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Climate warming vs ecological competition for marine tropical biodiversity and fisheries

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Abstract

Marine ecosystems, biodiversity and fisheries are under pressure worldwide because of global changes including climate warming and demographic pressure. In that regard, many scientists and stakeholders advocate the use of an ecosystem approach for fisheries integrating the numerous ecological and economic complexities at play, instead of focusing on the management of isolated target species. However, the way to operationalize such an ecosystem approach remains challenging, especially from the bioeconomic viewpoint. To achieve this, here we propose a model of intermediate complexity (MICE) relying on multi-species and multi-fleets dynamics. The model also takes into account climate change through a model of envelope for the biological growth of the fish species depending on the sea surface temperature. The model is calibrated for the small-scale fishery in French Guiana using time series of fishing landings and efforts from 2006 to 2018. From the calibrated model, we consider the business as usual (BAU) fishing intensity projection along with RCP climate scenarios derived from IPCC at the horizon 2100 in order to explore the impact of climate change on the ecosystem dynamics and on the fishery production. The results point out the detrimental impact in the long run of both climate change and ecological competition on fish biodiversity. The situation is particularly catastrophic in the pessimistic climate scenario as the results suggest the collapse of both biodiversity and fishing activities by 2100.

Keywords:

Marine biodiversity ; Multi-species ; Multi-fleet fishery ; Models of Intermediate Complexity (MICE) ; Climate change ; Exclusion principle

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1 Introduction

Global changes are exerting substantial pressures on marine ecosystems, their biodiversity, and associated ecosystem services [8, 52]. Since years 1950, a huge development of marine and coastal fisheries occurred to ensure food and economic security for human populations. This development resulted in an increase of about 20% in overfished marine stocks worldwide between 1975 and 2015 [23]. Climate change complicates and exacerbates the issues by inducing new - or intensifying existing - risks, uncertainties and vulnerabilities through e.g. changes in primary production and fish distribution, thus potentially affecting yields [43, 5].

In that context, designing management tools and public policies that ensure the long-term bioeconomic sustainability of marine fisheries has become a major challenge. In response, many scientists and experts advocate the use of an ecosystem-based fishery management (EBFM) [25]. EBFM aims at integrating the ecological and economic complexities of fisheries, instead of focusing on isolated target species [40, 16]. However how to operationalize EBFM in terms of models, scenarios, quantitative methods and indicators remains under debate [39, 35, 22, 32, 37, 36, 26]. The general objective of this article is to contribute to EBFM by investigating the sustainability of multi-species multi-fleet fisheries in a context of climate change.

Among the different ecological- economic complexities underlying EBFM, multi-species dynamics relating to trophic or ecological competition mechanisms constitute major ingredients. In that regard, Ecopath with Ecosim [13] and whole-of-ecosystem (or end-to-end) models, such as Atlantis [27] give major insights and numerical tools. A methodological alternative for EBFM is provided by models of intermediate complexity (MICE) [37]. MICE are context and question-driven, and aim to limit the complexity by focusing on the minimum components needed to address the main effects of the management question under consideration. Although they can integrate complex marine ecosystem dynamics under global changes, the economic and social processes underlying marine capture fisheries, and their interactions with marine ecosystem services and human well-being, MICE remain simple enough to allow easy adaptation and facilitate communication between disciplines. The use of MICE keeps with the relative simplicity of models currently supporting fisheries management as well as the ability to apply standard statistical methods for their calibration, while also accounting for broader ecosystem considerations, in relation to a limited number of well-defined management objectives. In particular the account of multi-fleet dimensions, technical interactions and joint production in mixed fisheries can be important bioeconomic ingredients of MICE as in Doyen *et al.* [22] and Tromeur & Doyen [48].

The account of climate is another important ingredient for EBFM. As Stock *et al.*[42], de Lange [18] and Lopes *et al.*[33] put forward, exploring the influence of climate change on marine resource dynamics is a key issue. Hence, it is demonstrated that climate change have a huge impact on ecological processes such as population distributions or population dynamics [34, 44]. However, the way to integrate it in a model of population dynamics remains under debate [10, 51]. Using models, Lehodey *et al.* [31], Steinmetz *et al.* [41] and Garza-Gil *et al.* [28] analyse the effects of climate on fisheries. More specifically, Brander [6] and Cheung *et al.*[11] argue that climate change and global warming, in particular through their effect on sea temperature, may be the strongest drivers of stock dynamics and harvest levels in the future. Diop *et al.* [20] and Lagarde *et al.* [29] highlight the bioeconomic interest of fishing strategies accounting for climate change. In that respect, the case of tropical fisheries is especially challenging, since a decrease of diversity is projected with climate warming.

The goal of this paper is to explore driving ecological and economic processes at play on a medium to long term time scale in an fished ecosystem dynamics. Particular attention is paid to the impact of climate change, the competition between fish species and the fishing efforts of different fleets. To achieve this, we here propose a MICE relying on multi-species, resource based and multi-fleets dynamics and also taking into account climate change through a model of envelope for the biological growth of the species depending on the sea surface temperature. The model is calibrated for the tropical small-scale fishery in French Guiana using time series of fishing landings and efforts from 2006 to 2018. From the calibrated model along with RCP climate scenarios derived from IPCC, we consider the business as usual (BAU) fishing intensity at the horizon 2100 in order to explore in the long run possible future ecosystem and fishery trajectories (IPBES).

