankton) obtained from the
 133 biogeochemical model and one benthos group were used as inputs for OSMOSE
 134 (one way coupling without any feedback). The distribution areas of HTL species
 135 obtained from multi-scale species distribution modelling (Hattab et al., 2014) were
 136 implemented in OSMOSE as a presence/absence map (Fig. 2). The end-to-end
 137 model presented in this paper is fully described in (Halouani et al., 2016). Thus, only
 138 a brief presentation of the model structure and parameterization is given in the
 139 present study.

140



141

142 Fig. 2. Conceptual model of the one-way coupling between OSMOSE and Eco3M-
 143 MED. OSMOSE species can prey upon both plankton and high trophic level species,
 144 depending on predator/prey size ratios and spatio-temporal prey availability
 145 (Halouani et al., 2016).

146 OSMOSE-GoG is an application of OSMOSE in the continental shelf of the Gulf of
147 Gabes, that is forced by the biogeochemical model Eco3M-Med to take into account
148 the dynamics of planktonic groups for the period 2001-2010 (Halouani et al., 2016).
149 The modelled area extends from the coastline to the isobath 200 m with a regular
150 grid of 1040 cells of $0.08^\circ \times 0.08^\circ$ degree latitude/longitude and covering the
151 geographical area from (33.1°N/35.3°N) to (9.9°E/13.3°E). The OSMOSE-GoG
152 model simulates the trophic interactions of high trophic level species through their
153 whole life cycles from eggs to adults at a time-step of a two-week period. For each
154 time step, an individual can potentially feed on any prey depending on maximum and
155 minimum predator/prey size ratios (Shin and Cury, 2004, 2001).

156 Eleven key species and one benthos group were explicitly represented in OSMOSE-
157 GoG: seven bony fish (i.e. *Trachurus trachurus*, *Sardina pilchardus*, *Sardinella aurita*,
158 *Engraulis encrasicolus*, *Diplodus annularis*, *Merluccius merluccius*, *Pagellus*
159 *erythrinus*), one cartilaginous fish (i.e. *Mustelus mustelus*), one cephalopod (i.e.
160 *Octopus vulgaris*) and two crustaceans (i.e. *Penaeus kerathurus*, *Metapenaeus*
161 *monoceros*). These species were selected according to their ecological and socio-
162 economic importance in the ecosystem of the Gulf of Gabes (Halouani et al., 2016).
163 The main parameters of the model, namely, growth, reproduction, mortality and
164 predation are presented in the appendix (Table A.1). The detailed description of
165 model parameters and assumptions of OSMOSE-GoG can be found in our previously
166 published paper (Halouani et al., 2016).

167 2.3. IndiSeas framework

168 2.3.1. Selection of indicators

169 In the framework of IndiSeas program (<http://www.indiseas.org/>) (Shin et al., 2012),
170 several indicators were selected to perform comparative analyses across different
171 exploited marine ecosystems. The main objective of this program is to select and
172 analyze a set of ecosystem indicators to assess the ecosystem impacts of fishing in a
173 context of changing environment and to provide decision support for fisheries
174 management. A panel of scientific and strategic criteria was adopted to select a set of
175 ecological indicators in support of ecosystem-based fisheries management. The
176 selection of indicators was guided by six criteria listed in Table 1. At the end of the
177 selection process, several types of ecological indicators (i.e biomass, landings, size
178 and trophic level based) were retained to track the effects of fishing (Table 2). To be
179 useful in fisheries decision-making, ecological indicators need to fulfill the three
180 following performance criteria (Rice and Rochet, 2005):

- 181 • Sensitivity: Does the indicator respond significantly to fishing (i.e. smoothly,
182 monotonically, and with high slope)?
- 183 • Specificity: The proportion of variance in the indicator attributed to fishing
184 pressure compared to environmental forcing.
- 185 • Responsiveness: Does the indicator respond to changes in fishing pressure on
186 short time scales?

187 Here, we contribute to evaluate the performance of selected indicators, by analyzing
188 their sensitivity to fishing pressure. The reliability of the indicators regarding the
189 specificity and responsiveness criteria was not evaluated.

190 Table 1: The list of criteria retained by the IndiSeas working group for the selection of
 191 ecological indicators (Shin et al., 2012)

Scientific criteria	Strategic criteria
Theory: indicators should have a firm theoretical basis reflecting well-defined ecological processes underlying fishing pressure	Tractability: indicators should be small in number, tractable for a range of ecosystems, and updated annually by regional experts
Sensitivity: trends in indicators should be sensitive to fishing pressure	Public awareness: the meaning of the indicators and their link to fishing should be intuitively understood by the general public
Measurability: indicators need to be routinely measurable and have historical data time-series available	Coordination: the selection of indicators must be linked to international frameworks and projects to create synergies (e.g. the CBD, European MSFD, Sea Around Us Project)

192

193 Table 2: List of indicators evaluated by OSMOSE-GoG

Indicator	Calculation	Label
Mean length of fish in the community	$\bar{L} = \frac{\sum_i L_i}{N}$ Where L_i is the length of individual i and N is the number of individuals in the community.	Mean length
Landings (by species)	Y_s	"Y Octopus vulgaris", "Y Merluccius merluccius", "Y Pagellus erythrinus", "Y Penaeus kerathurus",

Indicator	Calculation	Label
		"Y Metapenaeus monoceros", "Y Trachurus trachurus", "Y Sardina pilchardus", "Y Sardinella aurita", "Y Engraulis encrasicolus", "Y Diplodus annularis", "Y Mustelus mustelus"
Trophic level (by species)	$TL_s = 1 + \left(\frac{\sum_i Q_i \times TL_i}{\sum_i Q_i} \right)$ <p>Where TL_s is the trophic level of species s, Q_i the quantity of prey i consumed by species s and TL_i is the trophic level of the prey i.</p>	"TL Octopus vulgaris", "TL Merluccius merluccius", "TL Pagellus erythrinus", "TL Penaeus kerathurus", "TL Metapenaeus monoceros", "TL Trachurus trachurus", "TL Sardina pilchardus", "TL Sardinella aurita", "TL Engraulis encrasicolus", "TL Diplodus annularis", "TL Mustelus mustelus"
Biomass (by species)	B	"B Octopus vulgaris", "B Merluccius merluccius", "B Pagellus erythrinus", "B Penaeus kerathurus", "B Metapenaeus monoceros", "B Trachurus trachurus", "B Sardina pilchardus", "B Sardinella aurita", "B Engraulis encrasicolus", "B Diplodus annularis", "B Mustelus mustelus"
Large Fish Index: LFI ₂₀ , LFI ₃₀ and LFI ₄₀ These indicators were calculated by species group (i.e. surveyed species ¹ (surv), demersal species (dem) and all species (all))	<p>The proportion of large fish biomass in the assemblage.</p> $LFI_{40} = \frac{B_{40}}{B_{Total}}$ <p>Where B_{40} is the biomass of fish greater than 40 cm and B_{Total} is the total biomass of all fish in the sample.</p>	surv LFI 20 cm, surv LFI 30 cm, surv LFI 40 cm, dem LFI 20 cm, dem LFI 30 cm, dem LFI 40 cm, all LFI 20 cm, all LFI 30 cm, all LFI 40 cm

