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1 **Title:** Future trajectories of change for an Arctic deep-sea ecosystem connected  
2 to coastal kelp forests

3 **Running head:**

4 Future changes in Arctic ecosystem

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30 **Author Contributions**

31 DV, MC conceived and designed the research; DV performed the simulations; DV, MC  
32 analyzed the data; DV, MC, TP, XC contributed materials and analysis tools; DV, MC,  
33 TP, XC, KF, TW wrote and edited the manuscript.

34

35 **Abstract**

36 Environmental stressors related to climate change and other anthropogenic activities  
37 are impacting Arctic marine ecosystems at exceptional rates. Within this context,  
38 predicting future scenarios of deep-sea ecosystems and their consequences linked with  
39 the fate of coastal areas is a growing need and challenge. We used an existing food-web  
40 model developed to represent the outer basin of the Malangen fjord, a Northern  
41 Norwegian deep-sea ecosystem, to assess the potential effects of plausible future  
42 trajectories of change for major drivers in the area, including links to coastal kelp forests.  
43 We considered four major drivers (kelp particulate organic matter (POM) production  
44 entering the deep sea, fishing effort, king crab invasion, and ocean warming) to project  
45 12 future scenarios using the temporal dynamic module of Ecopath with Ecosim  
46 approach. Overall, we found that the impact of warming on the deep-sea ecosystem  
47 structure and functioning, as well as on ecosystem services, are predicted to be greater  
48 than changes in kelp forest dynamics and their POM production entering the deep-sea  
49 and the king crab invasion. Yet, the cumulative impacts are predicted to be more  
50 important than non-cumulative since some stressors acted synergistically. These results  
51 illustrate the vulnerability of sub-Arctic and Arctic marine ecosystems to climate change  
52 and consequently call for conservation, restoration, and adaptation measures in deep-  
53 sea and adjacent ecosystems. Results also highlight the importance of considering  
54 additional stressors affecting deep-sea communities to predict cumulative impacts in an  
55 ecosystem-based management and global change context and the interlinkages  
56 between coastal and deep-sea environments.

57

58 **Key words:** Arctic ecosystem, ecological indicators, Ecopath with Ecosim, future  
59 management scenarios, kelp detritus, restoration

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62

### 63 **Implications for practice:**

- 64 - Increasing temperature may cause high impacts at species level due to their  
65 thermal optimum ranges, triggering impacts at the ecosystem level.
- 66 - Ecological indicators showed the strongest impacts when increasing temperature  
67 was included in future predictions. These effects emphasize the vulnerability of  
68 Arctic marine ecosystems to climate change.
- 69 - Regime shifts in kelp organic matter production and a king crab invasion may  
70 produce more reduced but noticeable impacts at the deep-sea ecosystem level.
- 71 - In addition to temperature, considering additional stressors affecting deep-sea  
72 communities such as changes in kelp forest from coastal areas are important to  
73 predict cumulative impacts of the deep sea in an ecosystem-based management  
74 context, and calls for urgent conservation, adaptation, and restoration actions.

75

### 76 **Introduction**

77 Within the current scenario of a changing planet, environmental stressors related to  
78 climate change, together with other human impacts, are increasingly affecting marine  
79 communities from shallow water to bathyal and abyssal ecosystems (Ramirez-Llodra et  
80 al. 2011; Sweetman et al. 2017; Danovaro et al. 2017). The 20 years of warmer  
81 temperatures at the beginning of the twenty-first century have affected the phenology of  
82 organisms, the range, and distribution of species, and the composition and dynamics of  
83 communities (Smale et al. 2019). Under this context, predicting future scenarios and their  
84 consequences, and providing effective tools to policymakers, is a growing need and  
85 challenge. To respond to current global climate challenges, beneficial management  
86 strategies must be carried out such as increasing connectivity to ensure resilience to  
87 climate change (e.g. through the maintenance and increase of the area of high-quality  
88 habitats), the conservation of areas that have high environmental heterogeneity, the  
89 control of other anthropogenic threatening processes and ecological restoration (Gann  
90 et al. 2019).

91 Worldwide, numerous ecosystems are at risk of severe impacts. Warming events are  
92 predicted to be exaggerated in the Arctic, which is undergoing the most rapid change in  
93 climate (IPCC 2018), which may increase instances of storm surge or extreme weather  
94 (Cohen et al. 2020). Several studies have examined and assessed the impacts on  
95 ecosystem services caused by climate change in Arctic systems and highlighted the  
96 need for a better understanding of these impacts to reduce the risk of marine regime  
97 shifts (Rocha et al. 2015; Wernberg et al. 2019; Merzouk & Johnson 2011). Arctic fjords

98 may be particularly vulnerable to climate change because sea surface temperature is  
99 expected to increase faster in Arctic ecosystems than other ecosystems (IPCC 2018).  
100 Environmental changes are impacting the condition and distributions of Arctic species  
101 and ousting them from current food-webs (Frainer et al. 2017).

102 Kelp forests are phylogenetically diverse, structurally complex, and highly productive  
103 ecosystems of cold-water rocky marine coastlines (Wernberg et al. 2019). Particularly,  
104 *Laminaria hyperborea*, which forms extensive kelp forests in the northeastern Atlantic,  
105 has a very high annual production  $500 - 2,000 \text{ g C} \cdot \text{m}^{-2} \cdot \text{y}^{-1}$  (Pedersen et al. 2019). As  
106 much as 90% of this production is exported as particulate organic matter (POM) to  
107 adjacent ecosystems (Krause-Jensen & Duarte 2016). In this ecosystem, kelp POM  
108 connects coastal areas with deep-sea ecosystems and can provide shelter, substrate,  
109 or even food source for these deep-sea benthic communities (Ramirez-Llodra et al.  
110 2016). A recent study highlighted that changes in kelp POM biomass could produce  
111 noticeable changes in lower trophic levels in Arctic deep ecosystems (Vilas et al. 2020).  
112 Predicting changes to arctic kelp forests under rapidly changing environmental  
113 conditions remains a challenge (Filbee-Dexter et al. 2018). Climate change is expected  
114 to produce local losses of suitable habitats at low latitude ranges where climatic refugia  
115 are projected to be located (Assis et al. 2018). Warming sea temperature has direct and  
116 indirect impacts on kelp, and it promotes that kelp forests are increasing in northern  
117 latitudes, while they are declining in southern latitudes (Filbee-Dexter & Wernberg 2018).  
118 Therefore, climate change can alter distributions, densities, and behavior of herbivorous  
119 sea urchins and fish whose grazing action can strongly influence the abundance and  
120 distribution of kelp species (Filbee-Dexter & Scheibling 2014). It can also influence the  
121 likelihood of the establishment of invasive species through climate forcing distributions.  
122 For example, the King crab (*Paralithodes camtschaticus*) has expanded westwards from  
123 the Barents Sea to the northeastern Norwegian coast (Jørgensen & Nilssen 2011).

124 In response to degradation and all stressors affecting kelp forests, there is an  
125 increasing interest in their conservation, protection, and restoration of these systems  
126 (Bekkby et al. 2020). Ecological restoration is the process of assisting the recovery of an  
127 ecosystem that has been degraded, damaged, or destroyed (Society for Ecological  
128 Restoration International Science & Policy Working Group 2004) and it is globally  
129 recognized as a fundamental component for conservation (Aronson & Alexander 2013).  
130 When ecological restoration is enforced adequately and sustainably, it contributes to  
131 manifold beneficial outcomes including the protection of diversity, increasing ecosystem  
132 quality, delivering services, and supporting climate change adaptation and mitigation  
133 (Gann et al. 2019). Its standards highlight the importance of effectively engage a wide

134 range of stakeholders and using available scientific and local knowledge to achieve  
135 appropriate referenced ecosystem states using measurable ecological indicators (Gann  
136 et al. 2019). For instance, kelp ecosystem restoration experiences showed that selective  
137 relocation of herbivores, rebuilding of their predators, cleaning sediment of rock surfaces,  
138 and transplanting of kelp plants, are successful in restoring kelp forests and specially,  
139 when involving stakeholders (e.g. fishermen and local community) (Fujita 2011).  
140 Restoration and conservation efforts should be focus on maintaining kelp species and  
141 preserving ecosystem services and functioning (Hobbs & Harris 2001; Vergés et al.  
142 2019) as well as increasing ecosystem connectivity (Hodgson et al. 2009; Coleman et  
143 al. 2020).

144 Besides, the benefits of kelp forests to adjacent ecosystems, kelp forests provide  
145 shelter and habitat for multiple marine species, and associated with these habitats are  
146 organisms such as marine mammals, crustaceans, echinoderms, fish, and algae  
147 (Steneck et al. 2002). These ecosystems likely also contribute to large carbon sink and  
148 so playing an important role for mitigation and adaptation to climate change (Krause-  
149 Jensen et al. 2018; Filbee-Dexter & Wernberg in press). In addition, kelp forests are  
150 considered a nature-based defence upon coastal erosion and extreme storm events  
151 (Rebecca L. Morris et al. 2020). From a social and economic perspective, kelp forests  
152 provide important ecosystem services through harvesting to extract food, and  
153 pharmaceutical components (Vea & Ask 2011).

154 Kelp forests are increasingly threatened by a variety of impacts, including species  
155 invasions, ocean warming, and direct harvest (Wernberg et al. 2019). Those stressors  
156 affect kelp POM production, and consequently, they affect adjacent ecosystems where  
157 several marine organisms interact and feed on kelp POM (Ramirez-Llodra et al. 2016).  
158 Understanding how these multiple stressors, marine organisms, and ecosystems  
159 interact, connect, and influence each other is an issue of relevant importance. To  
160 address this challenge, a shift towards a more comprehensive analysis and management  
161 of human activities is needed, as underlined by the ecosystem-based management  
162 (EBM) approach (Leslie & McLeod 2007).

