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How the fishing effort control and environmental changes affect the sustainability of a tropical shrimp small scale fishery.

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## ABSTRACT

Global shrimp catches are reported primarily in association with large industrial trawling, but they also occur through small-scale fishing, which plays a substantial role in traditional communities. We developed an Ecopath model in north-eastern Brazil, and applied a temporally dynamic model (Ecosim) to evaluate the potential effects of different fishing effort control policies and environmental changes on marine resources and ecosystem between 2015 to 2030 with a case study for small-scale shrimp fishing, novelty for tropical region. These scenarios included different management options related to fishing controls (changing effort and closed season) and environmental changes (primary production changes). Our findings indicate that it is possible to maintain the same level of landings with a controlled reduction of bottom trawlers activities, for example, close to 10%, without compromising the ecosystem structure. This scenario provided better results than 3-4 months of closing the fishing season, which led to significant losses in catches of high market-value target species (white shrimp, *Penaeus schmitti* and pink shrimp, *Penaeus subtilis*). However, intense negative effects on biomass, catch and biodiversity indicators were reported in scenarios with decreasing primary production, from 2%, reinforcing the need to simulate and project the possible impacts caused by environmental change. However, the control of bottom trawling activity may help to reduce, even at low levels, the highly adverse effects due to primary production reduction. The impacts of climate change in a near future on organisms and ecosystems is an imminent reality, and therefore the search for measures for mitigating and even minimizing these impacts is crucial.

Keywords: Ecosystem Approach to Fisheries, EwE, Artisanal fisheries, Climate change, Trawling, Brazil

## 1 **1. Introduction**

2 Marine resources are one of the primary food sources in the world, contributing significantly to  
3 the food security and well-being of human society (Oyinlola et al., 2018); these resources are highly  
4 associated with environmental patterns or cycles and are frequently sensitive to anthropogenic  
5 pressures. Global climate change has modified local biodiversity in terms of the distribution, growth,  
6 fecundity, and recruitment of species, consequently affecting the catch amount and composition  
7 (Pörtner and Farrell, 2008; Roessig et al., 2004). Accelerated human population growth also implies an  
8 increase in the global food demand, which has consequently intensified the search for more effective  
9 methods of production, which are often unsustainable.

10 The reconstruction of global fishing trends (Cashion et al., 2018; Zeller et al., 2017), including  
11 Illegal, Unreported and Unregulated Fisheries (IUU) and discards, has revealed that purse seining and  
12 trawling fisheries are responsible for more than half of global catches. Despite having high levels of  
13 non-targeted catches, these fisheries may also have substantial adverse implications for marine  
14 habitats, particularly in the seabed structure and community biodiversity (Davies et al., 2018; Johnson  
15 et al., 2015; Ortega et al., 2018). The non-target catch (bycatch) may be divided into the part that is  
16 rejected at port or at sea, the one used for bait (industrial fisheries), or byproduct (commercially  
17 valuable species), as well as the amount consumed by the crew and local communities, primarily from  
18 small-scale fisheries (Davies et al., 2009; Gilman et al., 2014). Thus, the impact of fisheries on  
19 ecosystems appears to be counter-balanced by the beneficial role of the bycatch in the local  
20 community.

21 Global shrimp catches are reported primarily by large industrial trawlers, but some are also  
22 based on small-scale fishing, including non-motorized boats operating in estuaries and coastal waters,  
23 which play a major role in traditional communities (Gillett, 2008). Although their contribution to  
24 global discards are considered small (Zeller et al., 2017) mainly due to the remoteness of their landing  
25 sites and the decentralized nature of their activities, this sector provides an important source of  
26 income, employment and food to millions of people, making it one of the major economic activities in  
27 coastal communities around the world (Chollett et al., 2014). The lack of basic information (e.g., on  
28 species biology, catches, biomass, etc.) prevents researchers from evaluating the real impact of this  
29 activity on the ecosystem, posing a threat to its future sustainability (Andrew et al., 2007; Jeffers et al.,  
30 2019).

31 Frameworks and approaches have been developed to help evaluate the fishing impacts of multi-  
32 factor scenarios (Goti-Aralucea, 2019; Jones et al., 2018; Rezende et al., 2019; Rice, 2000), since  
33 human activities, marine organisms, and ecosystem changes interact and influence one another  
34 (Corrales et al., 2018). To address this challenge, a more comprehensive analysis and management of  
35 human activities and the environment is needed in accordance with an ecosystem-based management

36 approach (Rosenberg and McLeod, 2005). In this context, strategies based on the principles of  
37 adaptive co-management and the Ecosystem Approach to Fisheries (EAF) (Guanais et al., 2015) have  
38 become very promising in recent years (Serafini et al., 2017). The EAF is an effective framework for  
39 ecosystem management that considers “the knowledge and uncertainties about biotic, abiotic, and  
40 human components of ecosystems and their interactions, applying an integrated approach to fisheries  
41 within ecologically meaningful boundaries” (Garcia et al., 2003).

42 Studies, methods or policies based on EAF are recommended to understand and eventually  
43 mitigate the impacts of trawling. They have being applied to different countries (Jennings and Rice,  
44 2011), fisheries (Gianelli et al., 2018), resources (Cuervo-Sánchez et al., 2018) and environments  
45 (Rosa et al., 2014). The Code of Conduct for Responsible Fisheries (FAO, 1995) recommends that the  
46 entire catch, not only the targeted species, should be managed in an ecologically sustainable manner.  
47 To achieve this goal, the first step is to describe the fishing zones, target species, bycatch, and the  
48 factors that influence its variation, and how they are related. This knowledge is essential for assessing  
49 the measures used for appropriate management (e.g., closed fishing seasons, Marine Spatial Planning  
50 (MSP) or bycatch reduction devices (BRD)) (Bellido et al., 2011).

51 Among the tools considered within the EAF, the Ecopath with Ecosim (EwE) model  
52 (Christensen and Walters, 2004; Wolff et al., 2000) has been widely applied to characterize the trophic  
53 interactions and changes at the community level (Lira et al., 2018; Zhang et al., 2019) as well as to  
54 evaluate the effect of management policies on the environment and on ecosystem compensation  
55 (Halouani et al., 2016; Vasslides et al., 2017). In addition, the use of these approaches to forecast  
56 future cumulative impacts of human activities on aquatic food webs, such as fishing (Adebola and  
57 Mutsert, 2019; Piroddi et al., 2017) and stressors related to climate change (Bentley et al., 2019;  
58 Corrales et al., 2018; Serpetti et al., 2017), may be an interesting alternative to help manage  
59 ecosystems and their resources. However, particularly in countries with poorly managed fisheries  
60 (e.g., Brazil), studies are scarce.

61 In Brazil, shrimp are exploited by a multispecies fishery along the entire coastline and are  
62 caught primarily in shallow areas using motorized bottom trawl nets (Costa et al., 2007). Penaeidae  
63 species are the primary targets in Brazilian waters (Lopes, 2008). Shrimps of this family are captured  
64 by three fishery systems that differ in the size, technology and volume of the catch: the industrial,  
65 semi-industrial, and artisanal fleets (Dias-Neto, 2011). In the north-eastern region of Brazil, shrimp  
66 fishing is primarily performed by artisanal boats operating in shallow muddy coastal waters (Dias-  
67 Neto, 2011), involving more than 100,000 people and approximately 1,700 motorized and 20,000  
68 non-motorized boats (Santos, 2010), representing around 10% of the total landed marine fishery  
69 resources in the country (IBAMA, 2008).

70 Despite their socio-economic importance, the effects of policy regulations and environmental  
71 variations in the Brazilian shrimp fishery have never been assessed with EAF models, specifically in  
72 terms of the EwE approach. Therefore, in this study, we developed an Ecopath with Ecosim (EwE)  
73 food web model approach to the Sirinhaém coast as a case study of north-eastern Brazil, in order to  
74 evaluate the potential isolated and combined effects of different scenarios related to closed seasons,  
75 fishing effort and environmental changes, simulated up to 2030. We expect that our results could  
76 provide straightforward responses to the decision makers, specifically those related to small scale  
77 bottom trawlers, with solutions that meet both fisheries and conservation objectives.

78

## 79 **2. Methods**

### 80 *2.1. Study area*

81 The Barra of Sirinhaém (BSIR), which is located on the southern coast of Pernambuco, in north-  
82 eastern Brazil (Fig. 1), is influenced primarily by the nutrient supply of the Sirinhaém river. The  
83 climate is tropical, with a rainy season that occurs between May and October. The rainfall ranges from  
84 20 to 450 mm·month<sup>-1</sup>, the mean water temperature is 29°C, and the pH and salinity range between  
85 8.0 and 8.7 and 23 and 37, respectively (APAC, 2015; Mello, 2009). Fishing, the sugar cane industry  
86 and other farming industries are considered the primary productive activities in the region (CPRH,  
87 2011). Fishing is performed near the coast (Manso et al., 2003) and the main fishing zones are inside  
88 or close to the Marine Protected Areas around Santo Aleixo Island (MPAS of Guadalupe and Costa  
89 dos Corais) (Fig. 1). The spatial extent of the model corresponds to the shrimp fishing areas in the  
90 BSIR with depths ranging from 4 to 20 m, covering a total area of 75 km<sup>2</sup>.

### 91 *2.2. Trawl Fishery*

92 Bottom trawling in the BSIR of north-eastern Brazil, the main fishery assessed in this study, has  
93 the largest and most productive motorized fishing fleet in Pernambuco, corresponding to 50% of the  
94 shrimp production (Tischer and Santos, 2003), being an important source of income and food for the  
95 local population (Lira et al., 2010). This fishery is operated with fleet of twelve boats, from 1.5 to 3.0  
96 miles off the coast, mainly between 10 and 20 m depth, with set duration of 4 to 8 hours and boat  
97 velocity varying between 2 and 4 knots. Boats often have 8-10 m of length, horizontal opening net of  
98 6.1 m, mesh sizes of body and cod end of 30 mm and 25 mm, respectively. In Brazil, the regulations  
99 of this modality of fishery mostly involve a closed season (Dias-Neto, 2011; Santos, 2010) and  
100 fishermen and fisherwomen have the right to economic assistance during this time. However, despite  
101 its high relevance, Pernambuco is the only state in the region with no regulation. Shrimps of the  
102 Penaeidae family are the main targets: the pink shrimp (*Penaeus subtilis*), white shrimp (*Penaeus*  
103 *schmitti*), and seabob shrimp (*Xiphopenaeus kroyeri*) and the proportion of fish bycatch is 0.39 kg of  
104 fish captured for each 1 kg of shrimp (Silva Júnior et al., 2019). The fish bycatch is composed of 51

105 species, 38 genera and 17 families (Silva Júnior et al., 2019). The target shrimps and the most relevant  
106 non-target species were selected for model construction (Table S1).

### 107 2.3. Modelling approach

108 The Ecopath with Ecosim (EwE) version 6.6 (www.ecopath.org) approach has three primary  
109 modules: the mass-balance routine (Ecopath), the time dynamic routine (Ecosim) and the spatial-  
110 temporal dynamic module in Ecospace. Initially, a model was developed to quantify the trophic flows  
111 and to evaluate fishing impact among compartments of the BSIR from the first module in Ecopath.

112 The Ecopath model simplifies the complexity of marine ecosystem dynamics through a mass  
113 balance approach on a system of linear equations that considers parameters such as the biomass,  
114 production and consumption of the species to describe the trophic flows between biological  
115 compartments, thus allowing the investigation of the possible responses of the ecosystem to  
116 anthropogenic impacts such as habitat degradation and/or fishing (Christensen and Pauly, 1992;  
117 Christensen and Walters, 2004) (Appendix 1 for further details). The balanced Ecopath model (2011-  
118 2012) included 50 trophic groups with two primary producer groups, one zooplankton compartment,  
119 twelve macrobenthos groups, 35 fish groups, and one group of birds, turtles and detritus (Fig. 2). The  
120 fish groups were selected given the importance of their biomass and landings, their position in the  
121 water column (pelagic, demersal, and benthic) and their trophic guilds (Elliott et al., 2007; Ferreira et  
122 al., 2019) (Table S1). This model accounted for the landings and bycatch of the primary fleets  
123 operating in the area, including bottom trawlers, gillnets and line. Following Heymans et al. (2016)  
124 and Link (2010), we analyzed the balance and confidence of our model by observing a set of criteria  
125 and assumptions using the pre-balanced (PREBAL) diagnostics routine (Link, 2010) (Table S4 and  
126 Fig. S2 for further details). A full description and the sources of information for the input and output  
127 parameters in the baseline Ecopath model are presented in Appendix 2 (Table S1 to S5 and Fig. S1 to  
128 S5).

