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From species distributions to ecosystem structure and function: a methodological perspective

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1   Abstract

2   As species biology and ecology is profoundly influenced by climate, any climatic alteration

3   may have severe consequences on marine pelagic ecosystems and their food webs. It remains

4   challenging to estimate the influence of climate on both structural and functional properties of

5   food webs. In this study, we proposed an innovative approach to assess the propagating

6   effects of climate change on ecosystem food web. The approach is based on a sensitivity

7   analysis of a food-web model, a linear inverse model using a Monte Carlo method coupled

8   with a Markov Chain, in which changes in the values of parameters are driven by external

9   ecological niche model outputs. Our sensitivity analysis was restricted to parameters

10   regarding a keystone functional group in marine ecosystems, i.e. small pelagic fish. At the

11   ecosystem level, the consequences were evaluated using both structural and functional

12   ecological network indices. The approach is innovative as it is the first time that these three

13   methods were combined to assess ecological network indices sensitivity to future climatic

14   pressure. This coupling method was applied on the French continental shelf of the Bay of

15   Biscay for which a food-web model already exists and where future changes in the

16   distribution of small pelagic fish have already been examined through model building and

17   projections. In response to the sensitivity analysis corresponding to an increase in small

18   pelagics production only, our results suggested a more active system with an intense

19   plankton-small pelagics-seabirds chain and an efficient recycling to maximize detritus use in

20   the system in relation with detritus export. All results combined together seemed to be in

21   favor of a system adapting to sustain the tested increase in production of small pelagic

22   planktivores. Finally, regarding the innovative combination of numerical tools presented,

23   even if further investigations are still necessary to get a more realistic view of cumulative

24   effects resulting from one given pressure (or more) on a food web (e.g. altering different

25   biological compartments at the same time), the Ecological Network Analysis indices values

26   showed a higher variability under the scenarios of change. Our study thus pointed out a

27   promising methodology to assess propagating changes in structural and functional ecosystem

28   properties.

29   Keywords: climate-induced changes; food web; small pelagics; linear inverse model;

30   Ecological Network Analysis; ecological niche.

31

32 1. Introduction

33 The effects of climate change on biological and ecological systems is incontrovertible (Doney

34 and Sailley, 2013; Beaugrand et al., 2015a) and is likely to lead to unexpected modifications

35 in ecosystems functions (Scheffer et al., 2001; Scheffer and Carpenter, 2003; Beaugrand et

36 al., 2009) and associated services for humankind, with strong socio-economic implications

37 (Halpern et al., 2008). In the context of human-driven climate change, these modifications of

38 ecosystem structures, functions, and status are at least partly related to strong alterations of

39 lower trophic levels such as primary producers, primary consumers or planktivorous

40 organisms in aquatic environments (Parmesan and Yohe, 2003; Parmesan, 2006). Different

41 responses have been documented, including physiological effects of climate change on

42 organisms (Arrhenius, 1889; Magnuson et al., 1979), phenological shifts (Edwards and

43 Richardson, 2004) and potential changes in species spatio-temporal distributions (Quéro et al.,

44 1998; Stebbing et al., 2002; Hermant et al., 2010; Alekseenko et al., 2014). However, the

45 propagation of these alterations through the food webs and their consequences on the food-

46 web emerging properties remains poorly understood with only rare examples documented for

47 freshwater and marine systems (e.g. Woodward et al., 2010; Albouy et al., 2013; Chust et al.,

48 2014).

49

50 In line with these major issues, our paper proposes a methodology to investigate the

51 propagating effect of climate change on the trophic pathways and the functioning properties

52 of ecosystems. The study case was the Bay of Biscay French continental shelf, with a special

53 emphasis on the consequences of a change in the production of a keystone functional group,

54 i.e. the pelagic planktivorous fish. Here, we proposed for the first time a combination of three

55 numerical methods: (i) An Ecological Niche Model (ENM; Beaugrand et al., 2011; Lenoir et

56 al., 2011) investigating the environmental descriptors driving species distributions to estimate

57   the changes in the production of small planktivorous fish in relation to future climate

58   scenarios; (ii) A Linear Inverse Model using a Markov Chain Monte Carlo method (Kones et

59   al., 2006; Niquil et al., 2012) to determine the consequences of changes in small pelagics

60   production on the carbon flows of the Bay of Biscay French continental shelf food web; and

61   (iii) Calculation of Ecological Network Analysis indices (ENA; Ulanowicz, 1992; Patrício et

62   al., 2004; Baird et al., 2012; Saint-Béat et al., 2015) to assess the propagating consequences of

63   changes in the production of small pelagics on the whole food web. With this ecologically

64   meaningful study case, we are particularly interested in demonstrating whether ENA indices

65   are reflecting the propagating consequences of a change in one compartment balance. Indeed,

66   the recent European directives [e.g. Marine Strategy Framework Directive (MSFD), Water

67   Framework Directive (WFD)] stress the urgent need of development, test, and validation of

68   ecosystem health indicators. This study combining numerical methods allowed exploring the

69   consequences of climate-related changes on the food-web properties and ecosystem status.

70   Moreover, ENA indices (Ulanowicz, 1986) were proposed as 'candidate' indicators for the

71   common biodiversity indicators list of OSlo and PARis Convention [OSPAR] (Niquil et al.,

72   2014a), because they capture well the functional and structural properties of ecosystems

73   (Ulanowicz, 1992; Patricio et al., 2004; Baird et al., 2012; Saint-Béat et al., 2015).

74

75   This study aims to propose a numerical approach (i) to assess propagating changes in

76   structural and functional ecosystem properties and (ii) test the sensitivity of candidate

77   indicators to the climate change pressure for the common biodiversity indicators list of the

78   OSPAR Convention.

79

80   2. Materials and Methods

81   2.1. Study area

82   The study area considered in this work is the French continental shelf of the Bay of Biscay

83   (between the 30m- and 150m-isobaths), a Gulf of the North-East Atlantic Ocean located off

84   the western coast of France and the northern coast of Spain (48.5°N - 43.5°N and 8°W - 3°W;

85   Figure 1). This system is hydrodynamically complex, being influenced by upwelling events,

86   coastal run-off and river plumes, seasonal currents, eddies, internal waves, and tidal fronts

87   (Planque et al., 2004). The supply of freshwater is mainly provided by 5 rivers: the Loire, the

88   Garonne–Dordogne, the Adour, the Vilaine, and the Charente. All these hydrodynamic

89   processes are known to affect species populations (Varela, 1996; Lampert, 2001; Hily et al.,

90   2008). Ecosystem dynamics is also driven by anthropogenic pressures, the most important

91   being the multifleet fishery operating in the Bay of Biscay (Hily et al., 2008; Rochet et al.,

92   2012). In this respect, the study area is composed of ICES divisions VIIIa and VIIIb (ICES;

93   www.ices.dk) and has a total surface area of 102,585 km².

94   2.2 The Bay of Biscay French continental shelf LIM-MCMC model

95   This study was based on a Linear Inverse Model used to estimate processes difficult to

96   measure in the field, especially for large ecosystems, and, when combined to ENA indices,

97   characterize the ecosystem status of the Bay of Biscay French continental shelf and its

98   associated structural and functional properties (Chaalali et al., 2015) under varying

99   environmental conditions. The structural properties refer to the network of interactions (i.e.

100 presence or absence of pathways and pathway values) linking the species or groups of

101 species, whereas the functional properties correspond to the emergent properties describing

102 how the carbon flows through ecosystem boundaries.

103 The LIM was built as a combination of mass-balance equations (and potential *in situ*

104 measures of flow expressed as complementary equations) and inequalities which constrain

105 flow values. In most cases, constraints were based on the ecophysiology of the species

106 making up the model compartments (Niquil et al., 2012). LIM food webs are described as

107 linear functions of flows constrained between maximal and minimal boundaries and estimated

108 from empirical data. As the system of equalities is underdetermined, infinity of different

109 solutions exists. The Markov Chain Monte Carlo (MCMC) approach coupled with LIM

110 allows retrieving a large set of solutions of flow estimates from the multidimensional space of

111 all possible solutions (Van den Meersche et al., 2009). In this study, 1 million of values for

112 each of the 124 carbon flows were estimated by the LIM-MCMC. The species considered in

113 our LIM-MCMC model was the same as those of the Ecopath model by Lassalle et al. (2011)

114 with the exception of two species of tuna (added in the LIM-MCMC). Among the differences

115 between the two models, an important one was structural and corresponded to the reduction in

116 the number of functional groups from 32 to 18. More details can be found in Chaalali et al.

117 (2015), notably the empirical data sources used for network construction and model

118 parameterization (e.g. *in situ* measures of flow, ecophysiological constraints, and biomass).

119 The development of food-web models was made possible by the two successive phases of the

120 French coastal environmental research program (PNEC 1999-2003 and 2004-2007) that both

121 included a specific worksite on the Bay of Biscay and that thus greatly contributed to fill the

122 gaps that existed in the data concerning this area.

123

124 The LIM-MCMC represented an average year between 1994 and 2005. Small pelagics in the

125 Bay of Biscay were composed of the European anchovy, *Engraulis encrasicolus*, the

126 European pilchard, *Sardina pilchardus*, and the European sprat, *Sprattus sprattus*. All three

127 species were grouped into a single functional compartment named "pelagic planktivorous

128 fish" in the LIM-MCMC model according to their mainly planktivorous diets.

129 2.3. The Ecological Niche Model applied to small planktivorous fish

130 The ecological niches and the spatial distributions of the European anchovy, the European

131 pilchard, and the European sprat were estimated by the Non-Parametric Probabilistic

132   Ecological Niche (NPPEN) model (Beaugrand et al., 2011). The NPPEN model is described

133   in full details in Beaugrand et al. (2011) as well as in subsequent articles presenting different

134   study cases (e.g. Lenoir et al., 2011; Chaalali et al., 2013a; Frederiksen et al., 2013; Raybaud

135   et al., 2013; Goberville et al., 2015; Raybaud et al., 2015). The NPPEN model only requires

136   presence data and uses the Mahalanobis distance, which allows the consideration of the

137   correlations between explanatory variables (Farber and Kadmon, 2003). Based on presence-

138   only data, the NPPEN model calculates the probability of occurrence of a species as a

139   function of some key abiotic variables. In the Euclidean space of the niche, the probability of

140   occurrence is calculated for each combination of environmental variables. Then, an

141   interpolation is made to project the niche into the geographical space.

142

143   More practically, in this study, we used NPPEN models outputs and projections provided

144   during the BIODIMAR project (www.biodimar.org). The first step of NPPEN modeling had

145   consisted in the identification of the abiotic variables that condition the most the small

146   pelagics' ecological niches to model species probabilities of occurrence for the 'reference'

147   period. Four variables for which empirical data must be available at the species distribution

148   scale were tested and the NPPEN models were run with eleven combinations of variables to

149   assess the ability of each combination to reproduce the observed spatial distribution (Lenoir

150   and Beaugrand, 2008; Lenoir, 2011; Raybaud et al., submitted). For each of the three small

151   pelagics, the best combination was selected based on the Boyce Index (CBI; Hirzel et al.,

152   2006), a modification of the Boyce index (Boyce et al., 2002) especially designed for

153   presence-only models (Braunisch and Suchant, 2010). This index is based on a moving

154   window analysis on the predicted-to-expected (P/E) frequency curve and uses the Spearman

155   rank correlation coefficient to measure the monotonic increase of the curve. Values of CBI

156   vary from -1 for an inverse model to 1 for a perfect prediction. Values close to zero indicate a

157 random model. The abiotic variables retained in the models were the annual Sea Surface

158 Temperature (AVHRR-SST data for the period 1982-2009; Casey et al., 2010) and the

159 bathymetry (bathymetric data from the "Smith and Sandwell Global Seafloor topography";

160 Smith and Sandwell, 1997).

161

162 To establish projections of the future species probabilities of occurrence for the end of the

163 century (2090-2099), we used SST outputs from an Earth System Model : IPSL-CM5A-MR

164 (Bopp et al., 2013) and the latest generation of climate scenarios called RCPs (Representative

165 Concentration Pathways, (Moss et al. 2010)), which are a part of the fifth Intergovernmental

166 Panel on Climate Change (IPCC) assessment report (Taylor et al., 2012). Here, we used both

167 the intermediate scenario RCP4.5 (a scenario that stabilizes radiative forcing at 4.5 $W.m^{-2}$ in

168 2100 and projects a global temperature increase of 2°C) and the 'business-as-usual' scenario

169 RCP8.5 (a rising radiative forcing pathway leading to 8.5 $W.m^{-2}$ in 2100 and a global

170 temperature rise by more than 4°C (Knutti and Sedlacek, 2012)).

