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

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**Abstract :**

As species biology and ecology is profoundly influenced by climate, any climatic alteration may have
severe consequences on marine pelagic ecosystems and their food webs. It remains challenging to
estimate the influence of climate on both structural and functional properties of food webs. In this study,
we proposed an innovative approach to assess the propagating effects of climate change on ecosystem
food web. The approach is based on a sensitivity analysis of a food-web model, a linear inverse model
using a Monte Carlo method coupled with a Markov Chain, in which changes in the values of parameters
are driven by external Ecological Niche Model outputs. Our sensitivity analysis was restricted to
parameters regarding a keystone functional group in marine ecosystems, i.e. small pelagic fish. At the
ecosystem level, the consequences were evaluated using both structural and functional ecological
network indices. The approach is innovative as it is the first time that these three methods were combined
to assess ecological network indices sensitivity to future climatic pressure. This coupling method was
applied on the French continental shelf of the Bay of Biscay for which a food-web model already exists

and where future changes in the distribution of small pelagic fish have already been examined through model building and projections. In response to the sensitivity analysis corresponding to an increase in small pelagics production only, our results suggested a more active system with an intense plankton-small pelagics-seabirds chain and an efficient recycling to maximize detritus use in the system in relation with detritus export. All results combined together seemed to be in favor of a system adapting to sustain the tested increase in production of small pelagic planktivores. Finally, regarding the innovative combination of numerical tools presented, even if further investigations are still necessary to get a more realistic view of cumulative effects resulting from one given pressure (or more) on a food web (e.g. altering different biological compartments at the same time), the Ecological Network Analysis indices values showed a higher variability under the scenarios of change. Our study thus pointed out a promising methodology to assess propagating changes in structural and functional ecosystem properties.

**Highlights**

► We proposed a methodology to assess the propagation of climate-related changes in food webs. ► We combined ecosystem modeling with niche-based modeling and network analysis. ► The study case was the French Bay of Biscay continental shelf food web. ► We did a sensitivity analysis on the production of a key functional group, here the small pelagics. ► The system pelagic chain, overall activity, and recycling efficiency were altered.

1. Introduction

The effects of climate change on biological and ecological systems is incontrovertible (Doney and Sailley, 2013; Beaugrand et al., 2015a) and is likely to lead to unexpected modifications in ecosystems functions (Scheffer et al., 2001; Scheffer and Carpenter, 2003; Beaugrand et al., 2009) and associated services for humankind, with strong socio-economic implications (Halpern et al., 2008). In the context of human-driven climate change, these modifications of ecosystem structures, functions, and status are at least partly related to strong alterations of lower trophic levels such as primary producers, primary consumers or planktivorous organisms in aquatic environments (Parmesan and Yohe, 2003; Parmesan, 2006). Different responses have been documented, including physiological effects of climate change on organisms (Arrhenius, 1889; Magnuson et al., 1979), phenological shifts (Edwards and Richardson, 2004) and potential changes in species spatio-temporal distributions (Quéro et al., 1998; Stebbing et al., 2002; Hermant et al., 2010; Alekseenko et al., 2014). However, the propagation of these alterations through the food webs and their consequences on the food-web emerging properties remains poorly understood with only rare examples documented for freshwater and marine systems (e.g. Woodward et al., 2010; Albouy et al., 2013; Chust et al., 2014).

In line with these major issues, our paper proposes a methodology to investigate the propagating effect of climate change on the trophic pathways and the functioning properties of ecosystems. The study case was the Bay of Biscay French continental shelf, with a special emphasis on the consequences of a change in the production of a keystone functional group, i.e. the pelagic planktivorous fish. Here, we proposed for the first time a combination of three numerical methods: (i) An Ecological Niche Model (ENM; Beaugrand et al., 2011; Lenoir et 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 ($0.19 \pm 0.03$ to $0.21 \pm 0.03$)