129 Based on the Ecopath model, the Ecosim time dynamic module was applied and fitted to a time  
130 series from 1988 to 2014. This model is a time-dynamic approach based on initial parameters from  
131 Ecopath that simulate changes in the estimates of biomass and catch rates over time, given the changes  
132 primarily exerted by fishing and the environment (Christensen and Walters, 2004; Walters et al.,  
133 1997). These estimates are performed by multiple coupled differential equations derived from the  
134 Ecopath equation.

$$137 \quad \frac{dB_i}{dt} = g_i \sum_{j=1}^n Q_{ji} - \sum_{j=1}^n Q_{ij} + I_i - (M_i + F_i + e_i)B_i \text{ (eq. 1)}$$

135 where  $\frac{dB_i}{dt}$  is the growth rate in terms of biomass ( $B_i$ ) over time for group  $i$ ,  $g_i$  is the net growth  
136 efficiency (production/consumption ratio),  $I_i$  is the immigration rate,  $M_i$  is the natural mortality rate

138 (unrelated to predation),  $F_i$  is the fishing mortality rate and  $e_i$  is the emigration rate (Christensen et al.,  
139 2008).  $Q_{ij}$  and  $Q_{ji}$  are the total consumption by group  $i$  and the predation by all predators on group  $i$ ,  
140 respectively. The consumption rate calculations are based on the “foraging arena” theory (Ahrens et  
141 al., 2012; Walters et al., 1997) in which biomass  $B_i$  of prey is divided into two fraction: available prey  
142 (vulnerable) and unavailable prey (invulnerable fraction) which depend of the transfer rate ( $v_{ij}$ ). The  
143 vulnerability parameter in Ecosim represent the degree to which an increase in predator biomass will  
144 cause in predation mortality for a given prey, determining the food web controls (top-down vs.  
145 bottom-up) (Christensen et al., 2008). Values close to 1 (low vulnerability) lead to bottom-up control,  
146 since the growth of the predator biomass will not cause a substantial increase in predation mortality on  
147 its prey. In the opposite, vulnerability values higher than 10 may lead to top-down control in the food  
148 web, and the positive variation in predator biomass causes significant impacts in the biomass of its  
149 prey due to predation mortality (Christensen et al., 2008).

#### 150 2.4. Model Fitting

151 The Ecosim model was fitted to the shrimp species trawl catch data based on the official fishery  
152 reports, which is the longer and more accurate time series available for the 1988– 2014 period in the  
153 study area.

154 The near-surface chlorophyll-*a* concentration was applied as a primary production proxy from  
155 satellite image-processed data (Level-3) (source: <https://oceancolor.gsfc.nasa.gov/>) using an empirical  
156 relationship derived by *in situ* measurements and remote sensing (see Hu et al., (2012) for algorithm  
157 details). The mean chlorophyll-*a* data converted to  $t.km^{-2}$  was monthly obtained for October 1997 to  
158 December 2014 (*SEAWIFS* and *MODIS/AQUA* with resolutions of 9 km and 4 km, respectively) for  
159 the study area (8.56°S/8.68°S; 35.10°W/34.95°W) (see Fig. S6 for details). Therefore, the historical  
160 chlorophyll-*a* data was implemented as a forcing function of the primary production.

161 The vulnerabilities for each species/group that provided the best fit (measured by the weighted  
162 sum of squared deviations SS), was obtained, in three steps, using an iterative procedure of the “Fit to  
163 time Series” module of Ecosim. The first step determined the sensitivity of SS to vulnerabilities  
164 associated only with individual predator-prey interactions (Christensen et al., 2008). Secondly,  
165 anomalous patterns based on the time series values of relative primary productivity (forcing data, see  
166 above) were compiled. For the last step, both the vulnerability values and anomaly patterns were  
167 applied to reduce the SS. To assess the robustness of the fitted model, the landings estimates were  
168 compared using both the reported official and non-official catch statistics. The final vulnerability  
169 values used to provide the best fit are presented in Table S6.

#### 170 2.5. Measuring the uncertainty

171 To assess the sensitivity of the Ecosim output, the Monte Carlo routine was applied (Heymans  
172 et al., 2016), assuming changes based on the pedigree indicator (Corrales et al., 2018; Serpetti et al.,  
173 2017) on each basic Ecopath input parameters (B, P/B, Q/B, and EE). We performed 1000 Monte-  
174 Carlo simulation trials for each species/group of the model in order to determine the confidence  
175 intervals (CI: 5% and 95%) for the Ecosim outputs (fitted results and ecological indicators).

## 176 *2.6. Scenario simulation*

177 We propose a simulation and evaluation of the fishing management scenarios (FMS) and the  
178 responses of the target species (shrimps), bycatch and whole ecosystem using the Ecosim temporal  
179 dynamic module from the BSIR base model (2011-2012). Seventeen scenarios were simulated. These  
180 scenarios were related to closed period of the trawling fishery based on the number of months of  
181 maximum reproduction/recruitment activity of shrimp species and bycatch and on the current shrimp  
182 regulation in Brazil (Normative N°14 MMA/2004); increase and decrease of trawl fishing effort; and  
183 environmental drivers using primary production changes as proxy (Table 1). Thus, we evaluated  
184 scenarios with 4 (clos1s) and 3 months (clos2s) of closed fishing periods; scenarios (scenarios “inc”  
185 and “dec”) with increase (inc) and decrease (dec) in fishing effort by 10, 25, 50 and 100%; and  
186 scenarios with a decrease in the primary production from 0.5 to 10% (scenarios env1-env3),  
187 considering the expected variation, in our region, of the primary productivity given the predictable  
188 decreasing trend in the rainfall caused by climate change (Blanchard et al., 2012; Krumhardt et al.,  
189 2017; Lotze et al., 2019; Reay et al., 2007) (Table 1).

190 We considered a two-tiered approach, first looking at individual strategies (fishing and  
191 environmental drivers as reported above) then by the combination of these factors (fishing +  
192 environmental drivers). For this, the combined scenarios involving closed seasons (1) and effort  
193 control (2) that supplied the best results (considering the balance between increasing the catch and  
194 maintaining conservation indicators (e.g., biomass) were incorporated into the scenarios concerning  
195 the primary productivity (scenarios 3) to evaluate the cumulative effects of the three factors, into  
196 management measures. From the original configuration of the fitted model, here considered as the  
197 baseline simulation (Stand), the 17 scenarios were performed to assess the responses of the marine  
198 resources and ecosystem conditions to fifteen years, between 2015 to 2030 (Table 1).

## 199 *2.7. Indicator analysis*

200 The absolute values of the biomasses and catches for each trophic group in each simulated  
201 scenario from 2015 – 2030 were compared to the baseline model of constant effort (scenario - stand).  
202 The average ratio values (e.g., final biomass / initial biomass) for each scenario are represented by  
203 colour heatmaps indicating the increases or decreases in the biomass and catches from 2015 to 2030.  
204 Additionally, several indicators associated with the biomass, catch, size and trophic level were  
205 assessed to evaluate the response of the ecosystem to the different simulations over time (Table 2)

206 (Coll and Steenbeek, 2017). These indicators were then correlated over the period from 2015 to 2030  
207 by the Spearman's rank correlation (see Corrales et al. (2018); Piroddi et al. (2017)).

### 208 **3. Results**

#### 209 *3.1. Ecopath model*

210 A balanced Ecopath model was developed to represent the ecosystem function and to  
211 characterize the food web structure in the BSIR from 2011-2012. A full description and sources of  
212 information of the input and main output parameters for the fifty trophic groups (Fig. 2) of the baseline  
213 Ecopath model are presented in Appendix 2.

214 The values of the B, P/B, Q/B, EE and landings for all groups and fleets (Table 3) revealed that  
215 the invertebrates represented more than half of the total biomass, being 11% shrimps, while the  
216 biomass of the fish represented 14% of the total biomass. Among the fleets evaluated, gillnet and line  
217 represented 35% of the total landings, while the trawling corresponded to 75% in BSIR, with the  
218 shrimp species totalizing approximately 84% of the total catch.

219 Birds (TL = 4.26), Seaturtles (TL = 4.20) and piscivore fish such as *Trichiurus lepturus* - Tri.lep  
220 (TL = 4.19), *S. guachancho* - Sph.gua (TL = 4.06), *M. ancylodon* - Mac.anc (TL = 3.20) had the  
221 highest estimated trophic levels of the food web (Fig. 2) and the larger number of trophic pathways.  
222 Compared with the trawling fleet, the target of line and gillnet fleets was mostly the species with  
223 higher TL.

224 The herbivore/detritivore rate (H/D) was 2.21, indicating that the energy flowed in larger  
225 proportion mainly from the primary producers to the second trophic level in the BSIR food web (Table  
226 4). The Total System Throughput (TST) was 4060 t·km<sup>-2</sup>·y<sup>-1</sup>, with 25% due to consumption and 35%  
227 due to flows into detritus. The mean trophic level of the catch (TLc) was 2.89, and the rates of the  
228 TPP/TR and TPP/TB were 3.84 and 49.36 respectively, while the Finn's Cycling Index (FCI) was low  
229 (3.76), and the system overhead was 69%.

#### 230 *3.2. Historical ecosystem state*

231 The catches predicted from the Ecosim baseline model (Stand) were compared to the catch time  
232 series for the target shrimp species (*X. kroyeri*, *P. subtilis* and *P. schmitti*) (Fig. 3). The model was  
233 able to recreate the official values and trends in catches for these species (Fig. 3), reproducing the  
234 increased catches between 1994 and 1997 and between 2004 and 2007.

235 Except for the Kempton's biodiversity, which decreased from 1988 to 2014, the ecosystem  
236 indicators displayed similar trends over time in the structure of the BSIR (Fig. S7). The increases were  
237 related to different indexes (e.g., Fish B, Total C, MTI, mTLc, and TL catch) from 1994 to 1997 and  
238 2004 to 2007 (Fig. S7).

239 3.3. Back to the future

240 After closing the fishing period to the trawling fleet for 4 and 3 months (clo1s and clo2s), the  
241 model predicted a similar pattern of biomass and catches. In these scenarios, the bycatch fish, shrimp,  
242 birds and turtles increased in biomass compared to the baseline, while the biomass of the lower TL  
243 compartments (phytoplankton, zooplankton and other invertebrates) increased for clo1s and decreased  
244 for clo2s over time in the 2015-2030 projection (Fig. 4). Simulations of increased or decreased  
245 trawling efforts (e.g., inc(+50%), inc(+100%), dec(-25%) and dec(-50%)) indicated divergent effects,  
246 with differences being more evident in scenarios with effort changes above 25%. By reducing the  
247 effort, the biomass of the target species increased, as did the bycatch fish, birds and turtles, but to a  
248 lesser extent (Fig. 4). Scenarios with increased trawling effort projected a negative impact on biomass  
249 for the target species *P. schmitti* and *P. subtilis* and for the bycatch fish (e.g., *Hypanus guttata*,  
250 *Paralonchurus brasiliensis* and *Trichiurus lepturus*) (Fig. 4 and 5). Similar trends were noted during  
251 primary production (PP) scenarios (env1, env2 and env3).

252 Specifically, for the target species (*P. subtilis* and *P. schmitti*), with the reduction in fishing  
253 effort and in considering the closed season to trawling, the simulations projected progressive  
254 recoveries in the biomass of these species, almost doubling the initial biomass over time (Fig. 4 and 5).  
255 However, the increased trawling effort and primary production scenarios negatively impacted the  
256 biomass of these two shrimp species in comparison to the baseline scenario, with a reduction of 68%  
257 for *P. subtilis* and 86% for *P. schmitti* in the inc(+100%) scenario (Fig. 4 and 5). For *X. kroyeri*, there  
258 was a slightly positive variation in the biomass, from 0.06% to 0.28% when reducing the effort, while  
259 in the PP scenario (e.g., env3), the shrimp biomass declined from approximately 12% (Fig. 4 and 5).

260 In general, scenarios involving closed fishing periods, decreased trawling efforts and PP  
261 reduction led to few changes (e.g., dec(-10%)) and, in some cases reduced catches (e.g., clo1s, dec(-  
262 50%) and env2) of the shrimp and bycatch species (Fig. 6). Although in general, the increased effort  
263 projected an average increase capture of the shrimp species (Fig. 6) (*P. subtilis* for example), only in  
264 the short term (2015-2020), these scenarios involving increased effort (e.g., 10 to 50%) has shown a  
265 gain of 4-16% in the catch, being gradually reduced until 2030 (see Table S7). However, for *P.*  
266 *schmitti*, the trend projected a reduction of approximately 27% to 70% (e.g., inc(100%)) in catches  
267 between 2020 and 2030 (see Table S7). All the biomass and catch ratios for the shrimp species and  
268 FMS compared to the baseline scenario are available in the Table S7 and Fig. S8.