171

172 Finally, from two matrices (latitude x longitude) of probabilities of occurrence (for the

173 reference period, $P_{reference}$; and each RCP scenario tested, P_{RCP}), we calculated coefficients of

174 change for each geographic cell. These coefficients that vary between -1 and 1 were assessed

175 using the following formula:

176
$$C = \frac{P_{reference} - P_{RCP}}{P_{reference}}$$

177 As a coefficient value was computed per geographic cell, mean coefficients ($\bar{C}$) were then

178 calculated following the latitudinal gradient (i.e. by matrix rows). Both a maximum and

179 minimum mean coefficients ($\bar{C}$) were used to integrate the variability of NPPEN estimates

180 into the LIM-MCMC model for each RCP scenario as presented below.

181   2.4. Forcing of the Bay of Biscay LIM-MCMC model

182   A single change was applied to the LIM-MCMC model parameterization presented in

183   Chaalali et al. (2015). The pelagic planktivorous fish production was modified according to

184   simulations from the NPPEN inputs. Only a single perturbation was applied as the main

185   question of the present study was to assess the capacity of ENA indices to integrate changes at

186   the population level. Nonetheless, this perturbation was ecologically meaningful as we

187   selected a functional group demonstrated to be a key compartment of the system and as we

188   applied a change in the compartment parameters in accordance with outputs of ecological

189   niche models.

190   In the model of Chaalali et al. (2015), the production estimates were calculated by multiplying

191   Production/Biomass (P/B) ratios by biomass estimates for each of the three species and then

192   the production of the functional group was assessed as a sum of each product. Species P/B

193   ratios were the same as in Lassalle et al. (2011). Time series of pelagic fish biomass were

194   obtained from acoustic surveys conducted each spring in the Bay of Biscay (PELGAS

195   IFREMER cruises) between 1994 and 2005. Inter-annual variations in species biomass across

196   the period were used to calculate minimum and maximum production for the functional group

197   (as the species P/B varies little in comparison to inter-annual biomass variability).

198

199   Here, we hypothesized that the $\bar{C}$ values estimated from the NPPEN simulations would most

200   likely reflect a change in species biomass. We based on the ecological niche theory

201   suggesting a maximum of species density associated to a specific range of environmental

202   descriptors (Hutchinson, 1957). Higher probabilities of species occurrence predicted by

203   NPPEN simulations suggest more favorable environmental conditions and, from a

204   mechanistic point of view, a higher species reproductive success and population size, and

205   therefore biomasses. We thus used this ecological assumption instead of considering an

206 arbitrary value of change in biomass. Moreover, this relationship was already verified for

207 lower trophic level organisms, e.g. copepods, at species level, such as for *Calanus spp.*

208 (Helaouët et al., 2013) and *Acartia spp.* (Chaalali et al., 2013a; 2013b).

209

210 A positive $\bar{C}$ value corresponded to a decrease in species mean probability of occurrence

211 between the reference and future situations. To translate this probability change into a future

212 biomass and then production, the species biomass was multiplied by $1 - \bar{C}$ (with $\bar{C}$ being

213 comprised between 0 and 1). Inversely, for a negative $\bar{C}$, an increase in species average

214 probability of occurrence was predicted by the NPPEN model. Species biomasses were also

215 transformed using $1 - \bar{C}$ but this time, $\bar{C}$ was comprised between 0 and -1, leading to higher

216 biomass estimates.

217

218 For each small pelagic species, the minimum $\bar{C}$ was multiplied by the minimal biomass

219 estimated by PELGAS acoustic survey and inversely. By computing each species minimal

220 and maximal future biomasses, new boundaries for the pelagic planktivorous fish production

221 were calculated taking the two opposite extremes among these 6 values (i.e. 2 boundaries x 3

222 species) and the model was run with these new constraints on the production term. We

223 applied this procedure to better integrate the NPPEN-predicted decrease of pilchard

224 distribution range (by reducing the most the functional group production in the LIM-MCMC

225 using the minimum future pilchard biomass – acting on the production minimal boundary),

226 and the expected increase of European anchovy and sprat distribution ranges (by increasing

227 the most the functional group production in the LIM-MCMC using the maximum future

228 anchovy and sprat biomasses – acting therefore on the production maximal boundary) (Figure

229 2A). P/B ratios were left unchanged compared to the reference situation as no quantitative and

230 precise information exist on their potential evolution under climate change.

231

232   Even if the present sensitivity analysis realized on the LIM-MCMC model was only based on

233   a single modification of a given flow, i.e. the production of small pelagic fish, and therefore

234   did not aim to be a 'realistic' view of climate change impacts at population level, all the group

235   intrinsic flows (i.e. respiration, egestion, predation on and by this group) were modified

236   accordingly as they were, by construction, all related to each other (i.e. mass conservation

237   hypothesis) (see Chaalali et al., 2015 for more details). Thus, the temperature incidence on the

238   whole species metabolism (not only its production) was implicitly considered. One million of

239   iterations were calculated for the 1994-2005 period and for the two RCP scenarios (2090-

240   2099). The choice was made to perform one million of iterations in view of the quality of the

241   exploration of the solution space by the mirror technique (i.e. graphical analysis) (Kones et

242   al., 2006; Niquil et al., 2012).

243   2.5. Ecological Network Analysis

244   Ecological Network Analysis (ENA; Ulanowicz, 1986) was used to compute several indices

245   to compare the function of the Bay of Biscay French continental shelf food web nowadays

246   (1994-2005) and in the future (2090-2099), after climate alterations on pelagic planktivorous

247   fish production.

248   Various ENA indices were calculated (Table 1), namely Total System Throughput (T..),

249   Internal Ascendency (Ai), Internal Capacity (Ci), Internal Relative Ascendency (Ai/Ci),

250   Average Path Length (APL), Finn's Cycling Index (FCI), System Omnivory Index (SOI). The

251   Total System Throughput (T..) is computed as the sum of all flows in a food web and

252   therefore corresponds to the system activity (Ulanowicz, 1980; 1986; Latham, 2006). The

253   internal ascendency (Ai) describes the ecosystem development (Ulanowicz and Abarca-

254   Arenas, 1997), whereas the internal capacity (Ci) describes the system maximal stage of

255   development, and corresponds to the upper limit of the internal Ascendency (Ai). The internal

256 relative ascendency (Ai/Ci) provides a relative measure of the degree of organization of a

257 food web based only on internal flows. The Average Path Length (APL) is defined as the

258 average number of steps along the shortest path for all possible pairs of network nodes. Finn

259 (1980) proposed an index of the importance of recycling activity (FCI) corresponded to the

260 proportion of the sum of internal transfers plus imports involved in cycles (i.e. loops are

261 pathways beginning and ending in the same compartment). According to Ulanowicz (1986),

262 the System Omnivory Index (SOI) generally reflects the complexity of the linkages within an

263 ecosystem (in terms of organization).

264 A MATLAB routine, adapted from the one developed by Carole Lebreton and Markus

265 Schartau (GKSS Research Center, Geesthacht, Germany), was used to compute one ENA

266 index value per vector of flow estimates from the LIM-MCMC, leading for each ENA index

267 to 1 million values.

268

269 The Detritivory/Herbivory (D/H) ratio, calculated as the sum of flows originating from both

270 detritus and Dissolved Organic Carbon (DOC) compartments divided by the sum of flows

271 from phytoplankton, was also calculated. The D/H ratio measures the relative importance of

272 detritivory and herbivory activity in a given system (Ulanowicz, 1992).

273

274 The use of the LIM-MCMC approach allowed obtaining a likelihood distribution for each

275 flow and for ENA indices, based on one million of iterations. As a result, descriptive statistics

276 such as mean, minimum, maximum, and standard deviation values can be computed for each

277 flow and ENA index.

278 2.6. Comparison of flows and ENA indices between periods

279   The general distribution pattern of flows estimated by the three LIM-MCMCs (one for the

280   reference period "1994-2005", and the two other for the RCP scenarios) was first assessed

281   with a barplot including all estimated flows. The main changes in the food web were

282   graphically investigated by searching for the flows with a noticeable change in response to the

283   climate-induced changes in the production of pelagic planktivorous fish (i.e. the two RCPs).

284   These changes in flow estimates were also statistically analyzed using a comparison of flow

285   distributions between the reference period 1994-2005 and the RCP 4.5, and then the RCP 8.5.

286   The statistical analysis can be divided into three steps: (i) For a given flow, the mean value of

287   the flow for each of the two situations (i.e. reference and future under climate change) was

288   calculated; (ii) Scenarios were considered by pairs (e.g. reference-RCP 4.5 or reference-RPC

289   8.5). For the scenario having the distribution with the lowest mean, the quantiles 95, 90, 80,

290   70 and 65% were calculated. For the distribution with the highest mean, the quantiles 5, 10,

291   20, 30 and 35% were computed. (iii) Then, a test was performed to assess how much

292   distributions were overlapping. For example, at the 95%-5% interval, an overlap took place

293   when the quantile 95% of a distribution was superior to the quantile 5% of the other

294   distribution (Figure 2B). The levels of significance are fully described in Figure 2.

295

296   The values of the ENA indices estimated by the three LIM-MCMCs were plotted and also

297   statistically compared, using the same 'quantile interval' procedure as described above for

298   flows.

299

300   3. Results

301   In the LIM-MCMC under the RCP 4.5 and the RCP 8.5, an increased interval was applied on

302   the boundaries of the production of pelagic planktivorous fish. Values switched from [75 –

303 475] kgC.km^{-2}.y^{-1} for the reference period "1994-2005", to [72 - 486] kgC.km^{-2}.y^{-1} under RCP

304 4.5, and to [67 - 536] kgC.km^{-2}.y^{-1} under RCP 8.5.

305

306 The general pattern of mean flow estimates from the three LIM-MCMCs was graphically

307 comparable (Fig. S1 and Table S1). Considering the highest mean flow estimates, all models

308 presented a high gross primary production (flow number 1 in supplementary material) with

309 estimated mean values comprised between 2.4 • 10^5 kgC.km-2.y-1 and 2.9 • 10^5 kgC.km-2.y-

310 1 for the reference period and for the model under the RCP 4.5 respectively (Table S1). The

311 other highest flows identified in the different food webs were the same and were mainly

312 related to phytoplankton sedimentation (2), or to bacterial and detrital processes (e.g. mean

313 DOC consumption by bacteria (98), between 7.7 • 10^4 and 1.0 • 10^5 kgC.km^{-2}.y^{-1}; mean

314 bacterial respiration (114), between 4.5 • 10^4 and 6.2 • 10^4 kgC.km^{-2}.y^{-1}) (Table S1). Some

315 differences nonetheless did appear (Table 2). A high mean detritus export (i.e. detrital carbon

316 flows exported outside the ecosystem boundaries) (124) of 8.5 • 10^4 kgC.km^{-2}.y^{-1} was

317 calculated for the LIM-MCMC under RCP 8.5. It was almost 5 times higher than the estimate

318 for the LIM-MCMC under RCP 4.5 and for the LIM-MCMC for the reference period (Table

319 S1). This difference was "potentially significant" considering the quantiles' interval method

320 (Table 2). In addition, decreasing trends in detritus dissolution (89), DOC production by

321 bacteria (80), and DOC and detritus consumption by bacteria (flows with number 98 and 86)

322 were estimated, the latter being "potentially significant" (Table 2). No "trends" or "potentially

323 significant" differences were noticed for RCP 4.5 flow estimates compared to reference

324 period flow estimates, except for the consumption of detritus by bacteria (Table 2).