163 The modelling approach “Ecopath with Ecosim” (EwE) is being widely used as a tool  
164 for the analysis of marine ecosystems (Christensen et al. 2008; Colléter et al. 2015).  
165 Among these analyses, several studies used the temporal module of EwE (Ecosim) to  
166 assess cumulative impacts and predict future scenarios including climate change on  
167 marine systems (Bentley et al. 2017; Corrales et al. 2018; Serpetti et al. 2017). These  
168 studies illustrated the importance of including multiple stressors other than fisheries,

169 such as climate change, in an ecosystem-based management approach. In this study,  
170 we used a previously developed Ecopath food web model of an Arctic deep ecosystem  
171 associated with kelp exports (ADEAKE) of northern Norway (Vilas et al. 2020), to  
172 evaluate the potential effect of plausible future scenarios for major drivers in the study  
173 area. Four drivers accounting for local, regional, and global stressors were used in order  
174 to test twelve plausible future trajectories of change (or scenarios) that were conceived  
175 and prioritized considering experts' knowledge. Specifically, we considered fishing, kelp  
176 POM production, king crab invasion, ocean warming, and the cumulative effects of these  
177 changes

178

## 179 **Material and methods**

### 180 - Study area

181 The Arctic deep ecosystem associated with kelp exports (ADEAKE) of the northern  
182 Norway model (Vilas et al. 2020) represents the outer basin of the Malangen Fjord  
183 (69.529° N, 18.021° E). This fjord is in Troms and Finnmark county, Arctic Norway, and  
184 it is connected to the open sea by a sill (180 meters deep) (Fig. 1). Thus, its morphology  
185 provides a potentially excellent accumulation site for kelp POM from the surrounding  
186 coastal dense kelp forests (Filbee-Dexter et al. 2018). This ecosystem is considered  
187 particularly vulnerable in face of warming due to its location, which could cause shifts in  
188 species distribution, including invasive species such as the king crab, and consequently  
189 altering the whole food-web of the ADEAKE (IPCC 2018).

### 190 - Modelling approach

191 Ecopath with Ecosim (EwE) modelling approach was used to develop the ADEAKE  
192 model. The EwE approach is composed by three main modules: the ecosystem trophic  
193 mass balance analysis (Ecopath), and the temporal (Ecosim), and spatial-temporal  
194 dynamic (Ecospace) modules (Heymans et al. 2016; Christensen et al. 2014)

195 The existing EwE model represents an annual average situation in 2017, ranging  
196 from 400 to 450 meters depth and covering an area of 11.8 km<sup>2</sup> (Vilas et al. 2020). The  
197 Ecopath model was developed using Ecopath version 6.6, and it consisted of 36  
198 functional groups (FGs) with special emphasis on kelp POM because the model was  
199 built to assess the ecological role of kelp export into the deep-sea system. Two out of  
200 four detritus groups (marine snow, coarse kelp POM, fine kelp POM, and benthic  
201 detritus) represented the kelp secondary production. A functional group consists of

202 ontogenic fractions of a species, individual species, or groups of species that perform a  
 203 similar function in the ecosystem, i.e. have similar growth rates, consumption rates, diets,  
 204 habitats, and predators (Heymans et al. 2016).

205 The Ecosim module consists in a set of differential equations to describe biomass  
 206 dynamics:

207

$$208 \quad \frac{dB_i}{dt} = \left(\frac{P}{Q}\right)_i \cdot \sum Q_{ji} - \sum Q_{ji} + I_i - (M_i + F_i - e_i) \cdot B_i$$

209

210 where  $dB_i/dt$  is the growth rate of group  $i$  during time  $t$  in terms of its biomass  $B_i$ ;  $(P/Q)_i$   
 211 is the net growth efficiency of group  $i$ ;  $Q_{ij}$  is the consumption rate;  $M_i$  is the non-predation  
 212 mortality rate;  $F_i$  is the fishing mortality rate;  $e_i$  is the emigration, and  $I_i$  is the immigration  
 213 rate (Christensen & Walters 2004). Consumption rates ( $Q_{ij}$ ) are calculated based on the  
 214 ‘foraging arena’ theory, which divides the biomass of prey into a vulnerable and a non-  
 215 vulnerable fraction and the transfer rate of vulnerability between the two fractions  
 216 determines the trophic flow between the predator and the prey (Ahrens et al. 2012). The  
 217 vulnerability concept incorporates density-dependent processes and expresses how far  
 218 a group is from its carrying capacity (Christensen et al. 2008; Christensen & Walters  
 219 2004). For each predator-prey interaction, consumption rates are calculated as:

220

$$221 \quad Q_{ij} = \frac{a_{ij} \cdot v_{ij} \cdot B_i \cdot B_j \cdot T_i \cdot T_j \cdot M_{ij} / D_j}{v_{ij} + v_{ij} \cdot T_i \cdot M_{ij} + a_{ij} \cdot M_{ij} \cdot B_j \cdot T_j / D_j} \cdot f(Env_{function}, t),$$

222 where  $a_{ij}$  is the rate of effective search for  $i$  by  $j$ ;  $T_i$  represents prey relative feeding time;  
 223  $T_j$  the predator relative feeding time;  $M_{ij}$  is the mediation forcing effects;  $v_{ij}$  is the  
 224 vulnerability parameter;  $D_j$  represents the effects of handling time as a limit to  
 225 consumption rate (Ahrens et al. 2012; Christensen et al. 2008); and  $f(Env_{function}, t)$  is the  
 226 environmental response function that restricts the size of the foraging arena ( $C_{rcj}$ ) to  
 227 account for external environmental drivers changing over time, such as temperature  
 228 (Ahrens et al. 2012; Christensen et al. 2014).

229 The environmental response functions ( $f(Env_{function}, t)$ ), which link the species or FGs  
 230 dynamics with the environmental drivers, were first obtained from *AquaMaps* (Kesner-  
 231 Reyes et al. 2016), a global database on species distribution. These environmental  
 232 response functions are given as curves showing the minimum and maximum tolerance  
 233 levels and 10th and 90th preferable quantiles to the environmental parameters (in our



234 case, temperature). As a second step, these functions were modified using expert  
235 opinion from scientists to incorporate local knowledge. The final environmental  
236 preference functions for each FG (Fig. S1.1) were obtained by weighting the values of  
237 the species included in a FG to their relative biomass.

#### 238 - Simulations of future scenarios

239 We used the temporal dynamic module Ecosim to evaluate the effect of plausible  
240 future scenarios for major drivers in the study area after 83 years of simulation (2017-  
241 2100) (Table 1). Future scenarios were simulated without fitting the model to data due to  
242 the lack of specific time-series data and consequently, vulnerabilities could not be  
243 estimated as recommended (Christensen et al. 2008). Similar to previous temporal  
244 dynamic simulations (Vilas et al. 2020), we increased kelp POM vulnerability ( $v = 100$ )  
245 to allow a notable increase in consumption on detritus if the biomass of consumers  
246 increases and default values were set ( $v = 2$ ). Four drivers (fishing, kelp POM production,  
247 red king crab invasion, and temperature) were selected to condition the scenarios.  
248 Among these drivers, we selected twelve plausible future scenarios in the study area  
249 considering the knowledge of a group of regional experts (Table 1).

250 In the first scenario (Scn1) fishing effort, kelp POM production and sea water  
251 temperature were kept constant from 2017, which was the year for the Ecopath baseline  
252 model (Vilas et al. 2020). Fishing effort was modified in the second and third scenarios:  
253 the relative fishing effort was reduced to 50% for both operating fleets (gillnetters and  
254 shrimp trawlers) (Scn2), or increased 50% on gillnetters (Scn3) in order to reduce large  
255 fish feeders group biomass while keeping constant kelp POM production and  
256 temperature and without the invasion of the red king crab (Fig. 2a).

257 Regionally, we selected four scenarios, three of which were driven by kelp POM  
258 production drivers and one by a possible future biological invasion. Scenario 4 (Scn4)  
259 considered direct harvesting of kelp in the surrounding areas, which it is considered a  
260 rising activity in northern Norway (Stévant et al. 2017), and both kelp POM groups were  
261 forced to decrease their biomass by 50% (Fig. 2b). The second and third regional  
262 scenarios (Scn5 and Scn6, respectively) included kelp POM production as the main  
263 driver due to changing sea urchins (*Strongylocentrotus droebachiensis*) biomass in  
264 surrounding areas. Scn5 simulated a decrease in sea urchin population and recovery of  
265 barrens, so coarse kelp POM biomass was forced to increase while fine kelp POM  
266 biomass was forced to decrease (50%) because of the non-grazing process (Fig. 2b).  
267 These scenarios (Scn4, 5, and 6) included changes in kelp POM production while  
268 keeping constant fishing and temperature and without the invasion of the red king crab.

269 In contrast, Scn6 reflected a regime shift to barrens caused by an increase in sea urchins  
270 and destructive grazing of kelp, during which the biomass of coarse kelp POM decreased  
271 until negligible, and the amount of fine kelp POM biomass increased at first (due to the  
272 high grazing intensity of urchins on attached kelp (Filbee-Dexter et al. 2019) and then  
273 decreased as the urchins consumed the entire standing stock (Fig. 2b). The last regional  
274 scenario (Scn7) included the future invasion of the red king crab invasion, which is  
275 predicted for this region (Christiansen et al. 2015). The red king crab was added to the  
276 ADEAKE model with very small biomass and then it was forced to increase in the model  
277 until achieving the same biomass as other Ecopath models in a similar study area  
278 (Pedersen et al. 2018). This increase applied the same trend showed in other Norwegian  
279 fjords which the red king crab invaded (Oug et al. 2018) (Fig. 2c) while keeping fishing  
280 and kelp POM production constant.