194 ¹surveyed species: species sampled by researchers during routine surveys (for more
195 details: <http://www.indiseas.org/more-information>)

196 2.3.2. Simulation plans

197 In order to test the sensitivity of the selected indicators and evaluate their consistency
198 regardless of the fishing management plan, three simple contrasted fishing strategies
199 were simulated. These fishing strategies were targeting the following groups: i/ "LTL
200 strategy" targeting low trophic level species (e.g. forage species mainly feeding on
201 plankton); ii/ "HTL strategy" targeting high trophic level species (predatory species
202 including large demersal and large pelagic species) and iii/ "ALL strategy" targeting
203 all exploited species in the fishery. For each fishing strategy, a multiplier λ varying
204 from 0 to 5 was applied to the fishing mortality corresponding to the maximum
205 sustainable yield of the focus target species (F_{MSY}). Non-focus species were still
206 fished at their respective current fishing mortality (F_{curr}).

207
$$F_{target\ species} = \lambda \times F_{MSY}$$

208 Where $\lambda \in \{0, 0.2, 0.4, 0.6, 0.8, 1, 1.2, 1.4, 1.6, 1.8, 2, 2.2, 2.4, 2.6, 3, 3.4, 3.8, 4.2, 4.6, 5\}$.

209
$$F_{non\ target\ species} = F_{curr}$$

210 Where F_{curr} corresponds to the current fishing mortality of the non-target species.

211

212 The F_{MSY} of each target species was estimated by reconstructing the Yield to F curve
213 at equilibrium, while all other species were kept at their respective current fishing
214 mortalities F_{curr} . Given the stochastic nature of OSMOSE, 20 replicated runs per λ
215 value were simulated, then the outputs were averaged to estimate the ecological
216 indicators of Table 2. To account for a spin-up time allowing the model to reach
217 equilibrium, OSMOSE-GoG was run over 70 years of simulation. The average of
218 each indicator was then calculated over the last 10 years of simulation.

219 2.4. The screening criteria

220 In order to compare the simulated indicators response objectively (129 response
221 curves), three paradigms defining the desirable properties of an ecological indicator
222 were scrutinized. The aim of these paradigms is to identify the most sensitive
223 indicators to fishing pressure in the Gulf of Gabes. It is important to keep in mind that
224 these paradigms assess partially the reliability of indicators since they do not
225 evaluate their responsiveness and specificity.

226 **1st Paradigm:** The indicator value decreases with increasing fishing pressure.

227 This paradigm aims to facilitate the interpretation of indicators by managers
228 especially when they have to use a set of different indicators to assess the status of
229 marine ecosystems. Indeed, the decline of an indicator following an increase in
230 fishing effort is considered as an intuitive result. In order to determine the trend of an
231 indicator (positive or negative), a linear regression model was applied explaining the
232 response of the indicators (Y) as a function of the F_{MSY} multiplier ($Y = a \cdot \lambda + b$). Thus,
233 when the slope $a < 0$, the general trend is negative, which means that the indicator
234 decreases with the increase of fishing pressure.

235 **2nd paradigm:** The indicator responds linearly to an increase in fishing pressure.

236 The coefficient of determination R^2 of the linear regression model of each indicator
237 was used to test the linearity of their responses to fishing pressure. This paradigm
238 allows the identification of indicators that respond linearly to fishing in order to limit
239 their misinterpretation. Thereby, a good indicator should have a high R^2 (close to 1).

240

241 **3rd paradigm:** The consistency of the response of an indicator across fishing
242 strategies.

243 The aim is to identify indicators with similar responses across the three fishing
244 strategies. The objective is to simplify the monitoring of fishing impacts on the
245 ecosystem. For instance, after a possible change in fishing policy (targeting HTL or
246 LTL species) managers would not be constrained to use a different set of indicators.
247 In order to evaluate this property, the Spearman correlation coefficient was calculated
248 between the three fishing strategies, two by two for each ecological indicator.

249

250 **3. Results and Discussion**

251 3.1. Indicators' performance

252 Several indicators were simulated to analyze their responses to a gradual increase of
253 fishing pressure and to evaluate their respective performances. The response of the
254 54 indicators presented different shapes and trends depending on the fishing
255 strategy and target species. These differences essentially lay in the magnitude of the
256 response, the sign of the trend (positive or negative) and the linearity of indicators'
257 responses. Due to the differences in units, the outputs of the simulations were
258 centered and reduced to facilitate comparison between indicators (Fig. 3). The ALL
259 strategy caused a general decline in trophic levels of all species with the increase of
260 fishing mortalities, except for *Octopus vulgaris* and *Mustelus mustelus*. This result, in
261 addition to the reduction of the proportion of large fish in the community (i.e
262 surv.LFI.40.cm and dem.LFI.40.cm, see Fig. 3) can be seen as a manifestation of the
263 phenomenon of "Fishing down marine food webs". However, our findings showed
264 that, together with the potential of a gradual transition in species composition from

265 high to low trophic level species under fishing pressure (Pauly et al., 1998), the intra-
266 specific TL could also decrease in parallel. We also found that the application of a
267 high trophic level strategy could lead to an increase in biomass of forage species (e.g
268 *Sardina pilchardus*, *Sardinella aurita* and *Engraulis encrasicolus*) versus a decline in
269 top predators biomass (e.g *Mustelus mustelus*, *Merluccius merluccius*). This result
270 could be explained by the trophic cascade effects induced by the removal of
271 predators when subjected to high fishing pressure (Daskalov, 2002; Halouani et al.,
272 2015). Therefore, for the majority of species, especially the small pelagic fishes, we
273 found that the response of their indicators changed according to the fishing strategy.
274 *A contrario*, only the shark *Mustelus mustelus* presented the same negative trend in
275 biomass regardless of the fishing strategy in response to an increase of fishing
276 pressure. This is because *Mustelus mustelus* is at the top of the modelled foodweb
277 with no direct competitors, so could be directly affected by fishing and/or indirectly by
278 the decreasing of its preys' biomass when LTL or ALL trophic level strategies were
279 applied. This suggests that apex predators may be considered as species flagship
280 indicators to track the historical effects of fishing on the ecosystem. These results are
281 consistent with previous findings showing the usefulness of the high trophic level
282 indicator and the apex predator indicator to assess the environmental status of
283 marine ecosystems for an ecosystem-based management of fisheries (Bourdaud et
284 al., 2016). Overall, when the fishing strategy targeted all exploited species, most
285 indicators were performing well showing a significant negative trend (except yield
286 indicators) (Fig. 4A). However, only size-based indicators were appropriate for
287 assessing the state of the ecosystem when there were changes in the fishing
288 strategy.