325

326   The input flow estimated for the pelagic planktivorous fish increased with the RCP 8.5; the

327   input flow being defined as all the flows entering into a functional group. The mean input

328   flow estimate was $4.3 \cdot 10^3 \pm 0.3 \cdot 10^3$ kgC.km^{-2}.y^{-1} for the reference period *versus* $4.4 \cdot 10^3$

329   $\pm 0.3 \cdot 10^3$ kgC.km^{-2}.y^{-1} under RCP 4.5 and $4.9 \cdot 10^3 \pm 0.3 \cdot 10^3$ kgC.km^{-2}.y^{-1} under RCP 8.5

330   (Figure 3A). Distributions for this flow overlapped at the 80%-20% quantiles interval,

331   meaning a difference in flow estimates between the RCP 8.5 and the two other situations

332   "potentially significant". More specifically, the consumption of macrozooplankton by the

333   pelagic planktivorous fish (mazTOppl flow in Figure 4) presented a "trend" with a higher

334   estimate for RCP 8.5 compared to RCP 4.5 and the reference period and an overlap detected

335   when considering the largest intervals (Figure 4). The analysis of the other flows that were

336   expected as important to interpret the sensitivity analysis performed on climate-induced

337   changes in pelagic planktivorous fish production showed no differences under climate change

338   scenarios (Figure 4).

339

340   When looking at the main prey of the pelagic planktivorous fish, the input flows of

341   zooplanktonic groups between the reference period and the one estimated in 2090-2099 with

342   the RCP 8.5 expressed a slight increasing "trend" (Figure 5A), as overlap was detected at the

343   largest quantile interval 65%-35%. When considering prey of prey, a "potentially significant"

344   difference was noticed for the phytoplankton production under RCP 8.5, with overlapping

345   distributions being observed at quantile interval 80%-20% (Figure 5A).

346

347   Possibly in response to the increasing productions of planktonic groups (mentioned above), an

348   increasing trend of their detrital production was also predicted by the models (see Table S1

349   for more details). The predation exerted by seabirds on small planktivorous fish (i.e. flow

350   abbreviation pplTOsbr in Table S1) was also predicted to increase, especially with the RCP

351   8.5 scenario as an overlapping of flow estimates was also noticed at the 80%-20% quantiles

352   interval suggesting a "potentially significant" difference (Figure 3B). However, the seabirds

353   input flow was not predicted to significantly change despite the increased predation on

354   pelagic planktivorous fish (Figure 3A).

355

356   The analysis of the input flows to bacteria, detritus and DOC showed interesting "trends": a

357   decreasing trend in inputs to bacteria was predicted under the two RCP scenarios compared to

358   the reference period, inputs to detritus under RCP 8.5 had also a lower mean value compared

359   to the two other situations and the same was predicted for inputs to DOC (Figure 5B).

360

361   Regarding the ENA indices comparisons, no difference at any quantiles' interval was

362   observed for the internal ascendency Ai (mean values around [$6.7 \cdot 10^5 \pm 3.5 \cdot 10^4$ to $1.1 \cdot$

363      $10^6 \pm 2.0 \cdot 10^5$ kgC.km^{-2}.y^{-1}) or the system omnivory index SOI (0.19 ± 0.03 to 0.21 ± 0.03)

364   (Figure 6B, F). Regarding indices related to the system activity and organization (T.., Ci, and

365   Ai/Ci), some "trends" were observed under the RCP 4.5 scenario. When considering APL,

366   FCI, and the D/H ratio, changes were detected for the RCP 8.5 scenario. An important

367   decrease of the ratio of detritivory on herbivory (D/H) was noticed, passing from a mean of

368   1.2 ± 0.29 (reference period) to 0.8 ± 0.12 (RCP 8.5) (Figure 6G). Oppositely, and for the

369   same RCP scenario, the Finn Cycling Index (FCI) presented an increasing trend reaching an

370   estimate mean value of 0.16 ± 0.02 (RCP 8.5) *versus* 0.13 ± 0.01 for the reference period.

371   One index seemed to respond to both future climate scenarios: the Averaged Path Length

372   (APL) with a mean at 3.42 ± 0.24 for the RCP 4.5, and 3.26 ± 0.19 for the RCP 8.5. An

373   increasing "trend" (RCP 4.5) and a "potentially significant" positive difference (RCP 8.5) of

374   the APL was thus calculated when compared to the reference period (3.13 ± 0.10). One

375   should finally notice the systematic increase in variability (of both ranges between maximum

376   and minimum estimates and standard deviation) for both flows and ENA indices estimates

377   under the tested climate change scenarios (Figure 6).

378   4. Discussion

379   4.1. Potential propagating effects of changes in small pelagic fish production on other flow

380   values

381   The present sensitivity analysis based on the combination of Ecological Niche Modeling,

382   Linear Inverse Modeling, and ENA highlighted plausible changes in the Bay of Biscay food-

383   web features in response to climatic incidence on a single biological compartment production,

384   i.e. the pelagic planktivorous fish. Despite the similar general pattern of flow estimates

385   obtained from the three LIM-MCMC models (i.e. reference period and the two RCP

386   scenarios), respiration flows and egestion values of small pelagics increased in response to the

387   potential increase of temperature (Table S1). These results can be related to the expected more

388   active metabolism of fish under increasing temperature (e.g. Arrhenius, 1889; Brown et al.,

389   2004). In support to the higher nutritional needs of small pelagic fish caused by the increase

390   in their metabolism and production, the production of low (planktonic) trophic levels -

391   especially the macrozooplankton production and gross primary production - increased in the

392   LIM-MCMCs. The supplemental food intake was directly supported by the

393   macrozooplankton only (i.e. increase of mazTOppl flow value). This conclusion was more

394   likely linked to a methodological cause rather than the result of an ecological process. The

395   flows of consumption by small pelagics of other compartments (i.e. phytoplankton,

396   microzooplankton, and mesozooplankton) were constrained by more restrictive inequalities

397   than the consumption flow exerted on macrozooplankton. Owing to a more documented

398 literature existing on the subject, the inequalities on the flows relative to phytoplankton,

399 micro- and mesozooplankton compartments (e.g. respiration, exudation or/and egestion flows)

400 were more constrained and inter-related in the LIM-MCMC models. Consequently, the space

401 of solutions to explore was smaller. On the contrary, a higher flexibility was given to the flow

402 of predation on the macrozooplankton as we found fewer references on this topic. The LIM-

403 MCMC adjusted the nutritional needs of the pelagic planktonic fish compartment by

404 increasing the consumption operated on this group. The resulting increasing

405 macrozooplankton production was in turn supported by an increase in gross primary

406 production.

407

408 According to Bopp et al. (2013), the primary production in the Bay of Biscay is expected to

409 follow an opposite trend. Working on 10 Earth System models and 7 marine biogeochemical

410 models, these authors predicted a significant decrease of the Bay of Biscay productivity at the

411 end of the century in a climate change context. However, the biogeochemical models used in

412 their study were typical Nutrients-Phytoplankton-Zooplankton-Detritus (NPZD) models (with

413 varying degrees of complexity) and did not take into account high trophic level components

414 such as planktivorous fish feeding on zooplankton and potentially decreasing the grazing

415 pressure on primary producers. Moreover, complementary predictions of primary production

416 obtained from a regional model would be also needed to assess the quality and reliability of

417 the downscaling from these global models. The increase in primary production predicted here

418 by the LIM-MCMC models could be therefore interpreted as the only possibility for the

419 model algorithm to satisfy the mass-balances in response to the simulated increase in small

420 pelagics production.

421

422   The question remains, however, as to whether a (contradictory) decrease in primary

423   production as predicted by Bopp et al. (2013) will be antagonistic with the changes in small

424   pelagics distribution and production predicted by modeling. A complementary set of analysis

425   was already performed but not yet published (Saint-Béat and Chaalali, unpublished data) to

426   assess the consequences of a potential climate-induced drop in the net primary production

427   (NPP) of the Bay of Biscay as predicted by Bopp et al. (2013). The LIM-MCMC model

428   structure remained the same in this new exercise with, amongst other things, small pelagics

429   feeding on plankton. However, small pelagics productions were no longer modified. Only

430   NPP was changed according to plausible climate change scenarios. This additional work

431   following the same methodology suggested a potential discrepancy between the availability of

432   planktonic preys and the fish consumers' needs in the Bay of Biscay with respect to climate

433   change. Indeed, by forcing the LIM-MCMC with lower boundaries of NPP, we observed a

434   decrease in the consumption flows exerted by pelagic planktivorous fish (and therefore in

435   their production; Figure S1). Chust et al. (2014) got to similar conclusions, suggesting a

436   potential future drop in phytoplankton and zooplankton biomass in the Atlantic margin under

437   climate change with an expected trophic attenuation of the entire chain. Their work was based

438   on two distinct meso-scale models, i.e. POLCOMS-ERSEM and ROMS-NPZD. However,

439   these authors nuanced that uncertainties related to the use of single global and regional

440   models implies a need for caution while extending conclusions into high trophic levels.

441

442   Another potential propagating effect of the tested pelagic fish production increase was noted

443   and concerned bacteria that appeared to be less consumed by planktonic compartments under

444   future climate scenarios (shifting part of their diet on primary producers). This can be put in

445   relation with a decrease in the relative importance of the microbial loop in terms of total flows

446   involved, particularly under the worst-case scenario RCP 8.5 (Table S1). On the contrary,

447 detritus appeared to gain in importance for the planktonic groups in sustaining their increase

448 of production, especially under RCP 4.5. As a consequence, the changes in the production of

449 small pelagics may transitionally stimulate the detritivory path with fish eating more

450 planktonic preys and planktonic preys consuming detritus in higher proportions under RCP

451 4.5. But then, under more severe environmental conditions, the detritivory was predicted to be

452 far less intense leading to a strong detritus export outside the ecosystem boundaries. To

453 conclude on this modeling exercise, two scenarios of temperature increase appeared to lead to

454 two distinct system functioning.

455

456 At higher trophic levels, regarding the increased predation by seabirds, Luczak et al. (2011),

457 using a long-term series analysis, reached a similar conclusion of potential propagating effect

458 of temperature rise in the Bay of Biscay. This propagating effect took place in the mid-1990s

459 and consisted in the modification of a seabird northern range margin to follow the expanding

460 distribution of its preys, here anchovy and sardine. However, this study pointed one drawback

461 of the present modeling approach as potential spatial mismatches could occur in the future if

462 the rate of climate change turns even faster (Durant et al., 2007).

463 4.2. Potential incidence of changes in small pelagic fish production on the food-web

464 properties

465 The use of ENA indices in combination with the sensitivity analysis presented here allowed

466 the characterization of emergent properties of the food web and the identification of potential

467 changes in the overall flow organization pattern.

468

469 The D/H ratio showed an important decrease under the RCP 8.5 scenario that was not

470 calculated for the intermediate scenario (RCP 4.5) despite the relatively highest detritivory

471 highlighted by various flow values. The D/H ratio responded to the increase of particulate

472   detritus export (less detrital matter available and associated flow values) and to the

473   consequent lowering of detrital paths (both flows from bacteria and detritus; Table 2),

474   suggesting a shift from a detritivorous functioning under present conditions and moderate

475   climate change scenario (RCP 4.5) (Lassalle et al., 2011; Chaalali et al., 2015) to an

476   herbivorous functioning. In addition, the ecological interpretation of the D/H ratio in relation

477   with pressures and ecosystem stress remains controversial (Ulanowicz, 1992; Dame and

478   Christian, 2007; Niquil et al., 2014b).

479

480   The ecosystem total activity (T..) augmentation predicted for the end of the century (RCPs 4.5

481   and 8.5) seemed in accordance with the rise in small pelagic fish production and with the

482   exhaustive literature dedicated to the metabolic changes in relation with temperature (e.g.

