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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.

Highlights

► The controlled reduction of trawler can maintain the same level of landings. ► Closed season has significant losses in catches of high market-value species. ► Trawling reduction close to 10 % maintains the catch without harming the ecosystem. ► Intense negative effects were reported with the decrease of the Primary Production. ► Adverse effects of PP reduction can be minimized by controlling the trawl activity.

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

1. Introduction

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

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

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

Frameworks and approaches have been developed to help evaluate the fishing impacts of multi-factor scenarios (Goti-Aralucea, 2019; Jones et al., 2018; Rezende et al., 2019; Rice, 2000), since human activities, marine organisms, and ecosystem changes interact and influence one another (Corrales et al., 2018). To address this challenge, a more comprehensive analysis and management of human activities and the environment is needed in accordance with an ecosystem-based management approach (Rosenberg and McLeod, 2005). In this context, strategies based on the principles of adaptive co-management and the Ecosystem Approach to Fisheries (EAF) (Guanais et al., 2015) have become very promising in recent years (Serafini et al., 2017). The EAF is an effective framework for ecosystem management that considers "the knowledge and uncertainties about biotic, abiotic, and human components of ecosystems and their interactions, applying an integrated approach to fisheries within ecologically meaningful boundaries" (Garcia et al., 2003).

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

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

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

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

2. Methods

2.1. Study area

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

2.2. Trawl Fishery

Bottom trawling in the BSIR of north-eastern Brazil, the main fishery assessed in this study, has the largest and most productive motorized fishing fleet in Pernambuco, corresponding to 50% of the shrimp production (Tischer and Santos, 2003), being an important source of income and food for the local population (Lira et al., 2010). This fishery is operated with fleet of twelve boats, from 1.5 to 3.0 miles off the coast, mainly between 10 and 20 m depth, with set duration of 4 to 8 hours and boat velocity varying between 2 and 4 knots. Boats often have 8-10 m of length, horizontal opening net of 6.1 m, mesh sizes of body and cod end of 30 mm and 25 mm, respectively. In Brazil, the regulations of this modality of fishery mostly involve a closed season (Dias-Neto, 2011; Santos, 2010) and fishermen and fisherwomen have the right to economic assistance during this time. However, despite its high relevance, Pernambuco is the only state in the region with no regulation. Shrimps of the Penaeidae family are the main targets: the pink shrimp (*Penaeus subtilis*), white shrimp (*Penaeus schmitti*), and seabob shrimp (*Xiphopenaeus kroyeri*) and the proportion of fish bycatch is 0.39 kg of fish captured for each 1 kg of shrimp (Silva Júnior et al., 2019). The fish bycatch is composed of 51 species, 38 genera and 17 families (Silva Júnior et al., 2019). The target shrimps and the most relevant non-target species were selected for model construction (Table S1).

2.3. Modelling approach

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

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

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

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

where $\frac{dBi}{dt}$ is the growth rate in terms of biomass (B_i) over time for group i, g_i is the net growth efficiency (production/consumption ratio), I_i is the immigration rate, M_i is the natural mortality rate (unrelated to predation), F_i is the fishing mortality rate and e_i is the emigration rate (Christensen et al., 2008). Q_{ij} and Q_{ji} are the total consumption by group i and the predation by all predators on group i, respectively. The consumption rate calculations are based on the "foraging arena" theory (Ahrens et al., 2012; Walters et al., 1997) in which biomass B_i of prey is divided into two fraction: available prey (vulnerable) and unavailable prey (invulnerable fraction) which depend of the transfer rate (v_{ij}). The vulnerability parameter in Ecosim represent the degree to which an increase in predator biomass will cause in predation mortality for a given prey, determining the food web controls (top-down vs. bottom-up) (Christensen et al., 2008). Values close to 1 (low vulnerability) lead to bottom-up control, since the growth of the predator biomass will not cause a substantial increase in predation mortality on its prey. In the opposite, vulnerability values higher than 10 may lead to top-down control in the food web, and the positive variation in predator biomass causes significant impacts in the biomass of its prey due to predation mortality (Christensen et al., 2008).

2.4. Model Fitting

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

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

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

2.5. Measuring the uncertainty

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

2.6. Scenario simulation

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

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

2.7. Indicator analysis

The absolute values of the biomasses and catches for each trophic group in each simulated scenario from 2015 – 2030 were compared to the baseline model of constant effort (scenario - stand). The average ratio values (e.g., final biomass / initial biomass) for each scenario are represented by colour heatmaps indicating the increases or decreases in the biomass and catches from 2015 to 2030. Additionally, several indicators associated with the biomass, catch, size and trophic level were assessed to evaluate the response of the ecosystem to the different simulations over time (Table 2) (Coll and Steenbeek, 2017). These indicators were then correlated over the period from 2015 to 2030 by the Spearman's rank correlation (see Corrales et al. (2018); Piroddi et al. (2017)).

3. Results

3.1. Ecopath model

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

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

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

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

3.2. Historical ecosystem state

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

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

3.3. Back to the future

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

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

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

The ecosystem indicators calculated from the Ecosim outputs showed similar patterns in the scenarios temporarily closed to trawling. A significant increasing trend (*t*-test; $p<0.05$) in biomass-based indicators (Total B, Fish B and Inver B), such as trophic (mTLc and MTI) and size-based (MLFc) indexes (Fig. 7), was projected. In addition, those indicators increased over time with the effort reduction, except for the total and invertebrate catches for dec(-25%) to dec(-100%) scenarios (Fig. 7).

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

3.4. *Cumulative effects of the PP anomaly and FMS*

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

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

3.5. *Scenarios as decision support tools*

In general, the target and some non-target species biomasses benefit from decreased fishing pressure, but the catches are reduced. However, a controlled increase in trawling up to 10% led to promising results in terms of catches and biomass level maintenance. Our findings indicated that the effort-reduction conservation measures evaluated here (e.g., clo2s and dec(-50%)) have positive impacts on ecosystem health indicators (e.g., high TL biomasses and shrimp, mean trophic level of the ecosystem); however, they have a negative effect on catches at different trophic levels (Fig. 9). The opposite trend was noted with increased bottom trawling activity (Fig. 9). Adverse effects on all aspects of conservation and exploitation were reported with the environmental simulations (PP decrease on 2%) of the near future. These negative conditions resulting from PP were minimized with the implementation of management measures, especially with a 10% trawling reduction (Fig.9).

4. Discussion

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

4.1. Ecopath model

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

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

Energy flow in the food web was based mainly from the primary producers, while the indicators of the ecosystem structure in the BSIR model were similar to those of the others coastal models (Geers et al., 2016), with values of respiration and consumption lower than exports and detritus values, and a high value of total primary production/total respiration (TPP/TR). The BSIR model had higher Overhead (SO) than Ascendancy (AC), and low values of connectance index (CI) and Finn's Cycling Index (FCI), similar to the other coastal ecosystems, such as the Isla del Coco, Costa Rica (Fourriére et al., 2019), coral reef Media Luna, Honduras (Cáceres et al., 2016) and the temperate coastal lagoon Ria de Aveiro, Portugal (Bueno-Pardo et al., 2018). In mature systems, the Primary Production rate (TPP) is similar to the respiration flow (close to 1), while the total biomass of the ecosystem is larger than the TPP (Christensen et al., 2005; Odum, 1969), causing an accumulation of biomass within the system compared to the productivity (Corrales et al., 2017). PP-based ecosystems, with relatively low CI and FCI, suggests a low trophic complexity and reduced resilience level (Odum, 1969). These indicators are considered to be good indexes of the food web complexity, robustness and, indirectly, of the ecosystem maturity and stability (Christensen and Pauly, 1992; Saint-Béat et al., 2015). However, due to the dependence of this indexes to model structure (number of trophic compartments), they often do not reflect the structure of the ecosystem with accuracy (Bueno-Pardo et al., 2018; Christensen et al., 2005; Finn, 1976).

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

4.2. Ecosystem historical state

The Ecosim model was able to reproduce the catches and their trends for shrimp species (*P. subtilis, P. schmitti* and *X. kroyeri*) given our available time series data. The trends in our model showed the bottom-up role provided by environmental variability in the function and structure of the ecosystem. Similar results were obtained from other studies in the Mediterranean Sea (Coll et al., 2016; Macias et al., 2014), west coast of Scotland (Serpetti et al., 2017), West Florida, USA (Chagaris et al., 2015) and Barra del Chuy, Uruguay (Lercari et al., 2018). The nutrient availability, and consequently the primary production, is considered a key controller of biological processes, driving bottom-up processes in the food web (Piroddi et al., 2017). In the BSIR region, the species abundance is strongly associated with environmental drivers (Silva Júnior et al., 2019), for example, the highest chlorophyll concentration in the rainy season in shallow waters near the mouth of river, where the primary fisheries operate, and the sea surface temperature (SST) impact on shrimp abundance and consequently the fishing productivity (Lopes et al., 2018).

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

4.3. Fishing management scenarios (FMS) for the future

Banning trawling fishing as a management measure, whether for a time or an area, has promoted improvements in the ecosystem, with shrimp population recovery, reduced bycatch and benefits for birds, mammals and most fish stocks (Heath et al., 2014; Joseph John et al., 2018). These positive effects through the food web are not always directly related to decreases in anthropic activities, but could also cause indirect consequences to prey-predator relationships (Kempf et al., 2010; Meekan et al., 2018). Conversely, increased fishing efforts may cause significant negative impacts over time on the target species biomass (Ngor et al., 2018; Szuwalski et al., 2017), also indirectly affecting other groups in the food web (Gasche and Gascuel, 2013). In our long-term analysis, when considering the closed fishing period and effort reduction, the model predicted the increased abundance of several bycatch species as well as that of *P. subtilis* and *P. schmitti*. However, the fishing increase caused a decline in biomass for these groups, in the more intense fishing scenarios. For example, a slight decrease in bycatch biomass, primarily in predators of invertebrates, engendered a cascade effect in the food web, increasing the biomass of benthic invertebrates (except for *P. subtilis*, *P. schmitti* and *X. kroyeri*), zooplankton and primary producers (phytoplankton and macroalgae). In addition, the target species catches declined during the simulated season that was closed to bottom trawling. Shifts in fishing effort and catchability, fluctuations in population abundance, market-related factors and environmental change influence catch rates and may confound the potential effects of the management measures (Kerwath et al., 2013; Stefansson and Rosenberg, 2005). Nevertheless, an important step to investigating the impact of management strategies on conservation or environmental recovery includes the insertion and evaluation of multiple species at several trophic levels and their trophic interactions (Baudron et al., 2019; Christensen and Walters, 2005).

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

Temperature change simulations are most often reported, indicating the reduction in both the number of species and the trophic interactions in the ecosystem (Gibert, 2019; Petchey et al., 2010; Régnier et al., 2019). Doubleday et al. (2019) observed that the enrichment of CO_2 responsible for ocean acidification intensified the bottom-up and top-down control. The effects of warming and acidification is noted in Goldenberg et al. (2018) as a driver of changes in consumer assemblages in future oceans. Moreover, Nagelkerken et al. (2020) indicate cumulative and adverse changes in the whole trophic structure, emphasizing that the adaptive capacity of ecosystems with unbalanced food web to global change is weak and ecosystem degradation is likely. Specifically, in the BSIR, the environment and shrimp fishery dynamics are influenced by primary production fluctuation as controlled by precipitation patterns, which directly affect the fishing activity. The major importance of the temperature and precipitation in shrimp productivity is also reported by Lopes et al. (2018), highlighting that these fisheries could collapse in a warmer and drier future.