281 To predict the impact of warming waters on the ADEAKE, future sea surface  
282 temperature (SST) projections of the study area were obtained from the Royal  
283 Netherlands Meteorological Institute Climate explorer (<http://climexp.knmi.nl>) in order to  
284 extract the trend of these projections. SST projections under two contrasting scenarios  
285 of greenhouse emissions (RCP4.5 and RCP8.5) were used to calculate annual rates of  
286 SST change for both scenarios for each year from 2017 to 2100. Similar historical trends  
287 have been observed between SST and sea bottom temperature (SBT) in the area  
288 (Husum & Hald 2004). Therefore, estimated annual rates of SST change were applied  
289 to SBT values in the study area (Mankettikkara 2013). This method allowed us to  
290 calculate SBT projections under both scenarios of greenhouse emissions and assumed  
291 that rates of increasing SST are equal for SBT. The scenarios conducted to simulate  
292 potential impacts of ocean warming were RCP4.5 (Scn8) and RCP8.5 (Scn9), and they  
293 both included a constant fishing and kelp POM production and did not include the  
294 invasion of the red king crab (Fig. 2d).

295 In addition, three combinations of multiple impacts were performed in order to obtain  
296 combined scenarios. In the first combined scenario (Scn10), we merged the decreasing  
297 of sea urchin population (Scn5) and a red king crab invasion (Scn7) (Table 1).  
298 Afterwards, the least impacting combined future scenario (Scn11) was obtained adding  
299 the reduction of fishing effort (Scn2), the decreasing of sea urchin population (Scn5), and  
300 one the conservative SBT projection of SBT – (RCP4.5) (Scn8), without the invasion of  
301 the red king crab (Table 1). The most impacting combined future scenario (Scn12) was  
302 produced combining the increasing of fishing effort (Scn3), the increase of sea urchin  
303 population (Scn6), the red king crab invasion (Scn7), and the most extreme SBT  
304 projection of SST – RCP8.5 (Scn9).

305 - Model analysis and indicators

306 Biomass trends of selected functional groups were analyzed in order to test potential  
307 effects of plausible future scenarios. The groups were chosen considering their  
308 structuring importance in the deep-ecosystem and/or vulnerability under future scenarios  
309 (Vilas et al. 2020) and their relevance to show the change in ecosystem structure,  
310 functioning, and ecosystem services. A total of eight functional groups were included in  
311 the analysis: rays and skates, velvet belly, rabbit fish, blue whiting, large fish feeders,  
312 other commercial demersal fish, benthopelagic shrimps, and suprabenthos (see Vilas et  
313 al. 2020 for more information regarding the food-web structure and their functional  
314 groups).

315 Additionally, ecological indicator trends were obtained for each simulation in order to  
316 describe the ecosystem structure and functioning and were computed with two plug-ins  
317 commonly used: Ecological Network Analysis (ENA) and ECOIND. ENA indicators were  
318 extracted with ECOSAMPLER module (Steenbeek et al. 2018) and included: the Total  
319 System Throughput (TST,  $t \cdot km^{-2} \cdot year^{-1}$ ), export (Ex/TST), flow to detritus (FD/TST), the  
320 relative Ascendancy (A/C), the average mutual information (AMI), Finn's Cycling Index  
321 (FCI, %) and the Average Path Length (APL). The TST is the sum of all flows in the  
322 model and represents an overall measure of the "ecological size" of the system (Finn  
323 1976). Food-web model flows are expected to change under ecosystem impacts, so the  
324 TST, Ex/TST, and FD/TST would shift. The A/C is a measure of the food-web  
325 organization (Ulanowicz 2004) and its value is highly correlated with ecosystem maturity  
326 (Christensen 1995) so it decreases after being impacted. The AMI indicates the  
327 distribution of links in the food-web and the higher its value the more vulnerable becomes  
328 the ecosystem (Ulanowicz 2004). The FCI is the fraction of the ecosystem's throughput  
329 that is recycled to the TST and it decreases after ecosystem impacts (Finn 1976). The  
330 APL is the average number of groups through which each inflow passes weighted by the  
331 size of the inflows and its decreasing is an indicator of stress (Christensen 1995).

332 The ECOIND plug-in (Coll & Steenbeek 2017) allowed us to extract ecological  
333 indicators related to species traits (biomass, catch, trophic, size, and species-based).  
334 We focused on biomass-based indicators, trophic-based and catch-based indicators.  
335 Biomass-based indicators are based on the abundance of organisms in the food-web  
336 and we considered: biomass of commercial species, biomass of invertebrates' species,  
337 biomass of fish species, and the Kempton's diversity index. Next, four trophic-based  
338 indicators four indicators were selected based on the trophic level (TL): TL of the  
339 community (TLcom), TL of the community including organisms with  $TL \geq 2$  (TLcom2), TL

340 of the community including organisms with  $TL \geq 3.25$  (TLcom3.25) and TL of the  
341 community including organisms with  $TL \geq 4$  (TLcom4). We also selected 4 catch-based  
342 indicators: TL of the catch (TL C), fish catch (Fish C), invertebrates catch (Invertebrates  
343 C) and total catch (Total C).

#### 344 - Assessing uncertainty

345 Temporal dynamic simulations require quantifying uncertainties inherent in the  
346 simulations in order to facilitate decision-making. We performed an uncertainty  
347 assessment based on the pedigree values that describe the origin and uncertainty of  
348 input parameters used to parametrize the model based on their type (Christensen et al.  
349 2008; Christensen & Walters 2004). Afterwards, we used the pedigree information with  
350 associated confidence intervals for the input values in the Monte Carlo routine (MC) in  
351 Ecosim to evaluate uncertainty (Table S1) (Christensen & Walters 2004; Heymans et al.  
352 2016). MC routine is a statistical approach where random mass-balance models are  
353 constructed based on the uncertainty previously defined through pedigree values. For  
354 each MC run, input values of the baseline Ecopath models were randomly sampled from  
355 uniform distributions, with the width of distributions corresponding to the pedigree-  
356 specified input uncertainty level (Christensen & Walters 2004; Heymans et al. 2016).  
357 Results obtained from MC runs included probability distributions for the estimated  
358 parameters along and ecological indicators. 500 MC simulations were run, and 95% and  
359 5% percentile confidence intervals (CIs) were calculated to provide a good idea of the  
360 range of outputs. Subsequently, the correlation and significance between model outputs  
361 with time and its strength were measured using the nonparametric Spearman correlation  
362 (Spearman 1904). Additionally, changes of model outputs with time were checked using  
363 unlagged cross-correlation analysis (Venables & Ripley 2013).

364

## 365 **Results**

### 366 **Baseline Scenario – Scn1**

367 Under the baseline simulation (Scn1) in which fishing effort, kelp POM production,  
368 and sea water temperature were kept constant from 2017, the Ecosim model predicted  
369 changes in biomass trends for several FGs. This is due to the addition of the temperature  
370 effects to the baseline mass-balance model and the sensitivity of different species to the  
371 temperature range that was introduced when we moved to the temporal model. This  
372 impact of sub-optimal temperatures in the consumption rates of some FGs had  
373 cascading effects through the food web. For example, velvet belly was negatively

374 impacted by a sub-optimal temperature condition and this caused predation release on  
375 benthopelagic shrimps and suprabenthos, which biomass increased. In any case, we  
376 perform a relative comparison of scenarios to the baseline, thus this initial change is not  
377 affecting the comparison.

378 Biomass trend of rays and skates, large fish feeders, other commercial demersal fish,  
379 redfishes, benthopelagic shrimps, and suprabenthos increased (Fig. 3, 4, 5, 6 and Table  
380 S5). In contrast, the model predicted a decreasing trend for velvet belly, rabbit fish, and  
381 blue whiting (Fig. 3 and 4).

382 Under Scn1 a significant increasing trend for TST, FCI, and APL was predicted, while  
383 Ex/TST, FD/TST, A/C, and AMI decreased over time (Fig. 7 and Table S6). A significant  
384 increasing trend for Commercial B, Invertebrates B, Total B, TL community 3.25, TL  
385 community 4, Invertebrates C, and Total C was predicted (Fig. 8). On the other side,  
386 Demersal B, Fish B, TL community, TL community 2, TL C, and Fish C decreased over  
387 time (Fig. 8, and Table S7).

#### 388 **Fishing scenarios – Scn2 and Scn3**

389 Although both fishing scenarios were antagonists in terms of fishing effort (Table 1),  
390 both scenarios showed similar biomass trends for all selected functional groups between  
391 them and with respect to the baseline scenario (Fig. 3, 4, 5, and 6). Coinciding with that,  
392 ecological indicators showed similar trends between them and with respect to the  
393 baseline scenario except for small differences (Fig. 7 and 8). For example, decreasing  
394 trends on FD/TST were less strong for Scn2 and Scn3 than Scn1 (Fig. 7), and Scn3  
395 showed less strong decreasing trends for Fish C although it was significant too (Fig. 8  
396 and Table S7).

#### 397 **Changes kelp POM production scenarios – Scn4, Scn5, and Scn6**

398 Under scenarios with changes in kelp POM import, model results delivered similar  
399 biomass trends for most functional groups (Fig. 3, 4, 5, and 6) except for suprabenthos,  
400 for which non-significant change over time was found in Scn6 (Table S5).