483   Arrhenius, 1889; Brown et al., 2004). However, given the stable A_i/C_i values, the internal

484   organization of the ecosystem appeared to remain at a similar level not responding to a

485   change in key compartment production. Moreover, the value of this index suggested that the

486   major part of the ecosystem was not strongly organized. This non-organized part that

487   corresponds to the redundancy (i.e. parallel trophic pathways) constitutes the reserves of the

488   ecosystem and brings flexibility to the system by permitting its reorganization in case of

489   disturbance (Ulanowicz, 2009). The redundancy can also be associated to the system

490   omnivory (i.e. SOI index; Williams and Martinez, 2004 in Saint-Béat et al., 2015). Here, SOI

491   showed close values whatever the environmental conditions, meaning that the variance of the

492   prey trophic levels (for consumers) remained constant. This SOI index is often considered as

493   a possible indicator of anthropogenic pressure (Lobry et al., 2008; Selleslagh et al., 2012).

494   Nevertheless, this interpretation has to be nuanced. Despite the fact that omnivory may play

495   an important role in the stabilization of food webs in response to a perturbation (see McCann

496   and Hastings, 1997 in Saint-Béat et al., 2015), it does not have the same attenuation effect in

497   all systems, depending on the trophic levels altered by the perturbation (Vandermeer, 2006 in

498   Saint-Béat et al., 2015). Allesina et al. (2009) also suggested that the SOI index may only

499   relate to redundancy with no consequences for the food-web or ecosystem robustness to a

500   given pressure.

501

502   The cycling tended to increase in the intermediate scenario and even more in the "business-as-

503   usual" scenario. This fact *a priori* seemed in contradiction with the decrease in the bacterial

504   activity and the fall of detritivory observed under the RCP 8.5 scenario. This observation can

505   be mainly explained by the increase in values of flows involved in the detritus-

506   macrozooplankton-planktivorous pelagic fish-detritus loop. The higher cycling observed for

507   the "business-as-usual" scenario suggested that, in relation to a reduction of detritus (higher

508   exports outside the system), the system would compensate with a more efficient cycling

509   processes. This observation is also in favor of a more dissipative system as first proposed by

510   Baird et al. (1998). The higher cycling can be linked to the measure of the retention of carbon

511   within the ecosystem as depicted by the APL values. Indeed, despite the higher export of

512   detritus, the residency time of carbon was rising under climate change. According to Saint-

513   Béat et al. (2015) that discussed the link between ecosystem resilience and cycling, and

514   basing on De Angelis (1980), resilience could be linked to the time energy or matter stays

515   within the system. Cycling increases the residence time of matter within the system

516   (Herendeen, 1989 in Saint-Béat et al., 2015). Thus, the longer the residence time is, and the

517   less resilient the system could be (De Angelis, 1980). Therefore, the increase in cycling could

518   have a direct implication in terms of system resilience.

519

520   In conclusion, despite the methodological focus of the paper, all our results combined seemed

521   to be in favor of a system adapting to sustain the increased production of small pelagic

522 planktivores and comforting the view that this compartment could be assimilated to a

523 'biological pump' transporting carbon towards higher trophic levels in marine systems.

524 4.3. A methodology to assess "Good Environmental Status" (GES) in a context of climate

525 change

526 The sensitivity analysis on small pelagics production led to ENA indices estimates with a

527 higher variability under future climate scenarios. Despite the fact that the origin of the higher

528 ENA variability could be, to some extent, imputable to the larger boundaries set for the small

529 pelagics production, these results reinforced the observations made by a recent study (Niquil

530 et al., submitted). Previous authors demonstrated that ENA indices were sensitive to a

531 climatic shift in the Mediterranean Sea, affecting notably their variability. Also, the variance

532 is often used as a mathematical tool to integrate climate-driven changes (Rodionov, 2004;

533 Beaugrand, 2014; Beaugrand et al., 2015b).

534

535 As such, ENA indices constitute an interesting indicator integrating human-induced

536 environmental changes into food-web properties (e.g. Tomczak et al., 2013; Luong et al.,

537 2015; Schückel et al., 2015). This conclusion is promising in regards with EU evolving policy

538 and decisions for ecosystem-based fisheries management. Thus, European directives

539 expectations such as the Marine Strategy Framework Directive (MSFD) – which aims to

540 assess the human activities impacts on the environment taking into account both the structure,

541 function, and processes of marine ecosystems (EU, 2008), led to numerous studies on

542 ecosystem health indicators (Borja et al., 2013; Piroddi et al., 2015). In the MSFD context, the

543 OSPAR "COBAM - Food Webs expert group" proposed a list of nine indicators including

544 ENA indices. Nevertheless, only fishery indicators [i.e. Large Fish Indicator (LFI) and Mean

545 Trophic Level indicator (MTL)] are currently adopted as common indicators (Niquil et al.,

546 2014a). The LFI, which is defined as the biomass of fish above a length threshold

547   representing "large fish" expressed as a proportion of the total fish biomass (Greenstreet et al.,

548   2011; Fung et al., 2012), is explicitly presented as a food-web indicator by the MSFD (EU,

549   2010). The MTL gives information on the structural changes in the ecosystem as a result of

550   fishing and this impact could be generalized to the ecosystem level when using model-based

551   MTL (Shannon et al., 2014). However, even if these two indicators describe some important

552   features of the ecosystem and are presently tested in OSPAR regions, their scope is mainly

553   focusing on benthic-demersal fish species and therefore not yet giving the "holistic" view

554   recommended by the Food-Web COBAM expert group (Arroyo, pers. comm.).

555

556   The present work also emphasized the potential interest of considering ENA indices in

557   addition to these actual common indicators (i.e. LFI and MTL) to describe marine food webs.

558   More work still has to be done to gain insights on the joint effects of direct human pressures

559   and climate change on ENA indices. For instance, this could be achieved by dedicating future

560   modelling works to the alterations caused by climate and fisheries on the Bay of Biscay food-

561   web functioning, as the two pressures are known to interact together (Perry et al., 2005;

562   Planque et al., 2010).

563

576　Table 1: Description of ENA indices used: names, abbreviations, and ecological interpretation.

577

ENA indices names	Codes	Equations	What does this index measure?
Total System Throughput	T..	Sum of all flows, i.e. consumption, respiration, imports and exports	the total quantity of carbon flowing within the ecosystem boundaries
Internal Ascendency	A_i	$\sum_{i=1}^{n}\sum_{j=1}^{n} T_{ij} \times log\left[\frac{T_{ij} \times T..}{\sum_{q=0}^{n+2} T_{qj} \sum_{v=0}^{n+2} T_{iv}}\right]$	nternal organization and activity of the ecosystem
Internal Capacity of Development	C_i	$-\sum_{i=1}^{n}\sum_{j=1}^{n} T_{ij} \times log\left[\frac{T_{ij}}{T..}\right]$	the maximal possible Internal Ascendency
Internal relative Ascendency	A_iC_i	$\frac{Ai}{Ci}$	state of internal organization (represents the organized part)
Average Path Length	APL	$\frac{TST}{\sum_i Exports + \sum_i Respiration}$	retention of carbon
Finn's Cycling Index	FCI	$\frac{TST_c}{TST} = \sum_j \frac{\sum_i T_{ij} + Imports_j}{TST}$	proportion of flows involved in loops (cycling)
System Omnivory Index	SOI	$\frac{\sum_i OI_i \times log[Q_i]}{\sum_i log[Q_i]}$	degree of feeding on several trophic levels

Detritivory/Herbivory ratio	D/H	Sum of flows originating from detritus and DOC compartments divided by the sum of flows from phytoplankton	easure of the relative importance of detritivory and herbivory activity in a given system

578

Table 2: Comparisons of flow mean estimates between the reference period 1994-2005 and
the two RCP scenarios at the end of the century in 2090-2099 where '∗' signifies that a
difference is noticed (at least at the 70%-30% interval), whereas 'n.s.' signifies that no
difference is noticed (i.e. the distributions were overlapping above the 65%-35% interval). '-'
was used for a difference with a 65%-35% quantiles interval.

584

Flow description	Overlapping between $LIM\text{-}MCMC_{Ref}$ & $LIM\text{-}MCMC_{RCP\,4.5}$			Overlapping between $LIM\text{-}MCMC_{Ref}$ & $LIM\text{-}MCMC_{RCP\,8.5}$		
	Interval 95%-5%	Interval 80%-20%	Interval 70%-30%	Interval 95%-5%	Interval 80%-20%	Interval 70%-30%
Export of detritus	n.s.	n.s.	n.s.	n.s.	∗	∗
Detritus dissolution	n.s.	n.s.	n.s.	n.s.	n.s.	-
DOC Consumption by bacteria	n.s.	n.s.	n.s.	n.s.	n.s.	-
Production of DOC by bacteria	n.s.	n.s.	n.s.	n.s.	n.s.	∗
Consumption of detritus by bacteria	n.s.	n.s.	∗	n.s.	∗	∗

585

586

587

588   Figures captions

589

590   Figure 1: Study area of the Bay of Biscay continental shelf and locations of the main rivers

591   flowing into it. The shaded area corresponds to the French part of the continental shelf

592   (between 30- and 150-m isobaths), and represents the spatial extent of the LIM-MCMC.

593

594   Figure 2: Sketch diagram summarizing the methodological approach: **A.** Description of the

595   combination of Ecological Niche Modeling, Linear Inverse Modeling, and Ecological

596   Network Analysis. **B.** Description of the statistical comparison of flow and ENA indices

597   values between the 3 situations (i.e. reference, RCP 4.5, and RCP 8.5). By generalizing this

598   approach, an overlap at the 95%-5% quantiles interval was considered as 'significant', an

599   overlap at the 80%-20% quantiles interval was considered as 'potentially significant', and

600   both overlaps at the 70%-30% quantiles interval or at the largest quantiles interval 65%-35%

601   were considered as 'trends'.

602

603   Figure 3: **A.** Mean (with associated standard deviation) of input flows for pelagic

604   planktivorous fish and seabirds from the three LIM-MCMCs. White bars were for the

605   reference period 1994-2005, grey ones for the RCP 4.5 2090-2099, and the black ones for the

606   RCP 8.5 2090-2099. **B.** Mean of pelagic planktivorous fish consumption by seabirds (i.e. flow

607   abbreviation pplTOsbr in Table S1) for the three LIM-MCMCs. The color code for the bars

608   was the same as in the first panel.

609   The significance of the differences between the reference period and the future climate

610   situations was given regarding the overlapping of the estimates distributions. An 'a' or 'b'

611   code indicated if future scenario(s) differed from the reference period with additional'***'

612   code for overlapping at the 95%-5% quantiles interval, '**' for overlapping at the 80%-20%

613   quantiles interval, '*' for overlapping at the 70%-30% quantiles interval, and '.' for

614   overlapping at the largest quantiles interval 65%-35%.

615

616   Figure 4: Comparison of all the flow estimates concerning the macrozooplankton functional

617   group for the three LIM-MCMCs. White bars are for the reference period 1994-2005, grey

618   ones for the RCP 4.5 in 2090-2099, and the black for the RCP 8.5 in 2090-2099.

619   The significance of the differences between the reference period and the future climate

620   situations was given regarding the overlapping of the estimates distributions. An 'a' or 'b'

621   code indicated if future scenario(s) differed from the reference period with additional '***'

622   code for an overlapping at the 95%-5% quantiles interval, '**' for an overlapping at the 80%-

623   20% quantiles interval, '*' for an overlapping at the 70%-30% quantiles interval, and '.' for

624   an overlapping at the largest quantiles interval 65%-35%.