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    $1.2 \pm 0.29$ (reference period) to $0.8 \pm 0.12$ (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 $0.16 \pm 0.02$ (RCP 8.5) *versus* $0.13 \pm 0.01$ 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 $3.42 \pm 0.24$ for the RCP 4.5, and $3.26 \pm 0.19$ 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 $\pm$ 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 | $A_i$ | $\sum_{i=1}^{n}\sum_{j=1}^{n} T_{ij} \times log\left[\dfrac{T_{ij} \times T..}{\sum_{q=0}^{n+2} T_{qj} \sum_{v=0}^{n+2} T_{iv}}\right]$ | nternal organization and activity of the ecosystem |
| Internal Capacity of Development | $C_i$ | $-\sum_{i=1}^{n}\sum_{j=1}^{n} T_{ij} \times log\left[\dfrac{T_{ij}}{T..}\right]$ | the maximal possible Internal Ascendency |
| Internal relative Ascendency | $A_iC_i$ | $\dfrac{Ai}{Ci}$ | state of internal organization (represents the organized part) |
| Average Path Length | APL | $\dfrac{TST}{\sum_i Exports + \sum_i Respiration}$ | retention of carbon |
| Finn's Cycling Index | FCI | $\dfrac{TST_c}{TST} = \sum_j \dfrac{\sum_i T_{ij} + Imports_j}{TST}$ | proportion of flows involved in loops (cycling) |
| System Omnivory Index | SOI | $\dfrac{\sum_i OI_i \times log[Q_i]}{\sum_i log[Q_i]}$ | 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

579  Table 2: Comparisons of flow mean estimates between the reference period 1994-2005 and
580  the two RCP scenarios at the end of the century in 2090-2099 where '∗' signifies that a
581  difference is noticed (at least at the 70%-30% interval), whereas 'n.s.' signifies that no
582  difference is noticed (i.e. the distributions were overlapping above the 65%-35% interval). '-'
583  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

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

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

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

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

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

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 000$^{th}$ iteration

Flow 1
Flow 2

Flow 124

4
3
2
1

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 $_b$

Q 95% > Q 5% but no overlap at higher quantile intervals -> 'Significant' difference