401 Scn4 showed a significant increasing trend over time for FCI and APL and a  
402 significant decreasing trend for Ex/TST, A/C, and AMI, while FD/TST did not show any  
403 significant trend over time (Fig. 7 and Table S6). Similarly, the model predicted an  
404 increasing trend for TST, FCI, and APL under Scn5 and a decreasing trend for A/C and  
405 AMI. In contrast, Ex/TST trend was not significantly correlated under this scenario. Under  
406 Scn6, although the model predicted relevant change for all ENA indicators except FCI  
407 and APL, changes were less remarkable (Fig. 7).

408 Similar to the baseline scenario, ECOIND indicators showed an increasing trend for  
409 Commercial B, Invertebrates B, Total B, Kempton's index, TL community 3.25, TL  
410 community 4, Invertebrates C, and Total C under changing on kelp POM production  
411 scenarios except for Total B in Scn6 (Fig. 8). On the other hand, the model predicted a  
412 decreasing trend for demersal B, Fish B, TL community, TL community 2, TL C, and Fish  
413 C for these three scenarios. In contrast to the baseline scenario, changes in  
414 Invertebrates B, Total B, and TL community were not as strong under Scn4, Scn5, and  
415 Scn6 (Fig. 8).

#### 416 **Red king crab invasion scenario – Scn7**

417 Applying the king crab scenario (Scn7), the model predicted an increasing trend for  
418 rays and skates, redfishes, benthopelagic shrimps, and suprabenthos, while it predicted  
419 a decreasing trend for velvet belly, rabbit fish, and blue whiting (Fig. 3, 4, 5 and 6).  
420 Despite the similarity with the baseline scenario on FG biomass trend, changes in blue  
421 whiting and benthopelagic shrimps were smaller for Scn7 (Fig. 3).

422 Under this scenario, significant changes in ENA indicators were found for TST,  
423 Ex/TST, and FCI. Contrarily, the model did not predict any significant change in FD/TST,  
424 A/C, AML, and APL (Fig. 7). A notable increasing trend for Commercial B, Invertebrates  
425 B, Total B, Kempton's index, TL community 3.25, TL community 4, Invertebrates C and  
426 Total C was observed, while Demersal B, Fish B, TL community, TL community 2, TL C  
427 and Fish C decreased over time (Fig. 8). Despite ECOIND indicators showed the same  
428 trends compared with the baseline scenario, most of these indicators responded weaker  
429 over time (Fig. 8).

#### 430 **Impacts of ocean warming scenarios – Scn8 and Scn9**

431 Increasing temperature scenarios showed similar predicted effects on FG biomass.  
432 Under Scn8, rays and skates, large fish feeders, other commercial demersal fish,  
433 redfishes, benthopelagic shrimps, and suprabenthos biomass decreased whereas velvet  
434 belly, rabbit fish, and blue whiting biomass increased (Fig. 3, 4, 5, and 6). Scn9 obtained  
435 similar predictions except for velvet belly and large fish feeders', for which the biomass  
436 decreased and did not show significant change respectively (Fig. 3, 4, 5, and 6).

437 Under Scn8, the model predicted a decreasing trend for TST and increasing trends  
438 for the rest of ENA indicators. Contrarily, Scn9 did not show changes for TST, Ex/TST,  
439 FD/TST, and APL (Fig. 7). For ECOIND indicators, Commercial B, Invertebrates B Total  
440 B Kempton's Index, TLcom2, TLcom3.25 TLcom4, Invertebrate C, and Total C  
441 decreased, and Demersal B, Fish B TLcom TL C, and Fish C increased (Fig. 8). Scn9

442 showed similar trends for these indicators, except for TLcom which decreased under this  
443 scenario.

#### 444 **Cumulative scenarios – Scn10, Scn11 and Scn12**

445 In Scn10 biomass of velvet belly, rabbit fish and blue whiting decreased, while  
446 increased on rays and skates, redfishes, benthopelagic shrimps, and suprabenthos (Fig.  
447 3, 4, 5, and 6). On the contrary, Scn11 showed opposite biomass trends similarly to  
448 Scn12 except for velvet belly biomass which decreased (Fig. 3, 4, 5, and 6).

449 Considering ENA indicators, Scn10 showed a decreasing trend for TST and an  
450 increasing trend for Ex/TST, FD/TST, A/C, and APL (Fig. 7). Likewise, under Scn11, TST  
451 decreased, while Ex/TST, FD/TST, A/C, and AMI increased. Scn12 showed increasing  
452 trends for TST, Ex/TST, A/C, FCI, and APL, and decreasing trends for FD/TST and AMI  
453 (Fig. 7). Ecological indicators obtained similar predicted trends under Scn10 and 12 (Fig.  
454 8). Both of them showed increasing trends for Fish B, TLcom, TL C, and Fish C, while  
455 decreasing trends for Commercial B, Demersal B, Invertebrates B, Total B, Kempton's  
456 Index, TLcom2, TLcom3.25, Invertebrates C, and Total C. Scn11 showed decreasing  
457 trends for commercial B, invertebrates B, total B, Kempton's Index, TLcom2, TLcom3.25,  
458 TLcom4, Invertebrates C and Total C and increasing trends for Fish B, TLcom, TL C and  
459 Fish C (Fig. 8).

#### 460 **Common patterns**

461 In general, scenarios that included temperature increasing (Scn8, Scn9, Scn11, and  
462 Scn12) showed opposite biomass trends in most functional groups compared to the  
463 baseline scenario (Fig. 3). The rest of the scenarios (fishing effort, kelp POM production,  
464 and king crab invasion scenarios) showed similar biomass trends of most functional  
465 groups compared to the baseline (Fig. 3). Most scenarios showed increasing trends for  
466 FCI, and APL (Fig. 7), while they showed decreasing trends for Demersal B, TLcom,  
467 TLcom2, and TLcom4 (Fig. 8). Additionally, catch-based indicators and several biomass-  
468 based indicators changed their trends under increasing temperature scenarios (Scn8  
469 and Scn9) and cumulative scenarios (Scn10, Scn11, and Scn12) (Fig. 8).

470

#### 471 **Discussion**

472 Under the baseline scenario, most functional groups increased in biomass, including  
473 all commercial functional groups, while important FGs in terms of biomass decreased  
474 (velvet belly; rabbit fish; and blue whiting). This suggests that current sea bottom

475 temperature is favourable for these species and unfavourable for others or that these  
476 species are close to the limits of their thermal niches (Poloczanska et al. 2016). Other  
477 FGs showed increasing biomass trends (e.g. benthopelagic shrimps) possibly due to  
478 cascading effects since their predators declined in terms of biomass (Baum & Worm  
479 2009).

480 Overall, the fishing scenarios did not show noticeable impacts at species levels nor  
481 at ecosystem level. These results likely reflect the sustainability of current fishing  
482 activities and their moderate impact in this study area, which has also been pointed out  
483 in adjacent areas (Pedersen et al. 2016). A general study carried out in EU waters  
484 (Froese et al. 2018) identified the Norwegian Sea and the Barents Sea as the European  
485 Seas with the highest percentage of sustainably exploited stocks.

486 Similarly, predicted future changes in kelp POM production (Scn4, Scn5, and Scn6)  
487 showed limited changes in biomass over time for the investigated FGs. Only  
488 suprabenthos under Scn6 showed an opposite trend compared to the baseline scenario,  
489 with lower biomass correlation results. Small crustaceans are considered one of the most  
490 important feeders on kelp POM (Dunton & Schell 1987). At ecosystem level, these  
491 scenarios showed changes in the distribution of the flows (Ex/TST and FD/TST) linked  
492 to changes in the kelp POM production in coastal areas. Specifically, Scn6 did not show  
493 changes in FCI and APL neither strong decreasing on A/C and AMI like baseline  
494 scenario, so no change towards a more complex food-web and more mature ecosystem  
495 is expected under this scenario. Although kelp POM production scenarios did not highly  
496 impact the deep-sea ecosystem, among all the kelp POM production scenarios, the  
497 scenario of increasing sea urchins (Scn6) was the one that caused the highest impact.  
498 Therefore, the impacts of a regime shift to barrens caused by overgrazing sea urchins  
499 may propagate to surrounding deep ecosystems and negatively impact their structure,  
500 functioning, and resilience. This finding is especially interesting given the ubiquitous  
501 nature of shifts to sea urchin barrens (Filbee-Dexter & Scheibling 2014). Our modelling  
502 application suggests that these marine ecosystem shifts could impact surrounding deep  
503 ecosystems and highlights the importance of healthy kelp forest coastal ecosystems an  
504 effort to conserve and restore them (Layton et al. 2020; Fredriksen et al. 2020).

505 Under red king crab invasion scenario (Scn7), other commercial demersal fish and  
506 large fish feeders did not show relevant changes. These results are in line with those of  
507 Pedersen *et al.* (2018), which found small effects of red king crab on fish groups.  
508 However, dietary studies (Fuhrmann et al. 2017) indicated that king crab diet is based



509 on benthic invertebrates such as crustaceans, echinoderms, and mollusks and thus it  
510 may compete with fish species for the same source of food.

511 Local and regional stressors (fishing effort, kelp POM production, and invasive  
512 species) have been previously highlighted as potentially important for impacting at  
513 species and ecosystem level (Pedersen et al. 2018; Ramirez-Llodra et al. 2016).  
514 However, this study showed that these changes may have limited impacts in the  
515 ADEAKE at their modelled level in comparison with the global stressors (ocean  
516 warming).