The paper is structured as follows: Section 2 presents the case study, giving details about the coastal fishery in French Guiana; Section 3 details the bio-economic model and the scenarios used; Section 4 shows

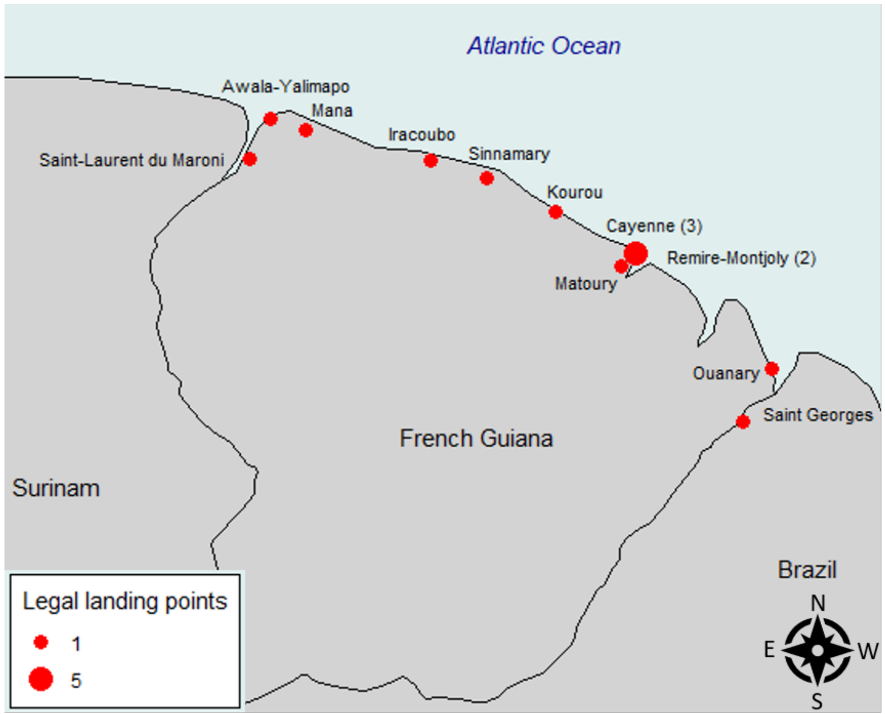


Figure 1: Map of French Guiana with legal landing points

the results including the scenario trajectories. Finally Section 5 discusses the results.

2 Case study

French Guiana is located in South America between Surinam and Brazil. Its coastline measure 350 km, which allows it to have an exclusive economic zone (EEZ) of 130,000km^2 including 50,000 km^2 of continental shelf. The coastal fishery in French Guiana is a small-scale fishery, operating in a 16 km offshore zone with depths from 0 to 20 m. In 2010, there were 14 legal landing points, distributed all along the coast, and the fishing areas are close to them because of the low capacity of boat autonomy [17] (Figure 1).

The fishery is exploited by 153 boats (in 2018), most of them being made in wood, although some are in aluminium and plastic. They are, for the major part, less than 12 meters long. There are four categories of boats which are locally named Pirogues (denoted hereafter by P), Canots créoles (denoted by CC), Canots créoles améliorés (denoted by CCA) and Tapouilles (denoted by T). The boats don't have the same size so they don't operate the fishery in the same way. The Tapouilles are the largest, with around 4 men in the boat and they go at sea for a period between 8 and 12 days. It is the only one with an inboard diesel engine. The second largest is the Canot créole amélioré with 3 men boarded for a period between 4 and 8 days. The Canot créole go at sea during 2 or 3 days with around 2 men boarded whereas the Pirogues go at sea for 1 day with one fisherman. The most used gears for all the fleets are drift nets although some fixed nets are used too. In the last two decades the coastal fishery in the French Guiana landed around 2 000 tons per year. The first fleet in terms of landing is the Canots créoles améliorés, holding around 71% of the total landing between 2006 and 2018, followed by the Canots créoles, the Tapouilles and the Pirogues with respectively 22,5%, 6% and 0.3%.

This coastal fishery is a non-selective fishery exploiting more than 30 fish species. The most harvested species are the Acoupa Weakfish *(Cynoscion acoupa)* followed by the Green Weakfish *(Cynoscion virescens)* and the Crucifix Catfish *(Sciades props)*, representing respectively around 42%, 18% and 11% of the total