625

626   Figure 5: **A.** Mean (with associated standard deviation) of input flows for planktonic

627   functional groups get from the three LIM-MCMCs. White bars were for the reference period

628   1994-2005, grey ones for the RCP 4.5 in 2090-2099, and the black for the RCP 8.5 in 2090-

629   2099. 'maz' was for macrozooplankton, 'mez' for mesozooplankton, 'miz' for

630   microzooplankton, and 'phy' for phytoplankton. **B.** Mean (with associated standard deviation)

631   of input flows for detrital and bacterial functional groups from the three LIM-MCMCs. White

632   bars were for the reference period 1994-2005, grey ones for the RCP 4.5 in 2090-2099, and

633   the black for the RCP 8.5 in 2090-2099. 'bac' was for bacteria, 'det' for particulate detritus,

634   and 'DOC' for dissolved organic carbon.

635   The significance of the differences between the reference period and the future climate

636   projections was given regarding the overlapping of the estimates distributions. An 'a' or 'b'

637   code indicated if future scenario(s) differed from the reference period with additional '***'

638 code for an overlapping at the 95%-5% quantiles interval, '**' for an overlapping at the 80%-

639 20% quantiles interval, '*' for an overlapping at the 70%-30% quantiles interval, and '.' for

640 an overlapping at the largest quantiles interval 65%-35%.

641

642 Figure 6: Comparison of ENA indices' estimates for the three LIM-MCMCs. Triangle and

643 diamond symbols were minimum and maximum estimates respectively. Dots were the mean

644 ENA values estimated from one million simulations of the LIM-MCMC. Associated standard

645 deviations were also shown. White, grey and black colors referred respectively to the

646 reference period, the RCP 4.5, and the RCP 8.5.

647 The significance of the differences between the reference period and the future climate

648 projections was given regarding the overlapping of the estimates distributions. An 'a' or 'b'

649 code indicated if future scenario(s) differed from the reference period with additional '***'

650 code for an overlapping at the 95%-5% quantiles interval, '**' for an overlapping at the 80%-

651 20% quantiles interval, '*' for an overlapping at the 70%-30% quantiles interval, and '.' for

652 an overlapping at the largest quantiles interval 65%-35%.

653

654

655   **A**

656

657

658

659

660

NPPEN,
Ecological Niche Model

Reference situation   *Future situation*

INPUTS

Presence data
+ Bathymetry &
temperature water   RCP scenarios

OUTPUTS   Probabilities of occurrence for each of the 3 species

Comparison between future and reference situations:
Calculation of coefficients of change

$$C = \frac{P_{ref} - Pf_{uture}}{P_{ref}}$$

If $C < 0$, $P_{future} > P_{ref}$
$C > 0$, $P_{future} < P_{ref}$

Estimation of the future biomass and production
for each species

$$Production = \left(\frac{P}{B}\right) \times B$$

$$B_{future} = (1 - C) \times B_{ref}$$

$$P_{future} = \left(\frac{P}{B}\right)_{ref} \times B_{future}$$

$$Production_{component} = \sum Production_{species}$$

LIM-MCMC,
Food-web model

Definition of LIM minimal and maximal
production boundaries

[Production$_{min}$ - Production$_{max}$]

Random sampling of solution space for each situation :

Reference situation
Future: under RCP 4.5
Future: under RCP 8.5

1000 000th iteration

4
3
2
1

Flow 1
Flow 2

Flow 1
Flow 2

....

Flow 124

Flow 124
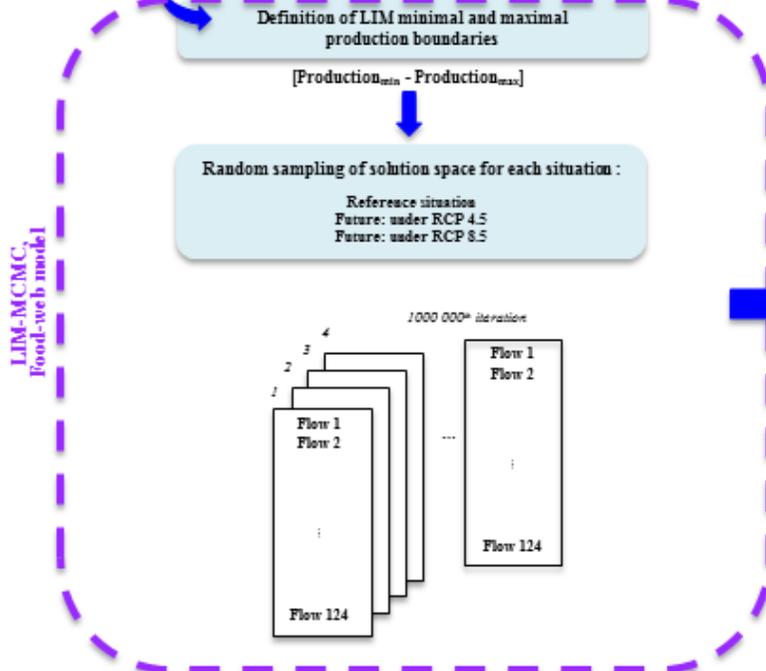
ENA,
Indices describing ecosystem functioning

Calculation of indices for each iteration and each situation:

F

F

F

Flow n

Flow 2

Flow 1

with associated uncertainty on
each flow and ENA estimates

661   **B**

Statistical comparisons

ENA index or flow 1 ₐ   ENA index or flow 1 ᵦ
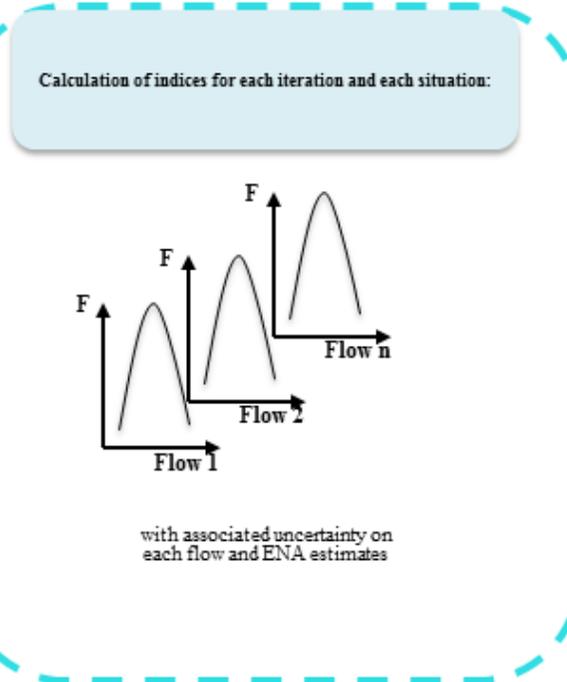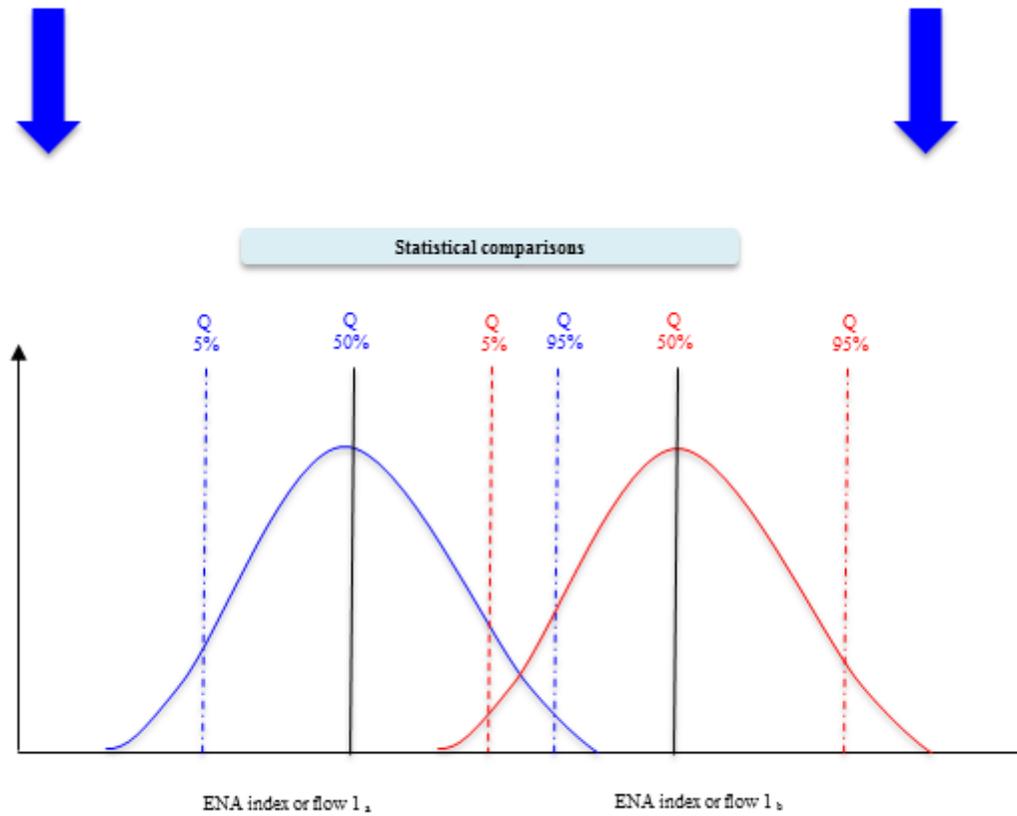
Q 95%> Q 5% but no overlap at higher quantile intervals -> 'Significant' difference