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

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

4.4. Uncertainty and limitations in BSIR

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

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

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

4.5. Management support tool

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

Some aspects of the BSIR that may be shared with other locations should be considered within the management framework. The shrimp fishing dynamics are well-defined yearly. Shrimp and bycatch are abundant and are mainly caught during the periods of highest primary production as a consequence of the rainfall (Silva Júnior et al., 2019). At the opposite, the lowest shrimp and bycatch abundances and catches are related to dry periods, which correspond to the peak of reproduction of these species (Eduardo et al., 2018; Lira et al., 2019; Lopes et al., 2017; Peixoto et al., 2018; Silva et al., 2016; Silva Júnior et al., 2015). Consequently, during the dry season, the trawling activities are basically inactive due to the decline in production (Eduardo et al., 2016; Silva Júnior et al., 2019; Tischer and Santos, 2003), barely covering the operating costs of the fishery. This phenomenon could be considered as a "*natural closed season*", or the economic unprofitability due to low shrimp and bycatch abundance that regulates the fishing activities. In addition to the importance of the target species, knowledge of the bycatch destination is crucial during the management process. In the BSIR, the incidental catch primarily removes juveniles (Eduardo et al., 2018; Lira et al., 2019; Silva Júnior et al., 2015), which are often consumed by the fishermen and local community as additional sources of food and income as a *byproduct* (Silva Júnior et al., 2019). Thus, a major decline in the capture of bycatch with the implementation of a management measure may cause negative effects from nutritional, economic and social viewpoints. In this way, the impact of the fishing activities on the ecosystems appears to be counter-balanced by the beneficial role of the bycatch in the local community. Although we are aware of the importance of this fishery bycatch for the local food security, we cannot disregard the fact of several fish species of bycatch (e.g., croaker, weakfish, jacks, snappers) has the longer life history, low spawning potential, and high commercial value when adults, and therefore need to be considered in future evaluations, including new information incorporating the socio-economic aspect.

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

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. However, other management measures could be incorporated into the model and better evaluated in the future, such as the application of Bycatch Reduction Devices (e.g., fisheye, grid and square mesh) used to exclude small fish, juveniles of species of high commercial value (e.g., croaker, weakfish, jacks, snappers) and other non-target species from the trawlers (Broadhurst, 2000; Eayrs, 2007; Larsen et al., 2017); an increase in the area and/or improvement in enforcing the existing Marine Protected Areas (e.g., MPA Guadalupe) as well as including other environmental drivers from the IPCC predictions (e.g., RPC4.5 and RPC8.5) (Reay et al., 2007). These measures would enable important and useful insights on the direct and indirect effects of climate changes, other management policies, and possible trade-offs at the ecosystem level. However, any management measures to be considered as successful to mitigate the fishing impacts depend on interactions among highly heterogeneous social, political, economic and conservation factors, which are especially relevant in small-scale fisheries such as our case study fishery.

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REFERENCES

Abdou, K., Halouani, G., Hattab, T., Romdhane, M.S., Frida Ben, Le Loc'h, F., 2016. Exploring the potential effects of marine protected areas on the ecosystem structure of the Gulf of Gabes using the Ecospace model. Aquat. Living Resour. 29, 202. https://doi.org/10.1051/alr/2016014

Adebola, T., Mutsert, K., 2019. Spatial simulation of redistribution of fishing effort in Nigerian coastal waters using Ecospace. Ecosphere 10, e02623. https://doi.org/10.1002/ecs2.2623

Ahrens, R.N.M., Walters, C.J., Christensen, V., 2012. Foraging arena theory. Fish Fish. 13, 41–59. https://doi.org/10.1111/j.1467-2979.2011.00432.x

Ainsworth, C.H., Pitcher, T.J., 2006. Modifying Kempton's species diversity index for use with ecosystem simulation models. Ecol. Indic. 6, 623–630. https://doi.org/10.1016/j.ecolind.2005.08.024

Alexander, K.A., Heymans, J.J., Magill, S., Tomczak, M.T., Holmes, S.J., Wilding, T.A., 2014. Investigating the recent decline in gadoid stocks in the west of Scotland shelf ecosystem using a foodweb model. ICES J. Mar. Sci. 72, 436–449. https://doi.org/10.1093/icesjms/fsu149

Andrew, N.L., Béné, C., Hall, S.J., Allison, E.H., Heck, S., Ratner, B.D., 2007. Diagnosis and management of small-scale fisheries in developing countries. Fish Fish. 8, 227–240. https://doi.org/10.1111/j.1467-2679.2007.00252.x

APAC, 2015. Agência Pernambucana de águas e clima [WWW Document]. URL http://www.apac.pe.gov.br/meteorologia/monitoramento-pluvio.php (accessed 2.2.17).

Baudron, A.R., Serpetti, N., Fallon, N.G., Heymans, J.J., Fernandes, P.G., 2019. Can the common fisheries policy achieve good environmental status in exploited ecosystems: The west of Scotland demersal fisheries example. Fish. Res. 211, 217–230. https://doi.org/10.1016/j.fishres.2018.10.024

Bauer, B., Horbowy, J., Rahikainen, M., Kulatska, N., Müller-Karulis, B., Tomczak, M.T., Bartolino, V., 2019. Model uncertainty and simulated multispecies fisheries management advice in the Baltic Sea. PLoS One 14, 1–22. https://doi.org/10.1371/journal.pone.0211320

Bellido, J.M., Santos, M.B., Pennino, M.G., Valeiras, X., Pierce, G.J., 2011. Fishery discards and bycatch: Solutions for an ecosystem approach to fisheries management? Hydrobiologia 670, 317–333. https://doi.org/10.1007/s10750-011-0721-5

Bentley, J.W., Hines, D., Borrett, S., Serpetti, N., Fox, C., Reid, D.G., Heymans, J.J., 2019. Diet uncertainty analysis strengthens model-derived indicators of food web structure and function. Ecol. Indic. 98, 239–250. https://doi.org/10.1016/j.ecolind.2018.11.008

Bentorcha, A., Gascuel, D., Guénette, S., 2017. Using trophic models to assess the impact of fishing in the Bay of Biscay and the Celtic Sea. Aquat. Living Resour. 30, 7. https://doi.org/10.1051/alr/2017006

Blanchard, J.L., Jennings, S., Holmes, R., Harle, J., Merino, G., Allen, J.I., Holt, J., Dulvy, N.K., Barange, M., 2012. Potential consequences of climate change for primary production and fish production in large marine ecosystems. Philos. Trans. R. Soc. B Biol. Sci. 367, 2979–2989. https://doi.org/10.1098/rstb.2012.0231

Bornatowski, H., Angelini, R., Coll, M., Barreto, R.R.P., Amorim, A.F., 2017. Ecological role and historical trends of large pelagic predators in a subtropical marine ecosystem of the South Atlantic. Rev. Fish Biol. Fish. 28, 241–259. https://doi.org/10.1007/s11160-017-9492-z

Broadhurst, M.K., 2000. Modifications to reduce bycatch in prawn trawls: A review and framework for development. Rev. Fish Biol. Fish. 10, 27–60. https://doi.org/10.1023/A:1008936820089

Brown, C.J., Fulton, E.A., Hobday, A.J., Matear, R.J., Possingham, H.P., Bulman, C., Christensen, V., Forrest, R.E., Gehrke, P.C., Gribble, N.A., Griffiths, S.P., Lozano-Montes, H., Martin, J.M., Metcalf, S., Okey, T.A., Watson, R., Richardson, A.J., 2010. Effects of climate-driven primary production change on marine food webs: Implications for fisheries and conservation. Glob. Chang. Biol. 16, 1194–1212. https://doi.org/10.1111/j.1365-2486.2009.02046.x

Bueno-Pardo, J., García-Seoane, E., Sousa, A.I., Coelho, J.P., Morgado, M., Frankenbach, S., Ezequiel, J., Vaz, N., Quintino, V., Rodrigues, A.M., Leandro, S., Luis, A., Serôdio, J., Cunha, M.R., Calado, A.J., Lillebø, A., Rebelo, J.E., Queiroga, H., 2018. Trophic web structure and ecosystem attributes of a temperate coastal lagoon (Ria de Aveiro, Portugal). Ecol. Modell. 378, 13–25. https://doi.org/10.1016/j.ecolmodel.2018.03.009

Cáceres, I., Ortiz, M., Cupul-Magaña, A.L., Rodríguez-Zaragoza, F.A., 2016. Trophic models and short-term simulations for the coral reefs of Cayos Cochinos and Media Luna (Honduras): a comparative network analysis, ecosystem development, resilience, and fishery. Hydrobiologia 770, 209–224. https://doi.org/10.1007/s10750-015-2592-7

Cashion, T., Al-Abdulrazzak, D., Belhabib, D., Derrick, B., Divovich, E., Moutopoulos, D.K., Noël, S.L., Palomares, M.L.D., Teh, L.C.L., Zeller, D., Pauly, D., 2018. Reconstructing global marine fishing gear use: Catches and landed values by gear type and sector. Fish. Res. 206, 57–64. https://doi.org/10.1016/j.fishres.2018.04.010

Chagaris, D.D., Mahmoudi, B., Walters, C.J., Allen, M.S., 2015. Simulating the Trophic Impacts of Fishery Policy Options on the West Florida Shelf Using Ecopath with Ecosim. Mar. Coast. Fish. 7, 44–58. https://doi.org/10.1080/19425120.2014.966216

Chollett, I., Canty, S.W.J., Box, S.J., Mumby, P.J., 2014. Adapting to the impacts of global change on an artisanal coral reef fishery. Ecol. Econ. 102, 118–125. https://doi.org/10.1016/j.ecolecon.2014.03.010

Christensen, V., Pauly, D., 1992. ECOPATH II - a software for balancing steady-state ecosystem models and calculating network characteristics. Science (80-.). 61, 169–185.

Christensen, V., Walters, C., 2005. Using ecosystem modeling for fisheries management: Where are we. Ices C. 19, 20–24.

Christensen, V., Walters, C.J., 2004. Ecopath with Ecosim: Methods, capabilities and limitations. Ecol. Modell. 172, 109–139. https://doi.org/10.1016/j.ecolmodel.2003.09.003

Christensen, V., Walters, C.J., Pauly, D., 2005. Ecopath with Ecosim: a user's guide. Fish. Cent. Res. Reports 154. https://doi.org/10.1016/0304-3800(92)90016-8

Christensen, V., Walters, C.J., Pauly, D., Forrest, R., 2008. Ecopath with Ecosim version 6 User Guide. Fish. Centre, Univ. Br. Columbia, Vancouver, Canada 281, 1–235.

Cloern, J.E., Foster, S.Q., Kleckner, A.E., 2014. Phytoplankton primary production in the world's estuarine-coastal ecosystems. Biogeosciences 11, 2477–2501. https://doi.org/10.5194/bg-11-2477-2014

Coll, M., Libralato, S., 2012. Contributions of food web modelling to the ecosystem approach to marine resource management in the Mediterranean Sea. Fish Fish. 13, 60–88. https://doi.org/10.1111/j.1467-2979.2011.00420.x

Coll, M., Navarro, J., Palomera, I., 2013. Ecological role, fishing impact, and management options for the recovery of a Mediterranean endemic skate by means of food web models. Biol. Conserv. 157, 108–120. https://doi.org/10.1016/j.biocon.2012.06.029

Coll, M., Palomera, I., Tudela, S., Dowd, M., 2008. Food-web dynamics in the South Catalan Sea ecosystem (NW Mediterranean) for 1978-2003. Ecol. Modell. 217, 95–116. https://doi.org/10.1016/j.ecolmodel.2008.06.013

Coll, M., Steenbeek, J., 2017. Standardized ecological indicators to assess aquatic food webs: The ECOIND software plug-in for Ecopath with Ecosim models. Environ. Model. Softw. 89, 120–130. https://doi.org/10.1016/j.envsoft.2016.12.004

Coll, M., Steenbeek, J., Sole, J., Palomera, I., Christensen, V., 2016. Modelling the cumulative spatial-temporal effects of environmental drivers and fishing in a NW Mediterranean marine ecosystem. Ecol. Modell. 331, 100–114. https://doi.org/10.1016/j.ecolmodel.2016.03.020

Corrales, X., Coll, M., Ofir, E., Heymans, J.J., Steenbeek, J., Goren, M., Edelist, D., Gal, G., 2018. Future scenarios of marine resources and ecosystem conditions in the Eastern Mediterranean under the impacts of fishing, alien species and sea warming. Sci. Rep. 8, 1–16. https://doi.org/10.1038/s41598-018-32666-x

Corrales, X., Ofir, E., Coll, M., Goren, M., Edelist, D., Heymans, J.J., Gal, G., 2017. Modeling the role and impact of alien species and fisheries on the Israeli marine continental shelf ecosystem. J. Mar. Syst. 170, 88–102. https://doi.org/10.1016/j.jmarsys.2017.02.004

Costa, R.C., Fransozo, A., Freire, F.A.D.M., Castilho, A.L., 2007. Abundance and Ecological Distribution of the “Sete-Barbas” Shrimp *Xiphopenaeus Kroyeri* (Heller , 1862) (Decapoda : Penaeoidea) in Three Bays of the Ubatuba Region , Southeastern Brazil. Gulf Caribb. Res. 19, 33–41. https://doi.org/10.18785/gcr.1901.04

CPRH, 2011. Área de Proteção Ambiental de Guadalupe. Recife.