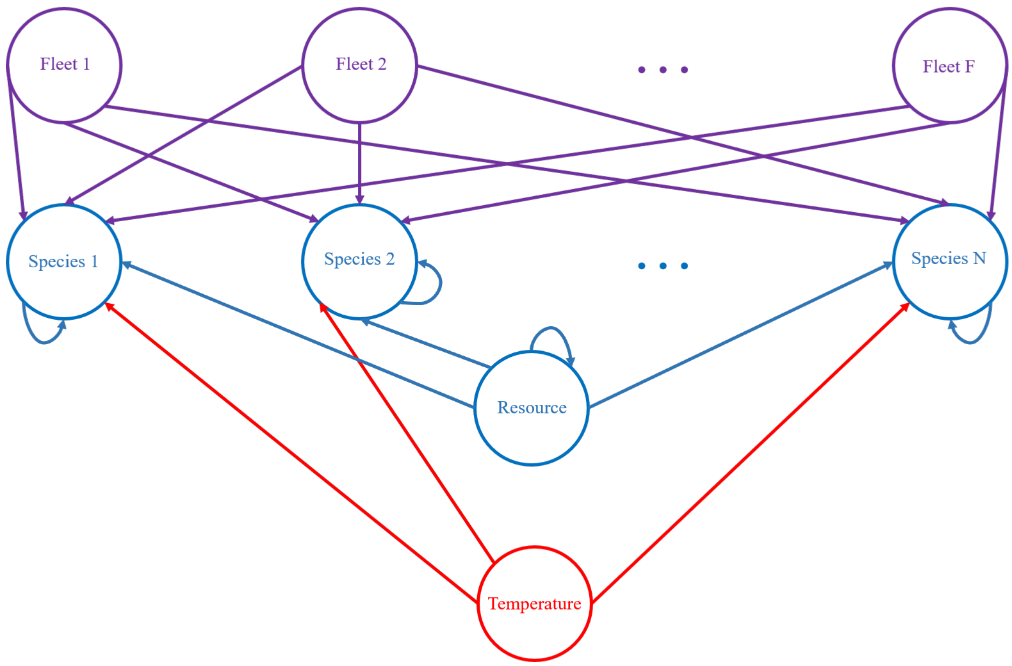


Figure 2: Conceptual bio-economic and ecosystem model

landing between 2006 and 2018. The coastal fishery in French Guiana is very important for the territory. It provides employment, contributes to food security but also human population self-sufficiency.

In the 2010s, this small-scale fishery was evaluated as viable [15, 14]. However, the INSEE (French National Institute for the Statistical and International Study) considers that the Guianese population is expected to double over the three next decades [19] thus inducing high future pressure on the coastal ecosystem.

Since 2006, observers of the IFREMER Fisheries Information System collect fishing landings and efforts data daily going on almost all the landing points up to 2016 and now only on some landing points (around the two third). These observations are then extrapolated in order to obtain values of fishing landing and efforts, at quarterly rate, for all the boats and all the landing points. Due to an undersampling for the pirogues, and as they represent only 0.3% of the total landing, we have chosen to neglect them in our analysis. Observed sea surface temperature data are extracted from the website of Earth System Research Laboratory [2]. As the coastal fleets operate at a depth of maximum 20 metres, the sea temperatures can be considered as homogeneous on the whole water column.

In this study, we focus on the period 2006-2018 and on the three species most fished by the coastal fishery in French Guiana, representing around 71% of the total landings on the considered period namely : Acoupa Weakfish, denoted by AW, Green Weakfish, denoted by GW (that are predators) and Crucifix Catfish, denoted CrC, which is at a lower trophic level.

3 Ecological-economic model and scenarios

Accounting for the climate impact, we consider an ecological-economic model for the fishery in line with models of intermediate complexity (MICE;[37, 22]). As captured by the conceptual model displayed in figure 2, the model relies on a multi-stocks and multi-fleet discrete time dynamics, accounting for the climate impact through the sea surface temperature (SST). The calibration of the model is made through the method of least squares on fishery catches.

3.1 Multi-stocks multi-fleet dynamics

Fished species are denoted by $i = 1, \dots, N$ while fleets are denoted by $f = 1, \dots, F$. It is assumed that the N fish species compete for the consumption of a common resource (e.g. phytoplankton, zooplankton), denoted by res, and that no trophic interaction occurs between these species. The growth of the different species is also assumed to depend on the SST, denoted by θ. Thus for every species, at each step $t+1$, the biomass $B_i(t+1)$ depends both on the biomass $B_i(t)$, the state of the resource $B_{res}(t)$, the temperature $\theta(t)$ (with a time lag) and harvesting $H_i(t)$ as follows:

$$B_i(t+1) = B_i(t)\Big(1 - M_i + g_i * a_{res,i} * B_{res}(t) * \gamma_i\big(\theta(t-\tau_i)\big)\Big) - H_i(t). \tag{1}$$

In the equation (1), M_i stands the mortality rate of the stock i. In the part of the equation representing the resource consumption of the species i, g_i stands for the growth efficiency of i and $a_{res,i}$ is the consumption rate of the predator i on the resource (in line with Ecosim formulation [50]). The term $\gamma_i(\theta(t-\tau_i))$ based on thermal envelopes of species together with a time delay τ_i is specified below in equation (5). Such a formulation captures the climate impact on species growth as in Ainsworth *et al.*[4] as well as Thompson *et al.* [45] regarding time delays.

The catches $H_i(t)$ of the species i at time t are derived from the harvests $H_{i,f}(t)$ of the different fleets f:

$$H_i(t) = \sum_{f=1}^{F} H_{i,f}(t) \tag{2}$$

The catches $H_{i,f}(t)$ of the stock i by the fleet f at time t are based on the Schaefer production function:

$$H_{i,f}(t) = q_{i,f} E_f(t) B_i(t). \tag{3}$$

where the variable $E_f(t)$ is the fishing effort of fleet f (time spent at sea) and $q_{i,f}$ measures the catchability of the stock i by the fleet f, which is the probability of a biomass unit of the stock i being caught by a boat of fleet f during one fishing effort unit.

The dynamics of the biomass $B_{res}(t)$ of the resource depends on the consumption of the different fish species through the relation [30, 7]:

$$B_{res}(t+1) = B_{res}(t)\Big(1 - \sum_{i=1}^{N} a_{res,i} B_i(t)\Big) + I(t), \tag{4}$$

where $I(t)$ corresponds to the external input (source) for this resource.