289



290

291 Fig. 3. Response of the set of indicators simulated by OSMOSE-GoG as a function of
 292 the F_{MSY} multiplier for each fishing strategy (ALL, HTL, LTL). The values of all
 293 indicators were centered and reduced.

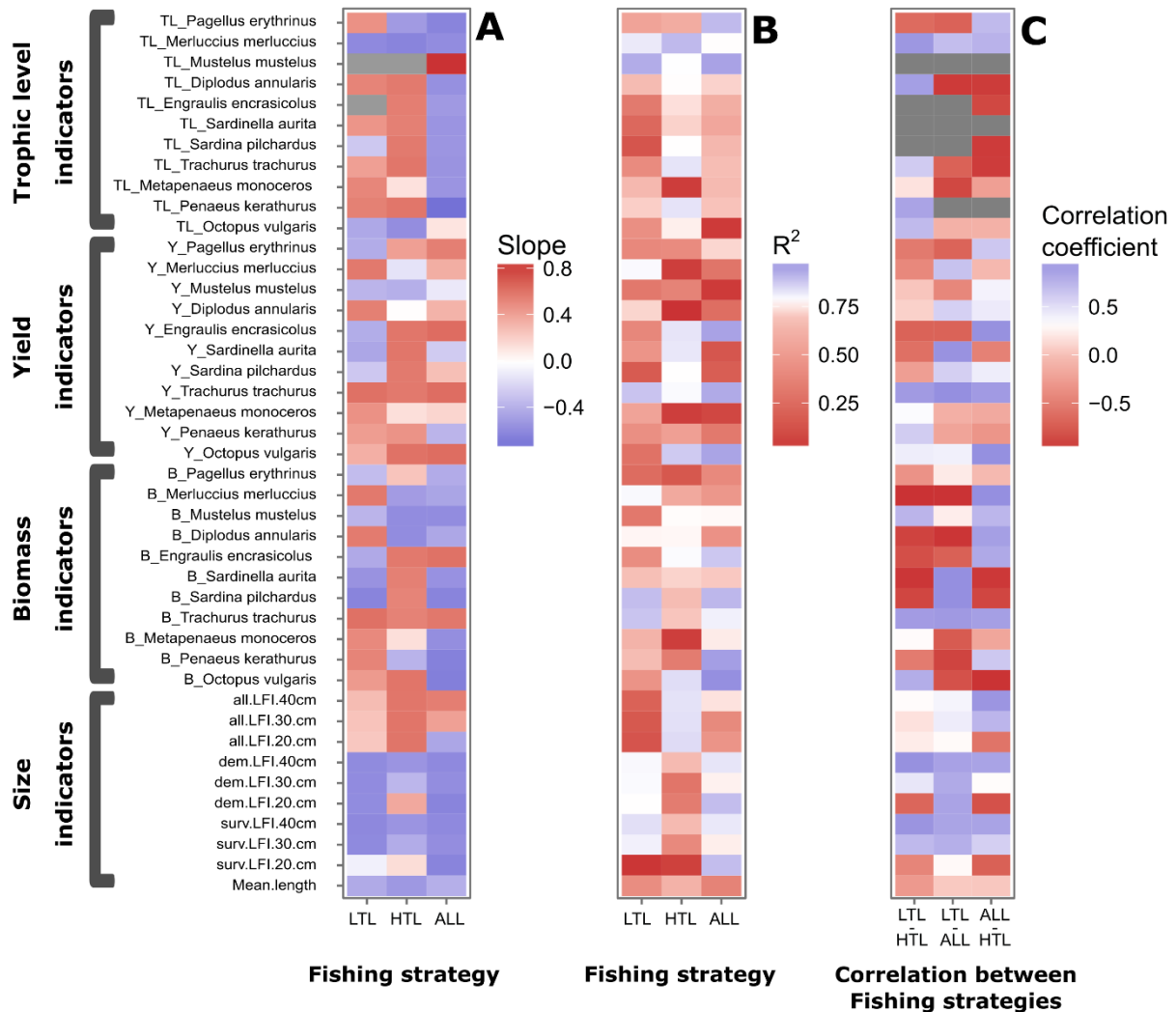
294 A threshold value of 0.8 for the R^2 of the linear regression applied to the response of
295 each indicator (indicator $\sim F_{MSY}$ multiplier) was adopted to select the indicators with
296 the most linear response. Results revealed that the presence of a significant linear
297 trend depended on the fishing strategy. For example, the response of trophic level
298 indicators was more linear with the HTL fishing strategy, in contrast with size-based
299 indicators which displayed a more linear response when ALL or LTL strategies were
300 applied (Fig. 4B). However, only the trophic level of top predators *Mustelus mustelus*
301 and *Merluccius merluccius* exhibited a linear response for the three fishing strategies.
302 Overall, the response of indicators was slightly more linear when the fishing strategy
303 targeted all species.

304

305 The responses of the majority of indicators were not consistent across the different
306 fishing strategies (Fig. 4C). Biomass indicators (especially for small pelagic fishes)
307 displayed a negative correlation between high and low trophic levels fishing
308 strategies. On the other hand, size-based indicators had the most consistent
309 response across fishing strategies, compared to other types of indicators. ALL and
310 HTL strategies were the two fishing strategies with the most similar impacts on the
311 ecosystem: the correlation between indicators produced by ALL and HTL fishing
312 strategies was higher than 0.8 for 35 % of indicators.

313 This observation suggests that the response of the Gulf of Gabes ecosystem to
314 fishing impacts was dependent on the status of top predators rather than on forage
315 species. These results are in agreement with previous studies highlighting the
316 ecological role of top predators in the stability of ecosystems (Heithaus et al., 2008).
317 This result could also be explained by the high proportion of top predators in the Gulf
318 of Gabes in comparison to other Mediterranean ecosystems (Halouani et al., 2015).