Cuervo-Sánchez, R., Maldonado, J.H., Rueda, M., 2018. Spillover from marine protected areas on the pacific coast in Colombia: A bioeconomic modelling approach for shrimp fisheries. Mar. Policy 88, 182–188. https://doi.org/10.1016/j.marpol.2017.10.036

Cury, P.M., Christensen, V., 2005. Quantitative ecosystem indicators for fisheries management. ICES J. Mar. Sci. 62, 307–310. https://doi.org/10.1016/j.icesjms.2005.02.003

Davies, R.W.D., Cripps, S.J., Nickson, A., Porter, G., 2009. Defining and estimating global marine fisheries bycatch. Mar. Policy 33, 661–672. https://doi.org/10.1016/j.marpol.2009.01.003

Davies, R.W.D., Cripps, S.J., Nickson, A., Porter, G., Watson, R.A., Baisre, J.A., FAO (Food and Agriculture Organization of the United Nations), Victorero, L., Watling, L., Deng Palomares, M.L., Nouvian, C., Okamura, H., Morita, S.H., Hokkaido, T.F., Ichinokawa, M., Eguchi, S., Wehrtmann, I.S., Arana, P., Barriga, E., Gracia, A., Pezzuto, P.R., Gillett, R., Johnson, A.F., Gorelli, G., Gorelli, G., Hiddink, J.G., Hinz, H., Jennings, S., Sciberras, M., Szostek, C.L., Hughes, K.M., Ellis, N., Rijnsdorp, A.D., McConnaughey, R.A., Mazor, T., Hilborn, R., Collie, J.S., Pitcher, C.R., Amoroso, R.O., Parma, A.M., Suuronen, P., Kaiser, M.J., Ramalho, S.P., Almeida, M., Esquete, P., Génio, L., Ravara, A., Rodrigues, C.F., Lampadariou, N., Vanreusel, A., Cunha, M.R., Musiello-Fernandes, J., Zappes, C.A., Hostim-Silva, M., Cashion, T., Al-Abdulrazzak, D., Belhabib, D., Derrick, B., Divovich, E., Moutopoulos, D.K., Noël, S.L., Palomares, M.L.D., Teh, L.C.L., Zeller, D., Pauly, D., Gianelli, I., Horta, S., Martínez, G., de la Rosa, A., Defeo, O., Chuenpagdee, R., Rocklin, D., Bishop, D., Hynes, M., Greene, R., Lorenzi, M.R., Devillers, R., Bellmann, C., Tipping, A., Sumaila, U.R., Shen, G., Heino, M., Oyinlola, M.A., Reygondeau, G., Wabnitz, C.C.C., Troell, M., Cheung, W.W.L., Belton, B., Thilsted, S.H., Davanso, T.M., Hirose, G.L., Herrera, D.R., Fransozo, A., Costa, R.C., Klemas, V., Watson, R.A., Revenga, C., Kura, Y., Mcclanahan, T.R., Pauly, D., Zeller, D., 2018. Target-based catch-per-unit-effort standardization in multispecies fisheries. Mar. Policy 148, 1–9. https://doi.org/10.1016/j.marpol.2017.06.018

Dell’Apa, A., Fullerton, A., Schwing, F., Brady, M.M., 2015. The status of marine and coastal ecosystem-based management among the network of U.S. federal programs. Mar. Policy 60, 249–258. https://doi.org/10.1016/j.marpol.2015.07.011

Dias-Neto, J., 2011. Proposta de plano nacional de gestão para o uso sustentável de camarões marinhos no Brasil, Ibama. Ibama, Brasília. https://doi.org/10.13140/2.1.4848.6089

Doubleday, Z.A., Nagelkerken, I., Coutts, M.D., Goldenberg, S.U., Connell, S.D., 2019. A triple trophic boost: How carbon emissions indirectly change a marine food chain. Glob. Chang. Biol. 25, 978–984. https://doi.org/10.1111/gcb.14536

Eayrs, S., 2007. A Guide to Bycatch Reduction in Tropical Shrimp-Trawl Fisheries, Revised. ed. FAO, Rome.

Eduardo, C., Andrade, R., Marins, Y., Hazin, F.H., Benevides, L., Nascimento, M., Oliveira, P.G., 2016.

Diagnóstico da pesca de arrasto de camarões marinhos no Estado de Pernambuco , Brasil. Biota Amaz. 6, 1–6. https://doi.org/https://dx.doi.org/1018561/2179-5746/biotaamazonia.v6n3o1-6

Eduardo, L.N., Lira, A.S., Frédou, T., Lucena-Frédou, F., 2018. Population structure and reproductive biology of Haemulopsis corvinaeformis (Perciformes, Haemulidae) in the south coast of Pernambuco, northeastern Brazil. Iheringia - Série Zool. 108, 1–8. https://doi.org/10.1590/1678-4766e2018007

Ehrnsten, E., Bauer, B., Gustafsson, B.G., 2019. Combined Effects of Environmental Drivers on Marine Trophic Groups – A Systematic Model Comparison. Front. Mar. Sci. 6, 1–14. https://doi.org/10.3389/fmars.2019.00492

Elliott, M., Whitfield, A.K., Potter, I.C., Blaber, S.J.M., Cyrus, D.P., Nordlie, F.G., Harrison, T.D., 2007. The guild approach to categorizing estuarine fish assemblages: A global review. Fish Fish. 8, 241–268. https://doi.org/10.1111/j.1467-2679.2007.00253.x

Falkowski, P., Barber, R., Smetacek, V., 1998. Biogeochemical controls and feedbacks on ocean primary production : Chemistry and biology of the oceans. Science (80-.). 281, 200–206.

FAO, 1995. Code of Conduct for Responsible Fisheries, Food and Agriculture Organization of the United Nations. Rome. https://doi.org/ISBN 92-5-103834-5

Ferreira, V., Le Loc'h, F., Ménard, F., Frédou, T., Frédou, F.L., 2019. Composition of the fish fauna in a tropical estuary: the ecological guild approach. Sci. Mar. 83, 133. https://doi.org/10.3989/scimar.04855.25a

Finn, J.T., 1976. Measures of ecosystem structure and function derived from analysis of flows. J. Theor. Biol. 56, 363–380. https://doi.org/10.1016/S0022-5193(76)80080-X

Fourriére, M., Alvarado, J.J., Cortés, J., Taylor, M.H., Ayala-Bocos, A., Azofeifa-Solano, J.C., Arauz, R., Heidemeyer, M., López-Garro, A., Zanella, I., Wolff, M., 2019. Energy flow structure and role of keystone groups in shallow water environments in Isla del Coco, Costa Rica, Eastern Tropical Pacific. Ecol. Modell. 396, 74–85. https://doi.org/10.1016/j.ecolmodel.2019.01.004

Fulton, E.A., Fuller, M., Smith, A.D.M., Punt, A., 2004. Ecological Indicators of the Ecosystem Effects of Fishing: Final Report, Australian Fisheries Management Authority. https://doi.org/https://doi.org/10.4225/08/585c169120a95

Garcia, S.M., Zerbi, A., Aliaume, C., Do Chi, T., Lasserre, G., 2003. The ecosystem approach to fisheries. FAO Fish. Tech. Pap. 443, 71. https://doi.org/10.1111/j.1467-2979.2010.00358.x

Gasche, L., Gascuel, D., 2013. EcoTroph: a simple model to assess fishery interactions and their impacts on ecosystems. ICES J. Mar. Sci. 70, 498–510. https://doi.org/10.1093/icesjms/fst016

Geers, T.M., Pikitch, E.K., Frisk, M.G., 2016. An original model of the northern Gulf of Mexico using Ecopath with Ecosim and its implications for the effects of fishing on ecosystem structure and maturity. Deep. Res. Part II Top. Stud. Oceanogr. 129, 319–331. https://doi.org/10.1016/j.dsr2.2014.01.009

Gianelli, I., Horta, S., Martínez, G., de la Rosa, A., Defeo, O., 2018. Operationalizing an ecosystem approach to small-scale fisheries in developing countries: The case of Uruguay. Mar. Policy 1–9. https://doi.org/10.1016/j.marpol.2018.03.020

Gibert, J.P., 2019. Temperature directly and indirectly influences food web structure. Sci. Rep. 9, 1–8. https://doi.org/10.1038/s41598-019-41783-0

Gillett, R., 2008. Global study of shrimp fisheries. Fish. Bethesda 475, 331 pp.

Gilman, E., Passfield, K., Nakamura, K., 2014. Performance of regional fisheries management organizations: Ecosystem-based governance of bycatch and discards. Fish Fish. 15, 327–351. https://doi.org/10.1111/faf.12021

Goldenberg, S.U., Nagelkerken, I., Marangon, E., Bonnet, A., Ferreira, C.M., Connell, S.D., 2018. Ecological complexity buffers the impacts of future climate on marine consumers. Nat. Clim. Chang. 8, 229–233. https://doi.org/10.1038/s41558-018-0086-0

Goti-Aralucea, L., 2019. Assessing the social and economic impact of small scale fisheries management measures in a marine protected area with limited data. Mar. Policy 101, 246–256. https://doi.org/10.1016/j.marpol.2017.10.039

Guanais, J.H.G., Medeiros, R.P., McConney, P.A., 2015. Designing a framework for addressing bycatch problems in Brazilian small-scale trawl fisheries. Mar. Policy 51, 111–118. https://doi.org/10.1016/j.marpol.2014.07.004

Guesnet, V., Lassalle, G., Chaalali, A., Kearney, K., Saint-Béat, B., Karimi, B., Grami, B., Tecchio, S., Niquil, N., Lobry, J., 2015. Incorporating food-web parameter uncertainty into Ecopath-derived ecological network indicators. Ecol. Modell. 313, 29–40. https://doi.org/10.1016/j.ecolmodel.2015.05.036

Halouani, G., Abdou, K., Hattab, T., Romdhane, M.S., Ben Rais Lasram, F., Le Loc'h, F., 2016. A spatio-temporal ecosystem model to simulate fishing management plans: A case of study in the Gulf of Gabes (Tunisia). Mar. Policy 69, 62–72. https://doi.org/10.1016/j.marpol.2016.04.002

Halouani, G., Le, F., Shin, Y., Velez, L., Hattab, T., 2019. An end-to-end model to evaluate the sensitivity of ecosystem indicators to track fishing impacts. Ecol. Indic. 98, 121–130. https://doi.org/10.1016/j.ecolind.2018.10.061

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

Heath, M.R., Cook, R.M., Cameron, A.I., Morris, D.J., Speirs, D.C., 2014. Cascading ecological effects of eliminating fishery discards. Nat. Commun. 5, 1–8. https://doi.org/10.1038/ncomms4893

Heymans, J.J., Coll, M., Libralato, S., Morissette, L., Christensen, V., 2014. Global patterns in ecological indicators of marine food webs: A modelling approach. PLoS One 9. https://doi.org/10.1371/journal.pone.0095845

Heymans, J.J., Coll, M., Link, J.S., Mackinson, S., Steenbeek, J., Walters, C., Christensen, V., 2016. Best practice in Ecopath with Ecosim food-web models for ecosystem-based management. Ecol. Modell. 331, 173–184. https://doi.org/10.1016/j.ecolmodel.2015.12.007

Hu, C., Lee, Z., Franz, B., 2012. Chlorophyll a algorithms for oligotrophic oceans: A novel approach based on three-band reflectance difference. J. Geophys. Res. Ocean. 117, 1–25. https://doi.org/10.1029/2011JC007395

Hughes, T.P., Kerry, J.T., Álvarez-Noriega, M., Álvarez-Romero, J.G., Anderson, K.D., Baird, A.H., Babcock, R.C., Beger, M., Bellwood, D.R., Berkelmans, R., Bridge, T.C., Butler, I.R., Byrne, M., Cantin, N.E., Comeau, S., Connolly, S.R., Cumming, G.S., Dalton, S.J., Diaz-Pulido, G., Eakin, C.M., Figueira, W.F., Gilmour, J.P., Harrison, H.B., Heron, S.F., Hoey, A.S., Hobbs, J.-P.A., Hoogenboom, M.O., Kennedy, E. V, Kuo, C., Lough, J.M., Lowe, R.J., Liu, G., McCulloch, M.T., Malcolm, H.A., McWilliam, M.J., Pandolfi, J.M., Pears, R.J., Pratchett, M.S., Schoepf, V., Simpson, T., Skirving, W.J., Sommer, B., Torda, G., Wachenfeld, D.R., Willis, B.L., Wilson, S.K., 2017. Global warming and recurrent mass bleaching of corals. Nature 543, 373.