269 The ecosystem indicators calculated from the Ecosim outputs showed similar patterns in the  
270 scenarios temporarily closed to trawling. A significant increasing trend ( $t$ -test;  $p < 0.05$ ) in biomass-  
271 based indicators (Total B, Fish B and Inver B), such as trophic (mTLc and MTI) and size-based  
272 (MLFc) indexes (Fig. 7), was projected. In addition, those indicators increased over time with the

273 effort reduction, except for the total and invertebrate catches for dec(-25%) to dec(-100%) scenarios  
274 (Fig. 7).

275 Under the 10% increased fishing effort scenarios (inc(+10%)), several indicators associated  
276 with the biomass, catch and size, primarily Fish B, Inver C and mTLco, presented a significant  
277 increasing pattern (Fig. 7) (*t*-test;  $p < 0.05$ ), although an increased effort of >50% (e.g., inc(+50%) and  
278 inc(+100%)) showed negative impacts on the Kempton's biodiversity (Kemp Q) and Inver B (*t*-test;  
279  $p < 0.05$ ). Strong negative effects (*t*-test;  $p < 0.05$ ) in all PP reduction scenarios, primarily for those with  
280 changes above 2% (env2 and env3), were reported (Fig. 7). The indicators predicted in the model, with  
281 confidence intervals assessed by Monte Carlo routine for each FMS, are presented in Fig. S9.

### 282 3.4. Cumulative effects of the PP anomaly and FMS

283 Among the individually evaluated FMS, the closed fishing periods (clo1s – 4 months) and the  
284 scenarios with little changes in effort (increase – 10% and decrease - 10%) showed the best balancing  
285 conditions, with minimal reduction to even improvement of catches (e.g., invertebrate capture) and  
286 conservation indicators (Fig. 8). These scenarios (clo1s; inc(+10%); dec(-10%)) were combined to  
287 drive environmental changes, in terms of reducing the PP to assess the cumulative effects of the  
288 impacts obtained from the PP change and FMS until 2030. Thus, among the climate change scenarios  
289 (Blanchard et al., 2012; Krumhardt et al., 2017; Lotze et al., 2019; Reay et al., 2007) and the time of  
290 our model (until 2030), the 2% is the lowest PP reduction rate, hence we have chosen as the most  
291 feasible PP scenario. The model projected a reduction of the impact on the biomass caused by the PP  
292 decrease with bottom trawl reduction control in 10% (dec(-10%)). However, the increased effort  
293 scenarios intensified the biomass decrease for shrimp and high TL species, which were already  
294 reduced by the decreasing PP (Fig. 8 and Fig. S8).

295 *P. subtilis* and *P. schmitti* showed the largest cumulative *P.* recovery in terms of biomass for the 4-  
296 month closed fishing period (clo1s+env1), followed by 10% effort reduction dec(-10%)+env1 (Fig. 8).  
297 The management measures related to effort control (clo1s, dec(+10%), inc(+10%)) led to few changes  
298 in the *X. kroyeri* biomass with PP reduction (Fig. 8). In terms of catch, the FMS over time barely  
299 changed the trends observed with the reduced PP for shrimp species, except for *X. kroyeri* (Fig. 8). All  
300 the biomass trends for each species, including bycatch and FMS compared to the env1 scenario, may  
301 be observed in Fig. S8.

### 302 3.5. Scenarios as decision support tools

303 In general, the target and some non-target species biomasses benefit from decreased fishing  
304 pressure, but the catches are reduced. However, a controlled increase in trawling up to 10% led to  
305 promising results in terms of catches and biomass level maintenance. Our findings indicated that the  
306 effort-reduction conservation measures evaluated here (e.g., clo2s and dec(-50%)) have positive

307 impacts on ecosystem health indicators (e.g., high TL biomasses and shrimp, mean trophic level of the  
308 ecosystem); however, they have a negative effect on catches at different trophic levels (Fig. 9). The  
309 opposite trend was noted with increased bottom trawling activity (Fig. 9). Adverse effects on all  
310 aspects of conservation and exploitation were reported with the environmental simulations (PP  
311 decrease on 2%) of the near future. These negative conditions resulting from PP were minimized with  
312 the implementation of management measures, especially with a 10% trawling reduction (Fig.9).

#### 313 **4. Discussion**

314 Although their contribution to global discards are considered small (Zeller et al., 2017), small-  
315 scale fisheries, primarily those operating in estuaries and coastal waters, play an important role in  
316 traditional communities (Gillett, 2008). On the Brazilian coast, limiting fishing efforts, closed fishing  
317 periods, and mesh size regulations (Dias-Neto, 2011; Gillett, 2008; Santos, 2010) are the currently  
318 applied management recommendations used to regulate the shrimp fisheries in this country. However,  
319 this is not the case for Barra of Sirinhaém (BSIR) in Pernambuco (Northeast Brazil), which is  
320 currently unregulated. Although they are applied in most parts of the country, these management  
321 strategies may be ineffective primarily due to weak fishery policy associated with limited fisher  
322 knowledge about formal norms and also given their traditional approaches to focusing on single  
323 species, without accounting for the ecosystem as a whole.

##### 324 *4.1. Ecopath model*

325 The present study provides, to the best of our knowledge, the first attempt to evaluate the  
326 potential impact to the shrimp fisheries in Brazil using an ecosystem-based approach with an EwE  
327 model. We developed a mass-balanced Ecopath model to describe the trophic interactions and energy  
328 fluxes, followed by a temporal dynamic Ecosim model to assess the response of the marine resources  
329 and ecosystem conditions under different fishing management scenarios (FMS) for the Barra of  
330 Sirinhaém coast as a case study for north-east Brazil.

331 The evaluation and validation of the structure and the outputs of the model was evaluated  
332 through the pre-balance (PREBAL) tool (Link, 2010), which identifies possible inconsistencies in  
333 input data (Heymans et al., 2016; Link, 2010). In general, our input data for the Ecopath model  
334 followed the general rules/principles of ecosystem ecology, similar to other studies (Alexander et al.,  
335 2014; Bentorcha et al., 2017).

336 Energy flow in the food web was based mainly from the primary producers, while the indicators  
337 of the ecosystem structure in the BSIR model were similar to those of the others coastal models (Geers  
338 et al., 2016), with values of respiration and consumption lower than exports and detritus values, and a  
339 high value of total primary production/total respiration (TPP/TR). The BSIR model had higher  
340 Overhead (SO) than Ascendancy (AC), and low values of connectance index (CI) and Finn's Cycling  
341 Index (FCI), similar to the other coastal ecosystems, such as the Isla del Coco, Costa Rica (Fourrière et

342 al., 2019), coral reef Media Luna, Honduras (Cáceres et al., 2016) and the temperate coastal lagoon  
343 Ria de Aveiro, Portugal (Bueno-Pardo et al., 2018). In mature systems, the Primary Production rate  
344 (TPP) is similar to the respiration flow (close to 1), while the total biomass of the ecosystem is larger  
345 than the TPP (Christensen et al., 2005; Odum, 1969), causing an accumulation of biomass within the  
346 system compared to the productivity (Corrales et al., 2017). PP-based ecosystems, with relatively low  
347 CI and FCI, suggests a low trophic complexity and reduced resilience level (Odum, 1969). These  
348 indicators are considered to be good indexes of the food web complexity, robustness and, indirectly, of  
349 the ecosystem maturity and stability (Christensen and Pauly, 1992; Saint-Béat et al., 2015). However,  
350 due to the dependence of this indexes to model structure (number of trophic compartments), they often  
351 do not reflect the structure of the ecosystem with accuracy (Bueno-Pardo et al., 2018; Christensen et  
352 al., 2005; Finn, 1976).

353 The high system overhead value in the BSIR, and the results reported for other indicators  
354 (TPP/TR; TPP/TB; AC, CI and FCI), suggest that the BSIR is an ecosystem in development with a  
355 low degree of resilience and low trophic complexity, similar to other coastal systems explored by  
356 fishing (Gulf of Mexico, Zetina-Rejón et al., 2015; Tunisia, Hattab et al., 2013; Israeli, Corrales et al.,  
357 2017; and China, Rahman et al., 2019)). Although different models presented similar patterns, given  
358 the high dynamics, as in the case of coastal ecosystems (e.g. bays, reefs, lagoons and shelves), it is not  
359 possible to set a reference level for all systems, regardless of size, depth, or type of ecosystems  
360 (Heymans et al., 2014). The shallow coastal zone, as the present study area, is influenced by different  
361 anthropogenic stressors (e.g., tourism, fishing, pollution, etc.), which can affect the ecosystem,  
362 providing barriers to evolution towards a more stable state, complex and mature of ecological  
363 succession (Bueno-Pardo et al., 2018). Therefore, these ecosystems require particular strategies to  
364 maintain the equilibrium state, such as ecosystem-based management integrating the different coastal  
365 and marine areas (Dell'Apa et al., 2015; Lazzari et al., 2019), considering the functional limits and the  
366 different stressors of each systems.

#### 367 4.2. Ecosystem historical state

368 The Ecosim model was able to reproduce the catches and their trends for shrimp species (*P.*  
369 *subtilis*, *P. schmitti* and *X. kroyeri*) given our available time series data. The trends in our model  
370 showed the bottom-up role provided by environmental variability in the function and structure of the  
371 ecosystem. Similar results were obtained from other studies in the Mediterranean Sea (Coll et al.,  
372 2016; Macias et al., 2014), west coast of Scotland (Serpetti et al., 2017), West Florida, USA (Chagaris  
373 et al., 2015) and Barra del Chuy, Uruguay (Lercari et al., 2018). The nutrient availability, and  
374 consequently the primary production, is considered a key controller of biological processes, driving  
375 bottom-up processes in the food web (Piroddi et al., 2017). In the BSIR region, the species abundance  
376 is strongly associated with environmental drivers (Silva Júnior et al., 2019), for example, the highest

377 chlorophyll concentration in the rainy season in shallow waters near the mouth of river, where the  
378 primary fisheries operate, and the sea surface temperature (SST) impact on shrimp abundance and  
379 consequently the fishing productivity (Lopes et al., 2018).

380 The historical reconstruction from the fitted model for the BSIR reported increases in indicators  
381 associated with the biomass, catch, size, trophic level and biodiversity between 1994 and 1997 and  
382 2004 and 2009, given the increase in primary productivity. This pattern could have been caused by  
383 climate anomalies (e.g., El Niño and La Niña), which directly influences the changes in terrestrial and  
384 marine environmental conditions at both global and regional scales. There are changes in the  
385 environmental variables over time, and the SST, precipitation, salinity and chlorophyll concentration  
386 are essential for understanding the effects of the ecosystem dynamics on marine populations (Cloern et  
387 al., 2014; Falkowski et al., 1998; Hughes et al., 2017) and consequently affecting the productivity,  
388 fisheries, pollution, ecosystem health, socioeconomics, and governance in coastal oceans (Sherman,  
389 2014a, 2014b). Anomalous climate events have been observed since 1950 and have been intensified  
390 with the effects of climate change, particularly during the 1997-1998, 2015-2016 (El Niño) and 2007-  
391 2008 (La Niña) (Trenberth, 2019) events, leading to profound impacts on biodiversity and humans,  
392 since floods, droughts, heat waves, and other environmental changes have modified the ecosystem  
393 dynamics of the region (Marrari et al., 2017; Rossi and Soares, 2017). Although a growing trend in  
394 biomass-based indicators (Total B, Fish B and Inver B) has been observed over time, a decline in the  
395 mean trophic level of the catch and the mean length of the fish community at the end of the analysis  
396 period was reported, which reflected the increased discards and invertebrate catches in the system. It is  
397 important to indicate that the historical model calibration and adjust was performed considering only  
398 shrimp groups fitted by time-series. Although, no time series were available for the bycatch (e.g.,  
399 squid, fishes, turtles and etc.) requiring caution when interpreting the results (Piroddi et al., 2017), in  
400 general, the historical reconstruction and predictions to future of our model were satisfactory. Often,  
401 due to absence of biomass or capture data of the non-target organisms, the studies with EwE  
402 approaches has no time series available for most groups, focusing mainly on main exploited species  
403 (Abdou et al., 2016; Bornatowski et al., 2017; Coll et al., 2013; Niiranen et al., 2012).