319 The important biomass of high trophic level species (e.g. *Octopus vulgaris*,
 320 *Merluccius merluccius*, *Mustelus mustelus*) could drive the intensity of top-down
 321 control in the ecosystem and then its dynamics. Hence, the ALL and HTL strategies
 322 exhibit similar pattern since they both target high trophic level species.



323

324 Fig. 4. Three facets of indicator responses to fishing, based on OSMOSE-GoG
 325 simulations by fishing strategy: The trend (graph "A"), the linearity of the response
 326 (graph "B") and the consistency of the responses between fishing strategies (graph
 327 "C"). In shaded areas, the indicator was not calculated because for some simulations,
 328 a species may no longer remain in the ecosystem due to a high increase in fishing
 329 mortality.

3.2. Which indicators for the Gulf of Gabes?

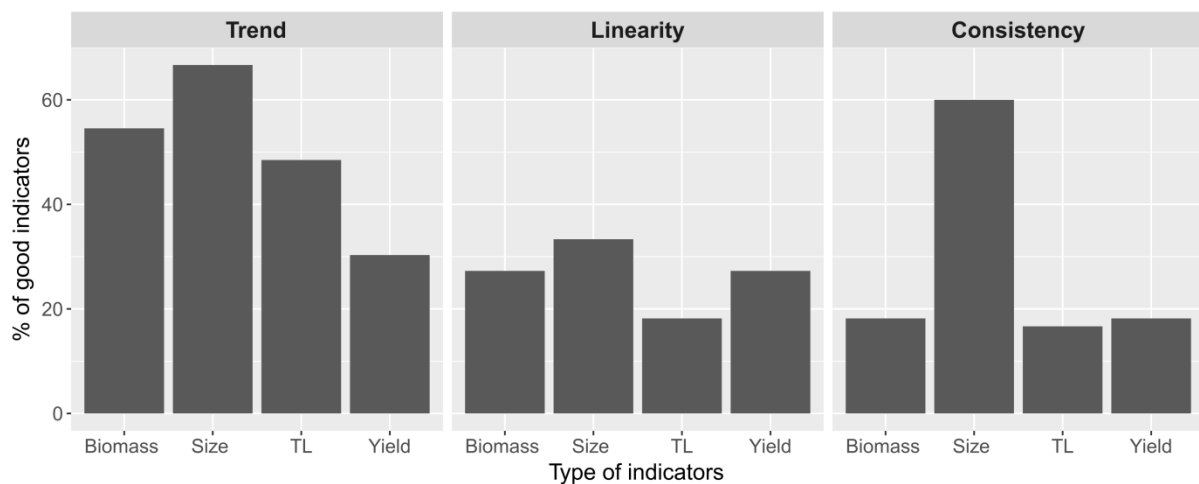
The choice of appropriate indicators for fisheries management in the Gulf of Gabes consisted in identifying the ones which were the most sensitive to fishing pressure, in particular providing the best trade-off between the three facets of indicators' sensitivity: the rate of the response, the linearity of the response, and the consistency of the response across fishing strategies. Overall, simulation results showed that the majority of indicators had quite similar performance regarding the trend and the linearity of their responses. Regarding the consistency of the responses across different fishing strategies, size-based indicators were the most robust to track ecosystem effects of fishing (Fig. 5). A focus on size-based indicators revealed that the two indicators dem.LFI.40cm (the proportion of the biomass of demersal fish larger than 40 cm in the fish community) and surv.LFI.40cm (the proportion of the biomass of surveyed fish species larger than 40 cm in the fish community) derived from the Large Fish Indicator (LFI) were the most suitable to detect a change in the status of the resources in the Gulf of Gabes due to fishing pressure.

These results are in line with previous findings in the North Sea where the large fish indicator was developed as a size-based indicator of fish community status (Shephard et al., 2011). Among the advantages of the LFI are its simplicity of calculation, cost effectiveness and theoretical transparency which makes it accessible to fishery managers and understandable by the public at large (Shephard et al., 2011). This indicator has also been adopted as OSPAR's fish community Ecological Quality Objective metric in the EU Marine Strategy Framework Directive (2010/477/EU, 2010).

In this study, the performance of indicators was evaluated using the end-to-end model OSMOSE-GoG developed for the Gulf of Gabes ecosystem, therefore, the

355 results of the simulations are not necessarily transposable to other ecosystems with
 356 different structure, functioning and environmental forcing. For example, an upwelling
 357 ecosystem, strongly driven by environmental conditions which act on the variability in
 358 fish recruitment, may require other types of indicators to assess the impact of fishing.
 359 Nevertheless, the results obtained for the Gulf of Gabes could still provide useful
 360 insights for indicators in other comparable ecosystems, especially in the
 361 Mediterranean Sea. This could be the case of the Adriatic Sea characterized by a
 362 large continental shelf and multi-gear and multispecies fisheries which are close to
 363 those found in the Gulf of Gabes (Coll et al., 2007; Halouani et al., 2015; Hattab et
 364 al., 2013).

365



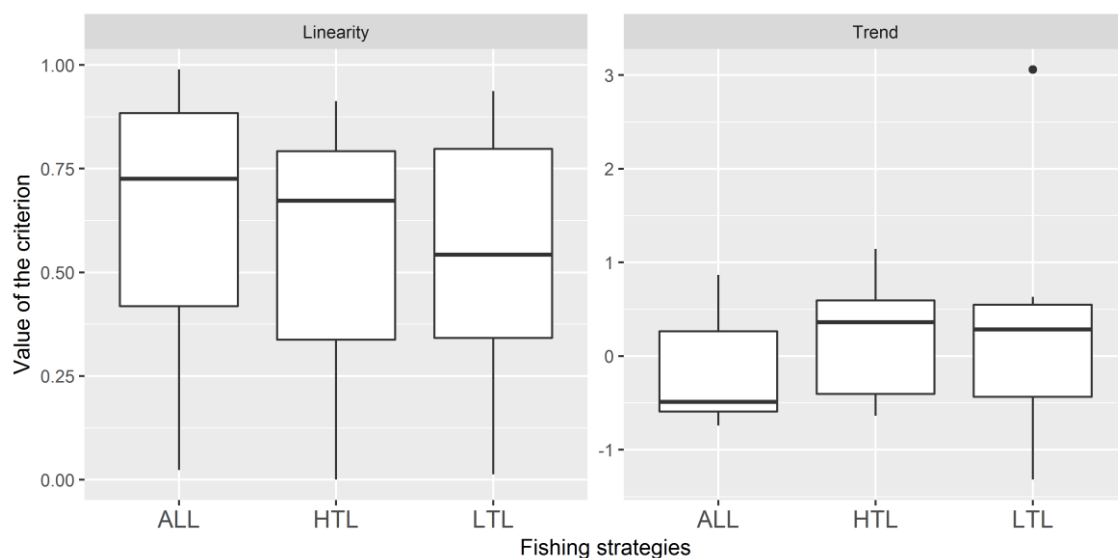
366

367 Fig. 5. Percentage of indicators that satisfy the criteria of each sensitivity facet. i/
 368 Trend: negative slope, ii/ Linearity: R^2 of the linear regression (indicator $\sim F_{MSY}$
 369 multiplier) higher than 0.8 and iii/ Consistency: consistent response between the
 370 three fishing strategies.