517 Global scenarios (Scn8 and Scn9) that included two global warming projections  
518 (RCP4.5 and RCP8.5, respectively) showed opposite trends on most FGs biomass in  
519 comparison with previous scenarios. In contrast to the baseline scenario, velvet belly,  
520 rabbit fish and blue whiting biomass increased because increasing ocean temperature  
521 under global warming scenarios places these species into their thermal tolerance  
522 thresholds and thus it rises their fitness. In fact, Arctic fish communities are currently  
523 suffering a rapid borealization and expanding their distribution northwards (Fossheim et  
524 al. 2015). For instance, blue whiting increased in warm waters in the Barents Sea  
525 (Aschan et al. 2013), and demersal species such as rabbit fish and velvet belly registered  
526 distribution shifts after increasing sea temperature over time in the Norwegian Sea  
527 (Skants 2019). Bentley *et al.* (2017) assessed the impact of ocean warming in the  
528 Norwegian and Barents Seas and indicated significant changes in ecosystem biomass  
529 composition including the decline of boreal functional groups. Similarly, Serpetti *et al.*  
530 (2017) investigated the impact of ocean warming in the West Coast of Scotland and  
531 suggested that declines of stock may be due to migration to cooler waters. In our study,  
532 other FGs' biomass showed increasing biomass trends like benthopelagic shrimps and  
533 it could be explained by trophic interactions processes like predation or competition  
534 (Kortsch et al. 2015). At ecosystem level, some of these indicators showed an increasing  
535 trend under these scenarios, suggesting a change towards a more chain-web structure  
536 and less mature structure. For example, the rise in AMI indicated that the ecosystem is  
537 becoming more constrained, efficient, unstable, and vulnerable (Ulanowicz & Abarca-  
538 Arenas 1997) under global warming scenarios, which is in line with the decreasing trend  
539 obtained in the Kempton's Index. This instability could be driven by biomass changes in  
540 important FGs driven by increasing on sea temperature in the ecosystem as previously  
541 mentioned.

542 Scn10 showed similar biomass trends as found under red king crab invasion scenario  
543 (Scn7), highlighting the impact of king crab biomass over the change on kelp POM

544 production. Scn10 results suggested that the synergic effect of king crab and change on  
545 kelp POM due to increasing of sea urchins in coastal areas could cause a change  
546 towards a more simplified food-web and immature ecosystem, namely decreasing its  
547 resilience and similar to warming scenarios (Scn8 and Scn9) impacts on deep-sea  
548 ecosystems. The other two cumulative impacts scenarios (Scn11 and Scn12) reflected  
549 the effect of temperature increasing and consequent changes in competition and trophic  
550 processes as already highlighted for Scn8 and Scn9. However, some indicators  
551 suggested different trends because of the cumulative effect of the different drivers  
552 considered under the scenario which complicated more its interpretation. For instance,  
553 the decreasing trend of AMI under Scn12 could be due to the cumulative decreasing  
554 trend of the impacts considered. Considering ecological indicators, total biomass results  
555 under warming scenarios are consistent with previous global studies (Free et al. 2019),  
556 which found gains in marine fisheries production/biomass in the Norwegian and Barents  
557 Sea for the past decades. Under Scn12, some biomass indicators showed stronger  
558 correlations over time compared to the warming scenario (Scn9). This scenario  
559 highlighted the importance to consider multiple stressors on future projections to properly  
560 assess changes in marine ecosystems. Cumulative impacts scenarios showed higher  
561 ecosystem effects than non-cumulative scenarios indicating that some stressors can act  
562 synergically and increase their impact when gathering.

563 Our model predicted ecosystem impacts in an Arctic ecosystem under multiple future  
564 scenarios including climate change effects, which, can contribute to the knowledge  
565 needed towards deep-sea ecosystems and how ecological restoration in coastal areas  
566 can impact adjacent ecosystems. The ADEAKE model displayed a decreasing resilience  
567 and ecosystem state under warming and cumulative impacts scenarios, highlighting the  
568 urgent need of considering the impact of several stressors together. Our study also  
569 shows that what may happen in coastal areas, in this case in kelp beds, can have an  
570 impact on deep-sea adjacent ecosystems, which highlights the relevance of ecosystem  
571 protection and restoration of such important areas. Ecological restoration, in fact, is  
572 recognized as a critical tool for mitigating and adapting to the impacts of climate change  
573 (Gann et al. 2019). A recent study (Eger et al. 2020) highlighted that a more holistic  
574 approach form of restoration that incorporates species interaction could increase the  
575 likelihood of success. Our modelling approach could be a suitable tool to further explore  
576 potential restoration scenarios through an integrated view (Frisk et al. 2011), for  
577 example, by extending the deep-sea model to the coastal areas and explicitly modelling  
578 the kelp bed – deep-sea ecosystem together.

579 Performing future simulations in ecology is considered an arduous task, especially  
580 without any calibration process under long-term scenarios (Dietze & Lynch 2019).  
581 Although results are helpful to indicate trends in future changes, these should be  
582 interpreted with caution since several limitations were found in this study. For instance,  
583 fishing scenarios (Scn2 and Scn3) as well as changes in kelp POM production scenarios  
584 (Scn4, Scn5 and Scn6) resulted in similar outputs which may indicate low sensitivity of  
585 our model to changes on these drivers. Poor sensitivity indicates either low impacts of  
586 these drivers on the modelled ecosystem (i.e. low fishing impact) or slight changes on  
587 drivers during future simulations. One of the main hurdles was the inability to fit the model  
588 due to the lack of specific time-series data that could affect the model application. This  
589 caused high uncertainty for most projections results and could strongly influence the  
590 intensity of biomass and ecological indicators changes. Despite this, we consider that  
591 our approach included methods to minimize as much as possible the negative effects of  
592 this limitation such as Monte Carlo routine. In addition, biomass predictions for most  
593 functional groups are likely to be artifacts of sea water temperature which was highlighted  
594 as the strongest driver in the study area. Another limitation was the lack of SBT  
595 projections under scenarios of greenhouse emissions, which if available could make  
596 future simulations more realistic in deep ecosystems. The model represents a deep  
597 ecosystem ranging from 400-450 metres depth and we used similar rates of change  
598 between reconstructed SST and SBT over time (Husum & Hald 2004). There is evidence  
599 that the upper ocean (above 700 metres) is warming similarly with climate change (Llovel  
600 et al. 2014). Despite the fact that predicting future deep-sea temperature changes is  
601 difficult (Klemas & Yan 2014), SBT projections were estimated taking into account the  
602 best available data. Additionally, new species could be incorporated into the food-web  
603 due to their migration into the system because of increasing sea temperature and thus it  
604 could represent a limitation on this study. These incoming species from southern areas,  
605 in the hemisphere north, could forage and interact with other species and alter the food-  
606 web (Blanchard 2015). A complete assessment of the spatiotemporal distribution of  
607 species in the study area should be performed to complement the analysis of future  
608 trajectories of change in order to include all species in the analysis. In addition, response  
609 functions to sea temperature were included from *AquaMaps* a global database using  
610 trapezoid shape (Kaschner et al. 2016), because we lacked specific response functions  
611 in the study area. Local sea temperature response functions would improve predictions  
612 under global warming scenarios, for example, alternative shapes and statistical models  
613 are increasingly used in order to define environmental response functions (Coll et al.  
614 2019; Serpetti 2019). Lastly, future analysis on the same ecosystem may include  
615 mediating effects (Harvey 2014) to verify the potential effects of non-trophic relationships

616 between kelp POM and other marine species following previous findings (Vilas et al.  
617 2020).

618       Regardless of these caveats, our results demonstrated the vulnerability of sub-Arctic  
619 Arctic deep-sea ecosystems to stressors, especially to sea warming. This calls for  
620 climate change mitigation, conservation and restoration of deep-sea ecosystems as well  
621 as adjacent ecosystems such as coastal kelp forests. Conservation and restoration of  
622 coastal kelp forest would ensure the maintenance of kelp POM inputs on adjacent deep-  
623 sea ecosystems, increasing the resilience on deep-sea systems and alleviate the  
624 negative effects of sea warming and species invasions.