3.2 Climate impact

Bioclimate envelopes for species also named environmental niche relates to physical and biological conditions that are suitable to a given species [10, 11]. The model of Bioclimate envelopes calculates the preference profiles by overlaying environmental data with maps of relative abundance of the species on a defined size grid. Candela *et al.* [9] use this kind of model to create a Half-Degree Species Environmental Envelope table which contains ranges of suitable and preferred temperatures. From this temperature table, we define the biological efficiency for every species i, denoted by $\gamma_i(\theta)$, in such a way that the efficiency equals 1 when the temperature level fits with the preferred temperature of the species while this efficiency is close to zero when the temperature is far from this preferred level. The figure 3 represents the biological efficiency for one species i as a function of temperature. In more mathematical terms, the biological efficiency of the species i depends on the preferred temperature $\theta_{i,opt}$ through the relation:

$$\gamma_i(\theta) = \exp\left(\frac{(\theta - \theta_{i,opt})^2}{\kappa_i^2}\right), \tag{5}$$

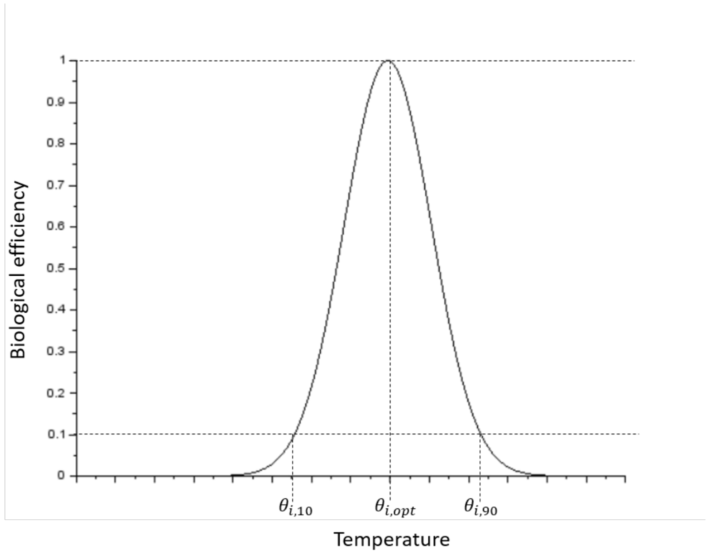


Figure 3: Biological efficiency for one species i as a function of temperature with $\theta_{i,10}$,$\theta_{i,opt}$ and $\theta_{i,90}$ represented

where the constant κ_i is defined by:

$$\kappa_i = \frac{\theta_{i,10} - \theta_{i,opt}}{\ln(0.1)^{\frac{1}{2}}}. \tag{6}$$

In the equation (6), the detrimental temperature $\theta_{i,10}$ is such that the temperature efficiency equals 10% for this level namely

$$\gamma_i(\theta_{i,10}) = 10\%.$$

For every species, temperature reference levels $\theta_{i,opt}$, $\theta_{i,10}$ and $\theta_{i,90}$ extracted from the website of Aquamaps [1] are listed in the Appendix A.1.

3.3 Fishing and climate scenarios

From the calibrated model, we make projections from current period t_0 until $T = 2100$ to explore what could can happen for both the fishery, fish biodiversity and the marine ecosystem in the future. In particular, we consider a business as usual (BAU) scenario for the fishing activity, and two contrasted climatic scenarios, RCP 8.5 and 2.6, relating to the last IPCC report[38].

The fishing BAU scenario: This scenario simulates fishing efforts based on the idea that the fishery and every fleets will continue its current dynamics. Considering a first order approximation of the current trends on the efforts of the different fleets, such BAU scenario reads as follows [21]:

$$E_f(t+1) = E_f(t)(1 + \delta_f^{hist}), \;\; t = t_0, \ldots, T \tag{7}$$

In the equation (7) δ_f^{hist} stands for growth rate of the efforts, based on the historical data. For the case study, the rates δ_f^{hist} of the different fleets are detailed in the Appendix A.2.

Climate scenario RCP 8.5: This climate scenario is a pessimistic projection proposed by the IPCC. In this scenario, the global SST is characterized by a mean increase of about 0.95°C for the near term (2031-2050) and a mean increase of 2.58°C for the end-of-century (2081-2100) with respect to to the recent past (1986-2005).

Climate scenario RCP 2.6: This scenario relies on an optimistic projection of IPCC. In this scenario, the global SST relates to a mean increase of about 0.64°C for the near term (2031-2050) and a mean increase of 0.73°C for the end-of-century (2081-2100) with respect to the recent past (1986-2005).

For each climatic scenario the temperature $\theta(t+1)$ at time $t+1$ depends on the temperature at time t, $\theta(t)$, and the rise in temperature at a rate (quarterly for the case study) denoted by Δ_{ω,t_f}, where ω represents the scenario and t_f the final time:

$$\theta_\omega(t+1) = \theta_\omega(t) + \Delta_{\omega,t_f} \tag{8}$$

We report in the table 1 the rise in temperature at a quarterly rate and the initials conditions, which are respectively $\theta_\omega(2005)$ and $\theta_\omega(2050)$ for the near term and for the end-of-century:

Table 1: Rise in temperature, at a quarterly rate, and initials conditions, for the near term and the end-of-century, for each climatic scenario ω.

Parameters	RCP 8.5	RCP 2.6
$\Delta_{\omega,2050}(*10^3)$	5.275 °C	3.56 °C
$\Delta_{\omega,2100}(*10^3)$	8.15 °C	0.45 °C
$\theta_\omega(2005)$	27.41 °C	27.41 °C
$\theta_\omega(2050)$	28.36 °C	28.05 °C

<u>*Resource's dynamic:*</u> To compute the projections of the biomass of the resource $B_{res}(t)$, we consider that the external input $I(t)$ for this resource varies according to a uniform random distribution, between its minimum, I_{low}, and maximum I_{high} calibration values as follows:

$$I(t) \sim \mathcal{U}(I_{low}, I_{high})$$

Moreover this uniform distribution is assumed to be an independently and identically distributed (i.i.d.).