404

#### 405 *4.3. Fishing management scenarios (FMS) for the future*

406 Banning trawling fishing as a management measure, whether for a time or an area, has  
407 promoted improvements in the ecosystem, with shrimp population recovery, reduced bycatch and  
408 benefits for birds, mammals and most fish stocks (Heath et al., 2014; Joseph John et al., 2018). These  
409 positive effects through the food web are not always directly related to decreases in anthropic  
410 activities, but could also cause indirect consequences to prey-predator relationships (Kempf et al.,  
411 2010; Meekan et al., 2018). Conversely, increased fishing efforts may cause significant negative

412 impacts over time on the target species biomass (Ngor et al., 2018; Szuwalski et al., 2017), also  
413 indirectly affecting other groups in the food web (Gasche and Gascuel, 2013). In our long-term  
414 analysis, when considering the closed fishing period and effort reduction, the model predicted the  
415 increased abundance of several bycatch species as well as that of *P. subtilis* and *P. schmitti*. However,  
416 the fishing increase caused a decline in biomass for these groups, in the more intense fishing scenarios.  
417 For example, a slight decrease in bycatch biomass, primarily in predators of invertebrates, engendered  
418 a cascade effect in the food web, increasing the biomass of benthic invertebrates (except for *P. subtilis*,  
419 *P. schmitti* and *X. kroyeri*), zooplankton and primary producers (phytoplankton and macroalgae). In  
420 addition, the target species catches declined during the simulated season that was closed to bottom  
421 trawling. Shifts in fishing effort and catchability, fluctuations in population abundance, market-related  
422 factors and environmental change influence catch rates and may confound the potential effects of the  
423 management measures (Kerwath et al., 2013; Stefansson and Rosenberg, 2005). Nevertheless, an  
424 important step to investigating the impact of management strategies on conservation or environmental  
425 recovery includes the insertion and evaluation of multiple species at several trophic levels and their  
426 trophic interactions (Baudron et al., 2019; Christensen and Walters, 2005).

427 Intense negative effects on biomass, catch and biodiversity indicators (e.g., Kempton's  
428 biodiversity - Kemp Q) were reported in decreasing scenarios from 1% PP, reinforcing the need to  
429 simulate and project the possible impacts caused by climate change. Although PP is critical in  
430 maintaining biodiversity and supporting fishery catches, predicting the responses of populations  
431 associated with primary production changes is complex (Brown et al., 2010). Climate change will  
432 impact the food web. Ocean warming, for example, has the capacity to drive an energetic collapse at  
433 the base of marine food webs, and this effect can propagate to higher trophic levels, subsequently  
434 leading to significant biomass decline within the entire food web (Ullah et al., 2018).

435 Temperature change simulations are most often reported, indicating the reduction in both the  
436 number of species and the trophic interactions in the ecosystem (Gibert, 2019; Petchey et al., 2010;  
437 Régnier et al., 2019). Doubleday et al. (2019) observed that the enrichment of CO<sub>2</sub> responsible for  
438 ocean acidification intensified the bottom-up and top-down control. The effects of warming and  
439 acidification is noted in Goldenberg et al. (2018) as a driver of changes in consumer assemblages in  
440 future oceans. Moreover, Nagelkerken et al. (2020) indicate cumulative and adverse changes in the  
441 whole trophic structure, emphasizing that the adaptive capacity of ecosystems with unbalanced food  
442 web to global change is weak and ecosystem degradation is likely. Specifically, in the BSIR, the  
443 environment and shrimp fishery dynamics are influenced by primary production fluctuation as  
444 controlled by precipitation patterns, which directly affect the fishing activity. The major importance of  
445 the temperature and precipitation in shrimp productivity is also reported by Lopes et al. (2018),  
446 highlighting that these fisheries could collapse in a warmer and drier future.

447 Our projections highlighted some evidences that the control of bottom trawling activity helped  
448 to reduce, even at low levels, the highly adverse effects due to primary production reduction. The  
449 impacts of climate change on organisms and ecosystems is an imminent reality, and therefore the  
450 search for measures for mitigating and even minimizing these impacts is crucial. Historically, less  
451 developed regions in terms of fishery governance, as in our case study those primarily associated with  
452 small-scale fisheries, are more vulnerable to climate change (Johnson and Welch, 2010) due to the  
453 greater difficulty of adapting to productivity loss scenarios (McIlgorm et al., 2010). Some climate  
454 change consequences might be locally positive for some areas and targeted populations with efficient  
455 management measures, but for many fisheries and species, the effects will be undesirable (Quentin  
456 Grafton, 2010), for example, the catch decrease in the BSIR.

457 At the ecosystem level, the increased effort scenarios and PP reduction did not reflect an overall  
458 improvement in marine resources. Thus, several ecological indicators displayed a downward trend,  
459 such as the Kempton's Q biodiversity Index, MTI, mTLc, and mTLco. An increase in the bycatch  
460 biomass has also been reported. Monitoring these ecosystemic indicators (Cury and Christensen, 2005;  
461 Fulton et al., 2004; Heymans et al., 2014) may help researchers to detect food web changes and  
462 ecosystem sensitivity to fishing (Coll and Steenbeek, 2017; Halouani et al., 2019; Shin et al., 2018).  
463 For example, significant decreases in Kempton's Q and MTI indices over time indicate negative  
464 effects on the ecosystem due to the decline of high trophic level species (Ainsworth and Pitcher, 2006;  
465 Piroddi et al., 2010), while the reduction of the mTLco is attributable to the reduction of the biomass  
466 for most ecosystem components, primarily the predators  $TL > 3.25$  (Coll et al., 2008; Corrales et al.,  
467 2018). The improvement of some of these indicators during the closed fishing period represented a  
468 rebuilding of the total biomass, including high trophic level species as well as discard reduction.  
469 However, the reduced capture of target species by bottom trawling must be better evaluated from a  
470 social-economic viewpoint.

#### 471 *4.4. Uncertainty and limitations in BSIR*

472 The integration of ecosystem models, such as the trophic models in fisheries management  
473 process, is appreciated because it can address fisheries policy questions (Baudron et al., 2019; Bauer et  
474 al., 2019; Christensen and Walters, 2005; Coll and Libralato, 2012). However, it depends on the  
475 ability of the ecosystem model to reproduce, in detail, the observed trends and patterns in nature  
476 (Christensen and Walters, 2005; Cury and Christensen, 2005; Steenbeek et al., 2018), usually  
477 including the environmental effects, uncertainty estimates and confidence limits (Ehrnsten et al., 2019;  
478 Guesnet et al., 2015). Recently, several data based gaps have been described in previous studies using  
479 EwE models (Ecopath, Ecosim and Ecospace) (Chagaris et al., 2015; Corrales et al., 2018; Geers et  
480 al., 2016), especially those related to the lack of trophic information with a temporal dimension,  
481 reliable historical catch data and fishing efforts, limited information on biomass (Piroddi et al., 2017)  
482 and migration among habitats for different species (Halouani et al., 2016).

483 Thus, developing this ecosystem approach, particularly on the north-east coast of Brazil, is a  
484 challenging task, primarily due to the difficulties involved in gathering and integrating good-quality  
485 local data (e.g., dietary information, fishing data, environmental features, etc.) as reported by Lira et  
486 al. (2018). Despite this concern, the BSIR model was built on the basis of local studies and specific  
487 sampling in the area to estimate the biomass of several groups (all fish and shrimp species), and the  
488 diets and stable carbon and nitrogen isotope compositions of the primary consumers (see  
489 Supplementary Information). However, the absence of time series data for a large number of groups  
490 (e.g., catches, biomass and fishing effort) is considered as our primary weakness. Alternatively, to  
491 minimize the limitations cited above, we performed a sensitivity analysis (Monte Carlo routine) to  
492 evaluate the uncertainty around model parameters and to assess, in our case, the biomass and  
493 ecological indicators (Christensen and Walters, 2004; Niiranen et al., 2012; Steenbeek et al., 2016). In  
494 addition, although we recognize the importance of incorporating specific periods of the closing  
495 season within scenarios, some major data, as for example the spawning parameters (egg production,  
496 egg-laying timing etc.), are lacking, hampering this analysis within the model.

497 We are confident that our study presents a satisfactory representation of the ecosystem structure  
498 and the fishing impact on the ecosystem and may be replicable to other small scale shrimp fisheries. In  
499 addition, incorporating additional tools to the current model, such as Ecospace, to investigate the  
500 potential impacts of spatial management plans (e.g., area closed to fishery), and tools to assess the  
501 cumulative effect of future climate change (e.g., sea temperature, species distribution change, and  
502 phenological changes) on small-scale fisheries would enable useful insights into the effects of various  
503 management policies and possible trade-offs at the ecosystem level.

#### 504 *4.5. Management support tool*

505 Multiple indicators were considered in the context of Ecosystem-Based Fishery Management to  
506 evaluate the potential effects of different FMS with the aim of providing a straightforward set of  
507 decision parameters to small-scale fisheries managers, specifically to bottom trawlers, to fulfil both  
508 fisheries and conservation management objectives in the near future. In general terms, the decreased  
509 trawling efforts were promising, with better fishing management performance than the closed fishing  
510 periods of 3 and 4 months, primarily due to significant losses in the catches of high market-value  
511 target species (e.g., the white shrimp *P. schmitti* and the pink shrimp *P. subtilis*) and bycatch fishes  
512 considered as *byproducts* in these scenarios.

513 Some aspects of the BSIR that may be shared with other locations should be considered within  
514 the management framework. The shrimp fishing dynamics are well-defined yearly. Shrimp and  
515 bycatch are abundant and are mainly caught during the periods of highest primary production as a  
516 consequence of the rainfall (Silva Júnior et al., 2019). At the opposite, the lowest shrimp and bycatch  
517 abundances and catches are related to dry periods, which correspond to the peak of reproduction of

518 these species (Eduardo et al., 2018; Lira et al., 2019; Lopes et al., 2017; Peixoto et al., 2018; Silva et  
519 al., 2016; Silva Júnior et al., 2015). Consequently, during the dry season, the trawling activities are  
520 basically inactive due to the decline in production (Eduardo et al., 2016; Silva Júnior et al., 2019;  
521 Tischer and Santos, 2003), barely covering the operating costs of the fishery. This phenomenon could  
522 be considered as a “*natural closed season*”, or the economic unprofitability due to low shrimp and  
523 bycatch abundance that regulates the fishing activities. In addition to the importance of the target  
524 species, knowledge of the bycatch destination is crucial during the management process. In the BSIR,  
525 the incidental catch primarily removes juveniles (Eduardo et al., 2018; Lira et al., 2019; Silva Júnior et  
526 al., 2015), which are often consumed by the fishermen and local community as additional sources of  
527 food and income as a *byproduct* (Silva Júnior et al., 2019). Thus, a major decline in the capture of  
528 bycatch with the implementation of a management measure may cause negative effects from  
529 nutritional, economic and social viewpoints. In this way, the impact of the fishing activities on the  
530 ecosystems appears to be counter-balanced by the beneficial role of the bycatch in the local  
531 community. Although we are aware of the importance of this fishery bycatch for the local food  
532 security, we cannot disregard the fact of several fish species of bycatch (e.g., croaker, weakfish, jacks,  
533 snappers) has the longer life history, low spawning potential, and high commercial value when adults,  
534 and therefore need to be considered in future evaluations, including new information incorporating the  
535 socio-economic aspect.

536 Within the particularities of our case study and without accounting for the effect of  
537 environmental changes, not adopting effort control measures for the current trawling conditions  
538 (baseline scenario) do not appear to cause major losses in terms of biomass and catches. However, it is  
539 clear that in the near future (2030), with the uncontrolled increase >50% in trawling combined with  
540 environmental changes, for example, in the rainfall or in primary production, significant adverse  
541 impacts will affect the ecosystem functioning. In these cases, bottom trawling control efforts can help  
542 to mitigate, even at low levels, these highly negative effects.

543 Our findings indicate that it is possible to maintain the same level of landings with a controlled  
544 reduction of bottom trawlers activities, for example, close to 10%, without compromising the  
545 ecosystem structure. However, other management measures could be incorporated into the model and  
546 better evaluated in the future, such as the application of Bycatch Reduction Devices (e.g., fisheye, grid  
547 and square mesh) used to exclude small fish, juveniles of species of high commercial value (e.g.,  
548 croaker, weakfish, jacks, snappers) and other non-target species from the trawlers (Broadhurst, 2000;  
549 Eayrs, 2007; Larsen et al., 2017); an increase in the area and/or improvement in enforcing the existing  
550 Marine Protected Areas (e.g., MPA Guadalupe) as well as including other environmental drivers from  
551 the IPCC predictions (e.g., RPC4.5 and RPC8.5) (Reay et al., 2007). These measures would enable  
552 important and useful insights on the direct and indirect effects of climate changes, other management  
553 policies, and possible trade-offs at the ecosystem level. However, any management measures to be  
554 considered as successful to mitigate the fishing impacts depend on interactions among highly

555 heterogeneous social, political, economic and conservation factors, which are especially relevant in  
556 small-scale fisheries such as our case study fishery.