IBAMA, 2008. Estatística da Pesca - 2007, Grandes regiões e unidades da federação. Brasília-DF.

Jeffers, V.F., Humber, F., Nohasiarivelo, T., Botosoamananto, R., Anderson, L.G., 2019. Trialling the use of smartphones as a tool to address gaps in small-scale fisheries catch data in southwest Madagascar. Mar. Policy 99, 267–274. https://doi.org/10.1016/j.marpol.2018.10.040

Jennings, S., Rice, J., 2011. Towards an ecosystem approach to fisheries in Europe: A perspective on existing progress and future directions. Fish Fish. 12, 125–137. https://doi.org/10.1111/j.1467-2979.2011.00409.x

Johnson, A.F., Gorelli, G., Jenkins, S.R., Hiddink, J.G., Hinz, H., Johnson, A.F., Gorelli, G., Hiddink, J.G., Hinz, H., Jenkins, S.R., Hiddink, J.G., Hinz, H., 2015. Effects of bottom trawling on fish foraging and feeding. Proc. Biol. Sci. 282, 20142336. https://doi.org/10.1098/rspb.2014.2336

Johnson, J.E., Welch, D.J., 2010. Marine fisheries management in a changing climate: A review of vulnerability and future options. Rev. Fish. Sci. 18, 106–124. https://doi.org/10.1080/10641260903434557

Jones, B.L., Unsworth, R.K.F., Udagedara, S., Cullen-Unsworth, L.C., 2018. Conservation concerns of small-scale fisheries: By-catch impacts of a Shrimp and Finfish Fishery in a Sri Lankan Lagoon. Front. Mar. Sci. 4, 1–13. https://doi.org/10.3389/fmars.2018.00052

Joseph John, L., Rebecca A, D., Hart, K.J., Clough, L.M., Johnson, J.C., 2018. Cascading Effects of Shrimp Trawling: Increased Benthic Biomass and Increase in Net Primary Production. bioRxiv 298323. https://doi.org/10.1101/298323

Kempf, A., Dingsør, G.E., Huse, G., Vinther, M., Floeter, J., Temming, A., 2010. The importance of predator-prey overlap: Predicting North Sea cod recovery with a multispecies assessment model. ICES J. Mar. Sci. 67, 1989–1997. https://doi.org/10.1093/icesjms/fsq114

Kerwath, S.E., Winker, H., Götz, A., Attwood, C.G., 2013. Marine protected area improves yield without disadvantaging fishers. Nat. Commun. 4, 1–6. https://doi.org/10.1038/ncomms3347

Krumhardt, K.M., Lovenduski, N.S., Long, M.C., Lindsay, K., 2017. Avoidable impacts of ocean warming on marine primary production: Insights from the CESM ensembles. Global Biogeochem. Cycles 31, 114–133. https://doi.org/10.1002/2016GB005528

Larsen, R.B., Herrmann, B., Sistiaga, M., Brinkhof, J., Tatone, I., Langård, L., Larsen, R.B., Herrmann, B., Sistiaga, M., Brinkhof, J., Tatone, I., Sistiaga, M., Brinkhof, J., Tatone, I., Langård, L., Herrmann, B., 2017. Performance of the Nordmøre Grid in Shrimp Trawling and Potential Effects of Guiding Funnel Length and Light Stimulation. Mar. Coast. Fish. 9, 479–492. https://doi.org/10.1080/19425120.2017.1360421

Lazzari, N., Becerro, M.A., Sanabria-Fernandez, J.A., Martín-López, B., 2019. Spatial characterization of coastal marine social-ecological systems: Insights for integrated management. Environ. Sci. Policy 92, 56–65. https://doi.org/10.1016/j.envsci.2018.11.003

Lercari, D., Defeo, O., Ortega, L., Orlando, L., Gianelli, I., Celentano, E., 2018. Long-term structural and functional changes driven by climate variability and fishery regimes in a sandy beach ecosystem. Ecol. Modell. 368, 41–51. https://doi.org/10.1016/j.ecolmodel.2017.11.007

Link, J.S., 2010. Adding rigor to ecological network models by evaluating a set of pre-balance diagnostics : A plea for PREBAL. Ecol. Modell. 221, 1580–1591. https://doi.org/10.1016/j.ecolmodel.2010.03.012

Lira, A.S., Angelini, R., Le Loc'h, F., Ménard, F., Lacerda, C., Frédou, T., Lucena Frédou, F., 2018. Trophic flow structure of a neotropical estuary in northeastern Brazil and the comparison of ecosystem model indicators of estuaries. J. Mar. Syst. 182, 31–45. https://doi.org/10.1016/j.jmarsys.2018.02.007

Lira, A.S., Viana, A.P., Eduardo, L.N., Fredóu, F.L., Frédou, T., 2019. Population structure, size at first sexual maturity, and feeding ecology of Conodon nobilis (Actinopterygii: Perciformes: Haemulidae) from the coasts of Pernambuco, north-eastern Brazil. Acta Ichthyol. Piscat. 49, 389–398. https://doi.org/10.3750/AIEP/02578

Lira, L., Mesquita, B., Souza, M.M.C., Leite, C.A., Leite, Ana Paula de Almeida Farias, A.M., Galvão, C., 2010. Diagnóstico socioeconômico da pesca artesanal do litoral de Pernambuco, Instituto. ed. Instituto Oceanário de Pernambuco, Recife. https://doi.org/10.1017/CBO9781107415324.004

Lopes, D., Frédou, F.L., Silva, E., Calazans, N., 2017. Reproductive cycle of seabob shrimp Xiphopenaeus kroyeri (Crustacea , Penaeidea) from the northeast coast of Brazil. Invertebr. Reprod. Dev. 61, 137–141. https://doi.org/10.1080/07924259.2017.1311951

Lopes, P.F.M., 2008. Extracted and farmed shrimp fisheries in Brazil: Economic, environmental and social consequences of exploitation. Environ. Dev. Sustain. 10, 639–655. https://doi.org/10.1007/s10668-008-9148-1

Lopes, P.F.M., Pennino, M.G., Freire, F., 2018. Climate change can reduce shrimp catches in equatorial Brazil. Reg. Environ. Chang. 18, 223–234. https://doi.org/10.1007/s10113-017-1203-8

Lotze, H.K., Tittensor, D.P., Bryndum-Buchholz, A., Eddy, T.D., Cheung, W.W.L., Galbraith, E.D., Barange, M., Barrier, N., Bianchi, D., Blanchard, J.L., Bopp, L., Büchner, M., Bulman, C.M., Carozza, D.A., Christensen, V., Coll, M., Dunne, J.P., Fulton, E.A., Jennings, S., Jones, M.C., Mackinson, S., Maury, O., Niiranen, S., Oliveros-Ramos, R., Roy, T., Fernandes, J.A., Schewe, J., Shin, Y.-J., Silva, T.A.M., Steenbeek, J., Stock, C.A., Verley, P., Volkholz, J., Walker, N.D., Worm, B., 2019. Global ensemble projections reveal trophic amplification of ocean biomass declines with climate change. Proc. Natl. Acad. Sci. 116, 12907–12912. https://doi.org/10.1073/pnas.1900194116

Macias, D., Garcia-Gorriz, E., Piroddi, C., Stips, A., 2014. Biogeochemical control of marine productivity in the Mediterranean Sea during the last 50 years. Global Biogeochem. Cycles 28, 897–907. https://doi.org/10.1002/2014GB004832.Received

Manso, V., Correa, I., Guerra, N., 2003. Morfologia e sedimentologia da Plataforma Continental Interna entre as Prais Porto de Galinhas e Campos-Litoral Sul de Pernambuco, Brasil. Pesqui. em Geociências 30, 17–25.

Marrari, M., Piola, A.R., Valla, D., 2017. Variability and 20-year trends in satellite-derived surface chlorophyll concentrations in large marine ecosystems around South and Western central America. Front. Mar. Sci. 4, 1–17. https://doi.org/10.3389/fmars.2017.00372

McIlgorm, A., Hanna, S., Knapp, G., Le Floc'H, P., Millerd, F., Pan, M., 2010. How will climate change alter fishery governance{glottal stop} Insights from seven international case studies. Mar. Policy 34, 170–177. https://doi.org/10.1016/j.marpol.2009.06.004

Meekan, M.G., McCormick, M.I., Simpson, S.D., Chivers, D.P., Ferrari, M.C.O., 2018. Never off the hook-how fishing subverts predator-prey relationships in marine teleosts. Front. Ecol. Evol. 6, 1–10. https://doi.org/10.3389/fevo.2018.00157

Mello, M.V.L. de, 2009. Parâmetros hidrológicos correlacionados com a biomassa e composição fitoplanctônica na região costeira adjacente a desembocadura do rio Sirinhaém (Pernambuco - Brasil). Universidade Federal dePernambuco.

Nagelkerken, I., Goldenber, S.U., Ferreir, C.M., Ullah, H., Conne, S.D., 2020. Trophic pyramids reorganize when food web architecture fails to adjust to ocean change. Science (80-.). 369, 829–832. https://doi.org/10.1126/science.aax0621

Ngor, P.B., McCann, K.S., Grenouillet, G., So, N., McMeans, B.C., Fraser, E., Lek, S., 2018. Evidence of indiscriminate fishing effects in one of the world's largest inland fisheries. Sci. Rep. 8, 1–12. https://doi.org/10.1038/s41598-018-27340-1

Niiranen, S., Blenckner, T., Hjerne, O., Tomczak, M.T., 2012. Uncertainties in a baltic sea food-web model reveal challenges for future projections. Ambio 41, 613–625. https://doi.org/10.1007/s13280-012-0324-z

Odum, E.P., 1969. The Strategy of Ecosystem Development. Science (80-.). 164, 262–270.