625

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636

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899 **TABLES**

900

901 Table 1. Summary of drivers and scenarios for the ADEAKE model from 2017 to 2100.

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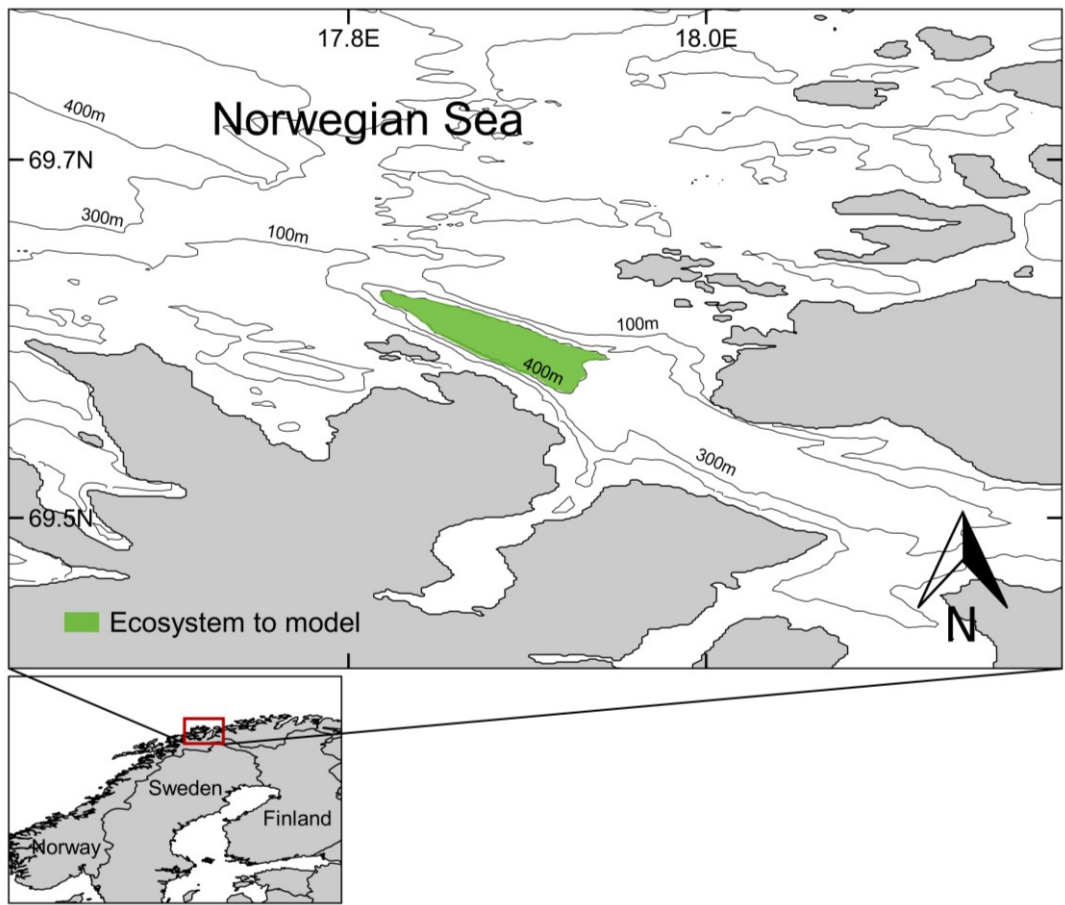
Scale	Driver/s	Scenario	Description
	Baseline	1	Constant fishing effort, constant kelp production, and constant temperature
Local	Fishing	2	Decreasing fishing effort (reducing 50% relative fishing effort)
		3	Increasing fishing effort (reducing 50% large benthic fish feeders' biomass)
Regional	Kelp POM production	4	50% decline of coarse and fine kelp biomass due to direct harvesting
		5	50% increase of coarse kelp POM biomass and 50% decline of fine kelp POM biomass due to decrease of sea urchins
		6	50% decline of coarse and fine kelp biomass due to increase of sea urchins
	Red king crab invasion	7	Invasion of the red king crab into the area
Global	Temperature	8	Moderate increasing of sea bottom temperature (scenario RCP4.5)
		9	Strong increasing of sea bottom temperature (scenario RCP8.5)

**Cumulative**

	Kelp POM production + red king crab invasion	10	Decreasing sea urchins and red king crab invasion (Scenario 5 + Scenario 7)
	Fishing + kelp POM production + temperature	11	Decreasing effort, decreasing sea urchins and RCP4.5 (Scenario 2 + Scenario 5 + Scenario 8) (Optimistic)
	Fishing + kelp POM production + red king crab invasion + temperature	12	Increasing fishing effort, increasing sea urchins, red king crab invasion and RCP8.5 (Scenario 3 + Scenario 6 + Scenario 7 + Scenario 9) (Pessimistic)

906

907 **FIGURES**



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909 Figure. 1. Study area located in Malangen fjord, northern Norway, and the Arctic deep  
910 ecosystem associated with kelp exports (ADEAKE) (green polygon).

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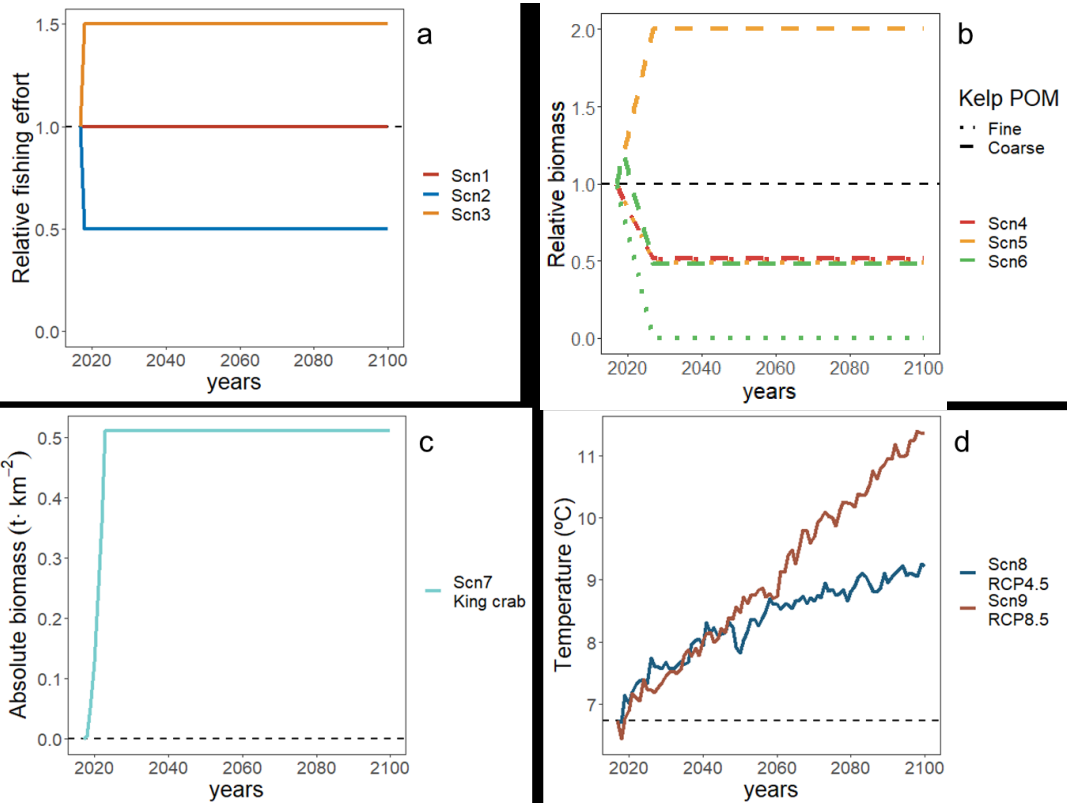
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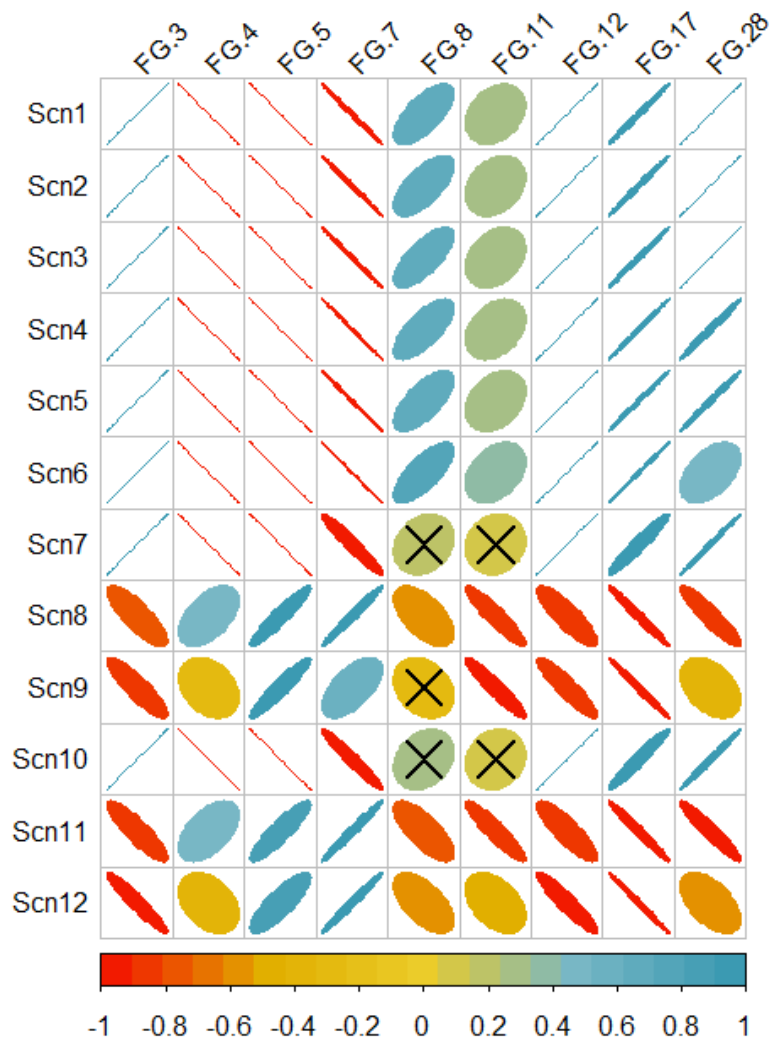


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924 Figure 2. Stressors in the ADEAKE model for the simulation period 2017-2100: (a)  
 925 relative fishing effort; (b) fine and coarse kelp POM production; (c) invasive species in  
 926 terms of absolute biomass ( $t \cdot km^{-2}$ ) of king crab; and (d) annual sea bottom temperature  
 927 ( $^{\circ}C$ ) under the two scenarios of IPCC projections.