557

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566

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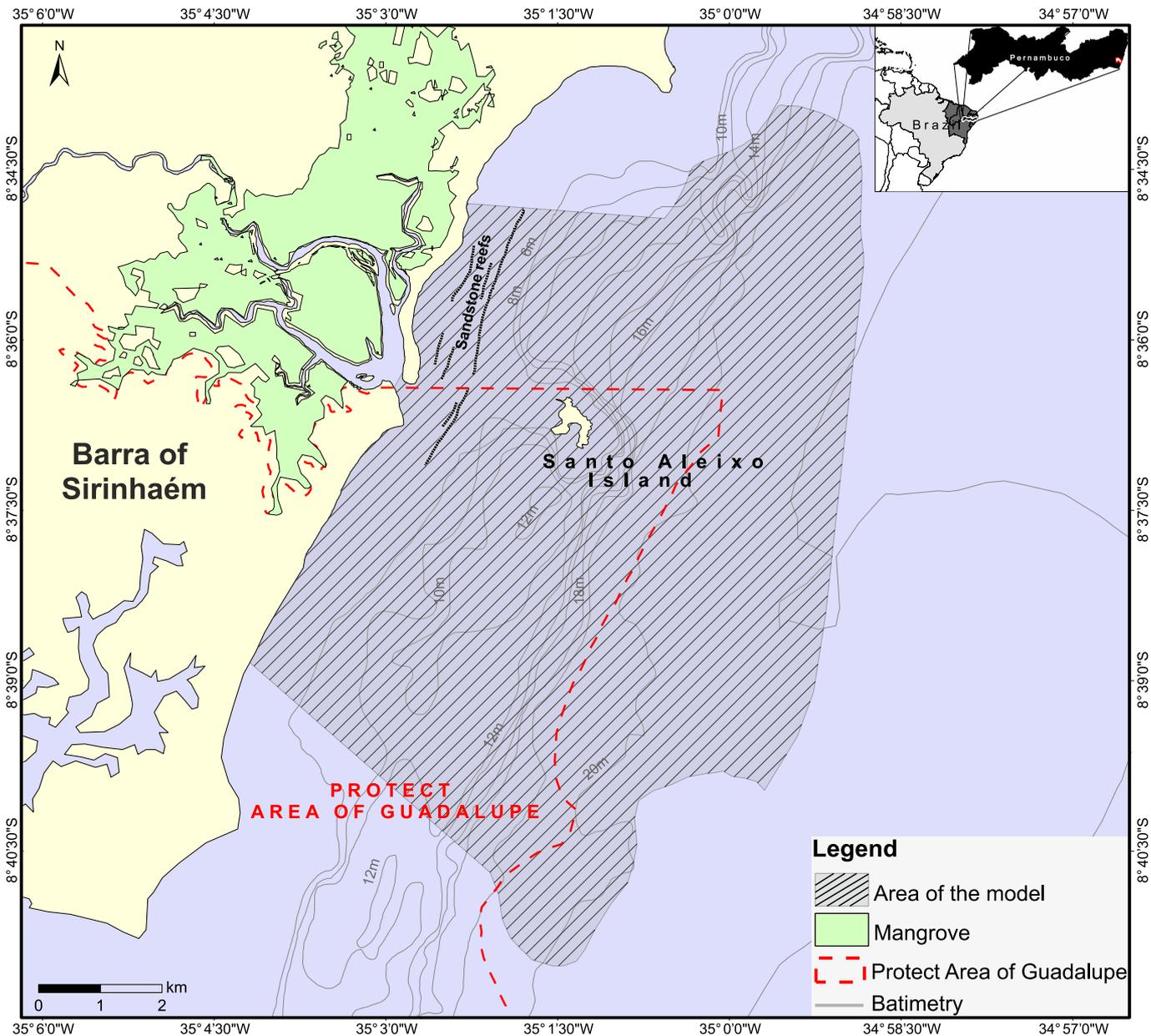
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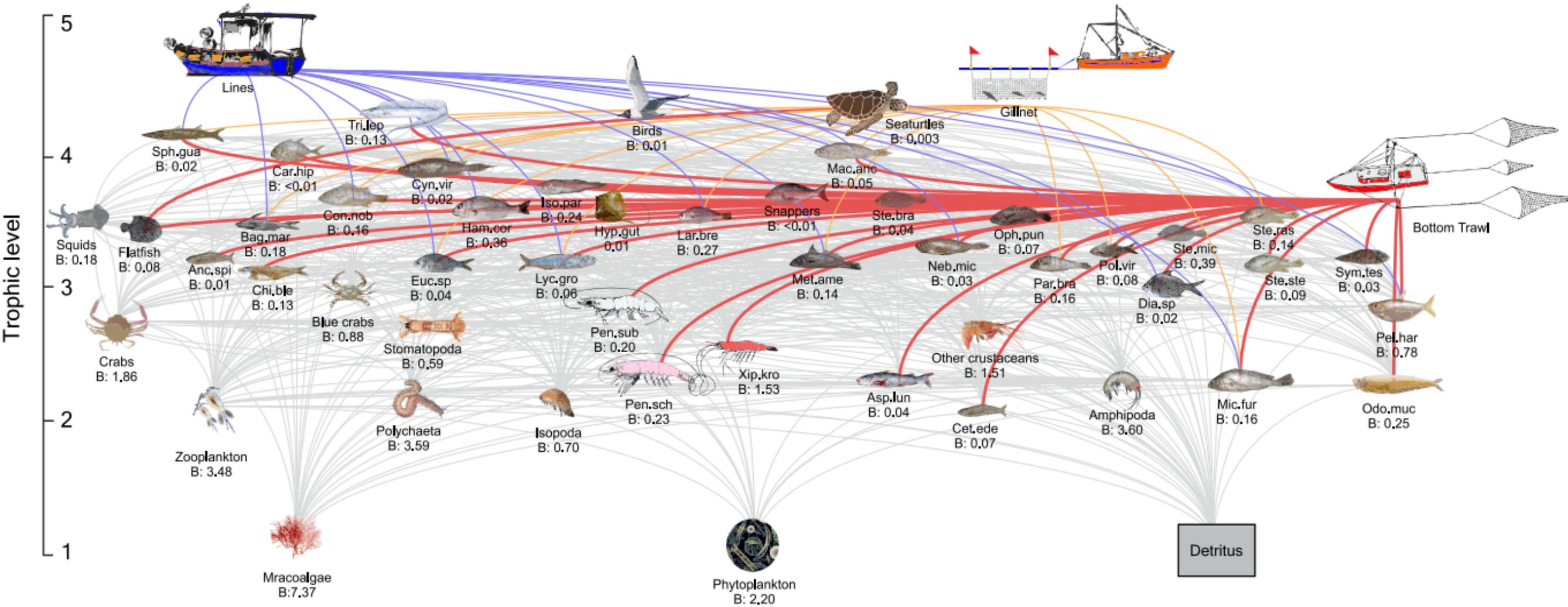
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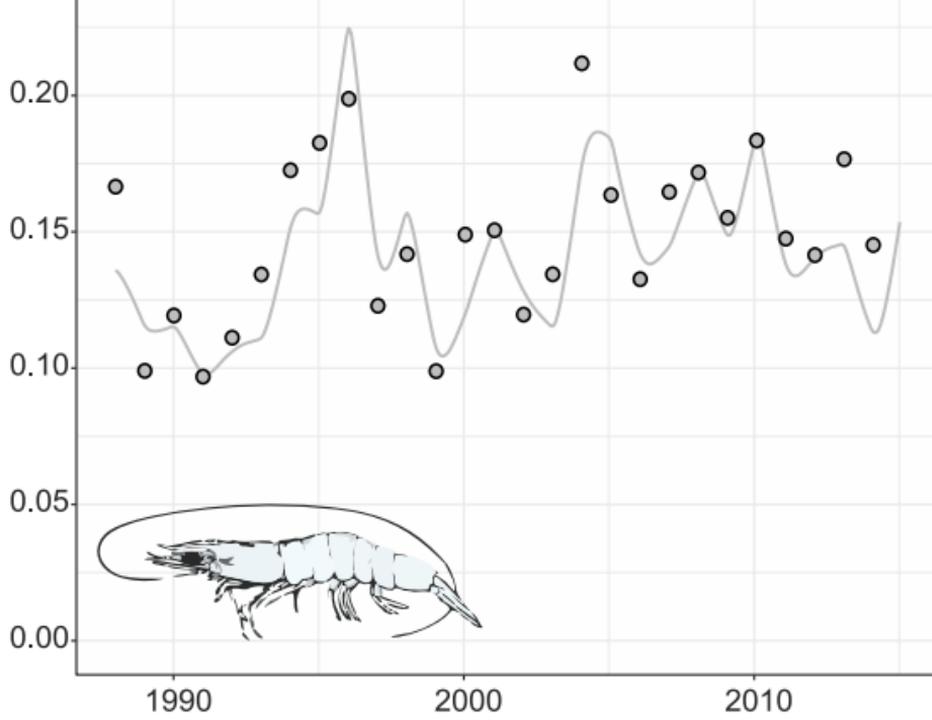
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*Pen.sch*

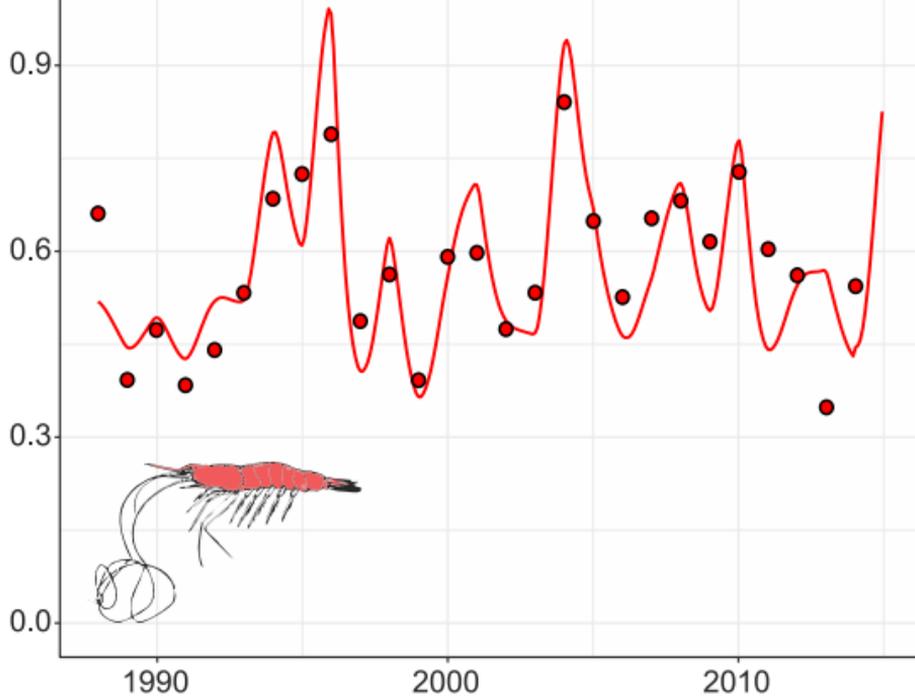
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*Xip.kro*

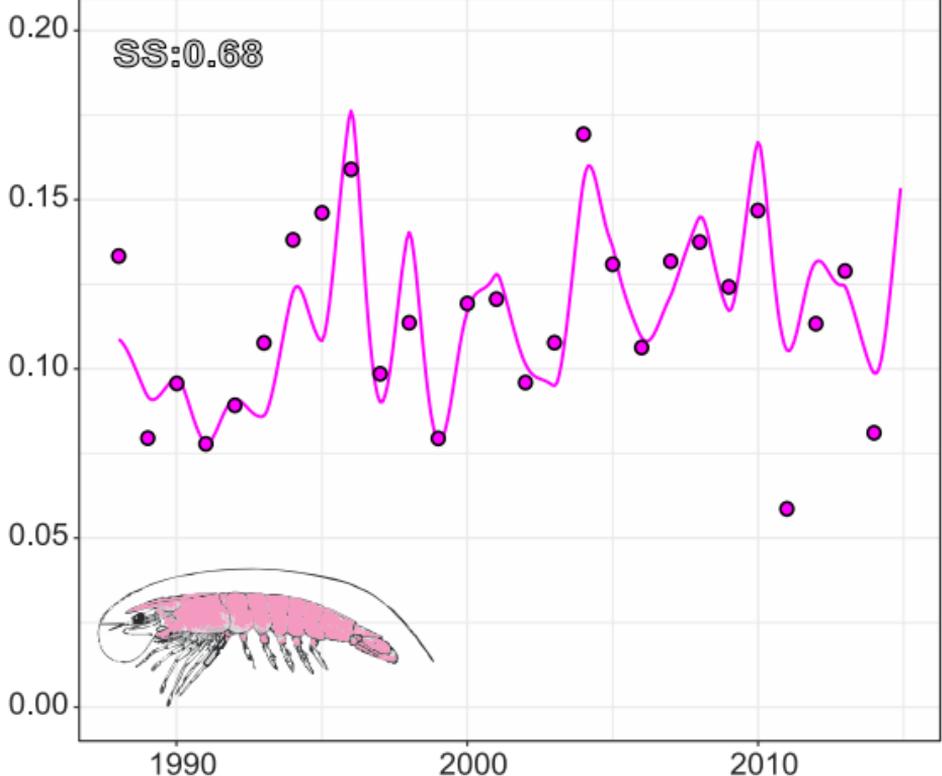
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Predicted Yield (Ton.Km<sup>-2</sup>)