Ortega, I., Colling, L.A., Dumont, L.F.C., 2018. Response of soft-bottom macrobenthic assemblages to artisanal trawling fisheries in a subtropical estuary. Estuar. Coast. Shelf Sci. 207, 142–153. https://doi.org/10.1016/j.ecss.2018.04.007

Oyinlola, M.A., Reygondeau, G., Wabnitz, C.C.C., Troell, M., Cheung, W.W.L., 2018. Global estimation of areas with suitable environmental conditions for mariculture species. PLoS One 13, 1–19. https://doi.org/10.1371/journal.pone.0191086

Peixoto, S.P., Calazans, N., Silva, E., Nole, L., Soares, R., Fredou, F., 2018. Reproductive cycle and size at first sexual maturity of the white shrimp Penaeus schmitti (Burkenroad, 1936) in northeastern Brazil. Lat. Am. J. Aquat. Res. 46, 1–9. https://doi.org/10.3856/vol46-issue1-fulltext-1

Petchey, O.L., Brose, U., Rall, B.C., 2010. Predicting the effects of temperature on food web connectance. Philos. Trans. R. Soc. B Biol. Sci. 365, 2081–2091. https://doi.org/10.1098/rstb.2010.0011

Piroddi, C., Coll, M., Liquete, C., Macias, D., Greer, K., 2017. Historical changes of the Mediterranean Sea ecosystem : modelling the role and impact of primary productivity and fisheries changes over time. Nat. Publ. Gr. 1–18. https://doi.org/10.1038/srep44491

Piroddi, C., Giovanni, B., Villy, C., 2010. Effects of local fisheries and ocean productivity on the northeastern Ionian Sea ecosystem. Ecol. Modell. 221, 1526–1544. https://doi.org/10.1016/j.ecolmodel.2010.03.002

Pörtner, H.O., Farrell, A.P., 2008. Physiology and Climate Change. Science (80-.). 322, 690 LP – 692. https://doi.org/10.1126/science.1163156

Quentin Grafton, R., 2010. Adaptation to climate change in marine capture fisheries. Mar. Policy 34, 606–615. https://doi.org/10.1016/j.marpol.2009.11.011

Rahman, M.F., Qun, L., Xiujuan, S., Chen, Y., Ding, X., Liu, Q., 2019. Temporal Changes of Structure and Functioning of the Bohai Sea Ecosystem: Insights from Ecopath Models. Thalass. An Int. J. Mar. Sci. https://doi.org/10.1007/s41208-019-00139-1

Reay, D., Sabine, C., Smith, P., Hymus, G., 2007. Intergovernmental Panel on Climate Change. Fourth Assessment Report, Intergovernmental Panel on Climate Change. https://doi.org/10.1038/446727a

Régnier, T., Gibb, F.M., Wright, P.J., 2019. Understanding temperature effects on recruitment in the context of trophic mismatch. Sci. Rep. 9, 1–13. https://doi.org/10.1038/s41598-019-51296-5

Rezende, G.A., Rufener, M.-C., Ortega, I., Ruas, V.M., Dumont, L.F.C., 2019. Modelling the spatio-temporal bycatch dynamics in an estuarine small-scale shrimp trawl fishery. Fish. Res. 219, 105336. https://doi.org/10.1016/j.fishres.2019.105336

Rice, J.C., 2000. Evaluating fishery impacts using metrics of community structure. ICES J. Mar. Sci. 57, 682–688. https://doi.org/10.1006/jmsc.2000.0735

Roessig, J.M., Woodley, C.M., Cech, J.J., Hansen, L.J., 2004. Effects of global climate change on marine and estuarine fishes and fisheries. Rev. Fish Biol. Fish. 14, 251–275. https://doi.org/10.1007/s11160-004-6749-0

Rosa, R., Carvalho, A.R., Angelini, R., 2014. Integrating fishermen knowledge and scientific analysis to assess changes in fish diversity and food web structure. Ocean Coast. Manag. 102, 258–268. https://doi.org/10.1016/j.ocecoaman.2014.10.004

Rosenberg, A.A., McLeod, K.L., 2005. Implementing ecosystem-based approaches to management for the conservation of ecosystem services. Mar. Ecol. Prog. Ser. 300, 270–274.

Rossi, S., Soares, M. de O., 2017. Effects of El Niño on the Coastal Ecosystems and Their Related Services. Mercator 16, 1–16. https://doi.org/10.4215/rm2017.e16030

Saint-Béat, B., Niquil, N., Asmus, H., Asmus, R., Bacher, C., Pacella, S.R., Johnson, G. a, David, V., Vézina, A.F., 2015. Trophic networks: How do theories link ecosystem structure and functioning to stability properties? A review. Ecol. Indic. 52, 458–471. https://doi.org/10.1016/j.ecolind.2014.12.017

Santos, M.D.C.F., 2010. Ordenamento Da Pesca De Camarões No Nordeste Do Brasil. Bol. Técnico-Científico do CEPENE 18, 91–98.

Serafini, T.Z., Medeiros, R.P., Andriguetto-Filho, J.M., 2017. Conditions for successful local resource management: lessons from a Brazilian small-scale trawling fishery. Reg. Environ. Chang. 17, 201–212. https://doi.org/10.1007/s10113-016-0990-7

Serpetti, N., Baudron, A.R., Burrows, M.T., Payne, B.L., Helaouët, P., Fernandes, P.G., Heymans, J.J., 2017. Impact of ocean warming on sustainable fisheries management informs the Ecosystem Approach to Fisheries. Sci. Rep. 7, 1–15. https://doi.org/10.1038/s41598-017-13220-7

Sherman, K., 2014a. Toward ecosystem-based management (EBM) of the world's large marine ecosystems during climate change. Environ. Dev. 11, 43–66. https://doi.org/10.1016/j.envdev.2014.04.006

Sherman, K., 2014b. Adaptive management institutions at the regional level: The case of Large Marine Ecosystems. Ocean Coast. Manag. 90, 38–49. https://doi.org/10.1016/j.ocecoaman.2013.06.008

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

Silva, E.F., Calazans, N., Nolé, L., Branco, T.C., Soares, R., Guerra, M.M.P., Frédou, F.L., Peixoto, S., 2016. Reproductive dynamics of the southern pink shrimp Farfantepenaeus subtilis in northeastern Brazil. Aquat. Biol. 25, 29–35. https://doi.org/10.3354/ab00653

Silva Júnior, C.A., Lira, A.S., Eduardo, L.N., Viana, A.P., Lucena-Frédou, F., Frédou, T., 2019. Ichthyofauna bycatch of the artisanal fishery of Penaeid shrimps in Pernambuco, Northeastern Brazil. Bol. do Inst. Pesca 45, 1–10. https://doi.org/10.20950/1678-2305.2019.45.1.435

Silva Júnior, C.A., Viana, A.P., Frédou, F.L., Frédou, T., 2015. Aspects of the reproductive biology and characterization of Sciaenidae captured as bycatch in the prawn trawling in the northeastern Brazil. Acta Sci. Biol. Sci. 37, 1. https://doi.org/10.4025/actascibiolsci.v37i1.24962

Steenbeek, J., Buszowski, J., Christensen, V., Akoglu, E., Aydin, K., Ellis, N., Felinto, D., Guitton, J., Lucey, S., Kearney, K., Mackinson, S., Pan, M., Platts, M., Walters, C., 2016. Ecopath with Ecosim as a model-building toolbox: Source code capabilities, extensions, and variations. Ecol. Modell. 319, 178–189. https://doi.org/10.1016/j.ecolmodel.2015.06.031

Steenbeek, J., Corrales, X., Platts, M., Coll, M., 2018. SoftwareX Ecosampler : A new approach to assessing parameter uncertainty in Ecopath with Ecosim. SoftwareX 7, 198–204. https://doi.org/10.1016/j.softx.2018.06.004

Stefansson, G., Rosenberg, A.A., 2005. Combining control measures for more effective management of fisheries under uncertainty: Quotas, effort limitation and protected areas. Philos. Trans. R. Soc. B Biol. Sci. 360, 133–146. https://doi.org/10.1098/rstb.2004.1579

Szuwalski, C.S., Burgess, M.G., Costello, C., Gaines, S.D., 2017. High fishery catches through trophic cascades in China. Proc. Natl. Acad. Sci. U. S. A. 114, 717–721. https://doi.org/10.1073/pnas.1612722114

Tischer, M., Santos, M.C.F., 2003. Composição E Diversidade Da Ictiofauna Acompanhante De Peneídeos No Litoral Sul De Pernambuco. Arq. Ciência do Mar 36, 105–118. https://doi.org/10.32360/acmar.v36i1-2.6605

Trenberth, K., 2019. The Climate Data Guide: Nino SST Indices (Nino 1+2, 3, 3.4, 4; ONI and TNI) [WWW Document]. Natl. Cent. Atmos. Res. Staff. URL https://climatedataguide.ucar.edu/climate-data/nino-sst-indices-nino-12-3-34-4-oni-and-tni (accessed 8.18.19).

Ullah, H., Nagelkerken, I., Goldenberg, S.U., Fordham, D.A., 2018. Climate change could drive marine food web collapse through altered trophic flows and cyanobacterial proliferation. PLoS Biol. 16, 1–21. https://doi.org/10.1371/journal.pbio.2003446

Vasslides, J.M., de Mutsert, K., Christensen, V., Townsend, H., 2017. Using the Ecopath with Ecosim Modeling Approach to Understand the Effects of Watershed-based Management Actions in Coastal Ecosystems. Coast. Manag. 45, 44–55. https://doi.org/10.1080/08920753.2017.1237241

Walters, C.J., Christensen, V., Pauly, D., Christensen, C. V, 1997. Structuring dynamic models of exploited ecosystems from trophic mass-balance assessments. Rev. Fish Biol. Fish. 7, 139–172. https://doi.org/Doi 10.1023/A:1018479526149

Wolff, M., Koch, V., Isaac, V., 2000. A Trophic Flow Model of the Caeté Mangrove Estuary (North Brazil) with Considerations for the Sustainable Use of its Resources. Estuar. Coast. Shelf Sci. 50, 789–803. https://doi.org/10.1006/ecss.2000.0611

Zeller, D., Cashion, T., Palomares, M., Pauly, D., 2017. Global marine fisheries discards: A synthesis of reconstructed data. Fish Fish. 19, 1–10. https://doi.org/10.1111/faf.12233

Zetina-Rejón, M.J., Cabrera-Neri, E., López-Ibarra, G.A., Arcos-Huitrón, N.E., Christensen, V., 2015. Trophic modeling of the continental shelf ecosystem outside of Tabasco, Mexico: A network and modularity analysis. Ecol. Modell. 313, 314–324. https://doi.org/10.1016/j.ecolmodel.2015.07.001

Zhang, H., Rutherford, E.S., Mason, D.M., Wittmann, M.E., Lodge, D.M., Zhu, X., Johnson, T.B., Tucker, A., 2019. Modeling potential impacts of three benthic invasive species on the Lake Erie food web. Biol. Invasions 21, 1697–1719. https://doi.org/10.1007/s10530-019-01929-7

Table 1

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 *bycatch* 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 *bycatch* 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%)	Decreasing fishing effort by 10, 25, 50 and 100% (no fishing)			
9	dec(-25%)				
10	dec(-50%)				
11	no_fishing dec(-100%)				
12	env1	Decreasing primary production (PP) by 2, 5 and 10% respectively	Environnemental	Biomass and catch patterns of shrimp and *bycatch* species are associated to environmental drivers (e.g., chlorophyll-a and rainfall).	4
13	env2				
14	env3				
15	clos + env	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	inc + env				
17	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

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	$t \cdot km^{-2}$	1
Fish B	Biomass (B) of fish	Sum of the biomass of fish species	Evaluate the dynamics of fish group	$t \cdot km^{-2}$	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	$t \cdot km^{-2}$	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	$t \cdot km^{-2} \cdot y^{-1}$	1
Fish C	Catch (C) of all fish	Sum of the catch of all fish species	Represent the dynamics of fish fisheries	$t \cdot km^{-2} \cdot y^{-1}$	1
Inver.C	Catch (C) of all invertebrate	Sum of the catch of all invertebrate species	Represent the dynamics of invertebrate fisheries	$t \cdot km^{-2} \cdot y^{-1}$	1
Disc	Total discarded catch	Sum of the catch of all species that are discarded	Assess the impact of fisheries with discards	$t \cdot km^{-2} \cdot y^{-1}$	3
mTLc	Tropic 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 lenght 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

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 ($t.km^{-2}$). See Table S1 to group name details.