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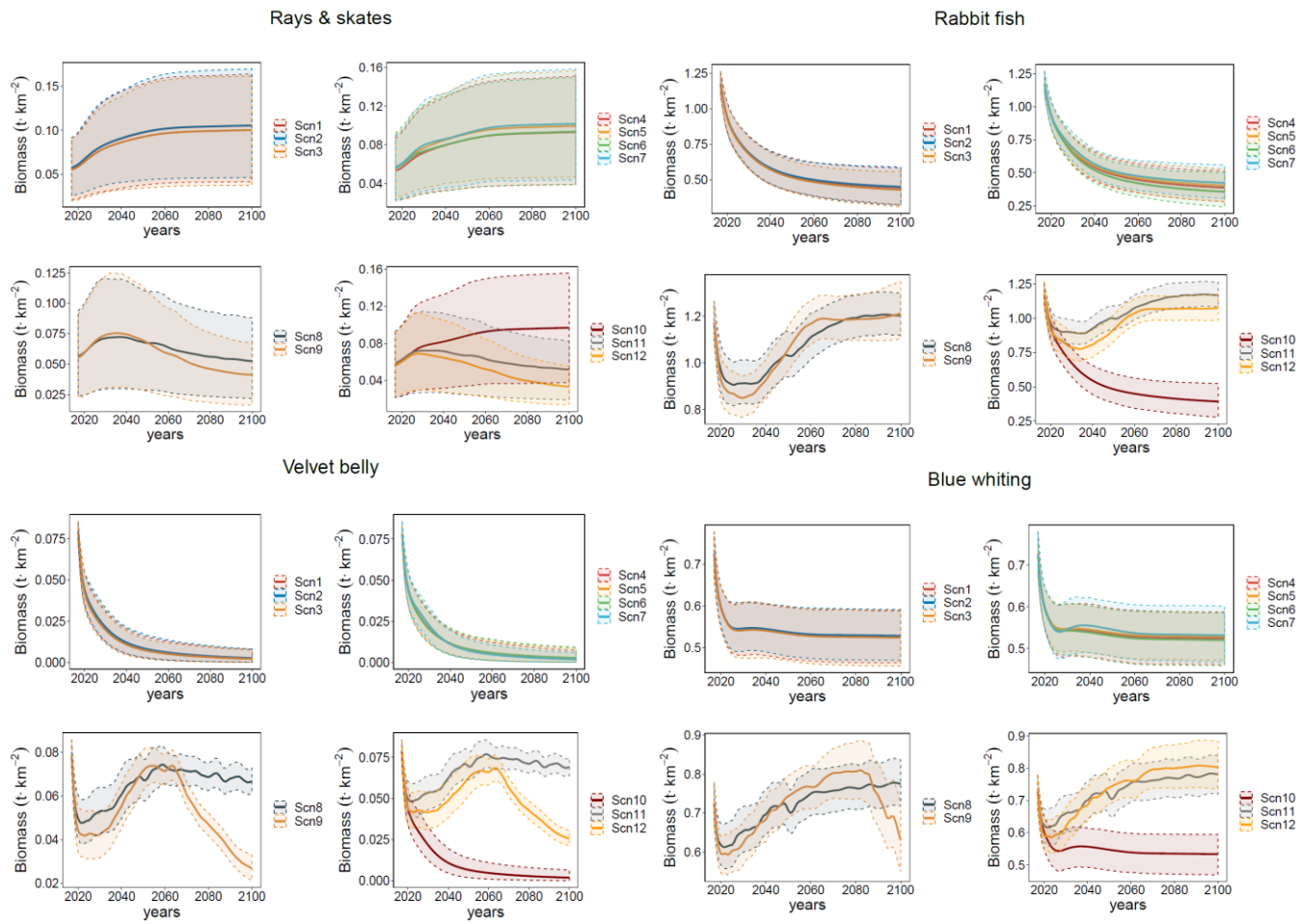


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930 Figure 3. Spearman's rank correlation between selected biomasses of functional groups  
 931 (FG) and time for the 12 future scenarios (Table 1). Positive correlations are in blue and  
 932 negative correlations in red. Legend colour shows the strength correlation coefficient  
 933 (rho-value) and its corresponding colour gradient. Colour intensity and the size of the  
 934 ellipses are proportional to the correlation coefficients, with more diffused and wider  
 935 ellipses representing lower correlation strengths. When the indicator is non-significant  
 936 ( $>0.01$ ), it is represented with an "X" symbol (rho and p-values are included in suppl.  
 937 material Table S2) (FG.3: rays and skates; FG.5: rabbit fish; FG.7: blue whiting; FG.8:  
 938 large fish feeders; FG.11: other commercial demersal fishes; FG.12: redfishes; FG.17:  
 939 benthopelagic shrimps; FG.28: suprabenthos.

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959 Figure 4. Predicted time series of mean absolute biomass (t·km<sup>-2</sup>) (solid line) for rays and skates, rabbit fish, velvet belly and blue whiting functional  
960 groups under 12 future scenarios (Table 1). Shadows represent the 5% and 95% percentiles obtained using the Monte Carlo routine.

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Large fish feeders

Other commercial demersal fishes

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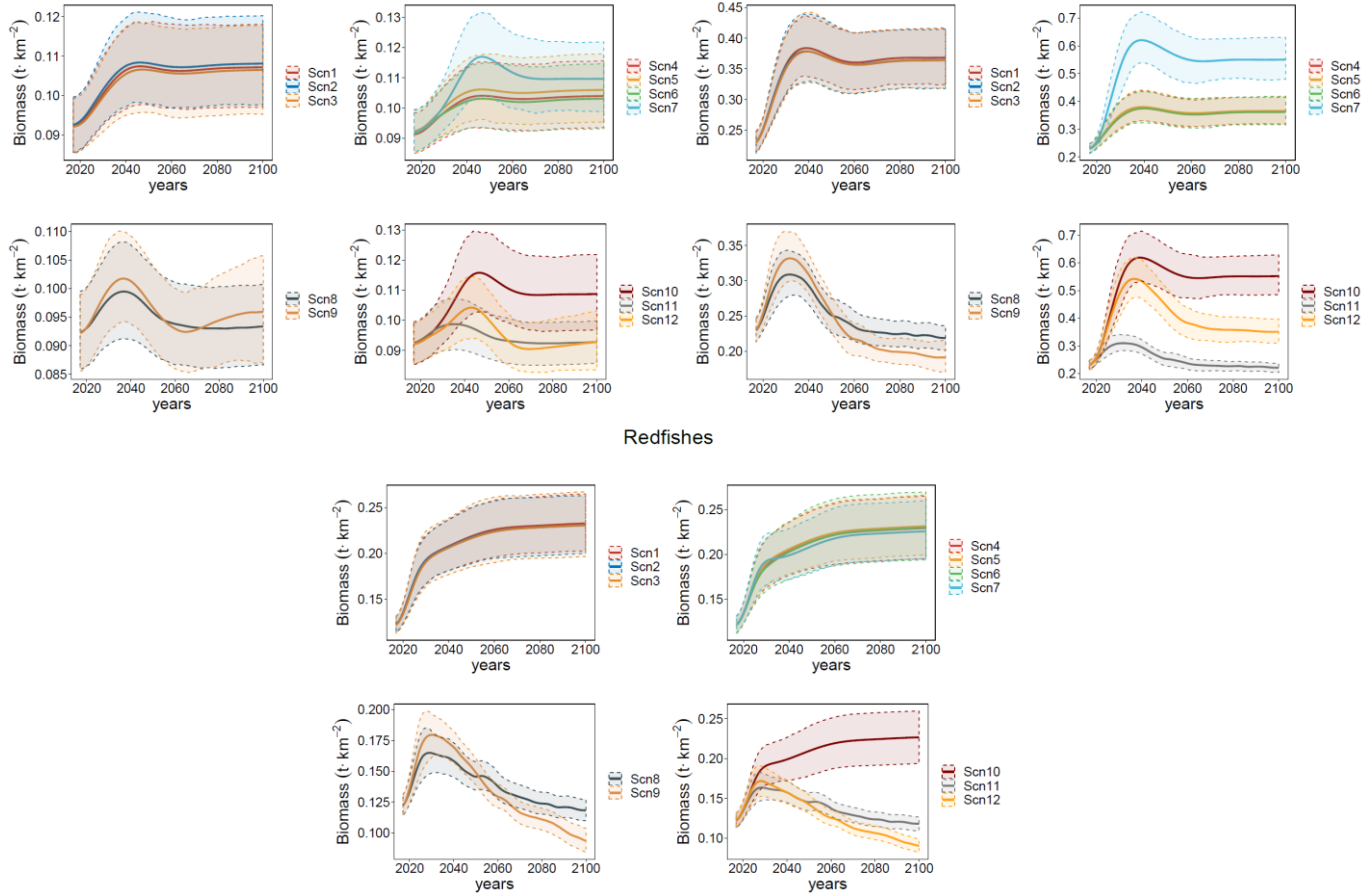
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Figure 5. Predicted time series of mean absolute biomass ( $t \cdot km^{-2}$ ) (solid line) for large fish feeders, other commercial demersal fishes and redfishes' functional groups under 12 future scenarios (Table 1). Shadows represent the 5% and 95% percentiles obtained using the Monte Carlo routine.