*Pen.sub*

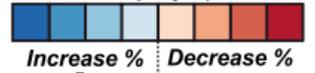
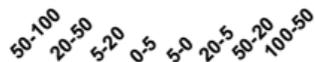
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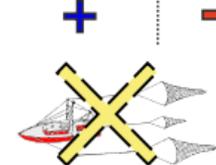
Year

# Trophic groups

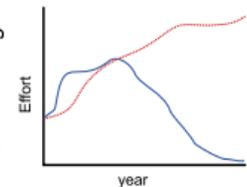
## Biomass variation



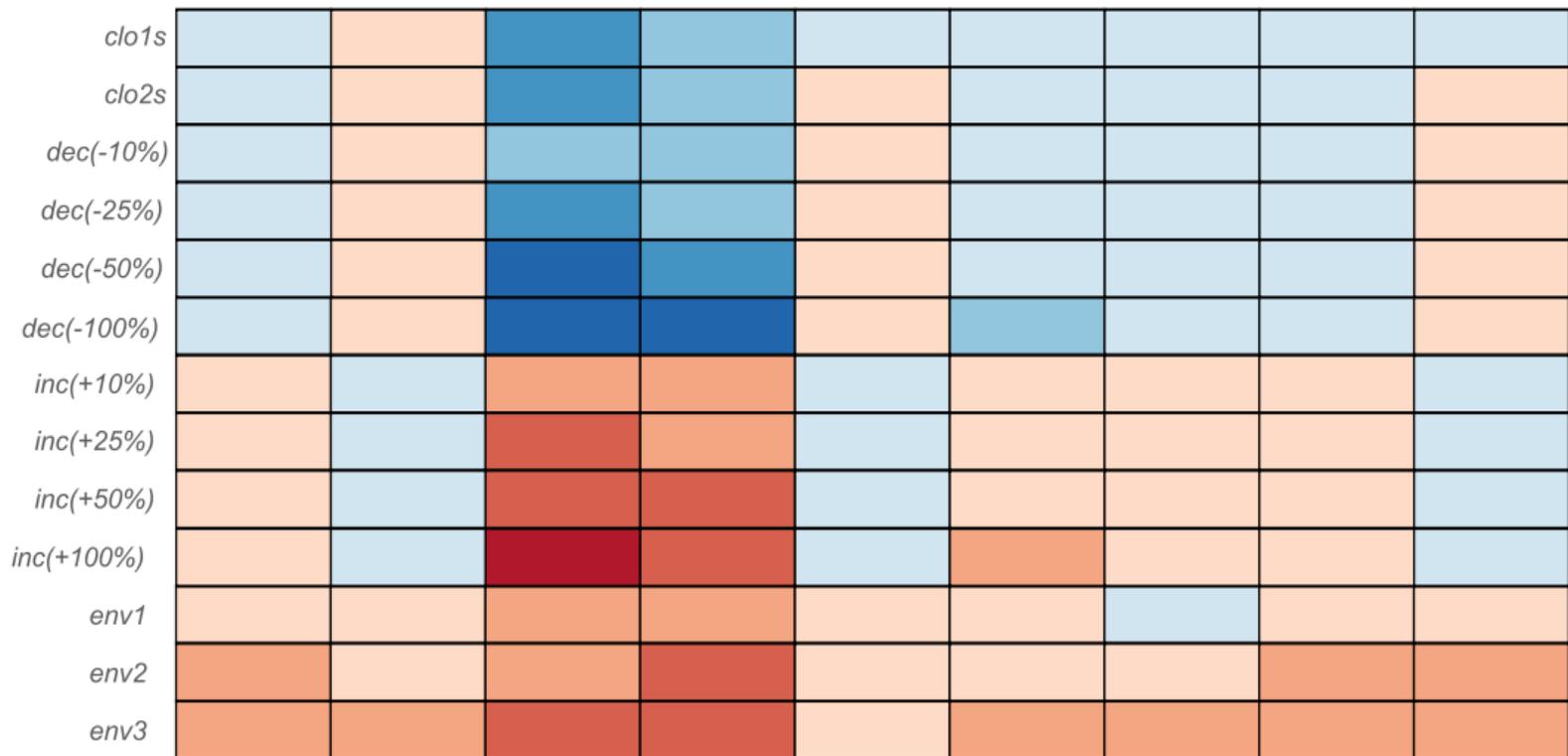
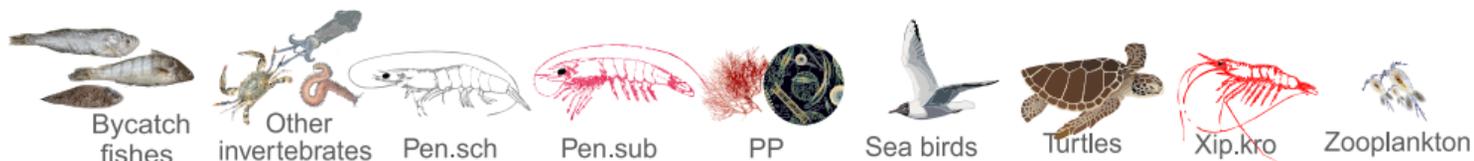
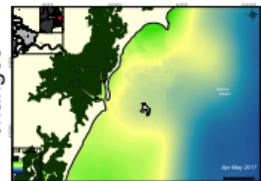
Closed season



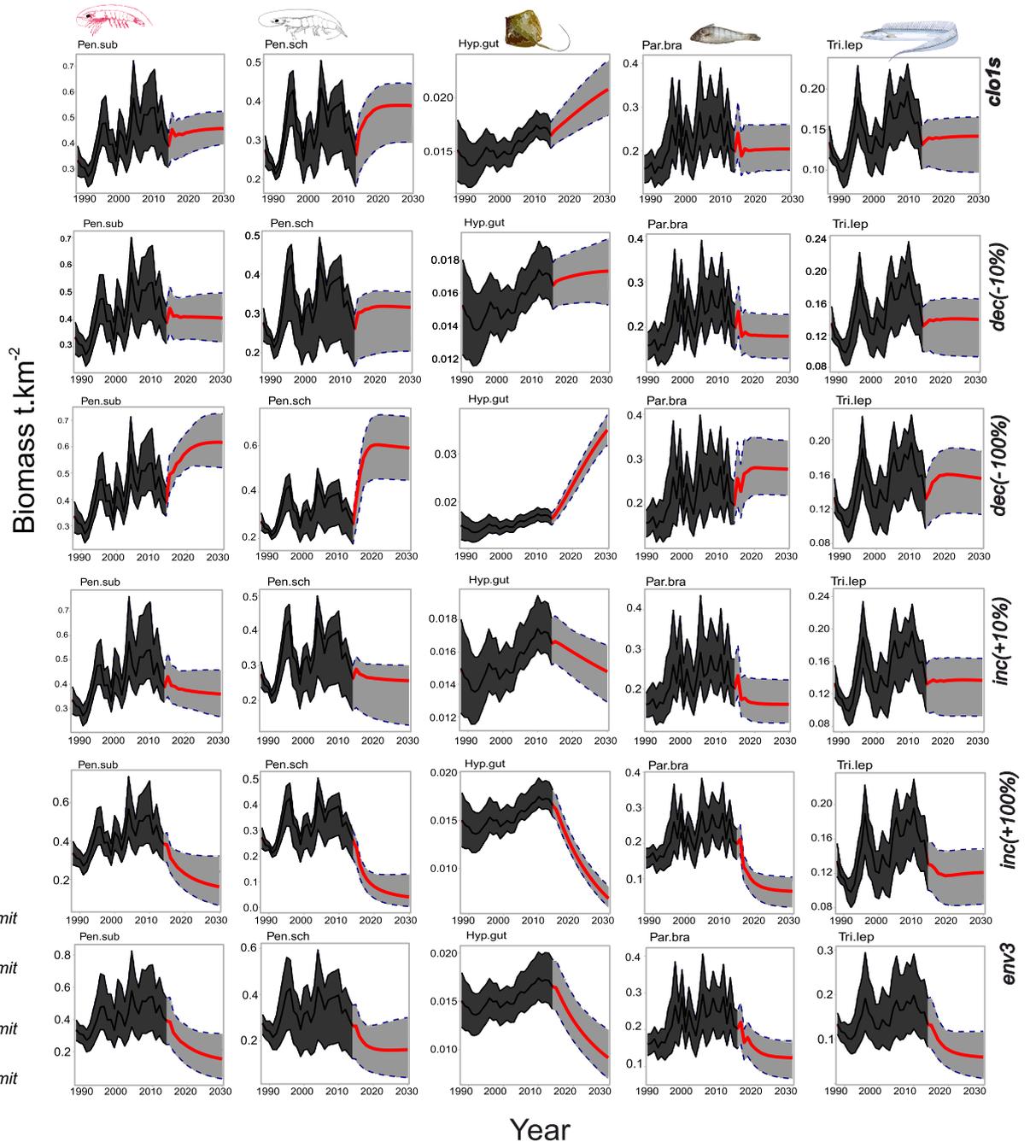
Effort change



changes



Primary production



# Catch variation



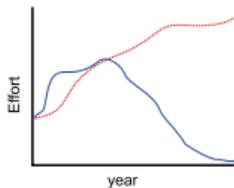
Increase %      Decrease %



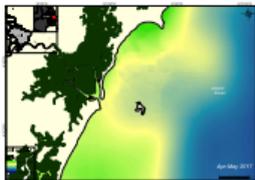
Closed season



Effort change



changes



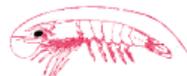
# Trophic groups



Bycatch fishes



Pen.sch



Pen.sub



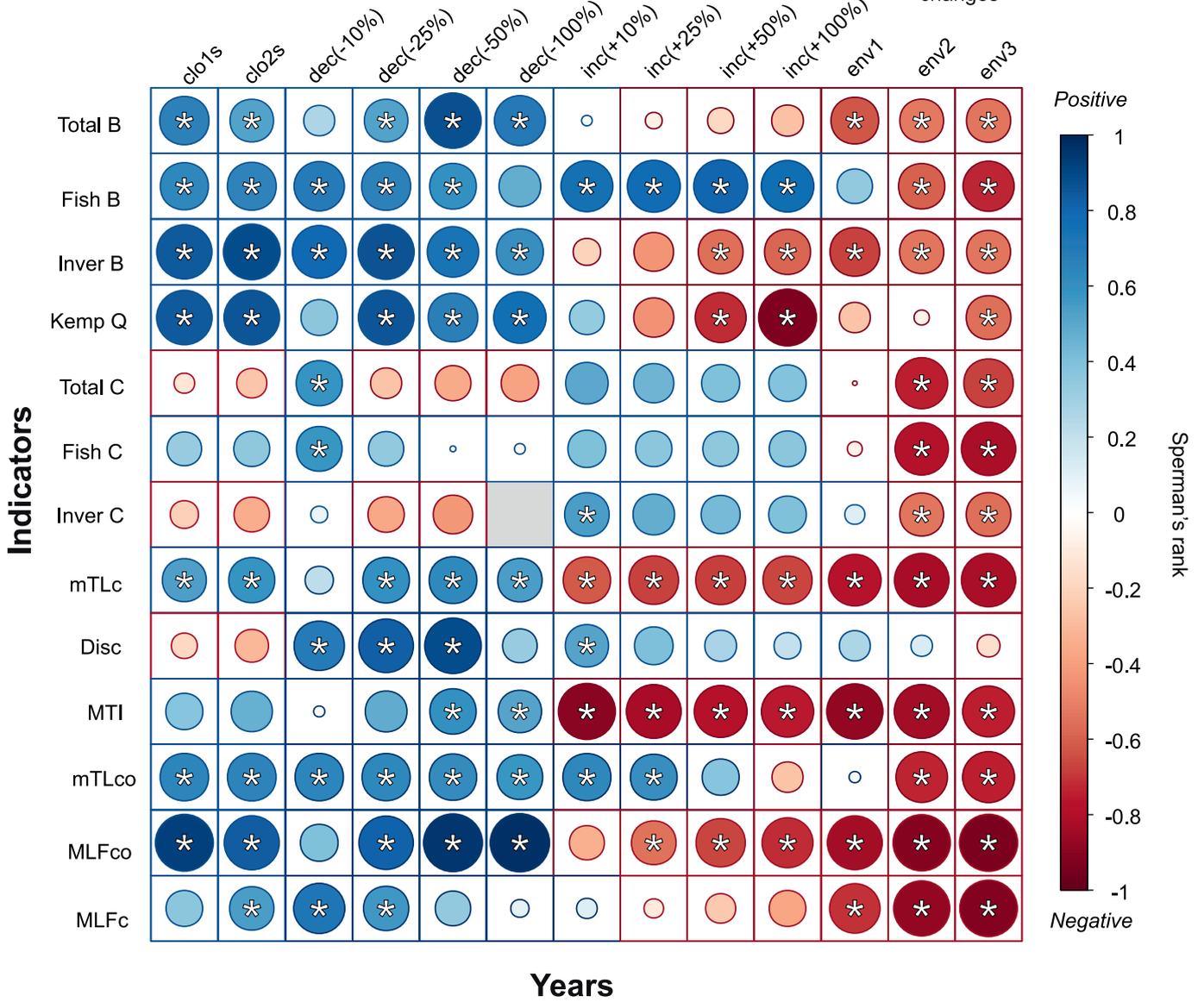
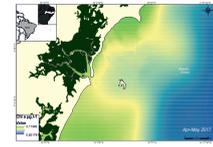
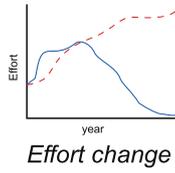
Xip.kro