662

663

664



665

666

667

668

669

670

671
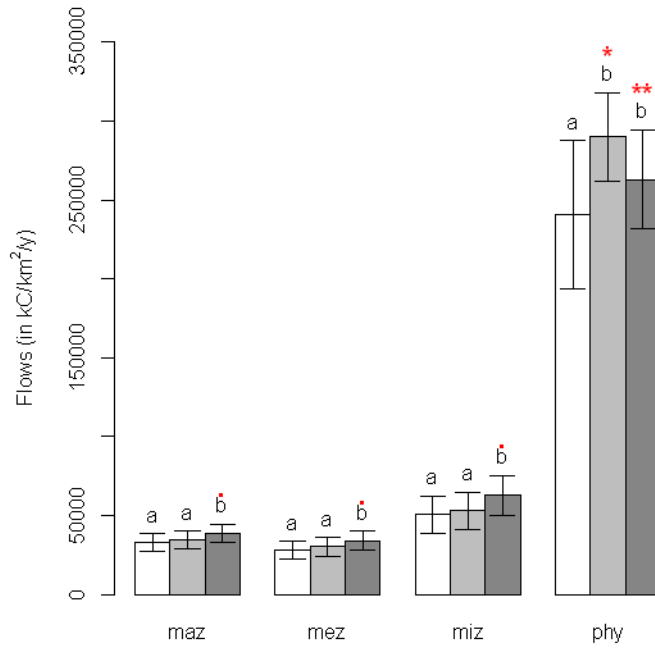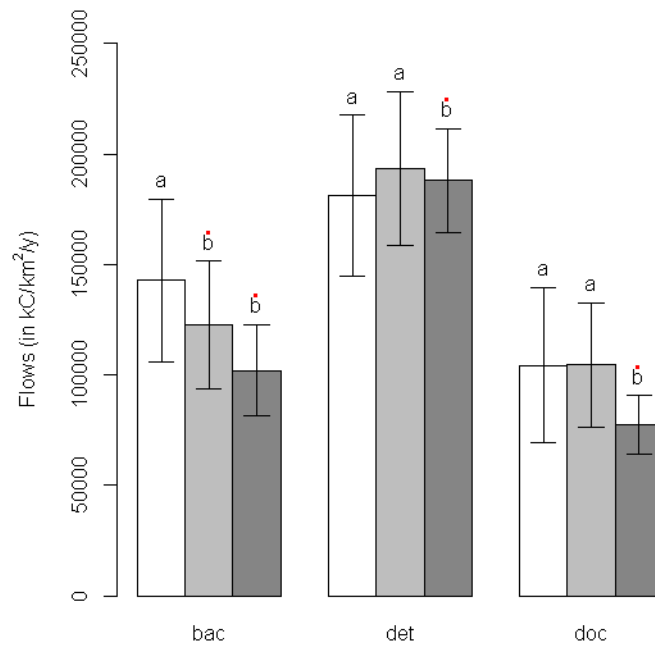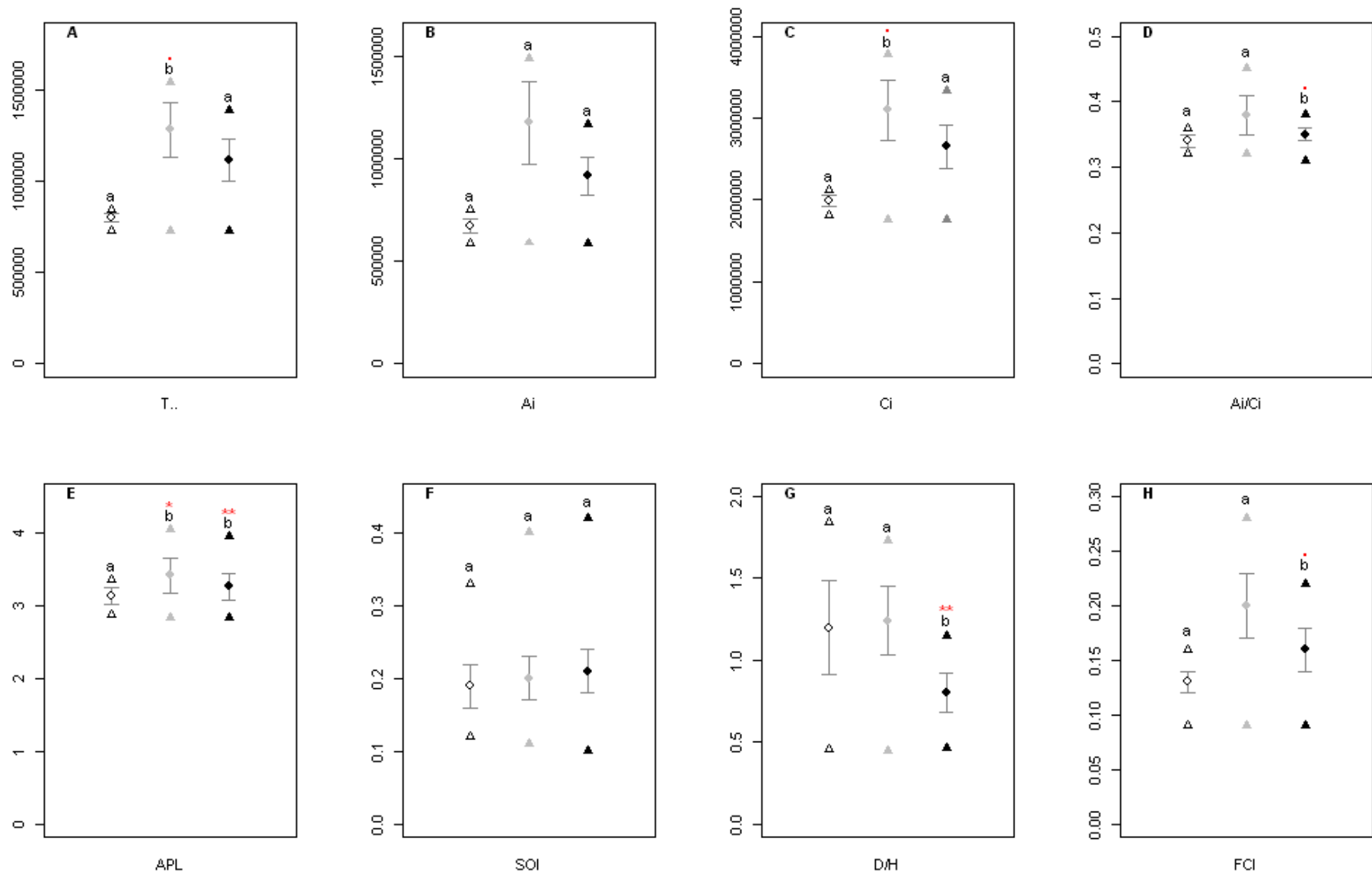
673    Table S1: List of all flows (in kgC.km$^{-2}$.y$^{-1}$) considered in the three LIM-MCMCs of the Bay
674    of Biscay French continental shelf. Means corresponded to the mean flow value calculated
675    from the one million simulations. The mean value was given with its standard deviation for
676    each LIM-MCMC model.