371

372 It appeared that ecological indicators were more efficient to reflect the ecosystem
373 effects of fishing in the Gulf of Gabes when the fishing strategy ALL was applied (Fig.
374 6). The results indicated that indicators are more likely to exhibit negative trends for
375 the ALL strategy than for the selective high and low trophic level fishing strategies.
376 Moreover, the results showed that the indicators' response was slightly more linear
377 when the fishing strategy did not target high or low trophic levels specifically. This
378 suggests that the ALL strategy, which is more similar to the debated Balanced
379 Harvesting strategy (Froese et al., 2016; Garcia et al., 2012; Jacobsen et al., 2014),
380 since less selective than the high and low trophic level fishing strategies, would lead
381 to more predictable and less ambiguous response of indicators in the Gulf of Gabes.
382 This could be explained by the fact that the effects of the trophic cascade are likely to
383 be more pronounced when very selective fishing strategies are applied.

384



385

386 Fig. 6. The response of indicators by fishing strategy regarding the paradigms of
387 linearity (high R^2 corresponds to a linear response) and trend (negative slope
388 corresponds to a decreasing trend).

389 Using model simulations proved to be useful to understand the response of
390 ecological indicators to fishing pressure. However, there are some limitations
391 inherent to complexity of the ecosystem models. Indeed, a large amount of data from
392 different sources and different degree of uncertainties were used to implement the
393 end-to-end approach. For example, some input parameters were obtained from other
394 Mediterranean ecosystems (e.g. egg size, egg weight or relative fecundity).
395 Moreover, these parameters were measured or estimated in different periods.
396 Thereby, there is a need to perform a rigorous sensitivity analysis on the response of
397 simulated indicators to the OSMOSE-GoG parameter setting (e.g. the predator-prey
398 size ratios which drive the dynamics of the food web). Furthermore, the paradigms
399 proposed in this study only focused on the sensitivity criteria, while it is essential to
400 also consider the responsiveness and the specificity criteria to identify a set of
401 ecological indicators useful for ecosystem monitoring and management advice.

402 **Next steps**

403 The indicators examined in this study were part of the panel of indicators selected by
404 the IndiSeas working group (Coll et al. 2016; Shin et al. 2010) on the basis of criteria
405 adapted from (Rice and Rochet, 2005) to evaluate the status of marine ecosystems
406 in support of an ecosystem approach to fisheries: (i) the theoretical basis and the
407 ecological processes underlying the ecological indicators, (ii) the measurability and
408 existence of data time series, (iii) the general public awareness, and (iv) the
409 sensitivity of indicators to fishing. The last criterion was clearly lacking supporting
410 evidence and was difficult to quantify on the basis of observations only (Shin et al.
411 2012) so the use of ecosystem models and simulations is necessary to assess the
412 performance of indicators in this regard. The present study is a step towards a better
413 use of indicators in support of ecosystem-based management. However, since the
414 status of the ecosystem is the result of multiple factors it becomes necessary to
415 consider the environmental effects and the potential synergism or antagonism
416 between climate forcing and fishing pressure (Fu et al., 2018; Planque et al., 2010;
417 Travers-Trolet et al., 2014). In the context of multiple drivers potentially influencing
418 marine ecosystems, there are few or no ecological indicators that can be considered
419 exclusive to fishing (Shin et al., 2010). Hence there is a need to evaluate the
420 specificity of indicators to fishing impacts. In the Gulf of Gabes, the size-based
421 indicators, Dem.LFI.40.cm and surv.LFI.40.cm have proved to be the most sensitive
422 to changes in fishing pressure. However, in case of contrasted environmental
423 conditions, it is necessary to understand the capacity of these indicators to
424 disentangle exploitation pressure from climate drivers so indicators are properly
425 interpreted. Moreover, it is also important to consider the responsiveness of
426 indicators to evaluate the rapidity of their responses to a change in fishing pressure.

427 This is all the more important for managers and decision-makers who need to
428 evaluate the effectiveness of management plans on a short term basis (Rice and
429 Rochet, 2005). The evaluation of all of these components of indicators' performance
430 could benefit from a comparative approach across ecosystems with contrasted
431 exploitation status and environmental forcing. The evaluation of the Large Fish
432 Indicator as the most sensitive ecosystem indicator to fishing in the Gulf of Gabes
433 may help to provide a more efficient and focused monitoring of the fishery. In order to
434 ensure the sustainability of marine resources, next step would be to identify LFI's
435 thresholds to trigger actions to meet conservation and exploitation management
436 objectives.

437

438 **4. Conclusion**

439 Developing an end-to-end model was a first step to improve our understanding of the
440 trophic functioning of the food web and simulate fishing impacts across trophic levels
441 in the Gulf of Gabes ecosystem. This first step has proved to be challenging, due to
442 the complexity of model parameterization and some limitations related to the large
443 amount of data from heterogeneous nature, sources and format integrated in the
444 model. In this study, OSMOSE-GoG was used as a tool to test the performance of
445 different ecological indicators in detecting changes in fishing pressure in order to
446 provide support for decision-making. The results of this study suggested that
447 Dem.LFI.40.cm and Surv.LFI.40.cm were the most suitable indicators to detect a
448 change in status of the Gulf of Gabes due to fishing pressure. Nonetheless, it is
449 important to keep in mind that the Large Fish Indicator is appropriate to reflect
450 exploitation impacts on the fish community structure; however, it is not a metric to
451 evaluate ecosystem health. Thus, to fulfill the objectives of fisheries management of

452 the Gulf of Gabes it is important not to consider exclusively the Large Fish Indicator
453 to monitor fishing impacts. The challenge of assessing the possible direct and indirect
454 fishing effects on the ecosystem requires the implementation of a set of ecological
455 indicators to enhance understanding of the management actions and their effects in
456 an ecosystem context.