*clo1s*  
*clo2s*  
*dec(-10%)*  
*dec(-25%)*  
*dec(-50%)*  
*dec(-100%)*  
*inc(+10%)*  
*inc(+25%)*  
*inc(+50%)*  
*inc(+100%)*

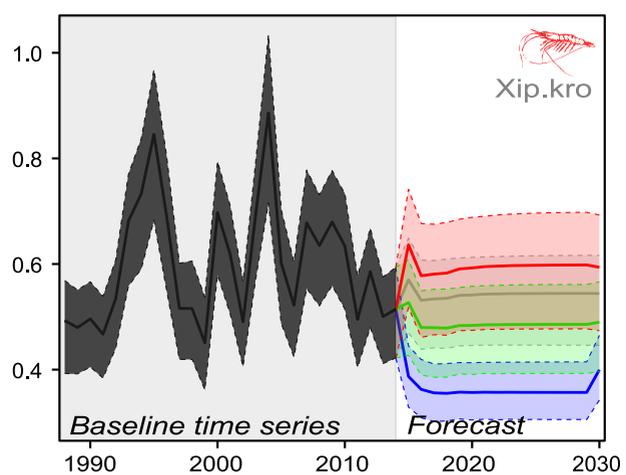
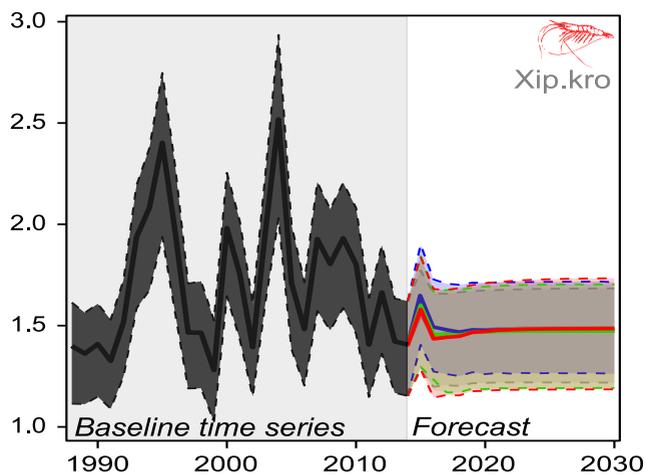
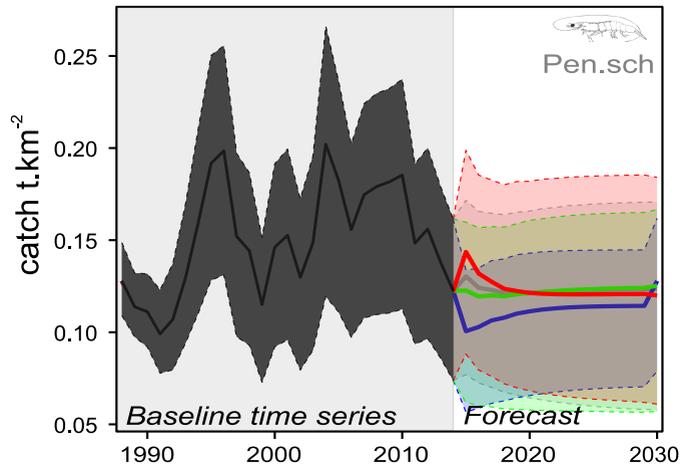
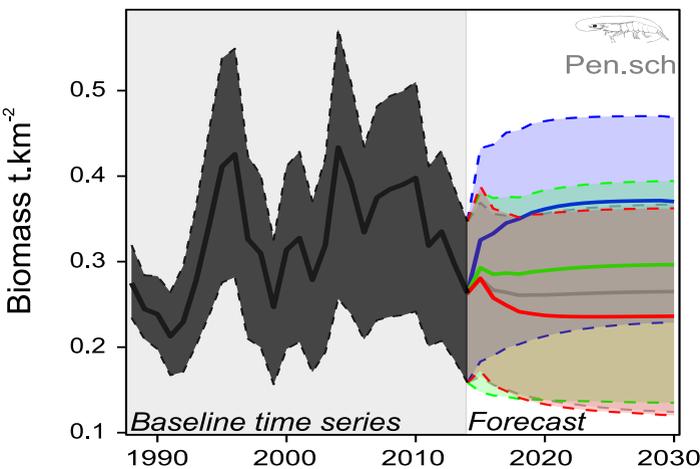
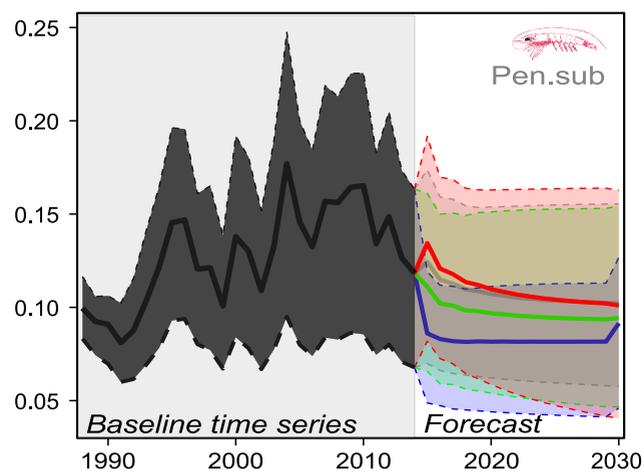
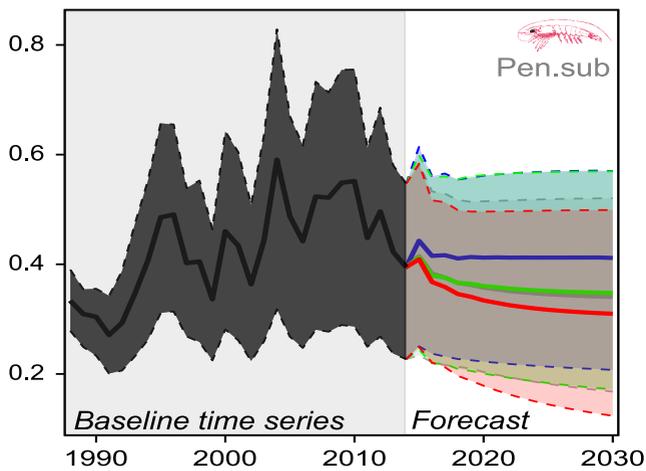
*env1*  
*env2*  
*env3*

<i>clo1s</i>			
<i>clo2s</i>			
<i>dec(-10%)</i>			
<i>dec(-25%)</i>			
<i>dec(-50%)</i>			
<i>dec(-100%)</i>			
<i>inc(+10%)</i>			
<i>inc(+25%)</i>			
<i>inc(+50%)</i>			
<i>inc(+100%)</i>			
<i>env1</i>			
<i>env2</i>			
<i>env3</i>			

Primary production



Scenarios — env1 — inc(+10%)+env1 — clo1s+env1 — dec(-10%)+env1



Year

	clo1s	clo2s	inc(+10%/a)	inc(+25%/a)	inc(+50%/a)	inc(+100%/a)	dec(-10%/a)	dec(-25%/a)	dec(-50%/a)	dec(-100%/a)	env1	env2	env3	clo1s+env1	inc(+10%/a)+env1	dec(-10%/a)+env1
Trophic level> 3.25 Biomass	≡	≡	≡	≡	≡	⦿	≡	≡	⦿	⦿	⦿	⦿	⦿	≡	⦿	⦿
Trophic level< 3.25 Biomass	⦿	⦿	⦿	⦿	⦿	⦿	⦿	⦿	⦿	⦿	≡	≡	⦿	⦿	≡	≡
Shrimp biomass	⦿⦿⦿	⦿⦿⦿	⦿	⦿⦿⦿	⦿⦿⦿⦿	⦿⦿⦿⦿	⦿⦿	⦿⦿⦿	⦿⦿⦿⦿	⦿⦿⦿⦿	⦿	⦿⦿⦿	⦿⦿⦿⦿	⦿⦿	⦿	≡
Mean TL of the ecosystem	≡	≡	≡	≡	≡	≡	≡	≡	≡	≡	≡	≡	⦿	≡	≡	≡
Trophic level of catch	≡	≡	≡	≡	≡	⦿	≡	≡	≡	⦿	≡	≡	≡	⦿⦿⦿	⦿⦿⦿⦿	⦿⦿⦿⦿
Total catches	⦿⦿⦿	⦿⦿⦿	⦿⦿	⦿⦿⦿	⦿⦿⦿⦿	⦿⦿⦿⦿	⦿	⦿⦿	⦿⦿⦿	⦿⦿⦿⦿	⦿⦿	⦿⦿⦿	⦿⦿⦿⦿	⦿⦿⦿	⦿⦿	⦿⦿
Shrimp catches	⦿⦿⦿⦿	⦿⦿⦿⦿	⦿⦿	⦿⦿⦿	⦿⦿⦿⦿	⦿⦿⦿⦿	⦿	⦿⦿	⦿⦿⦿	⦿⦿⦿⦿	⦿⦿⦿	⦿⦿⦿⦿	⦿⦿⦿⦿	⦿⦿⦿⦿	⦿⦿	⦿⦿
Bycatch fish catches (TL>3,5)	⦿⦿	⦿	⦿	⦿⦿	⦿⦿⦿	⦿⦿	≡	⦿	⦿⦿	⦿⦿⦿	⦿	⦿⦿	⦿	⦿⦿	⦿	⦿
Bycatch fish catches (TL<3,5)	⦿⦿⦿⦿	⦿⦿⦿	⦿⦿	⦿⦿⦿	⦿⦿⦿⦿	⦿⦿⦿⦿	⦿⦿	⦿⦿⦿	⦿⦿⦿⦿	⦿⦿⦿⦿	⦿	⦿⦿⦿	⦿	⦿⦿⦿	⦿⦿	⦿⦿



The indicator remain constant



Relative increase or decrease of the indicator less than 5% compared to the reference scenario



Relative increase or decrease of the indicator between 5% and 10% compared to the reference scenario



Relative increase or decrease of the indicator between 10% and 20% compared to the reference scenario



Relative increase or decrease of the indicator more than 20% compared to the reference scenario

Table 1. Fishing management scenarios simulated to Barra of Sirinhaém Ecosim model between 2015 to 2030.