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

Table 4

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

Parameters	Value	Units
Ecosystem properties		
Sum of all consumption (TC)	1029.88	$t{\cdot}km^{-2}{\cdot}y^{-1}$
Sum of all exports (TE)	1182.09	$t{\cdot}km^{-2}{\cdot}y^{-1}$
Sum of all respiratory flows (TR)	416.14	$t{\cdot}km^{-2}{\cdot}y^{-1}$
Sum of all flows into detritus (TD)	1432.14	$t{\cdot}km^{-2}{\cdot}y^{-1}$
Total system throughput (TST)	4060.26	$t{\cdot}km^{-2}{\cdot}y^{-1}$
Sum of all production (TP)	1886.05	$t{\cdot}km^{-2}{\cdot}y^{-1}$
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	$t{\cdot}km^{-2}{\cdot}y^{-1}$
Net system production (NSP)	1181.95	$t{\cdot}km^{-2}{\cdot}y^{-1}$
Total biomass (excluding detritus) (TB)	32.38	$t.km^{-2}$
Total catch (Tc)	1.37	$t{\cdot}km^{-2}{\cdot}y^{-1}$
Ecosystem maturity		
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^{-1}
Food web structure		
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	–
Model reability		
Ecopath pedigree index	0.65	–
Transfer efficiency total	18.14	%

Fig. 1

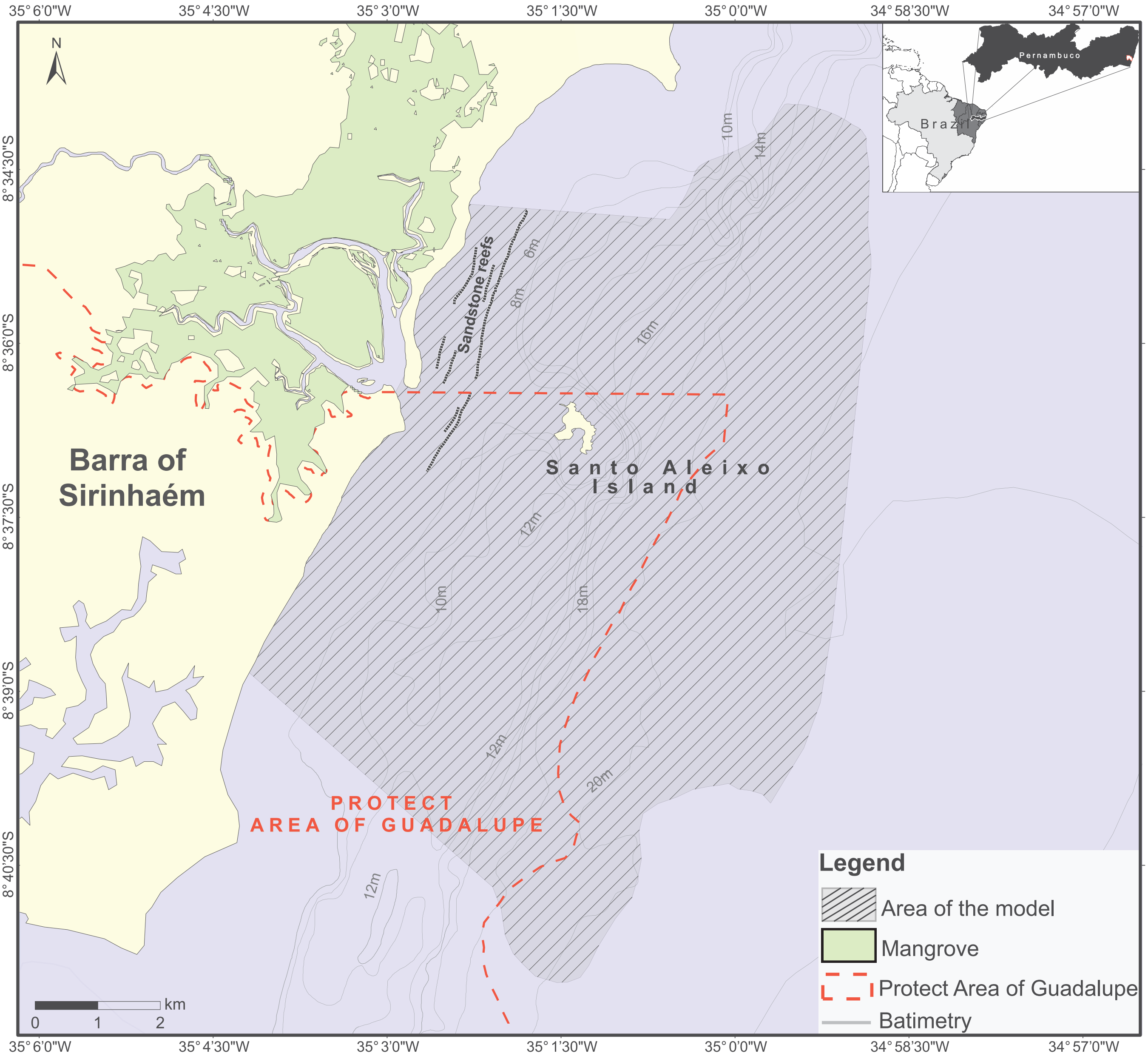

35° 6'0"W
35° 4'30"W
35° 3'0"W
35° 1'30"W
35° 0'0"W
34° 58'30"W
34° 57'0"W
8° 34'30"S
8° 36'0"S
8° 37'30"S
8° 39'0"S
8° 40'30"S
N
Pernambuco
Brazil
Sandstone reefs
6m
8m
10m
14m
16m
12m
18m
20m
Santo Aleixo Island
Barra of Sirinhaém
PROTECT AREA OF GUADALUPE
Legend
Area of the model
Mangrove
Protect Area of Guadalupe
Batimetry
km
0
1
2

Fig 2

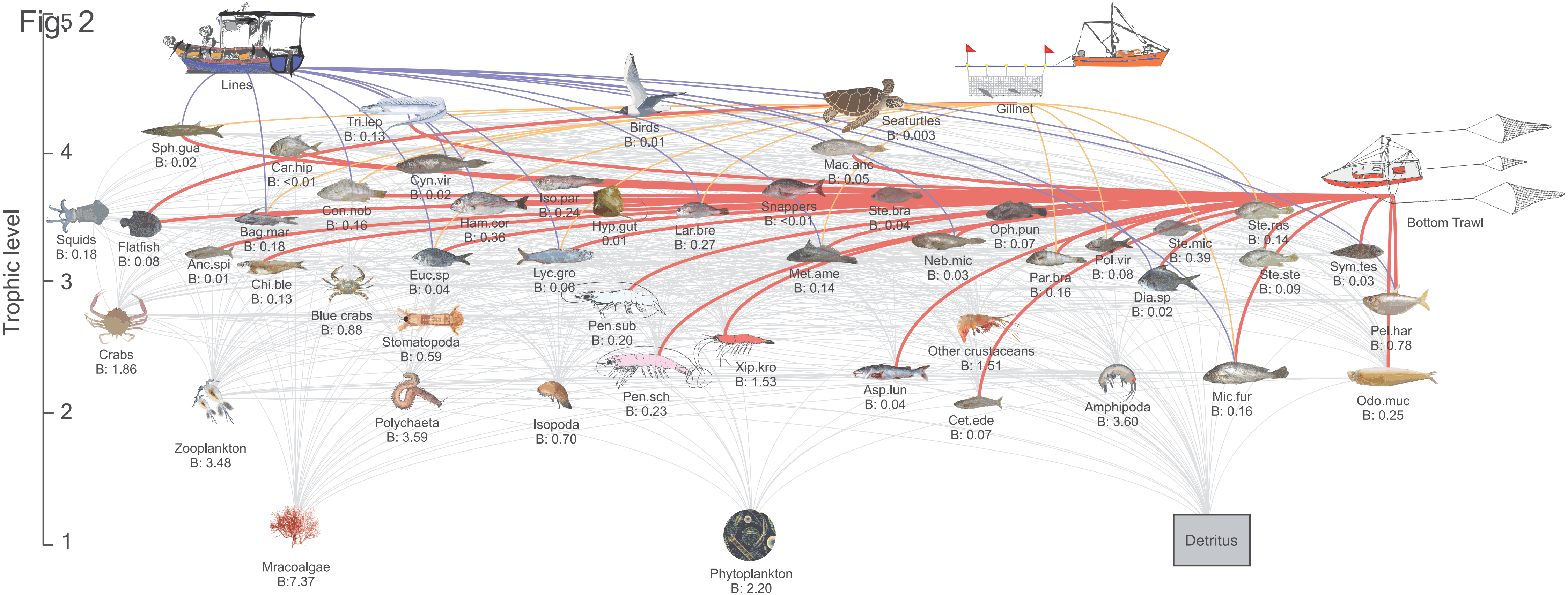
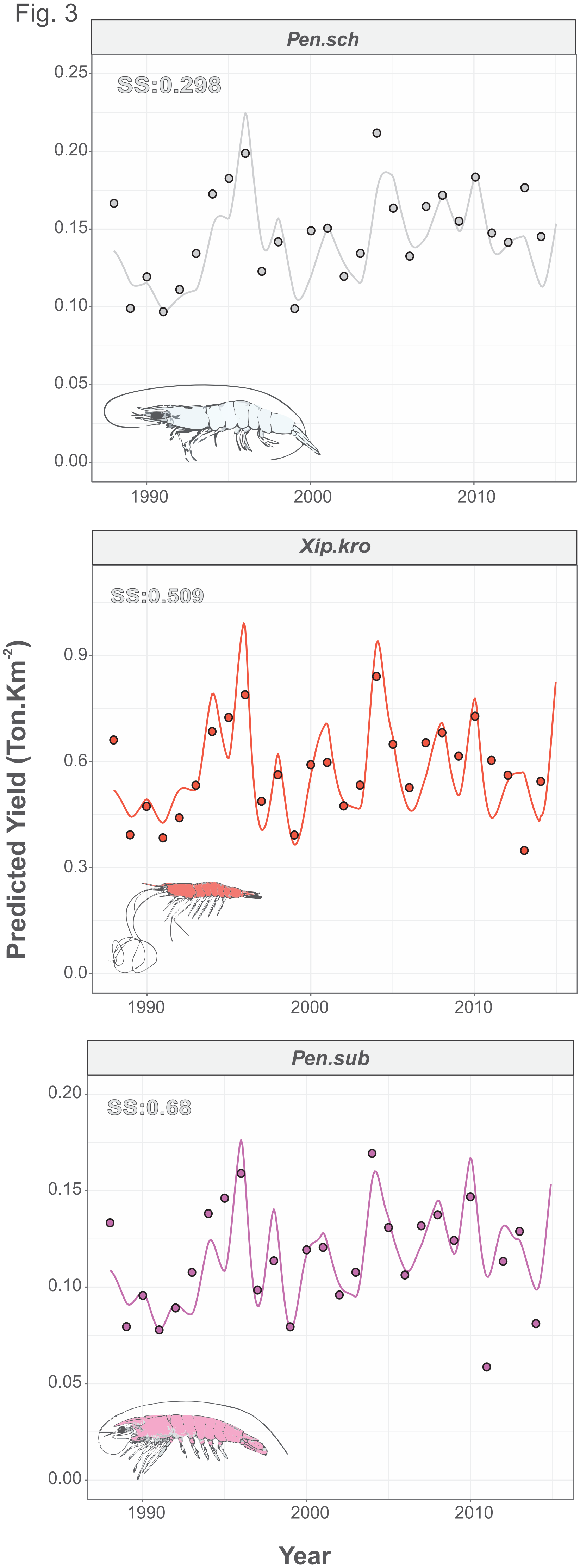

Trophic level
1
2
3
4
5
Lines
Gillnet
Bottom Trawl
Birds
B: 0.01
Seaturtles
B: 0.003
Tri.lep
B: 0.13
Sph.gua
B: 0.02
Car.hip
B: <0.01
Cyn.vir
B: 0.02
Mac.anc
B: 0.05
Con.nob
B: 0.16
Iso.par
B: 0.24
Snappers
B: <0.01
Ste.bra
B: 0.04
Squids
B: 0.18
Flatfish
B: 0.08
Bag.mar
B: 0.18
Ham.cor
B: 0.36
Hyp.gut
0.01
Lar.bre
B: 0.27
Oph.pun
B: 0.07
Ste.ras
B: 0.14
Anc.spi
B: 0.01
Chi.ble
B: 0.13
Euc.sp
B: 0.04
Lyc.gro
B: 0.06
Met.ame
B: 0.14
Neb.mic
B: 0.03
Pol.vir
B: 0.08
Ste.mic
B: 0.39
Sym.tes
B: 0.03
Par.bra
B: 0.16
Dia.sp
B: 0.02
Ste.ste
B: 0.09
Blue crabs
B: 0.88
Crabs
B: 1.86
Pen.sub
B: 0.20
Pel.har
B: 0.78
Stomatopoda
B: 0.59
Other crustaceans
B: 1.51
Xip.kro
B: 1.53
Asp.lun
B: 0.04
Mic.fur
B: 0.16
Odo.muc
B: 0.25
Pen.sch
B: 0.23
Amphipoda
B: 3.60
Zooplankton
B: 3.48
Polychaeta
B: 3.59
Isopoda
B: 0.70
Cet.ede
B: 0.07
Mracoalgae
B:7.37
Phytoplankton
B: 2.20
Detritus

Fig. 3



Pen.sch
SS:0.298
0.25
0.20
0.15
0.10
0.05
0.00
1990
2000
2010
Xip.kro
SS:0.509
0.9
0.6
0.3
0.0
Pen.sub
SS:0.68
Predicted Yield (Ton.Km^{-2})
Year

Captions figures

Fig. 1 Barra of Sirinhaém, Pernambuco, north-eastern Brazil, the area of the model (hachured area 75 km^2).