457

458 **5. Acknowledgements**

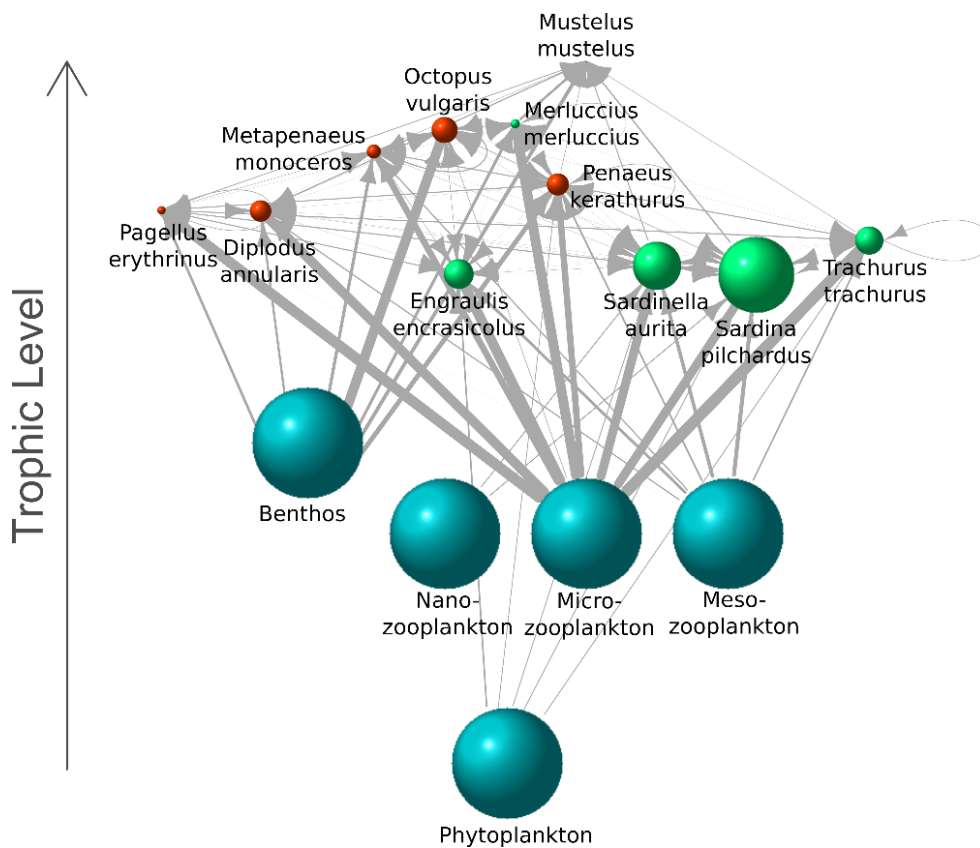
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470 **6. Appendices**

471 Table A.1. Summary of growth, reproduction, mortality and predation parameters for
 472 each of the 11 species modelled in the OSMOSE-GoG model. K , L_{∞} and t_0 : the von
 473 Bertalanffy growth parameters; b : the exponent of the allometric length–weight
 474 relationship; c : constant of proportionality of the allometric length-weight relationship;
 475 s_{mat} : size at maturity; φ : relative fecundity; a_{max} : longevity; M_s : mortality rate due to
 476 predation from other species that are not explicitly considered in the model; F : annual
 477 fishing mortality rate; s_{rec} : size of recruitment.

Species	Growth					Reproduction		Mortality				Predation	
	K (y^{-1})	L_{∞} (cm)	t_0 (y)	b	c ($g \cdot cm^{-3}$)	s_{mat} (cm)	φ ($egg \cdot g^{-1}$)	a_{max} (y)	M_s (y^{-1})	F (y^{-1})	s_{rec} (cm)	Min ratio	Max ratio
<i>Octopus vulgaris</i> (sp1)	1.24	159.01	-0.06	3.66	7.41E-05	95.7	0.1	1.1	2.46	0.25	90	25	13
<i>Penaeus kerathurus</i> (sp2)	0.69	18.03	-0.30	3.14	3.90E-06	12.7	7705	3	0.44	0.35	8	75	6
<i>Metapenaeus monoceros</i> (sp3)	1.36	19.33	0.02	3.23	0.0045	12.2	9713	2.2	2.23	0.45	8	50	6
<i>Trachurus trachurus</i> (sp4)	0.20	42.30	-0.54	2.89	0.0114	21.0	1655	9	0.51	0.25	11	70	8
<i>Sardina pilchardus</i> (sp5)	0.41	19.20	-0.94	3.06	0.0065	12.5	360	5	0.60	0.35	9	300	8
<i>Sardinella aurita</i> (sp6)	0.24	26.48	-1.78	2.93	0.0061	14.3	337	7	0.50	0.25	11	300	8
<i>Engraulis encrasicolus</i> (sp7)	0.36	17.19	-1.01	3.16	0.0042	8.0	444.6	4	0.80	0.01	9	130	8
<i>Diplodus annularis</i> (sp8)	0.16	22.64	-2.00	3.09	0.0140	10.6	400	8	0.61	0.45	9	25	6
<i>Mustelus mustelus</i> (sp9)	0.06	199.00	-3.82	3.04	0.0043	117.2	0.01	20	0.47	0.08	50	14	7
<i>Merluccius merluccius</i> (sp10)	0.19	102.85	-0.79	3.12	0.0036	25.4	202	20	0.40	0.10	9	18	7
<i>Pagellus erythrinus</i> (sp11)	0.14	35.79	-1.63	2.71	0.0301	13.6	150	9	0.15	0.35	11	25	5

478



479

480 Fig. A.1. A schematic diagram of OSMOSE-GoG food web. Spheres represent
 481 the modelled HTL species and LTL groups on a trophic scale. The volume of the
 482 sphere is proportional to the species relative biomasses (except for LTL groups).
 483 Solid arrows represent the trophic links between predators and their prey. The
 484 thickness of the arrows corresponds to the proportion of prey species in the diet of
 485 predator species. (Halouani et al., 2016)