Scenarios	Description	Axis	Justification	Source
1 Stand	Baseline model without change of fishing months		-	-
2 clo1s	Included closed fishing season based on the peak of reproduction and recruitment of the shrimp species (4 months)	Temporal	Shrimp and <i>bycatch</i> species present specific breeding and recruitment seasons from December to July	1, 2, 3
3 clo2s	Included closed fishing season based on the peak of reproduction and recruitment of the shrimp and <i>bycatch</i> species (3 months)			
4 inc(+10%)	Increasing fishing effort by 10, 25, 50 and 100%	Effort	Stock status based in traditional approaches indicates that the fleet exploits shrimp species close or at maximum exploitation rates	1
5 inc(+25%)				
6 inc(+50%)				
7 inc(+100%)				
8 dec(-10%)				
9 dec(-25%)	Decreasing fishing effort by 10, 25, 50 and 100% (no fishing)			
10 dec(-50%)				
11 no_fishing				
12 dec(-100%)	Decreasing primary production (PP) by 2, 5 and 10% respectively	Environmental	Biomass and catch patterns of shrimp and <i>bycatch</i> species are associated to environmental drivers (e.g., chlorophyll-a and rainfall).	4
13 env1				
14 env2				
15 env3	Scenarios of best balancing conditions, in terms of catch and conservation indicators, combined with reducing primary productivity.	Minimise or maximize the impacts obtained by environmental change		
16 clos + env				
17 inc + env				
18 dec + env				

1-Lopes et al. (2017), Peixoto et al. (2018) and Silva et al. (2016);2- Normative N°14 MMA/2004;3-Silva Júnior et al. (2015) and Eduardo et al. (2018); 4- Blanchard et al. (2012); Krumhardt et al. (2017); Lotze et al. (2019); Reay et al. (2007)

Table 2. Ecological indicators considered to evaluate the changes on the ecosystem over time.

Code	Ecosystems Attributes	Description	Goal	Units	Reference
Total B	Total biomass	Sum of the biomass of all groups in the ecosystem (excluding detritus)	Quantify general changes at the ecosystem level	t km <sup>-2</sup>	1
Fish B	Biomass (B) of fish	Sum of the biomass of fish species	Evaluate the dynamics of fish group	t km <sup>-2</sup>	1
Inver.B	Biomass (B) of invertebrate	Sum of the biomass of invertebrate species	Evaluate the dynamics of invertebrates in response to fishing and predation	t km <sup>-2</sup>	1
Kemp.Q	Kempton's biodiversity index (Q)	Represents the slope of the cumulative species abundance curve	Measure the effects of mortality on species diversity	-	2
Total C	Total Catch (C)	Sum of the catch of all species in the ecosystem	Represent the dynamics of fisheries	t km <sup>-2</sup> y <sup>-1</sup>	1
Fish C	Catch (C) of all fish	Sum of the catch of all fish species	Represent the dynamics of fish fisheries	t km <sup>-2</sup> y <sup>-1</sup>	1
Inver.C	Catch (C) of all invertebrate	Sum of the catch of all invertebrate species	Represent the dynamics of invertebrate fisheries	t km <sup>-2</sup> y <sup>-1</sup>	1
Disc	Total discarded catch	Sum of the catch of all species that are discarded	Assess the impact of fisheries with discards	t km <sup>-2</sup> y <sup>-1</sup>	3
mTLc	Trophic level (TL) of the catch	Represents the mean trophic level only of species catch	Evaluate the fishing fleet strategy	-	4
mTLco	Trophic level (TL) of the community (including all organisms)	Represents the mean trophic level weighted by biomasses of all species in the ecosystem	Evaluate the fishing fleet strategy	-	5
MTI	Marine trophic index (including organisms with TL ≥ 3.25)	Represents the mean trophic level only of species catch with a trophic level ≥ 3.25	Evaluate the fishing effect in top food-web	-	6
MLFco	Mean length (ML) of fish community	Represents the mean length weighted by biomasses only of fish species	Observe the trends or change of fish size in the ecosystem	cm	7
MLFc	Mean length (ML) of fish catch	Represents the mean length only of fish species	Represent the size dynamics catch species in the ecosystem	cm	7

1 : Hilborn and Walters (1992); 2 : Ainsworth and Pitcher (2006) ; 3 : Zeller et al. (2017) ; 4: Gascuel et al. (2011) ;5 : Shannon et al. (2014); 6 :Pauly and Watson (2005) 7 :Ravard et al., (2014) and Rochet and Trenkel (2003)

Table 3. Basic inputs and estimated outputs (in bold) of the groups of the Barra of Sirinhaém Ecopath model (BSIR), Pernambuco, northeast of Brazil. TL: trophic level; B: biomass; P/B: production–biomass ratio; Q/B: consumption–biomass ratio; EE: ecotrophic efficiency and Landings (t.km<sup>-2</sup>). See Table S1 to group name details.

	Group name	TL					Landings (t.km <sup>-2</sup> )		
			B (t.km <sup>-2</sup> )	P/B (year <sup>-1</sup> )	Q/B (year <sup>-1</sup> )	EE	Trawling	Gillnet	Line
1	Macroalgae	<b>1</b>	7.370	13.25	-	<b>0.75</b>	-	-	-
2	Phytoplankton	<b>1</b>	2.200	682.00	-	<b>0.32</b>	-	-	-
3	Zooplankton	<b>2.05</b>	3.480	50.21	150.65	<b>0.69</b>	-	-	-
4	Polychaeta	<b>2.13</b>	<b>3.596</b>	3.60	25.52	0.95	-	-	-
5	Amphipoda	<b>2.23</b>	<b>3.607</b>	6.64	34.51	0.95	-	-	-
6	Blue crabs	<b>2.92</b>	<b>0.880</b>	2.00	8.00	0.9	-	-	-
7	Crabs	<b>2.7</b>	<b>1.860</b>	5.23	10.82	0.95	-	-	-
8	Isopoda	<b>2.05</b>	<b>0.706</b>	13.75	34.51	0.95	-	-	-
9	Pen.sub	<b>2.79</b>	0.208	5.25	13.45	<b>0.94</b>	0.1075	-	-
10	Pen.sch	<b>2.3</b>	0.230	3.75	13.45	<b>0.88</b>	0.1770	-	-
11	Stomatopoda	<b>2.69</b>	<b>0.597</b>	23.68	85.27	0.95	-	-	-
12	Xip.kro	<b>2.52</b>	1.533	10.40	26.00	<b>0.99</b>	0.5013	-	-
13	Other crustaceans	<b>2.61</b>	<b>1.512</b>	5.80	19.20	0.95	-	-	-
14	Squids	<b>3.44</b>	0.18	6.40	36.50	<b>0.86</b>	-	-	-
15	Flatfish	<b>3.37</b>	0.087	3.07	11.26	<b>0.41</b>	0.0018	<0.0001	-
16	Anc.spi	<b>3.15</b>	0.012	2.68	13.30	<b>0.92</b>	0.0003	-	-
17	Asp.lun	<b>2.23</b>	0.042	2.27	12.50	<b>0.65</b>	0.0012	-	-
18	Bag.mar	<b>3.43</b>	0.183	2.30	8.49	<b>0.54</b>	0.0059	0.0067	0.0554
19	Car.hip	<b>3.96</b>	0.0001	0.46	6.66	<b>0.61</b>	<0.0001	-	-
20	Cet.ede	<b>2.00</b>	0.072	2.29	53.42	<b>0.63</b>	0.0022	-	-
21	Chi.ble	<b>3.06</b>	0.135	3.05	20.19	<b>0.99</b>	0.0045	-	-
22	Con.nob	<b>3.59</b>	0.164	3.22	8.78	<b>0.04</b>	0.0059	0.0031	0.0009
23	Cyn.vir	<b>3.82</b>	0.027	2.53	5.00	<b>0.86</b>	0.0010	0.0005	0.0020
24	Dia.sp	<b>2.91</b>	0.027	2.90	10.61	<b>0.47</b>	0.0005	-	0.0001
25	Euc.sp	<b>3.11</b>	0.042	1.33	12.84	<b>0.36</b>	0.0008	0.0004	0.0001
26	Ham.cor	<b>3.54</b>	0.366	2.48	11.19	<b>0.11</b>	0.0140	-	0.0017
27	Hyp.gut	<b>3.51</b>	0.015	0.35	2.68	<b>0.17</b>	0.0004	-	-
28	Iso.par	<b>3.72</b>	0.246	1.93	8.13	<b>0.35</b>	0.0082	-	-
29	Lar.bre	<b>3.5</b>	0.275	2.49	8.48	<b>0.47</b>	0.0100	0.0165	0.0006
30	Snappers	<b>3.61</b>	0.006	0.27	6.47	<b>0.57</b>	0.0001	-	-
31	Lyc.gro	<b>3.11</b>	0.068	3.03	20.69	<b>0.76</b>	0.0025	0.0004	0.0006
32	Mac.anc	<b>3.91</b>	0.051	1.75	8.20	<b>0.97</b>	0.0020	0.0018	0.0786
33	Met.ame	<b>3.15</b>	0.140	2.15	7.19	<b>0.56</b>	0.0039	0.0002	0.0323
34	Mic.fur	<b>2.25</b>	0.162	2.69	6.90	<b>0.29</b>	0.0033	0.0051	0.0207
35	Neb.mic	<b>3.26</b>	0.037	1.44	8.50	<b>0.76</b>	0.0011	-	0.0017
36	Odo.muc	<b>2.21</b>	0.257	4.58	17.70	<b>0.82</b>	0.0087	-	-
37	Oph.pun	<b>3.42</b>	0.077	1.93	10.88	<b>0.44</b>	0.0021	-	-
38	Par.bra	<b>3.12</b>	0.162	3.89	8.70	<b>0.87</b>	0.0060	0.0018	-
39	Pel.har	<b>2.81</b>	0.783	2.90	81.00	<b>0.72</b>	0.0268	-	0.0004
40	Pol.vir	<b>3.21</b>	0.083	3.83	12.05	<b>0.21</b>	0.0031	0.0004	-
41	Sph.gua	<b>4.07</b>	0.028	0.49	4.65	<b>0.99</b>	0.0009	0.0001	0.0093
42	Ste.bra	<b>3.61</b>	0.047	2.19	12.90	<b>0.89</b>	0.0016	-	-
43	Ste.mic	<b>3.36</b>	0.396	5.47	11.07	<b>0.35</b>	0.0148	-	-
44	Ste.ras	<b>3.47</b>	0.148	3.56	8.09	<b>0.83</b>	0.0062	<0.0001	0.0002
45	Ste.ste	<b>3.2</b>	0.094	2.11	11.60	<b>0.46</b>	0.0031	-	-
46	Sym.tes	<b>3.17</b>	0.031	1.27	10.51	<b>0.83</b>	0.0012	-	-
47	Tri.lep	<b>4.2</b>	0.139	1.68	3.62	<b>0.51</b>	0.0023	0.0001	0.0687
48	Birds	<b>4.26</b>	0.015	5.40	80.00	<b>0</b>	-	-	-
49	Seaturtles	<b>4.2</b>	0.003	0.15	22.00	<b>0</b>	-	-	-
50	Detritus	<b>1</b>	-	-	-	<b>0.17</b>	-	-	-

Table 4. Ecosystem attributes, ecological and flow indicators of the Barra of Sirinhaém Ecopath model, Pernambuco, northeast of Brazil.

Parameters	Value	Units
<b>Ecosystem properties</b>		
Sum of all consumption (TC)	1029.88	tkm <sup>-2</sup> y <sup>-1</sup>
Sum of all exports (TE)	1182.09	tkm <sup>-2</sup> y <sup>-1</sup>
Sum of all respiratory flows (TR)	416.14	tkm <sup>-2</sup> y <sup>-1</sup>
Sum of all flows into detritus (TD)	1432.14	tkm <sup>-2</sup> y <sup>-1</sup>
Total system throughput (TST)	4060.26	tkm <sup>-2</sup> y <sup>-1</sup>
Sum of all production (TP)	1886.05	tkm <sup>-2</sup> y <sup>-1</sup>
Mean trophic level of the catch (TLc)	2.89	–
Gross efficiency (catch/net p.p.)	0.00085	–
Calculated total net primary production (TNPP)	1598.09	tkm <sup>-2</sup> y <sup>-1</sup>
Net system production (NSP)	1181.95	tkm <sup>-2</sup> y <sup>-1</sup>
Total biomass (excluding detritus) (TB)	32.38	t.km <sup>-2</sup>
Total catch (Tc)	1.37	tkm <sup>-2</sup> y <sup>-1</sup>
<b>Ecosystem maturity</b>		
Total primary production/total respiration (TPP/TR)	3.84	–
Total primary production/total biomass (TPP/TB)	49.36	–
Total biomass/total throughput (TB/TST)	0.008	y <sup>-1</sup>
<b>Food web structure</b>		
Connectance Index (CI)	0.26	–
System Omnivory Index (SOI)	0.27	–
Finn's Cycling Index (FCI)	3.76	% TST
Finn's mean path length (FML)	2.54	-
Ascendancy (AS)	30.05	%
System Overhead (SO)	69.95	%
Herbivore/Detritivore rate (H/D)	2.21	–
<b>Model reability</b>		
Ecopath pedigree index	0.65	–
<b>Transfer efficiency total</b>	18.14	%