4 Results

4.1 Calibration of the model

The calibration of the bio-economic model for the case study in French Guiana has been done using the data and time series of IFREMER Fisheries Information System at quarterly rate over the period 2006-2018. The scientific software SCILAB has been used for the numerical computations and in particular the optimization underlying the least square method. In this paper, we focused on $N = 3$ fish species (Acoupa Weakfish, Green Weakfish and Crucifix Catfish) and $F = 3$ fleets (Canots créoles, Canots créoles améliorés and Tapouilles). The estimation of all the parameters including the mortality rate M_i of each species i, the catchability $q_{i,f}$ of each species relative to each fleet f, the terms of interactions $a_{i,res}$ between the species and the resource, the growth efficiency of each species g_i, the initial biomass in $t_0 = 2006$ of each species $B_i(t_0)$ and the time lag for each species τ_i obtained are given in the Appendix A.3. The main outputs of the model include the calibrated catches by species $H_i(t)$ as defined in equation (2), the catches by fleets denoted by $H_f(t) = \sum_f H_{i,f}(t)$, the total catch $H(t) = \sum_f H_f(t)$ and the calibrated biomass $B_i(t)$ of each stock i.

The figure 4 compares the historical and calibrated catches by fleets, stocks and the aggregated catches. We can see in the three cases (fleet's catches, stock's catches and aggregated catches) that the historical (dark blue points) and the calibrated model (black curve) values are close. Even if the historical values show more variability than the estimated ones, the model outputs fit well the historical outputs.

4.2 Projections and scenarios outcomes

As explained in the section 3.3, we apply the fishing business as usual scenario, with two contrasted climatic scenarios at the horizon $T = 2100$.

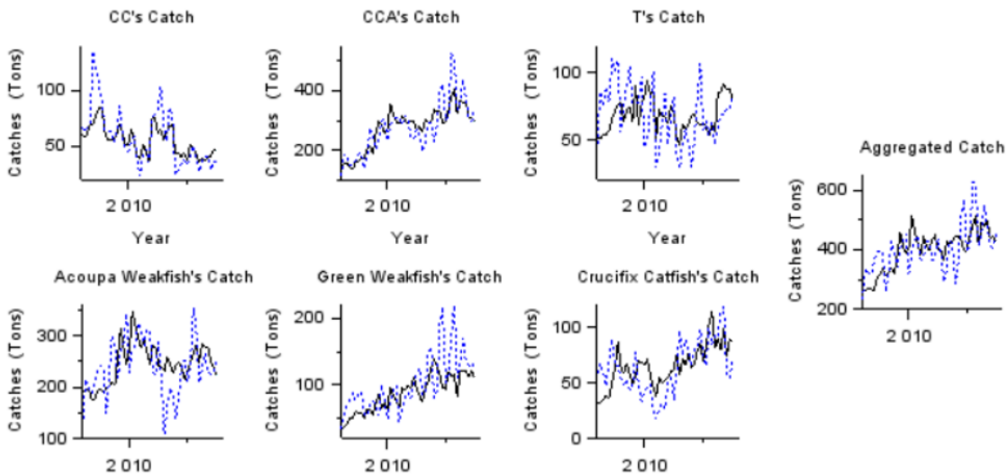


Figure 4: Historical (dark blue points) and calibrated (black curve) catches by fleets (first row), stocks (second row) and aggregated (last graph)

In the climate optimistic case with scenario RCP 2.6 (figure 5), we can observe in the long run extinctions of two species namely the AW around year 2045 and the GW around year 2080 by contrast to the third species CrC whose biomass remains at high levels until 2100 (figure 5c). The two species extinctions entail the collapse of the AW and GW catches and consequently, from 2080, all the catch relies on the CrC fishing (figure 5b second row). The growth of the CrC's fishing induces a decrease of the CrC's biomass in the long run as displayed in (figure 5 third column). It can be also noted that the CCA'S and the T's harvesting increase during the period of the projections whereas CC's catches decrease (figure 5b first row). This is consistent with the projected efforts (figure 5a) since the effort growth rate δ_{CC}^{hist} is negative whereas the rates δ_{CCA}^{hist} and δ_{T}^{hist} are positive (Appendix A.2). The increases of CCA's and T's fisheries, even if the CrC's biomass decrease, are due to a compensation between this decline and the high growth in fishing efforts. Finally, it can be noticed that the development of CCA's and T's catches makes it possible a major growth for the global harvest of the fishery over the whole period (figure 5b right).

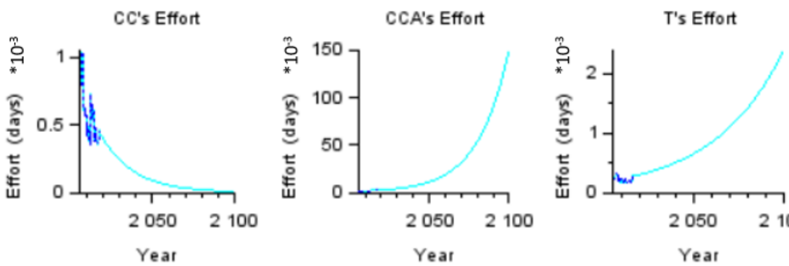
In the pessimistic climate scenario RCP 8.5 displayed in figure 6, we can observe a collapse in the long run of both fish biodiversity and harvest. Figure 6b shows extinctions in the long run of all the three fish species: from 2043 for the AW, from 2065 for the GW and from 2070 for the CrC. Hence, the catches of each stock as well as the aggregated catch also equal 0 in the long run (figure 6a). In this scenario, as captured by Figure 6b (right hand side), the biomass of the resource growths exponentially from 2050, because its consumption by the species vanishes.