662

663

664

668

669

A

B

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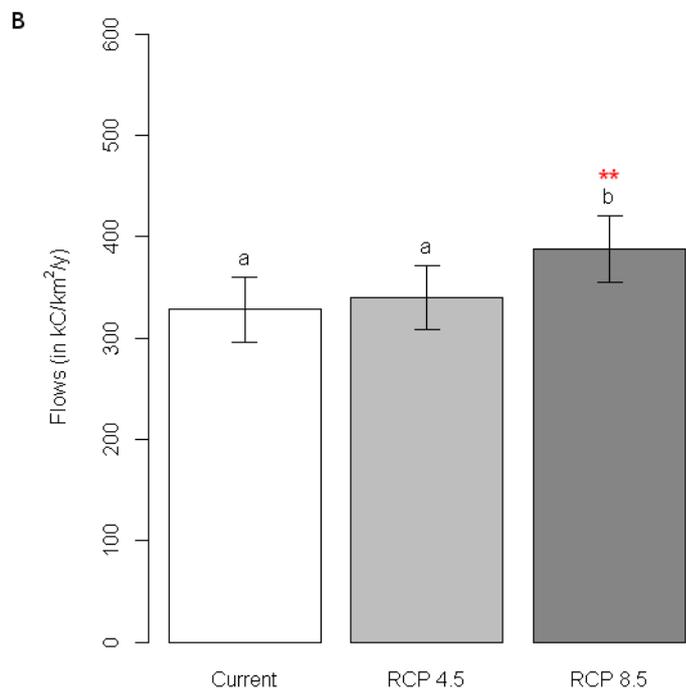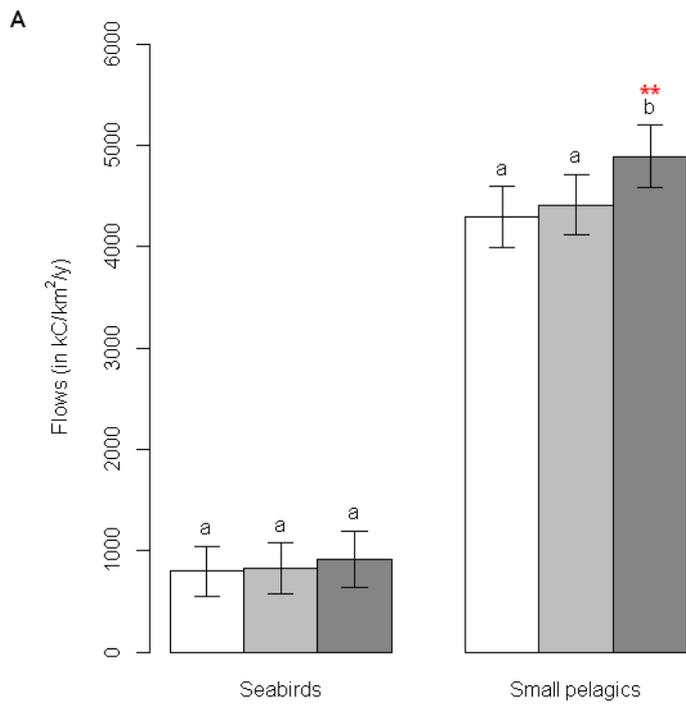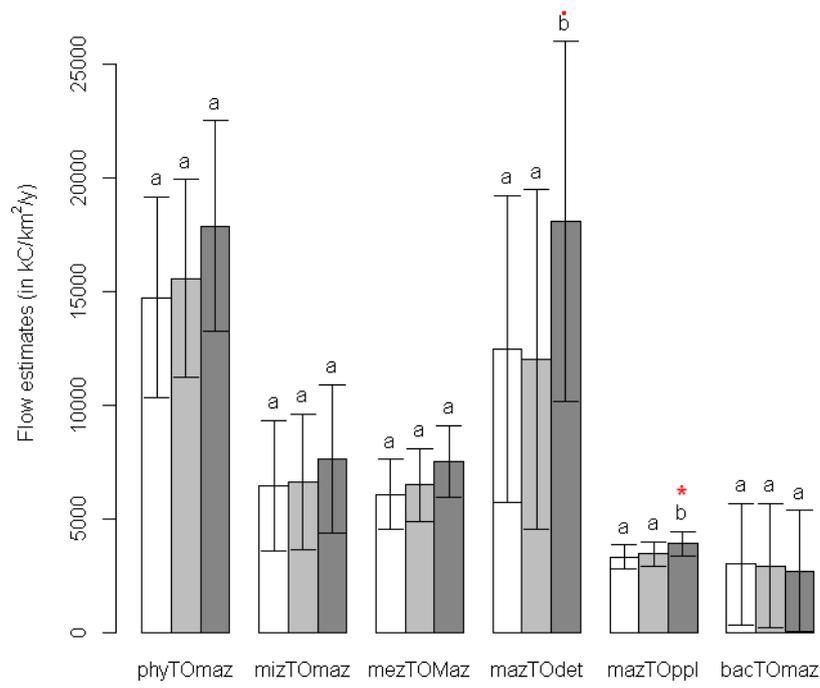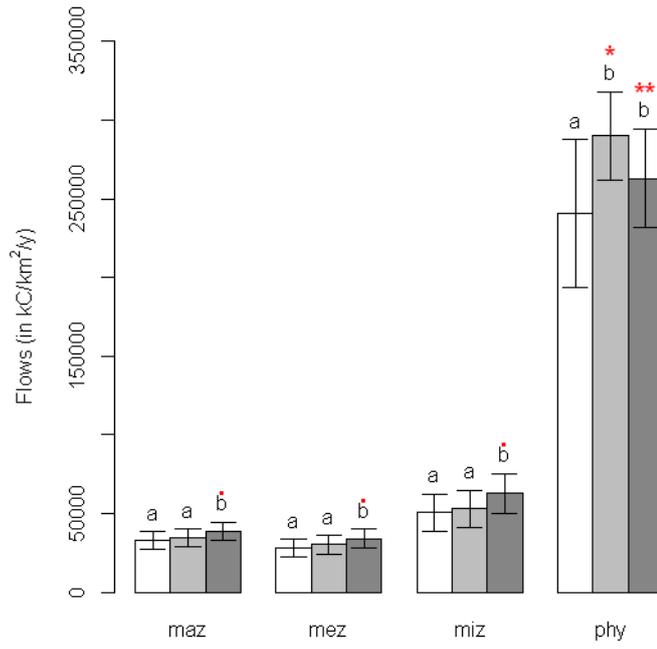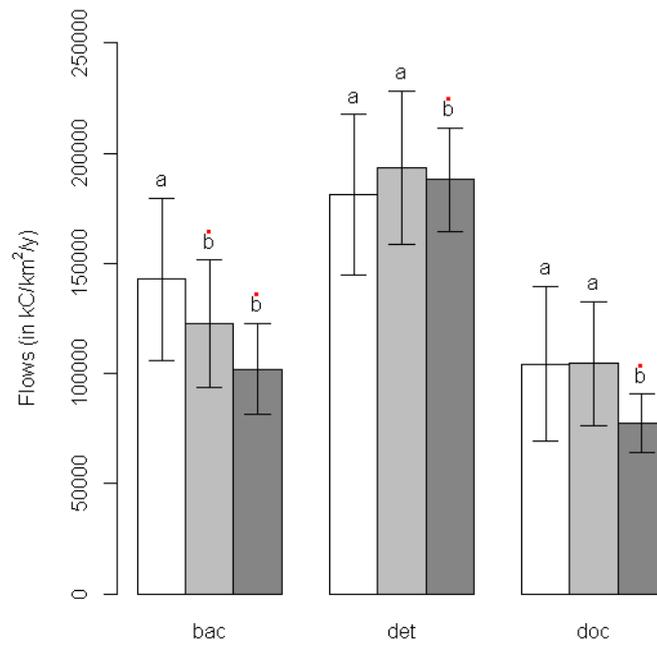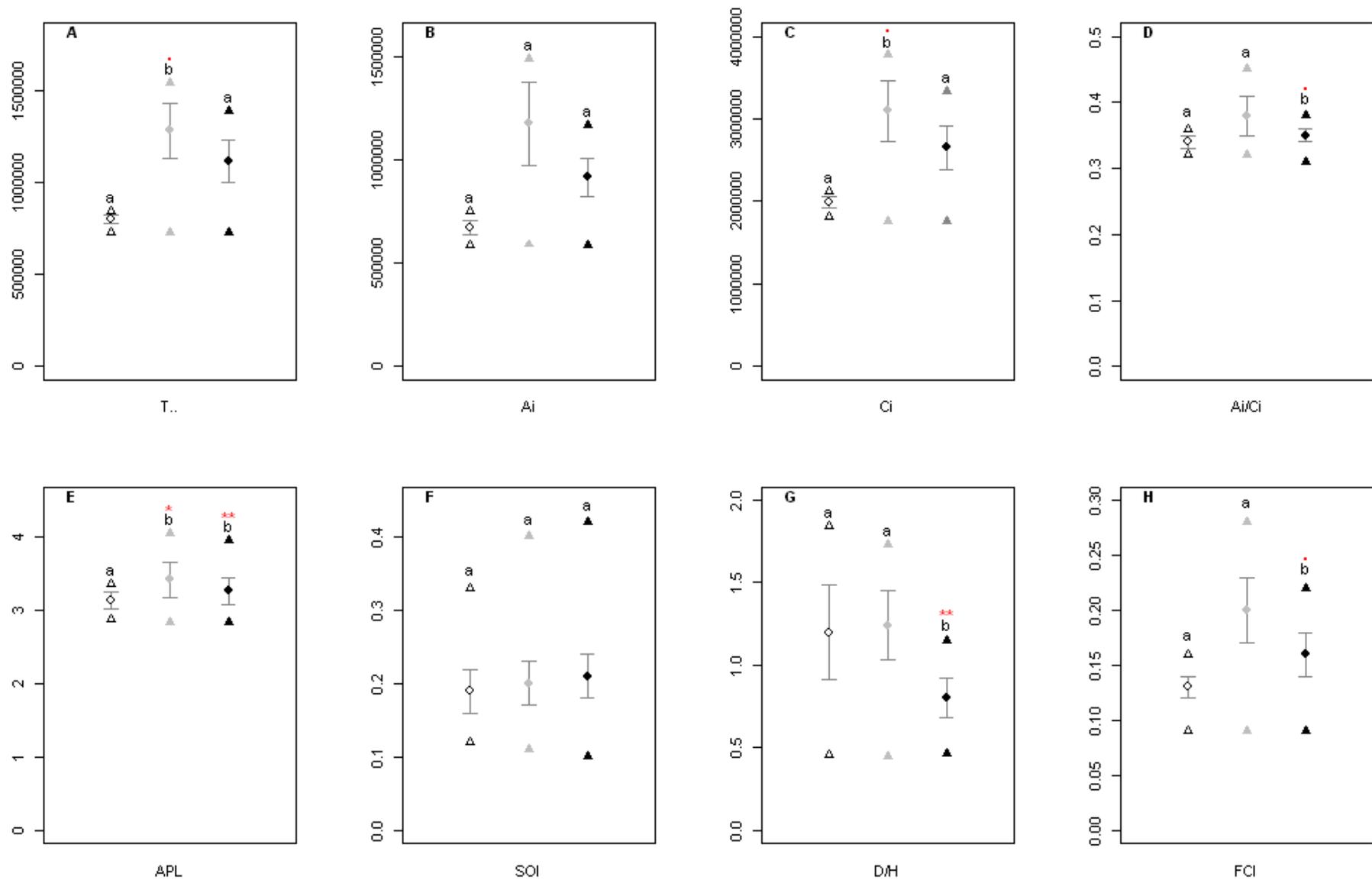
673   Table S1: List of all flows (in kgC.km^{-2}.y^{-1}) considered in the three LIM-MCMCs of the Bay
674   of Biscay French continental shelf. Means corresponded to the mean flow value calculated
675   from the one million simulations. The mean value was given with its standard deviation for
676   each LIM-MCMC model.

Flow description	Abbreviation	LIM-MCMC$_{Ref.}$		LIM-MCMC$_{RCP\,4.5}$		LIM-MCMC$_{RCP\,8.5}$	
		Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
Gross phytoplankton production	gppTOphy	240520.97	47168.65	290133.92	28141.59	263087.43	31485.83
Production of detritus by phytoplankton	phyTOdet	109643.10	23059.88	107973.80	24347.02	117567.17	15583.96
Phytoplankton exudation	phyTOdoc	23905.83	8572.46	31770.35	12705.93	23913.23	8449.22
Grazing of phytoplankton by macrozooplankton	phyTOmaz	14726.88	4430.58	15572.07	4347.19	17870.38	4641.28
Grazing of phytoplankton by mesozooplankton	phyTOmez	8118.38	2204.63	8774.16	2403.84	9657.66	2474.11
Grazing of phytoplankton by microzooplankton	phyTOmiz	40071.54	10057.47	42250.08	10349.57	50253.15	10398.22
Grazing of phytoplankton by meiofauna	phyTOmef	8567.72	6236.27	16567.82	11536.12	6485.36	4537.67
Grazing of phytoplankton by benthic deposit feeders	phyTOdep	556.91	277.23	555.29	277.65	551.09	273.96
Consumption of phytoplankton by benthic suspension feeders	phyTOsus	408.08	276.39	400.47	276.44	403.11	276.43
Consumption of phytoplankton by pelagic planktivores	phyTOppl	107.71	58.00	105.90	57.83	108.48	57.87
Production of detritus by microzooplankton	mizTOdet	17934.00	8034.80	18353.36	8416.56	23124.80	10013.98
Excretion of doc by microzooplankton	mizTOdoc	13226.23	5266.06	13859.16	4724.70	14744.91	4911.51
Grazing of microzooplankton by macrozooplankton	mizTOmaz	6441.45	2876.43	6609.50	2999.11	7618.33	3272.78
Grazing of microzooplankton by mesozooplankton	mizTOmez	15939.68	3444.81	16940.61	3605.40	19358.33	3818.97
Consumption of microzooplankton by suspension feeders	mizTOsus	358.71	334.80	356.21	334.81	357.66	331.59
Consumption of microzooplankton by pelagic planktivores	mizTOppl	88.26	47.59	86.79	47.45	88.91	47.49
Consumption of microzooplankton by pelagic piscivores	mizTOpps	17.66	6.39	17.73	6.42	17.98	6.48
Production of detritus by mesozooplankton	mezTOdet	6253.57	2658.35	6620.78	2799.35	7633.84	3245.76
Excretion of doc by mesozooplankton	mezTOdoc	4813.35	1671.46	5393.34	1929.32	5776.18	1896.98
Grazing of mesozooplankton by macrozooplankton	mezTOmaz	6061.94	1547.82	6475.51	1591.82	7515.56	1582.10
Consumption of mesozooplankton by suspension feeders	mezTOsus	474.90	417.92	496.66	445.73	485.80	428.38
Consumption of mesozooplankton by carnivorous/necrophageous invertebrates	mezTOcbi	72.51	19.62	72.31	19.59	72.05	19.50
Consumption of mesozooplankton by demersal benthivores	mezTOdbn	76.22	14.08	76.21	14.07	76.20	14.06
Consumption of mesozooplankton by pelagic planktivores	mezTOppl	787.22	398.29	774.78	398.66	793.25	397.40