Fig. 2 Food web of the Barra of Sirinhaém Ecopath model (BSIR). The grey lines are the trophic paths and the orange, red and blue lines are the catches of the fleets. B is biomass in $t \cdot km^{-2}$.

Fig. 3 Comparison between the estimated landing time series from the Ecosim model (lines) and official logbooks of landings (1988-2014) in the Barra of Sirinhaém Ecopath model, Pernambuco, north-eastern Brazil.

Fig. 4 Average biomass variations for each trophic group obtained by Fishing Management Scenario simulation towards the future from 2015 – 2030 compared to the baseline model (constant effort). Blue and red-coloured gradients indicate increased and decreased biomass, respectively.

Fig. 5 Biomass predicted in the model with a confidence interval of 95% by Monte Carlo routine (1000 runs) for some groups in the scenarios clo1s, dec(-10%), dec(-100%), inc(+10%), inc(+100%) and env3. Pen.sub: *Penaeus subtilis*; Pen.sch: *Penaeus schmitti*; Xip.kro: *Xiphopenaeus kroyeri*.; Hyp.gut: *Hypanus guttata*; Par.bra: *Paralonchurus brasiliensis* and Tri.lep: *Trichiurus lepturus*.

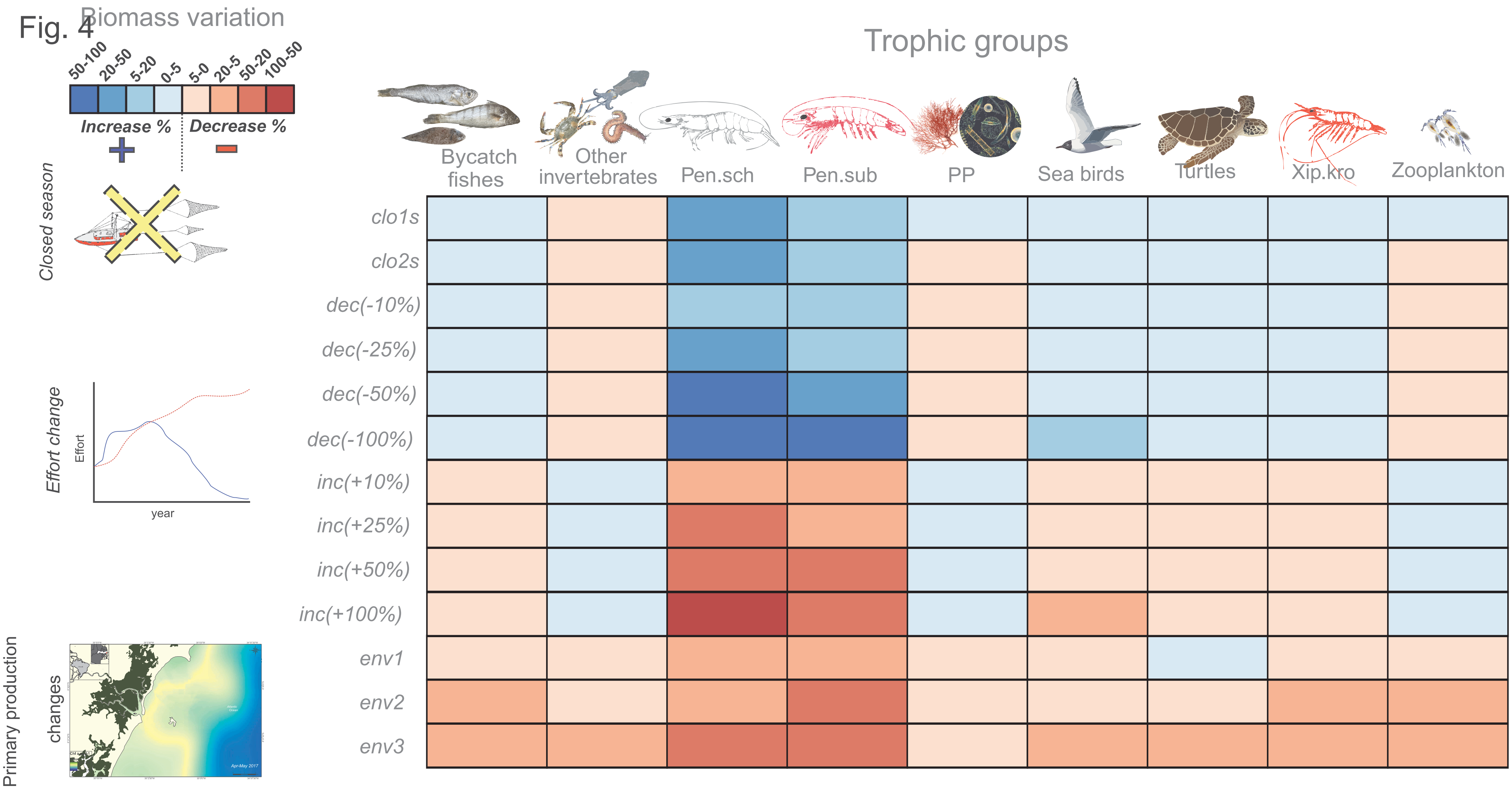
Fig. 6 Average catch variation for shrimp and by fish catch as simulated using the Fishing Management Scenarios towards the future from 2015 – 2030 compared to the baseline model (effort constant). The blue and red-coloured gradient indicates increased and decreased catches, respectively.

Fig. 7 Spearman's rank correlation between ecological indicators (see Appendix Table 2 for detail) and the temporal scale for the future scenarios (2015 – 2030, see Table 1 for detail) in the Barra of Sirinhaém, Pernambuco, north-eastern Brazil. The blue to red coloured gradients indicate positive and negative correlations, respectively. The colour intensity and size of the circles are proportional to the correlation coefficients Rho. The significant correlation between the indicators and over time (*t*-test, $p < 0.05$) are represented with a white * symbol. Total B: Total biomass, Fish B: Biomass of fish, Inver.B: Biomass of invertebrate, Kemp.Q: Kempton's biodiversity index, Total C: Total Catch, Fish C: Catch of all fish, Inver.C: Catch of all invertebrate, Disc: Total discarded catch, mTLc: Tropic level of the catch, mTLco: Trophic level of the community (including all organisms), MTI: Marine trophic index (including organisms with TL $\geq$ 3.25), MLFco: Mean length of fish community, MLFc: Mean length of fish catch.

Fig. 8 Comparison between the predicted biomass ($t.km^{-2}$) and catch ($t.km^{-2}.year^{-1}$) for shrimp species from cumulative scenarios for PP anomalies and simulated fisheries management towards the future from 2015 to 2030 (see plot legend for details). The black line represents historical model predictions and the coloured lines represent different scenarios. Shadows represent the 5% and 95% percentiles obtained using the Monte Carlo routine with 1000 runs. Pen.sub: *Penaeus subtilis*; Pen.sch: *Penaeus schmitti*; and Xip.kro: *Xiphopenaeus kroyeri*.

Fig. 9 Summary of the projected responses in fishing management plans and environmentally driven previsions in terms of conservation and exploitation indicators. For more detail about each scenario, see Table 1.

Fig. 4



Biomass variation
50-100
20-50
5-20
0-5
5-0
20-5
50-20
100-50
Increase %
Decrease %
Closed season
Effort change
Effort
year
Primary production changes
Apr-May 2017
Trophic groups
Bycatch fishes
Other invertebrates
Pen.sch
Pen.sub
PP
Sea birds
Turtles
Xip.kro
Zooplankton
clo1s
clo2s
dec(-10%)
dec(-25%)
dec(-50%)
dec(-100%)
inc(+10%)
inc(+25%)
inc(+50%)
inc(+100%)
env1
env2
env3

Fig. 5

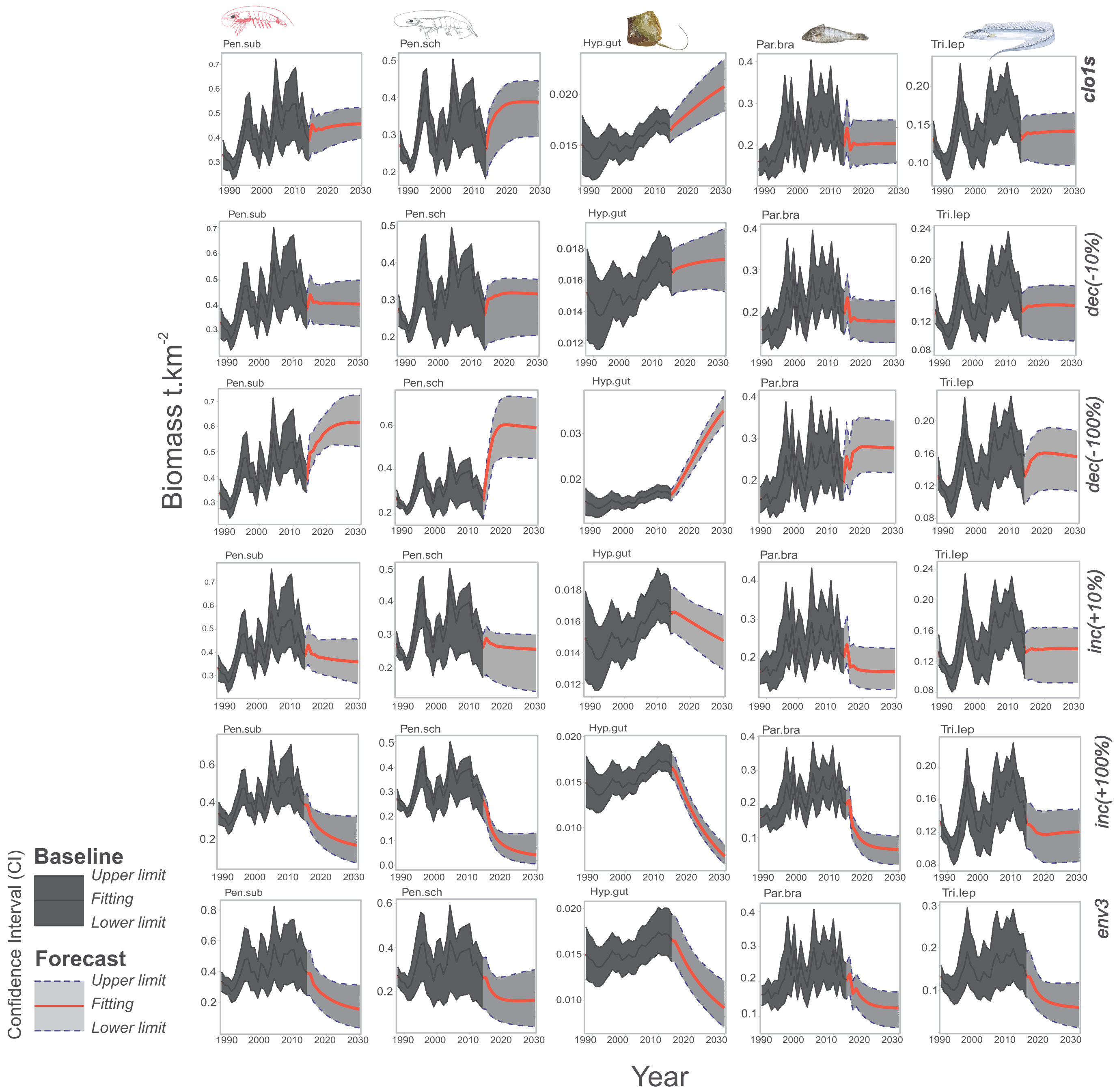
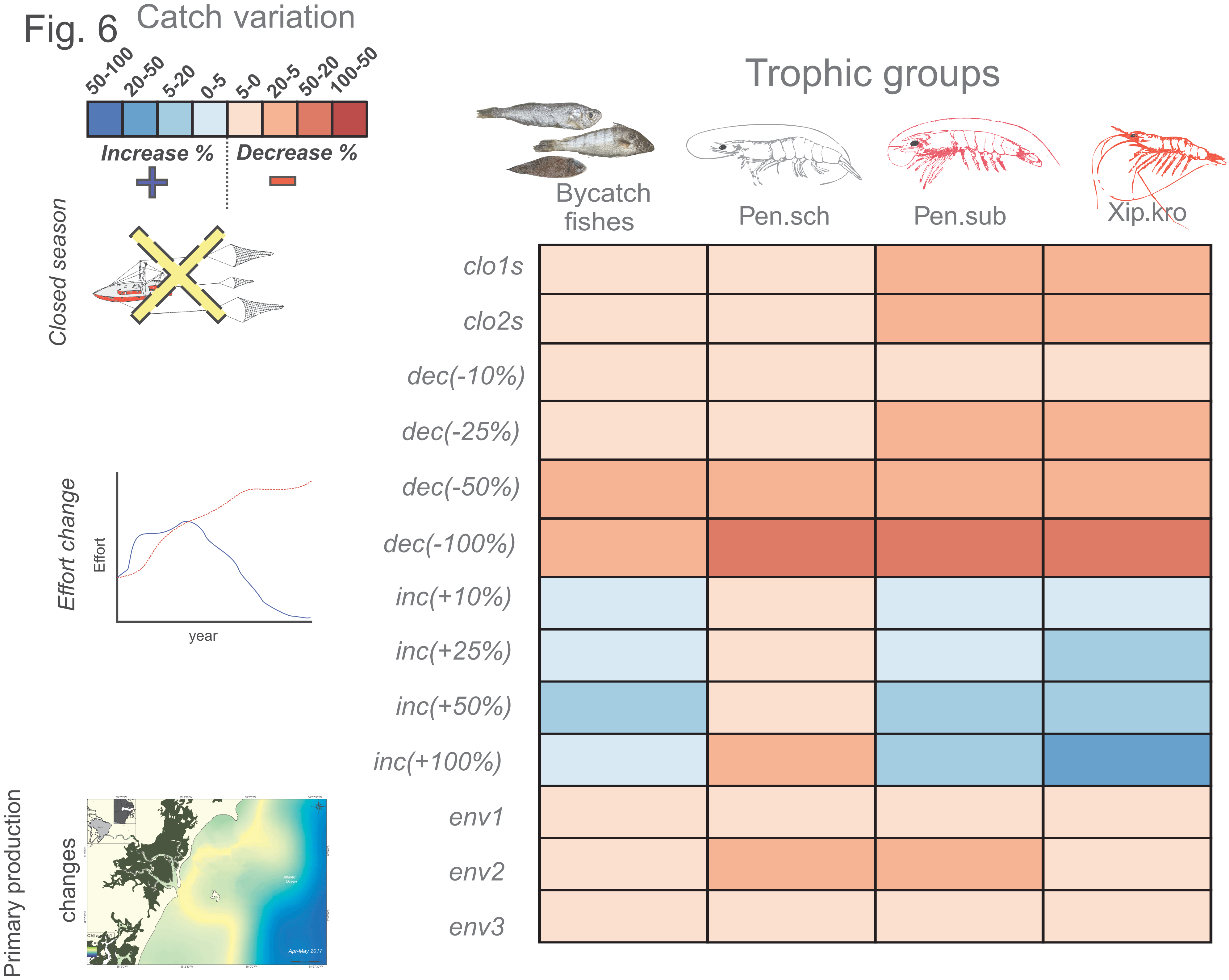