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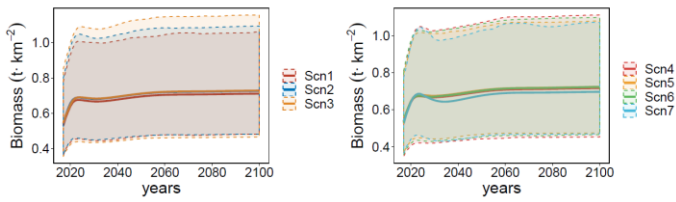
### Benthopelagic shrimps

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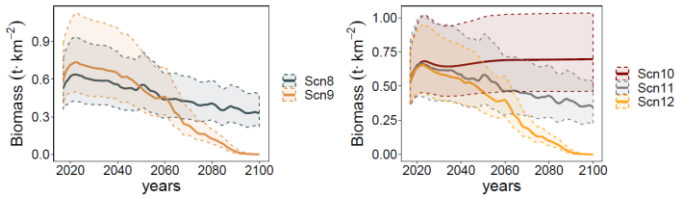


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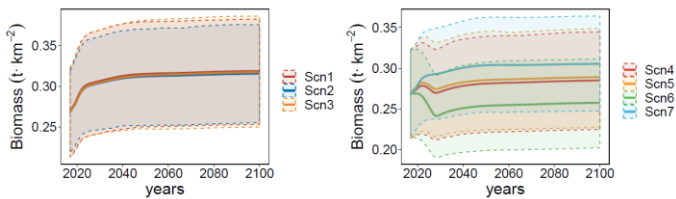
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### Suprabenthos

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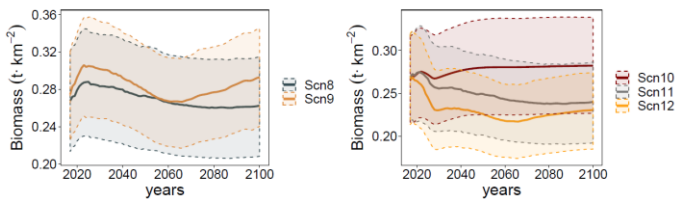


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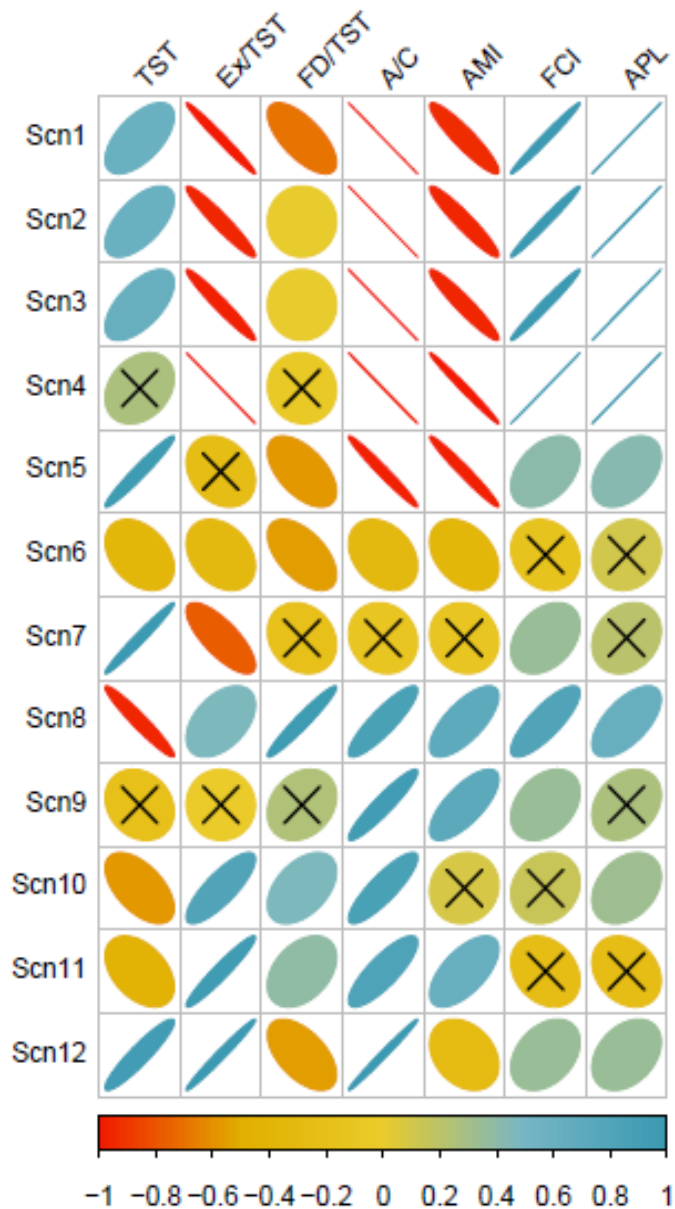
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999 Figure 6. Predicted time series of mean absolute biomass (t·km<sup>-2</sup>) (solid line) for  
1000 benthopelagic shrimps and suprabenthos functional groups under 12 future scenarios  
1001 (Table 1). Shadows represent the 5% and 95% percentiles obtained using the Monte  
1002 Carlo routine.

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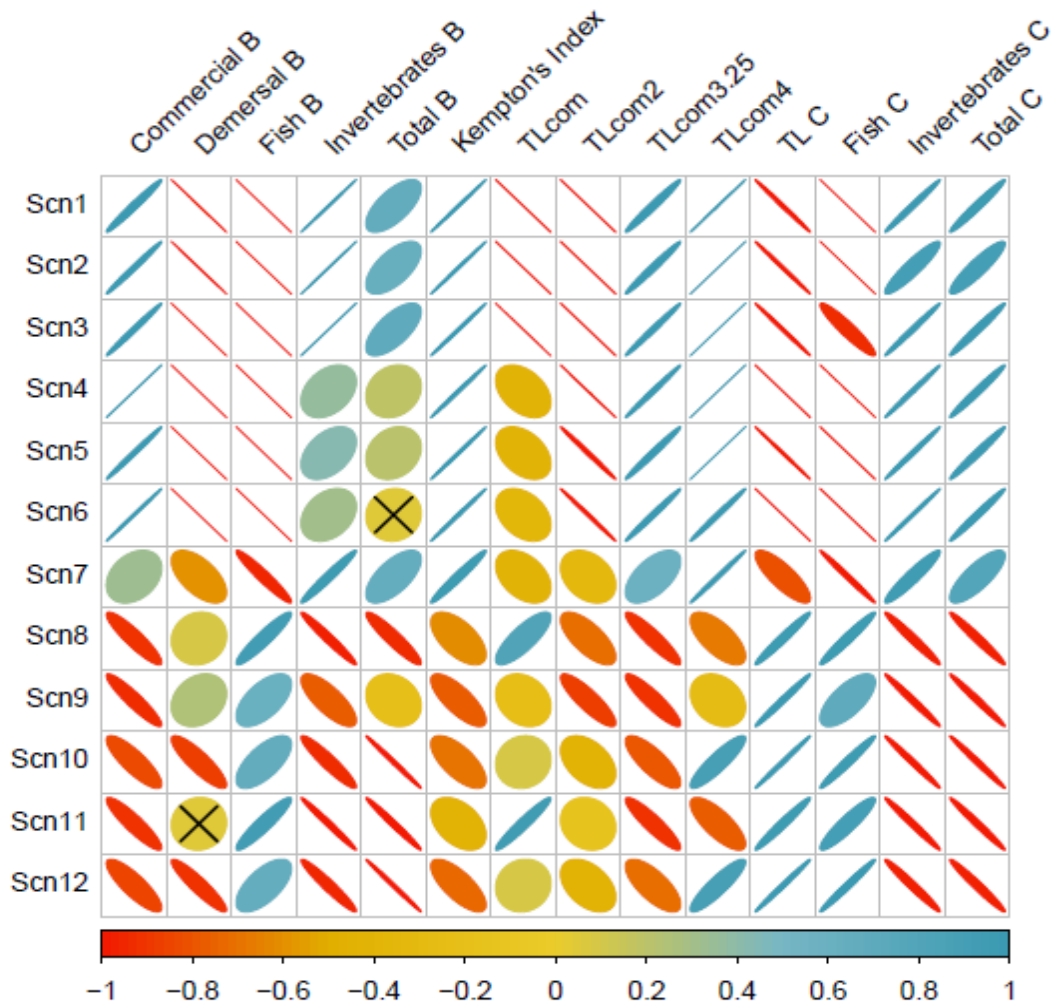


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1005 Figure 7. Spearman's rank correlation between selected ENA indicators and time for the  
 1006 12 future scenarios (Table 1). Positive correlations are in blue and negative correlations  
 1007 in red. Legend colour shows the strength correlation coefficient (rho-value) and its  
 1008 correspondent colour gradient. Colour intensity and the size of the ellipses are  
 1009 proportional to the correlation coefficients, with more diffused and wider ellipses  
 1010 representing lower correlation strengths. When the indicator is non-significant (>0.01), it  
 1011 is represented with an "X" symbol (rho and p-values are included in suppl. material Table  
 1012 S3).

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1016 Figure 8. Spearman's rank correlation between selected ECOIND indicators and time for  
 1017 the 12 future scenarios (Table 1). Positive correlations are in blue and negative  
 1018 correlations in red. Legend colour shows the strength correlation coefficient (rho-value)  
 1019 and its correspondent colour gradient. Colour intensity and the size of the ellipses are  
 1020 proportional to the correlation coefficients, with more diffused and wider ellipses  
 1021 representing lower correlation strengths. When the indicator is non-significant (>0.01), it  
 1022 is represented with an "X" symbol (rho and p-values are included in suppl. material Table  
 1023 S4).

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1032 Additional Supplementary material may be found in the online version of this article:

1033 **Appendix 1** Supplementary figures: Revised environmental preference functions of each  
1034 functional group (Fig. S1).

1035 **Appendix 2** Supplementary tables: Confidence intervals used to describe the  
1036 uncertainty for each functional group (FG) and each input parameter of the balanced  
1037 Ecopath model (Table S1), Rho and p-values of Spearman correlation of FGs' biomass  
1038 (Table S2), Ecological Network Analysis indicators (Table S3) and ECOIND indicators  
1039 (Table S4) over time, unlagged cross-correlation validation of FGs' biomass (Table S5),  
1040 Ecological Network Analysis indicators (Table S6) and ECOIND indicators (Table S7)  
1041 over time.

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