Consumption of mesozooplankton by pelagic piscivores	mezTOpps	353.09	55.14	354.88	55.17	359.32	54.99
Consumption of mesozooplankton by cephalopods	mezTOcep	5.73	2.36	5.73	2.36	5.69	2.34
Consumption of macrozooplankton by carnivorous/necrophageous invertebrates	mazTOcbi	40.68	11.06	40.57	11.06	40.41	10.98
Consumption of macrozooplankton by cephalopods	mazTOcep	26.51	16.75	26.48	16.70	26.24	16.57
Consumption of macrozooplankton by demersal benthivores	mazTOdbn	38.42	9.69	38.44	9.70	38.42	9.68
Production of detritus by macrozooplankton	mazTOdet	12468.28	6742.81	11992.82	7490.59	18090.02	7914.96
Consumption of macrozooplankton by marine mammals	mazTOmma	2.00	1.51	2.00	1.51	2.00	1.51
Consumption of macrozooplankton by pelagic planktivores	mazTOppl	3306.36	540.39	3445.01	538.82	3896.90	540.22
Consumption of macrozooplankton by seabirds	mazTOsbr	113.02	70.78	117.29	72.99	128.71	80.58
Consumption of meiofauna by carnivorous/necrophageous invertebrates	mefTOcbi	131.52	34.74	131.06	34.61	130.73	34.50
Consumption of meiofauna by benthic deposit feeders	mefTOdep	107.30	98.00	106.28	97.26	106.53	97.63
Production of detritus by meiofauna	mefTOdet	30475.98	15458.82	44113.76	13946.61	16884.59	6341.14
Consumption of benthic deposit feeders by carnivorous/necrophageous invertebrates	depTOcbi	165.40	83.67	164.63	83.25	163.92	82.79
Consumption of benthic deposit feeders by cephalopods	depTOcep	29.87	24.28	29.79	24.20	29.55	24.08
Consumption of benthic deposit feeders by demersal benthivores	depTOdbn	33.87	21.98	33.87	21.97	33.91	22.01
Consumption of benthic deposit feeders by demersal piscivores	depTOdps	11.98	7.52	11.97	7.52	11.93	7.49
Production of detritus by benthic deposit feeders	depTOdet	746.02	341.29	742.45	340.12	738.61	336.87
Consumption of benthic suspension feeders by carnivorous/necrophageous invertebrates	susTOcbi	218.55	91.28	218.33	91.86	217.90	90.54
Consumption of benthic suspension feeders by cephalopods	susTOcep	30.43	24.80	30.45	24.74	30.18	24.55
Consumption of benthic suspension feeders by demersal benthivores	susTOdbn	34.39	22.15	34.40	22.14	34.41	22.17
Consumption of benthic suspension feeders by demersal piscivores	susTOdps	12.05	7.54	12.04	7.53	12.00	7.50
Production of detritus by benthic suspension feeders	susTOdet	990.00	406.04	992.79	411.51	991.62	405.08
Consumption of carnivorous/necrophageous invertebrates by cephalopods	cbiTOcep	26.93	14.69	26.88	14.68	26.74	14.60
Consumption of carnivorous/necrophageous invertebrates by demersal benthivores	cbiTOdbn	57.93	14.06	57.91	14.05	57.94	14.05
Consumption of carnivorous/necrophageous invertebrates by demersal piscivores	cbiTOdps	24.83	5.54	24.82	5.54	24.72	5.52
Production of detritus by	cbiTOdet	287.92	185.25	285.99	184.19	285.30	184.48

carnivorous/necrophageous invertebrates						
Consumption of carnivorous/necrophageous invertebrates by pelagic piscivores	cbiTOpps	7.98	2.22	8.02	2.23	8.13	2.24
Consumption of demersal benthivores by carnivorous/necrophageous invertebrates	dbnTOcbi	2.58	0.51	2.57	0.51	2.56	0.50
Consumption of demersal benthivores by cephalopods	dbnTOcep	0.17	0.17	0.17	0.17	0.17	0.17
Production of detritus by demersal benthivores	dbnTOdet	74.35	29.35	74.32	29.32	74.35	29.32
Consumption of demersal benthivores by demersal piscivores	dbnTOdps	5.11	0.48	5.11	0.48	5.09	0.48
Consumption of demersal benthivores by pelagic piscivores	dbnTOpps	2.51	0.38	2.52	0.38	2.55	0.38
Consumption of demersal benthivores by marine mammals	dbnTOmma	0.17	0.17	0.17	0.17	0.17	0.17
Consumption of demersal benthivores by seabirds	dbnTOsbr	0.15	0.14	0.15	0.14	0.15	0.14
Production of detritus by demersal piscivores	dpsTOdet	23.63	9.41	23.63	9.41	23.57	9.39
Consumption of demersal piscivores by cephalopods	dpsTOcep	6.88	1.85	6.87	1.85	6.82	1.84
Consumption of demersal piscivores by marine mammals	dpsTOmma	4.21	1.69	4.21	1.68	4.21	1.68
Consumption of pelagic planktivores by cephalopods	pplTOcep	34.51	14.30	34.52	14.32	34.42	14.32
Production of detritus by pelagic planktivores	pplTOdet	1272.92	504.55	1334.44	518.92	1488.86	575.57
Consumption of pelagic planktivores by demersal piscivores	pplTOdps	22.09	6.55	22.08	6.54	22.06	6.52
Consumption of pelagic planktivores by marine mammals	pplTOmma	35.67	18.90	35.72	18.91	35.89	19.02
Consumption of pelagic planktivores by pelagic piscivores	pplTOpps	9.39	3.48	9.44	3.50	9.58	3.53
Consumption of pelagic planktivores by seabirds	pplTOsbr	328.27	32.09	339.72	31.85	388.04	32.75
Consumption of pelagic piscivores by cephalopods	ppsTOcep	33.90	10.09	33.86	10.07	33.58	9.97
Production of detritus by pelagic piscivores	ppsTOdet	118.25	49.58	118.91	49.79	120.46	50.26
Consumption of pelagic piscivores by marine mammals	ppsTOmma	8.88	6.10	8.86	6.08	8.79	6.03
Consumption of pelagic piscivores by seabirds	CppsTOsbr	33.50	12.97	34.19	13.03	36.41	13.12
Consumption of cephalopods by carnivorous/necrophageous invertebrates	cepTOcbi	6.22	1.68	6.20	1.68	6.18	1.67
Consumption of cephalopods by demersal benthivores	cepTOdbn	2.87	1.31	2.87	1.31	2.87	1.31
Production of detritus by cephalopods	cepTOdet	83.05	57.70	82.84	57.60	82.22	57.15
Consumption of cephalopods by demersal piscivores	cepTOdps	1.18	0.30	1.18	0.30	1.18	0.30
Consumption of cephalopods by marine mammals	cepTOmma	10.14	7.31	10.12	7.29	10.09	7.28
Consumption of cephalopods by pelagic piscivores	cepTOpps	3.33	1.37	3.35	1.37	3.39	1.38

Production of detritus by seabirds	sbrTOdet	258.16	102.64	266.49	105.50	297.57	117.71
Production of detritus by marine mammals	mmaTOdet	30.56	23.16	30.53	23.11	30.61	23.18
Production of doc by bacteria	bacTOdoc	37462.67	13318.44	33082.52	12202.16	24168.66	9009.68
Consumption of bacteria by benthic deposit feeders	bacTOdep	357.12	326.60	354.29	324.39	355.22	324.58
Consumption of bacteria by benthic suspension feeders	bacTOsus	336.28	313.82	332.27	312.63	333.53	317.19
Consumption of bacteria by meiofauna	bacTOmef	29712.37	12463.49	15108.55	10238.75	16428.74	11875.08
Consumption of bacteria by macrozooplankton	bacTOmaz	2984.05	2682.27	2918.56	2729.42	2692.18	2668.30
Consumption of bacteria by microzooplankton	bacTOmiz	10314.92	2712.86	10512.21	2934.69	12523.69	3521.98
Detritus consumption by bateria	detTObac	38502.59	15847.09	18080.69	11218.36	24675.68	12851.46
Detritus consumption by deposit feeders	detTOdep	406.83	211.00	406.02	210.91	402.67	208.30
Detritus consumption by suspension feeders	detTOsus	271.68	192.76	266.81	192.55	269.37	194.97
Detritus dissolution	detTOdoc	24996.00	20519.47	20441.96	16866.41	8722.25	6154.18
Detritus consumption by meiofauna	detTOmef	50264.94	35910.84	101316.53	32864.56	25397.40	11066.37
Detritus consumption by macrozooplankton	detTOmaz	2505.62	2269.69	2640.41	2363.64	3058.57	2913.08
Detritus consumption by mesozooplankton	detTOmez	4119.58	1079.91	4448.42	1194.34	4949.41	1238.10
Detritus consumption by microzooplankton	detTOmiz	27740.45	6982.95	28729.84	8259.47	34917.26	10712.21
Detritus consumption by carnivorous/necrophageous invertebrates	detTOcbi	57.48	35.70	57.23	35.50	56.89	35.30
Detritus consumption by demersal benthivores	detTOdbn	4.08	1.61	4.08	1.61	4.08	1.61
Detritus consumption by demersal piscivores	detTOdps	1.58	0.40	1.58	0.40	1.57	0.39
Detritus consumption by seabirds	detTOsbr	316.66	173.96	327.10	179.69	356.87	200.71
Doc consumption by bacteria	docTObac	104404.08	35129.15	104547.32	28152.30	77325.23	13184.57
Respiration by phytoplankton	phyTOres	34414.83	26328.44	66164.00	17372.96	36277.81	20589.75
Respiration by microzooplankton	mizTOres	24120.92	6662.49	25268.76	6852.98	32383.19	11731.12
Respiration by mesozooplankton	mezTOres	9279.10	2922.53	9893.00	3216.81	11247.51	3269.43
Respiration by macrozooplankton	mazTOres	16724.68	7554.99	18553.45	8100.45	16532.30	7325.52
Respiration by meiofauna	mefTOres	57830.22	26096.67	88641.80	21391.06	31189.66	10406.88
Respiration by benthic deposit feeders	depTOres	441.02	176.74	439.13	175.87	437.57	174.63
Respiration by benthic suspension feeders	susTOres	563.82	199.85	564.00	202.04	562.94	198.47
Respiration by carnivorous/necrophageous invertebrates	cbiTOres	285.73	185.02	285.68	184.57	284.21	183.73
Respiration by demersal benthivores	dbnTOres	146.48	32.01	146.50	31.98	146.51	31.97
Respiration by demersal piscivores	dpsTOres	32.43	9.72	32.39	9.72	32.29	9.69
Respiration by pelagic planktivores	pplTOres	2563.21	534.93	2613.06	544.69	2885.17	601.60
Respiration by pelagic piscivores	ppsTOres	168.43	55.00	169.13	55.21	170.89	55.57
Respiration by cephalopods	cepTOres	82.76	57.61	82.81	57.63	82.07	57.08
Respiration by seabirds	sbrTOres	533.44	189.58	551.96	195.78	612.60	215.13
Respiration by marine mammals	mmaTOres	30.51	23.10	30.54	23.11	30.54	23.15