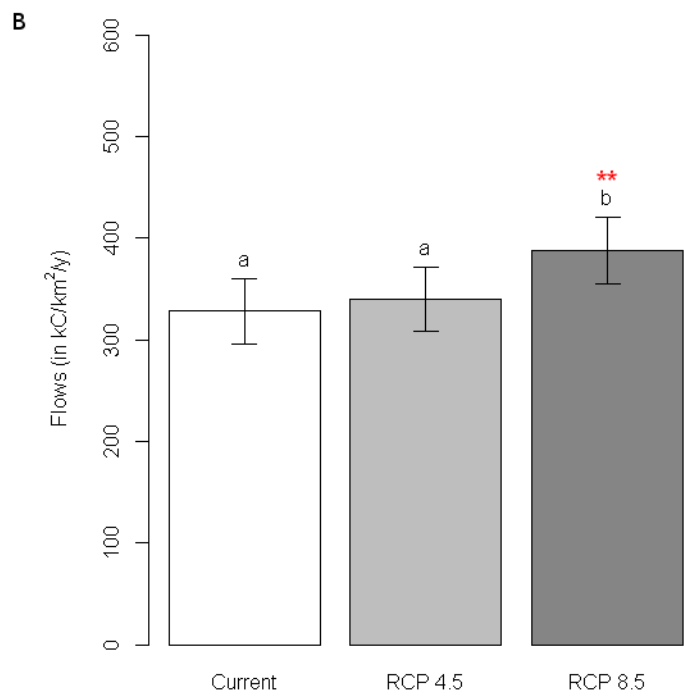| Flow description | Abbreviation | LIM-MCMC$_{Ref.}$ | | LIM-MCMC$_{RCP 4.5}$ | | LIM-MCMC$_{RCP 8.5}$ | |
|---|---|---|---|---|---|---|---|
| | | Mean | Standard deviation | Mean | Standard deviation | Mean | Standard deviation |
| Gross phytoplankton production | gppTOphy | 240520.97 | 47168.65 | 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 |

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|---|---|---|---|---|---|---|
| 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 |

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|---|---|---|---|---|---|---|
| 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 |

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| 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 |

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| 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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| | 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. |

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|---|---|---|---|---|---|---|
| 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. |

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|---|---|---|---|---|---|---|
| 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. |

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|---|---|---|---|---|---|---|
| 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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696    References
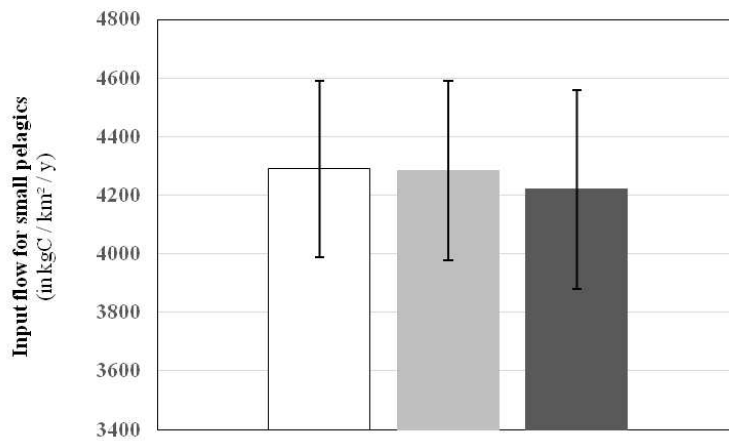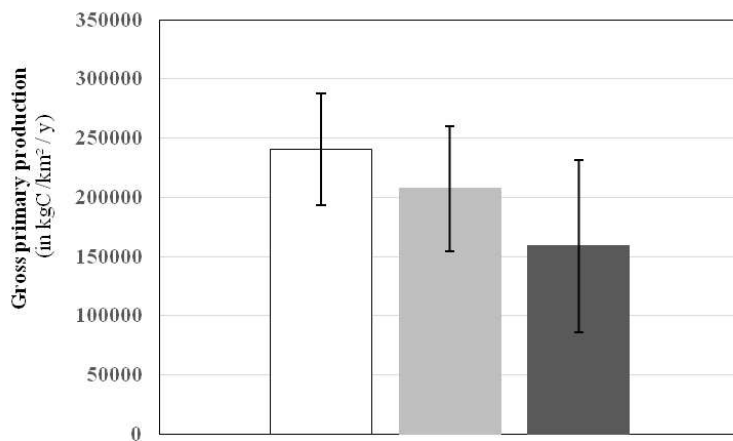
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