486

487 **7. References**

- 488 2010/477/EU: Commission Decision of 1 September 2010 on criteria and
489 methodological standards on good environmental status of marine waters
490 (notified under document C(2010) 5956) Text with EEA relevance, 2010. , OJ
491 L.
- 492 Alekseenko, E., Raybaud, V., Espinasse, B., Carlotti, F., Queguiner, B., Thouvenin,
493 B., Garreau, P., Baklouti, M., 2014. Seasonal dynamics and stoichiometry of
494 the planktonic community in the NW Mediterranean Sea: a 3D modeling
495 approach. *Ocean Dyn.* 64, 179–207. <https://doi.org/10.1007/s10236-013-0669-2>
- 497 Ben Mustapha, K., Afli, A., 2007. Quelques traits de la biodiversité marine de Tunisie:
498 Proposition d'aires de conservation et de gestion (MedSudMed Technical
499 Documents No. 3). Rome, Italy.
- 500 Bourdaud, P., Gascuel, D., Bentorcha, A., Brind'Amour, A., 2016. New trophic
501 indicators and target values for an ecosystem-based management of fisheries.
502 *Ecol. Indic.* 61, 588–601. <https://doi.org/10.1016/j.ecolind.2015.10.010>
- 503 Coll, M., Santojanni, A., Palomera, I., Tudela, S., Arneri, E., 2007. An ecological
504 model of the Northern and Central Adriatic Sea: Analysis of ecosystem
505 structure and fishing impacts. *J. Mar. Syst.* 67, 119–154.
506 <https://doi.org/10.1016/j.jmarsys.2006.10.002>
- 507 Coll, M., Steenbeek, J., Sole, J., Palomera, I., Christensen, V., 2016. Modelling the
508 cumulative spatial–temporal effects of environmental drivers and fishing in a
509 NW Mediterranean marine ecosystem. *Ecol. Model.*
510 <https://doi.org/10.1016/j.ecolmodel.2016.03.020>
- 511 Daskalov, G.M., 2002. Overfishing drives a trophic cascade in the Black Sea. *Mar.*
512 *Ecol. Prog. Ser.* 225, 53–63.
- 513 Drira, Z., Kmiha-Megdiche, S., Sahnoun, H., Hammami, A., Allouche, N., Tedetti, M.,
514 Ayadi, H., 2016. Assessment of anthropogenic inputs in the surface waters of
515 the southern coastal area of Sfax during spring (Tunisia, Southern
516 Mediterranean Sea). *Mar. Pollut. Bull.*
517 <https://doi.org/10.1016/j.marpolbul.2016.01.035>
- 518 FAO (Ed.), 2016. Contributing to food security and nutrition for all, The state of world
519 fisheries and aquaculture. Rome.
- 520 Froese, R., Walters, C., Pauly, D., Winker, H., Weyl, O.L.F., Demirel, N., Tsikliras,
521 A.C., Holt, S.J., 2016. A critique of the balanced harvesting approach to
522 fishing. *ICES J. Mar. Sci.* 73, 1640–1650.
523 <https://doi.org/10.1093/icesjms/fsv122>
- 524 Fu, C., Travers-Trolet, M., Velez, L., Grüss, A., Bundy, A., Shannon, L.J., Fulton,
525 E.A., Akoglu, E., Houle, J.E., Coll, M., Verley, P., Heymans, J.J., John, E.,
526 Shin, Y.-J., 2018. Risky business: The combined effects of fishing and
527 changes in primary productivity on fish communities. *Ecol. Model.* 368, 265–
528 276. <https://doi.org/10.1016/j.ecolmodel.2017.12.003>
- 529 Garcia, S.M., 2003. The ecosystem approach to fisheries: issues, terminology,
530 principles, institutional foundations, implementation and outlook. Food &
531 Agriculture Org.
- 532 Garcia, S.M., Kolding, J., Rice, J., Rochet, M.-J., Zhou, S., Arimoto, T., Beyer, J.E.,
533 Borges, L., Bundy, A., Dunn, D., Fulton, E.A., Hall, M., Heino, M., Law, R.,
534 Makino, M., Rijnsdorp, A.D., Simard, F., Smith, A.D.M., 2012. Reconsidering

535 the Consequences of Selective Fisheries. *Science* 335, 1045–1047.
536 <https://doi.org/10.1126/science.1214594>

537 Guyennon, A., Baklouti, M., Diaz, F., Palmieri, J., Beuvier, J., Lebaupin-Brossier, C.,
538 Arsouze, T., Béranger, K., Dutay, J.-C., Moutin, T., 2015. New insights into the
539 organic carbon export in the Mediterranean Sea from 3-D modeling.
540 *Biogeosciences* 12, 7025–7046. <https://doi.org/10.5194/bg-12-7025-2015>

541 Halouani, G., Ben Rais Lasram, -->Frida, Shin, Y.-J., Velez, L., Verley, P., Hattab, T.,
542 Oliveros-Ramos, R., Diaz, F., Ménard, F., Baklouti, M., Guyennon, A.,
543 Romdhane, M.S., -->Le Loc'h, F., 2016. Modelling food web structure using
544 an end-to-end approach in the coastal ecosystem of the Gulf of Gabes
545 (Tunisia). *Ecol. Model.* 339, 45–57.
546 <https://doi.org/10.1016/j.ecolmodel.2016.08.008>

547 Halouani, G., Gascuel, D., Hattab, T., Lasram, F.B.R., Coll, M., Tsagarakis, K.,
548 Piroddi, C., Romdhane, M.S., Le Loc'h, F., 2015. Fishing impact in
549 Mediterranean ecosystems: an EcoTroph modeling approach. *J. Mar. Syst.*
550 150, 22–33. <https://doi.org/10.1016/j.jmarsys.2015.05.007>

551 Hattab, T., Albouy, C., Ben Rais Lasram, F., Somot, S., Le Loc'h, F., Leprieur, F.,
552 2014. Towards a better understanding of potential impacts of climate change
553 on marine species distribution: a multiscale modelling approach. *Glob. Ecol.*
554 *Biogeogr.* 23, 1417–1429. <https://doi.org/10.1111/geb.12217>

555 Hattab, T., Ben Rais Lasram, F., Albouy, C., Romdhane, M.S., Jarboui, O., Halouani,
556 G., Cury, P., Le Loc'h, F., 2013. An ecosystem model of an exploited southern
557 Mediterranean shelf region (Gulf of Gabes, Tunisia) and a comparison with
558 other Mediterranean ecosystem model properties. *J. Mar. Syst.* 128, 159–174.
559 <https://doi.org/10.1016/j.jmarsys.2013.04.017>

560 Hattour, A., Ben Mustapha, K., 2013. Le couvert végétal marin dans le golfe de
561 Gabès: Cartographie et réseau de surveillance de l'herbier de Posidonie.
562 Publication de l'Inst.Natn.Sci.Tech.Mer.