5 Discussion

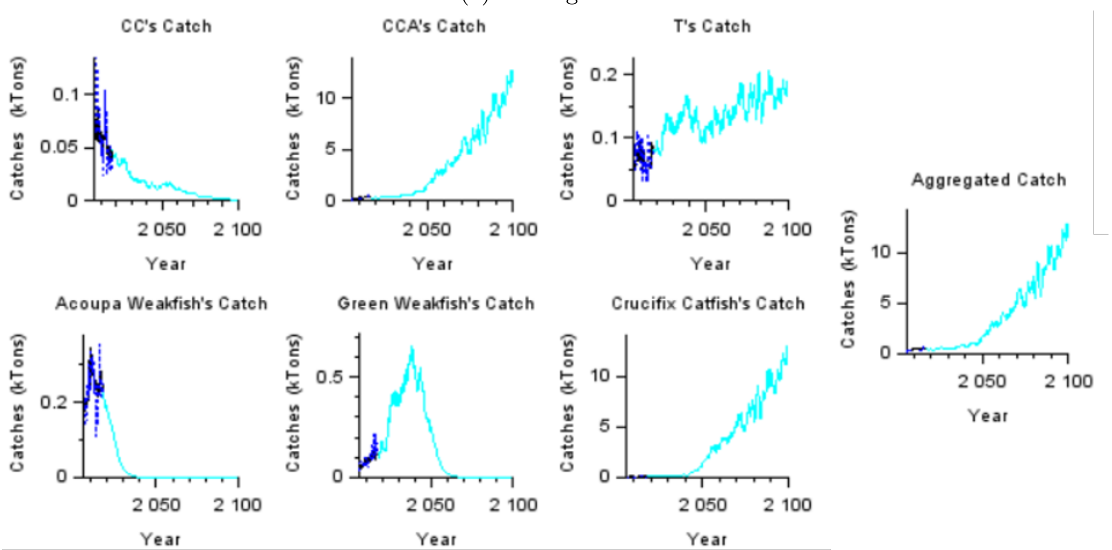
In this section, several points are developed: the interest of Models of Intermediate Complexity, the detrimental impact of climate change on populations' dynamics, the interpretation of a biological calibrated parameter, the identification of the ecological driver of the populations' dynamics and finally the way to improve the sustainability of the coastal fishery in French Guiana.

5.1 The benefits of the Models of Intermediate Complexity (MICE)

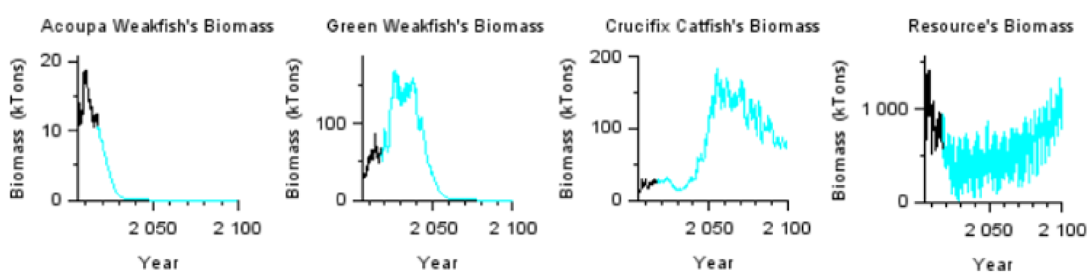
In contrast to whole-of-ecosystems or end-to-end models like Atlantis models [27] for example, which integrate complex marine ecosystem dynamics under global changes, the economic processes underlying marine fisheries, and their interactions with marine ecosystem services and human well-being, Models of Intermediate



(a) Fishing efforts for each fleet

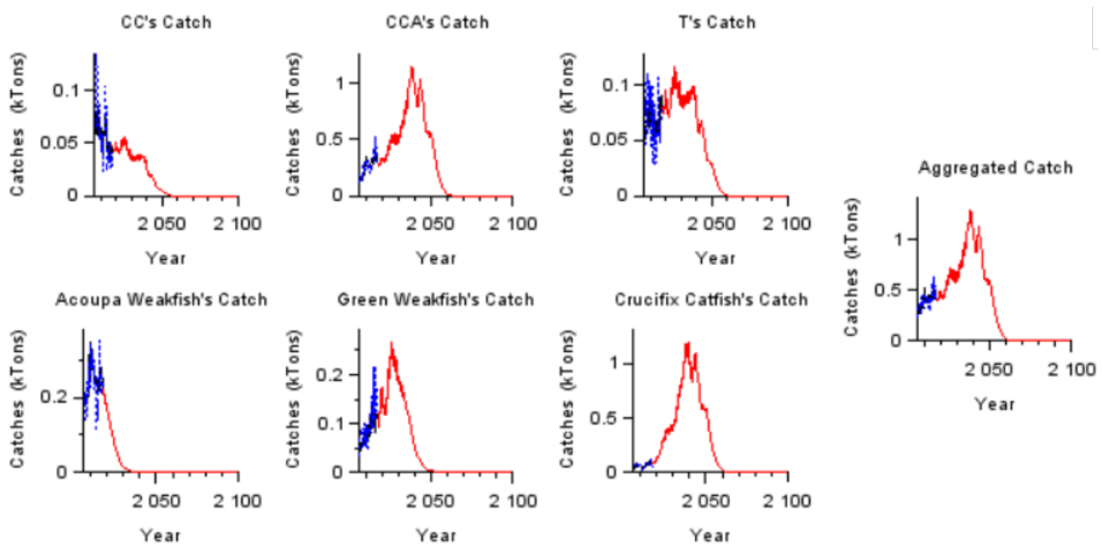


(b) Catches by fleets (first row), stocks (second row) and aggregated (middle of the two rows)