Respiration by bacteria	bacTOres	61739.26	19293.67	60319.61	16369.42	45498.90	9425.38
Export of benthic deposit feeders	depTOexp	0.02	0.01	0.02	0.01	0.02	0.01
Export of benthic suspension feeders	susTOexp	0.41	0.22	0.41	0.22	0.41	0.22
Export of carnivorous/necrophageous invertebrates	cbiTOexp	3.61	1.93	3.61	1.93	3.61	1.93
Export of demersal benthivores	dbnTOexp	16.27	0.14	16.27	0.14	16.26	0.14
Export of demersal piscivores	dpsTOexp	11.67	0.86	11.67	0.85	11.66	0.85
Export of pelagic planktivores	pplTOexp	23.50	4.04	23.50	4.04	23.51	4.04
Export of pelagic piscivores	ppsTOexp	31.01	9.89	31.00	9.90	30.81	9.76
Export of cephalopods	cepTOexp	5.37	1.64	5.37	1.63	5.38	1.63
Import of detritus	impTOdet	502.65	262.80	508.33	262.37	509.04	262.50
Export of detritus	detTOexp	31974.94	22556.17	16794.58	14119.21	85130.63	18977.48

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Table S2: Comparisons between all flow means from the reference period 1994-2005 and the
climate future projections (i.e. both RCPs in 2090-2099). The test of overlapping of estimates
was realized with different overlapping intervals. '∗' signifies that a difference is noticed (at
least at the 70%-30% interval), whereas 'n.s.' signifies that no difference is noticed (i.e. the
distributions were overlapping above the 65%-35% interval). '-' was used for a difference
with a 65%-35% quantiles interval.

	Overlapping between $LIM\text{-}MCMC_{ref.}$ & $LIM\text{-}MCMC_{RCP4.5}$			Overlapping between $LIM\text{-}MCMC_{ref.}$ & $LIM\text{-}CMC_{RCP8.5}$		
Flow description	**95-5 %**	**80-20 %**	**70-30 %**	**95-5 %**	**80-20 %**	**70-30 %**
Gross phytoplankton production	n.s.	n.s.	∗	n.s.	n.s.	∗
Production of detritus by phytoplankton	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Phytoplankton exudation	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Grazing of phytoplankton by macrozooplankton	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Grazing of phytoplankton by mesozooplankton	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Grazing of phytoplankton by microzooplankton	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Grazing of phytoplankton by meiofauna	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Grazing of phytoplankton by benthic deposit feeders	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Consumption of phytoplankton by benthic suspension feeders	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Consumption of phytoplankton by pelagic planktivores	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Production of detritus by microzooplankton	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Excretion of doc by microzooplankton	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Grazing of microzooplankton by macrozooplankton	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Grazing of microzooplankton by mesozooplankton	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Consumption of microzooplankton by suspension feeders	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Consumption of microzooplankton by pelagic planktivores	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Consumption of microzooplankton by pelagic piscivores	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Production of detritus by mesozooplankton	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Excretion of doc by mesozooplankton	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Grazing of mesozooplankton by macrozooplankton	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Consumption of mesozooplankton by suspension feeders	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Consumption of mesozooplankton by carnivorous/necrophageous	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

invertebrates						
Consumption of mesozooplankton by demersal benthivores	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Consumption of mesozooplankton by pelagic planktivores	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Consumption of mesozooplankton by pelagic piscivores	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Consumption of mesozooplankton by cephalopods	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Consumption of macrozooplankton by carnivorous/necrophageous invertebrates	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Consumption of macrozooplankton by cephalopods	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Consumption of macrozooplankton by demersal benthivores	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Production of detritus by macrozooplankton	n.s.	n.s.	n.s.	n.s.	n.s.	-
Consumption of macrozooplankton by marine mammals	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Consumption of macrozooplankton by pelagic planktivores	n.s.	n.s.	n.s.	n.s.	n.s.	*
Consumption of macrozooplankton by seabirds	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Consumption of meiofauna by carnivorous/necrophageous invertebrates	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Consumption of meiofauna by benthic deposit feeders	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Production of detritus by meiofauna	n.s.	n.s.	n.s.	n.s.	n.s.	*
Consumption of benthic deposit feeders by carnivorous/necrophageous invertebrates	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Consumption of benthic deposit feeders by cephalopods	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Consumption of benthic deposit feeders by demersal benthivores	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Consumption of benthic deposit feeders by demersal piscivores	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Production of detritus by benthic deposit feeders	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Consumption of benthic suspension feeders by carnivorous/necrophageous invertebrates	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Consumption of benthic suspension feeders by cephalopods	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Consumption of benthic suspension feeders by demersal benthivores	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Consumption of benthic suspension feeders by demersal piscivores	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Production of detritus by benthic	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

suspension feeders						
Consumption of carnivorous/necrophageous invertebrates by cephalopods	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Consumption of carnivorous/necrophageous invertebrates by demersal benthivores	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Consumption of carnivorous/necrophageous invertebrates by demersal piscivores	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Production of detritus by carnivorous/necrophageous invertebrates	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Consumption of carnivorous/necrophageous invertebrates by pelagic piscivores	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Consumption of demersal benthivores by carnivorous/necrophageous invertebrates	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Consumption of demersal benthivores by cephalopods	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Production of detritus by demersal benthivores	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Consumption of demersal benthivores by demersal piscivores	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Consumption of demersal benthivores by pelagic piscivores	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Consumption of demersal benthivores by marine mammals	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Consumption of demersal benthivores by seabirds	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Production of detritus by demersal piscivores	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Consumption of demersal piscivores by cephalopods	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Consumption of demersal piscivores by marine mammals	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Consumption of pelagic planktivores by cephalopods	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Production of detritus by pelagic planktivores	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Consumption of pelagic planktivores by demersal piscivores	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Consumption of pelagic planktivores by marine mammals	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Consumption of pelagic planktivores by pelagic piscivores	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Consumption of pelagic planktivores by seabirds	n.s.	*	*	n.s.	n.s.	n.s.
Consumption of pelagic piscivores by cephalopods	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Production of detritus by pelagic piscivores	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

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Consumption of pelagic piscivores by marine mammals	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Consumption of pelagic piscivores by seabirds	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Consumption of cephalopods by carnivorous/necrophageous invertebrates	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Consumption of cephalopods by demersal benthivores	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Production of detritus by cephalopods	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Consumption of cephalopods by demersal piscivores	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Consumption of cephalopods by marine mammals	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Consumption of cephalopods by pelagic piscivores	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Production of detritus by seabirds	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Production of detritus by marine mammals	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Production of doc by bacteria	n.s.	n.s.	*	n.s.	n.s.	n.s.
Consumption of bacteria by benthic deposit feeders	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Consumption of bacteria by benthic suspension feeders	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Consumption of bacteria by meiofauna	n.s.	n.s.	*	n.s.	*	*
Consumption of bacteria by macrozooplankton	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Consumption of bacteria by microzooplankton	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Detritus consumption by bateria	n.s.	n.s.	*	n.s.	*	*
Detritus consumption by deposit feeders	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Detritus consumption by suspension feeders	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Detritus dissolution	n.s.	n.s.	-	n.s.	n.s.	n.s.
Detritus consumption by meiofauna	n.s.	n.s.	n.s.	n.s.	n.s.	-
Detritus consumption by macrozooplankton	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Detritus consumption by mesozooplankton	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Detritus consumption by microzooplankton	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Detritus consumption by carnivorous/necrophageous invertebrates	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Detritus consumption by demersal benthivores	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Detritus consumption by demersal piscivores	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Detritus consumption by seabirds	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

Doc consumption by bacteria	n.s.	n.s.	-	n.s.	n.s.	n.s.
Respiration by phytoplankton	n.s.	n.s.	n.s.	n.s.	*	*
Respiration by microzooplankton	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Respiration by mesozooplankton	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Respiration by macrozooplankton	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Respiration by meiofauna	n.s.	n.s.	*	n.s.	n.s.	-
Respiration by benthic deposit feeders	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Respiration by benthic suspension feeders	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Respiration by carnivorous/necrophageous invertebrates	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Respiration by demersal benthivores	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Respiration by demersal piscivores	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Respiration by pelagic planktivores	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Respiration by pelagic piscivores	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Respiration by cephalopods	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Respiration by seabirds	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Respiration by marine mammals	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Respiration by bacteria	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Export of benthic deposit feeders	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Export of benthic suspension feeders	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Export of carnivorous/necrophageous invertebrates	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Export of demersal benthivores	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Export of demersal piscivores	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Export of pelagic planktivores	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Export of pelagic piscivores	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Export of cephalopods	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Import of detritus	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Export of detritus	n.s.	*	*	n.s.	n.s.	n.s.

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Figure S1: Estimates obtained from a preliminary LIM-MCMC approach based on the drop of primary production estimated by Bopp et al. (2013); for more details see Saint-Béat et al. (in prep.). White bars were for the reference situation '1994-2005', light grey bars for the scenario RCP 4.5 at the horizon 2090-2099 and dark grey bars for the scenario RCP 8.5 at the horizon 2090-2099.

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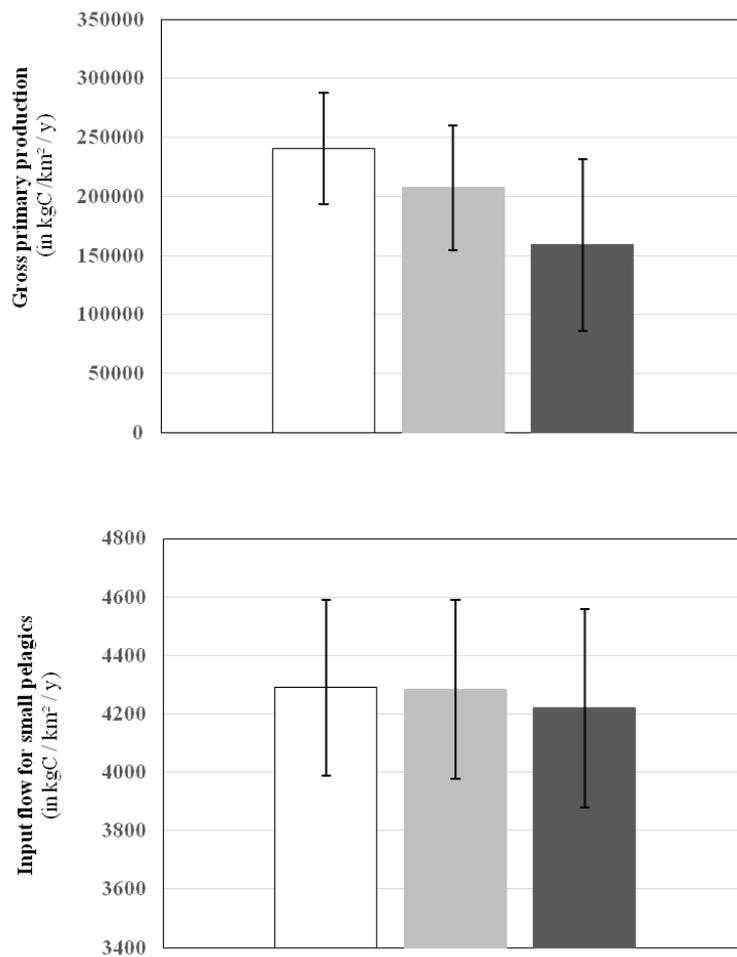
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