Pen.sub
Pen.sch
Hyp.gut
Par.bra
Tri.lep
clo1s
dec(-10%)
dec(-100%)
inc(+10%)
inc(+100%)
env3
Biomass t.km^{-2}
Year
Confidence Interval (CI)
Baseline
Upper limit
Fitting
Lower limit
Forecast
Upper limit
Fitting
Lower limit

Fig. 6



Catch variation
50-100
20-50
5-20
0-5
5-0
20-5
50-20
100-50
Increase %
Decrease %
Closed season
Effort change
Effort
year
Primary production
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

Fig. 7

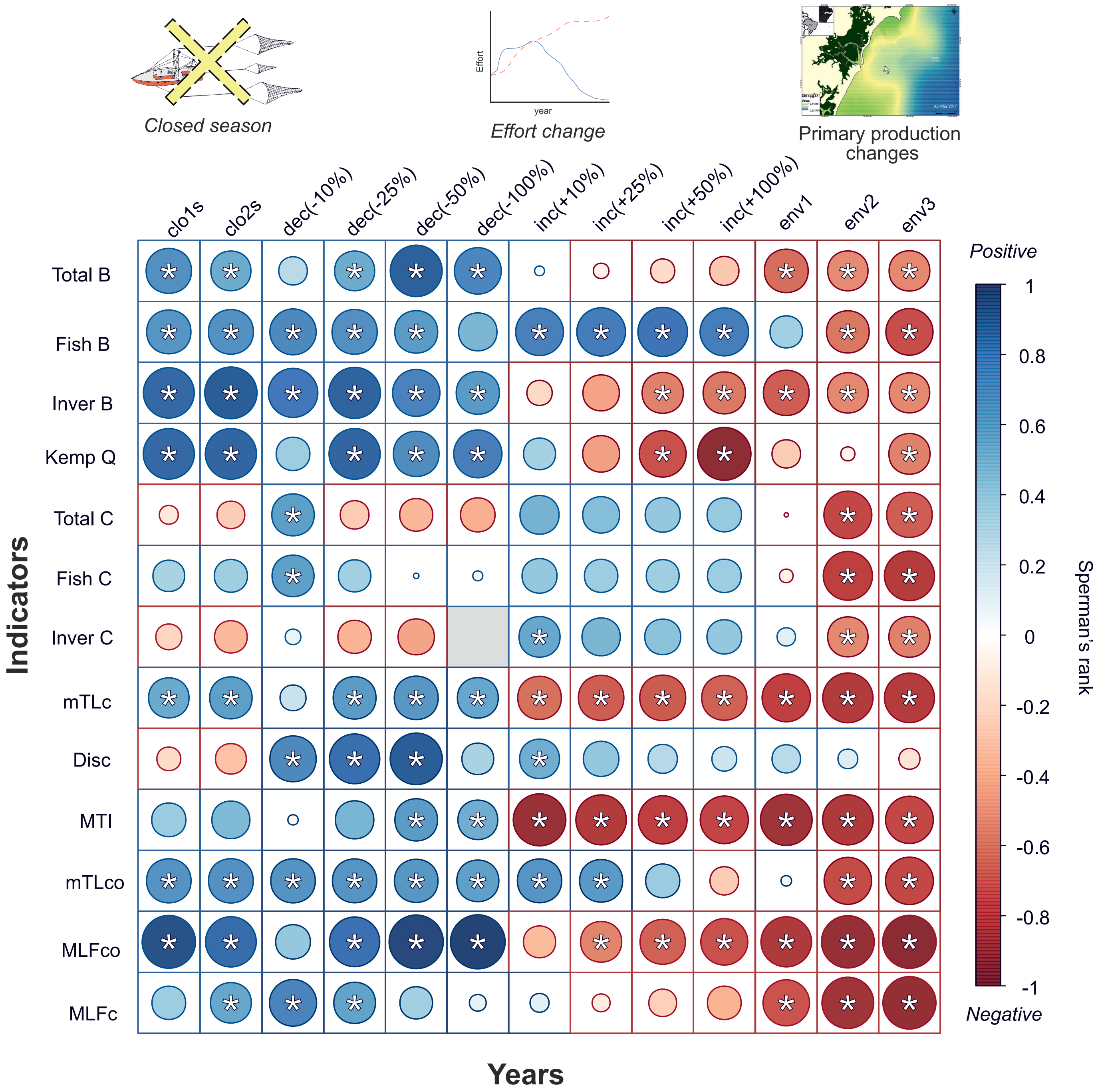
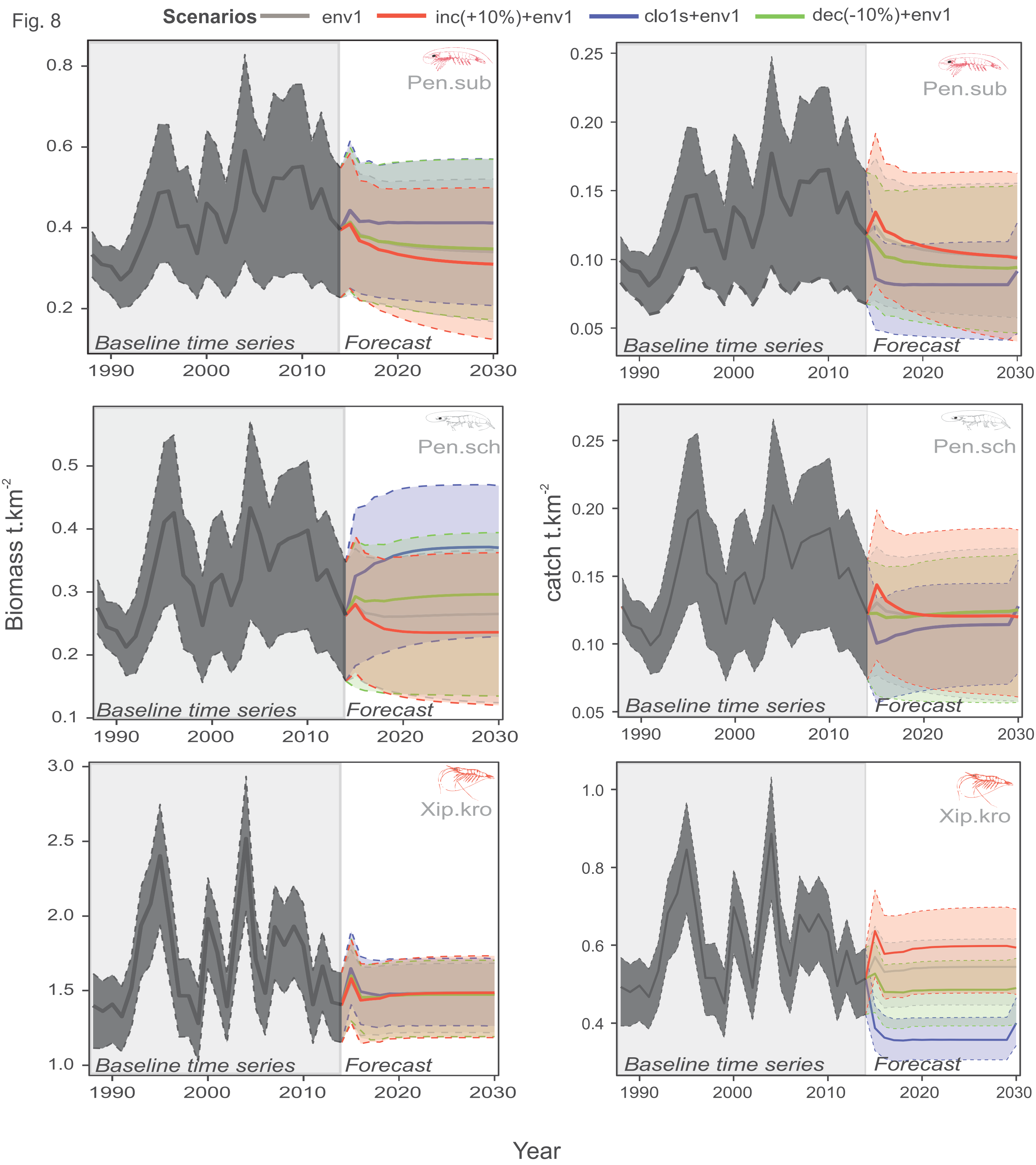

Closed season
Effort
year
Effort change
Primary production changes
clo1s
clo2s
dec(-10%)
dec(-25%)
dec(-50%)
dec(-100%)
inc(+10%)
inc(+25%)
inc(+50%)
inc(+100%)
env1
env2
env3
Indicators
Total B
Fish B
Inver B
Kemp Q
Total C
Fish C
Inver C
mTLc
Disc
MTI
mTLco
MLFco
MLFc
Years
Positive
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
Negative
Sperman's rank

Fig. 8



Scenarios
env1
inc(+10%)+env1
clo1s+env1
dec(-10%)+env1
Pen.sub
Pen.sch
Xip.kro
Baseline time series
Forecast
Biomass t.km-2
catch t.km-2
Year

Fig. 9

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