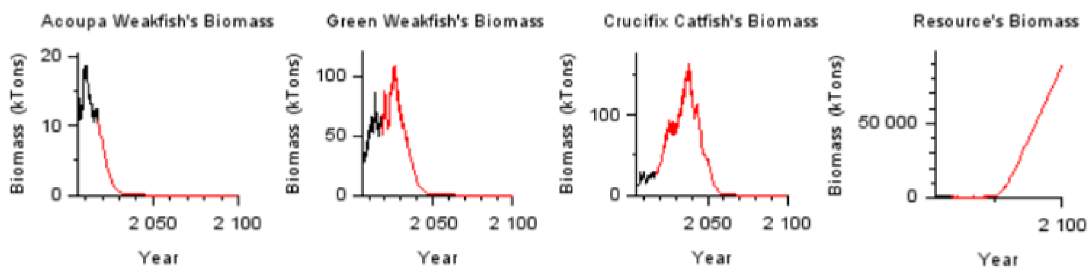


(c) Biomass for each stock

Figure 5: Scenario BAU (fishing) and RCP 2.6 (climate): historical (dark blue points) and projected (blue curve) fishing efforts (first row); historical (dark blue points), calibrated (black curve) and projected (blue curve) catches by fleets (second row), stocks (third row) and aggregated (middle of the two middle rows) and calibrated (black curve) and projected (blue curve) biomass for each stock (last row)



(a) Catches by fleets (first row), stocks (second row) and aggregated (middle of the two rows)



(b) Biomass for each stock

Figure 6: Scenarios BAU and RCP 8.5: historical (dark blue points), calibrated (black curve) and projected (red curve) catches by fleets (first row), stocks (second row) and aggregated (middle of the two first rows) and calibrated (black curve) and projected (red curve) biomass for each stock (last row)

Complexity aim at limiting the complexity taken into account. MICE indeed focus on the minimum components and interactions needed to address the main effects of the management question under consideration. Plagànyi *et al.* [37] advocate to use MICE models in ecosystem modelling and present their principles. MICE attempt to explain the underlying ecological processes for a limited group of populations (typically <10) subject to fishing and anthropogenic interactions and include at least one explicit representation of an ecological process. Our paper followed this MICE approach as in [15, 22] to integrate the dynamics of 3 fished stocks and a resource, interactions of competition, 3 fleets harvesting the three fish species along with the impact of global warming. As seen in the section 4.1, our model accurately represents the ecosystem dynamics that we intend to manage through harvesting strategies. In other words, a Model of Intermediate Complexity can be useful to answer economic or ecological questions and thereby contribute to the first step of an ecosystem approach. Moreover, as the species taken into account represent around 71% of the total landing, the MICE model can give major insights into the sustainability of the coastal fishery in French Guiana.

5.2 The detrimental impact of global warming on biodiversity and catches

In order to evaluate the impact of climate change, the biomass and catch trajectories are compared for the two contrasted climatic scenarios (figures 5 and 6). In term of species, the largest difference is for the species CrC as, in the pessimistic case, an extinction occurs whereas, in the optimistic case, the stock is viable until 2100. Moreover, for the other species AW and GW, it can be observed that the extinctions occur earlier for the pessimistic case than for the optimistic case. Thus the loss of biodiversity in the RCP 8.5 is much more severe as compared to RCP 2.6. A major driver of such a loss of biodiversity and extinctions of fish species relates to the thermal envelopes and notably preferred temperatures $\theta_{i,opt}$ which differ between species as detailed in Appendix A.1. In that regard, table 4 shows that CrC benefits from high temperatures as compared to the two other species. In particular, both $\theta_{i,opt}$ and $\theta_{i,90}$ temperature thresholds are the highest for the CrC. Furthermore, as quantified by $\theta_{i,opt}$ in table 4 in the Appendix A.1 the ranking of species namely $\theta_{AW,opt} < \theta_{GW,opt} < \theta_{CrC,opt}$ explains the sequence of fish species declines since AW first collapses followed by GW and then by CrC.

Regarding fishing production, the difference between the two extreme climate scenarios is also very important. For the pessimistic scenario, the species extinctions result in a collapse of the whole fishing landings and production whereas, in the optimistic case, the fishery globally persists and even grows via the CrC catches.

These findings highlight that environmental changes, here climate warming, are a major driving force of the ecosystem dynamics and ecosystem services of the coastal area of the French Guiana. It turns out that this impact is here negative on both the biodiversity and the provisioning ecosystem service (seafood) underpinning fishing activities. This result is consistent with the works of Cheung *et al.* [12] who prove that the increase of the SST in the equatorial area significantly alters negatively the maximum catch potential. For the French Guiana, [20] also point out similar detrimental impacts of climate warming for the shrimp fishery.

5.3 Interpretation of climate times lags

In this part of the discussion, we focus on the species climate time lags τ_i which play a role in the dynamics (equation (1)) through the thermal envelope defined in equation (5). It turns out that these time lags parameters are closely related to parameters named 'resilience' in Fishbase [3]. Such resilience value denoted here by t_i^{*2} is the minimal time to double the biomass of each species i and thus characterizes the duration for maturity of species and their velocity of growth. In other words, a low t^{*2} means fast growth and a low age at maturity. The values for the three species considered in our case study are reported on Table 2 and compared to time lags τ_i.