563 Heithaus, M.R., Frid, A., Wirsing, A.J., Worm, B., 2008. Predicting ecological
564 consequences of marine top predator declines. *Trends Ecol. Evol.* 23, 202–
565 210. <https://doi.org/10.1016/j.tree.2008.01.003>

566 Jackson, J.B.C., Kirby, M.X., Berger, W.H., Bjorndal, K.A., Botsford, L.W., Bourque,
567 B.J., Bradbury, R.H., Cooke, R., Erlandson, J., Estes, J.A., Hughes, T.P.,
568 Kidwell, S., Lange, C.B., Lenihan, H.S., Pandolfi, J.M., Peterson, C.H.,
569 Steneck, R.S., Tegner, M.J., Warner, R.R., 2001. Historical Overfishing and
570 the Recent Collapse of Coastal Ecosystems. *Science* 293, 629–637.
571 <https://doi.org/10.1126/science.1059199>

572 Jacobsen, N.S., Gislason, H., Andersen, K.H., 2014. The consequences of balanced
573 harvesting of fish communities. *Proc. R. Soc. B Biol. Sci.* 281.
574 <https://doi.org/10.1098/rspb.2013.2701>

575 Lasram, F.B.R., Hattab, T., Halouani, G., Romdhane, M.S., Le Loc'h, F., 2015.
576 Modeling of beta diversity in tunisian waters: predictions using generalized
577 dissimilarity modeling and bioregionalisation using fuzzy clustering. *PloS One*
578 10, e0131728.

579 Papaconstantinou, C., Farrugio, H., 2000. Fisheries in the Mediterranean. *Mediterr.*
580 *Mar. Sci.* 1, 5–18.

581 Pauly, D., Christensen, V., Dalsgaard, J., Froese, R., Torres, F., 1998. Fishing Down
582 Marine Food Webs. *Science* 279, 860–863.
583 <https://doi.org/10.1126/science.279.5352.860>

584 Plagányi, É.E., Food, Nations, A.O. of the U., 2007. Models for an ecosystem
585 approach to fisheries. Food and Agriculture Organization of the United
586 Nations, Rome.

587 Planque, B., Fromentin, J.-M., Cury, P., Drinkwater, K.F., Jennings, S., Perry, R.I.,
588 Kifani, S., 2010. How does fishing alter marine populations and ecosystems
589 sensitivity to climate? *J. Mar. Syst.*, Impact of climate variability on marine
590 ecosystems: A comparative approach 79, 403–417.
591 <https://doi.org/10.1016/j.jmarsys.2008.12.018>

592 Rice, J., Rochet, M., 2005. A framework for selecting a suite of indicators for fisheries
593 management. *ICES J. Mar. Sci.* 62, 516–527.
594 <https://doi.org/10.1016/j.icesjms.2005.01.003>

595 Sasaki, T., Furukawa, T., Iwasaki, Y., Seto, M., Mori, A.S., 2015. Perspectives for
596 ecosystem management based on ecosystem resilience and ecological
597 thresholds against multiple and stochastic disturbances. *Ecol. Indic.* 57, 395–
598 408. <https://doi.org/10.1016/j.ecolind.2015.05.019>

599 Shephard, S., Reid, D.G., Greenstreet, S.P.R., 2011. Interpreting the large fish
600 indicator for the Celtic Sea. *ICES J. Mar. Sci.* 68, 1963–1972.
601 <https://doi.org/10.1093/icesjms/fsr114>

602 Shin, Y.-J., Bundy, A., Shannon, L.J., Blanchard, J.L., Chuenpagdee, R., Coll, M.,
603 Knight, B., Lynam, C., Piet, G., Richardson, A.J., Group, the I.W., 2012.
604 Global in scope and regionally rich: an IndiSeas workshop helps shape the
605 future of marine ecosystem indicators. *Rev. Fish Biol. Fish.* 22, 835–845.
606 <https://doi.org/10.1007/s11160-012-9252-z>

607 Shin, Y.-J., Cury, P., 2004. Using an individual-based model of fish assemblages to
608 study the response of size spectra to changes in fishing. *Can. J. Fish. Aquat.*
609 *Sci.* 61, 414–431. <https://doi.org/10.1139/f03-154>

610 Shin, Y.-J., Cury, P., 2001. Exploring fish community dynamics through size-
611 dependent trophic interactions using a spatialized individual-based model.
612 *Aquat. Living Resour.* 14, 65–80.

613 Shin, Y.-J., Houle, J.E., Akoglu, E., Blanchard, J.L., Bundy, A., Coll, M., Demarcq, H.,
614 Fu, C., Fulton, E.A., Heymans, J.J., Salihoglu, B., Shannon, L., Sporic, M.,
615 Velez, L., 2018. The specificity of marine ecological indicators to fishing in the
616 face of environmental change: A multi-model evaluation. *Ecol. Indic.* 89, 317–
617 326. <https://doi.org/10.1016/j.ecolind.2018.01.010>

618 Shin, Y.-J., Shannon, L.J., Bundy, A., Coll, M., Aydin, K., Bez, N., Blanchard, J.L.,
619 Borges, M. de F., Diallo, I., Diaz, E., others, 2010. Using indicators for
620 evaluating, comparing, and communicating the ecological status of exploited
621 marine ecosystems. 2. Setting the scene. *ICES J. Mar. Sci.* 67, 692–716.

622 Travers, M., Shin, Y.-J., Shannon, L., Cury, P., 2006. Simulating and testing the
623 sensitivity of ecosystem-based indicators to fishing in the southern Benguela
624 ecosystem. *Can. J. Fish. Aquat. Sci.* 63, 943–956. <https://doi.org/10.1139/f06-003>

625

626 Travers-Trolet, M., Shin, Y.-J., Shannon, L.J., Moloney, C.L., Field, J.G., 2014.
627 Combined Fishing and Climate Forcing in the Southern Benguela Upwelling
628 Ecosystem: An End-to-End Modelling Approach Reveals Dampened Effects.
629 *PLoS ONE* 9, e94286. <https://doi.org/10.1371/journal.pone.0094286>

630 Worm, B., Barbier, E.B., Beaumont, N., Duffy, J.E., Folke, C., Halpern, B.S., Jackson,
631 J.B.C., Lotze, H.K., Micheli, F., Palumbi, S.R., Sala, E., Selkoe, K.A.,
632 Stachowicz, J.J., Watson, R., 2006. Impacts of Biodiversity Loss on Ocean

633 Ecosystem Services. *Science* 314, 787–790.
634 <https://doi.org/10.1126/science.1132294>
635 Zucchetto, M., Venier, C., Taji, M.A., Mangin, A., Pastres, R., 2016. Modelling the
636 spatial distribution of the seagrass *Posidonia oceanica* along the North African
637 coast: Implications for the assessment of Good Environmental Status. *Ecol.*
638 *Indic.* 61, Part 2, 1011–1023. <https://doi.org/10.1016/j.ecolind.2015.10.059>
639