We can see that the parameters given by Fishbase are consistent with the times lags τ_i obtained by the model. In particular, the CrC's growth is faster than the AW's and GW's growths and the CrC's age at maturity is lower than the AW's and GW's age at maturity. Consequently climate change affects the population state rather instantly for the CrC, while it impacts the two other species (weakfishes) with a

Table 2: Minimal time to double, $t_{*2,i}$, for each stock i

Parameters	Acoupa Weakfish (AW)	Green Weakfish (GW)	Crucifix Catfish (CrC)
$t_{*2,i}$	1,4 to 4,4 years	4.5 to 14 years	less than 15 months
τ_i (months)	12	48	0

delay. These results suggest that our model captures age structured processes underlying the dynamics of species. Said differently, it paves the road for age structured models as proposed in Quinn and Deriso [**?**].

5.4 The Tilman exclusion principle as a major driver

As represented by equation (4) in the section 3.1, the fish species compete for the consumption of a common resource entitled 'res'; thus we are in a context of multi-species competition for a limiting factor. Tilman *et al.* [46, 47] investigated this kind of ecosystem dynamics and put forward a so-called 'exclusion principle' [30]. They indeed demonstrated that the stock with the lowest resource requirement at equilibrium, denoted by $B^*_{res,i}$, displaces all other stocks. In that respect, in Table 3, we compute the resource stocks at equilibrium in the long run[1] for each stock i and for the scenarios RCP 2.6 together with BAU efforts for fishing.

Table 3: Resource requirement in equilibrium, $B^*_{res,i}(t)$ (ktons), for each stock i for 2085

Parameter	Acoupa Weakfish (AW)	Green Weakfish (GW)	Crucifix Catfish (CrC)
$B^*_{res,i}(2085)(ktons)$	10,718	1,420	704

Table 3 shows that CrC is the species with the lowest resource requirement in 2085. Such a result is consistent with the trajectories derived from the model and the scenario (BAU - RCP 2.6) and plotted in Figure 5c as, at this date, the CrC has the highest biomass while the two others species are extinct. Such finding confirms that the exclusion principle is an important ecological driver of ecosystem dynamics. However, It is important to notice that this exclusion mechanism depends on the sea surface temperature. SST $\theta(t_{2085}) = 28.11°C$ for this climate scenario in 2085 is indeed closer to $\theta_{CrC,opt} = 27,9°C$ the optimal temperature of CrC as compared to $\theta_{i,opt}$ temperatures for both the AW ($\theta_{AW,opt} = 25.94°C$) and the GW ($\theta_{GW,opt} = 27.59°C$) (see A.1). In other words, the temperature at year 2085 favors CrC dynamics through the biological efficiency $\gamma(\theta)$. Therefore climate and exclusion mechanisms interplay for the extinctions of the AW and GW in this climate scenario 2.6.

Such interplay differs in other parts of the marine area in French Guiana. In particular, in the continental shelf of French Guiana, between 20 and 50 meter depth, it has been shown that, based on functional and taxonomic fish diversity comparisons, environmental filtering is a more important driving force than competitive exclusion [49]. High ecosystem production and the large surface area of the shelf - the two dimensions of the resources according to the niche theory [**?**] - are the main factors to explain why competition does not strongly matter in that case. By contrast, on the coastal area we are interested in for the study of the

[1]From dynamics (1), we consider the stocks at equilibrium in year 2085 to obtain $B^*_{res,i}$

$$B^*_{res,i} = \frac{M_i + \sum_{f=1}^{F} q_{i,f} * E_f(t_{2085})}{\gamma_i\Big(\theta(t_{2085} - \tau_i)\Big) * g_i * a_{res,i}}. \tag{9}$$

with t_{2085} corresponds to the value of the first quarter of year 2085.

coastal fishery, the fish community differs and turns out to be more tolerant to large environmental variations including high salinity variations arising from the estuary. Said differently, the coastal ecosystem is more sensitive to ecological processes, such as competition, than the continental shelf ecosystem. It would be interesting to investigate the taxonomic and functional diversity of the coastal fish community to confirm this interpretation.

5.5 Policy recommendations for French Guiana fisheries

In the 2010s, the small-scale fishery of French Guiana was evaluated as viable [15, 14]. However, the human demographic pressure raises concerns about the sustainability of this fishery as the INSEE (French National Institute for the Statistical and International Study) considers that the Guianese population should double over the three next decades [19] which should entail high pressures on the marine and coastal resources. Other vulnerabilities for this coastal fishery, as for many tropical small-scale fisheries, relate both to the lack of data and policy failures to efficiently managed the fishery access [24]. The present study also points to major vulnerabilities relating to climate changes. The results in the pessimistic climatic scenario indeed indicate that the coastal fishery will collapse around 2070 while in the optimistic climatic scenario (RCP 2.6) the coastal fishery will solely rely on one species (the Crucifix Catfish) from 2080. It can be noticed that in the latter scenario the Crucifix Catfish biomass decreases between 2050 and 2100, which leads us to extrapolate the extinction of the Crucifix Catfish after 2100, suggesting major threats for the viability of the French Guiana's coastal fishery as a whole in the long run. Said differently, the coastal fishery's sustainability seems low in the face of climate change. As underlined at the beginning of the paper, the coastal fishery in French Guiana is a non selective fishery. So in order to sustain it, a first strategy could rely on the development of more selective management applying to the local situation in French Guiana, with recommendations on techniques that allow to target specific species [35, 15] Furthermore, another way to increase the sustainability of the coastal fishery in French Guiana, is to determine ecological-economic and EBFM policies based on eco-viability [**?**], resilience [**?**] or multi-species Maximum Sustainable Yield (MMSY) [48, 29].

6 Conclusion

This paper exhibits leading processes for the ecosystem and harvesting dynamics of the coastal fishery in French Guiana and more globally for tropical small scale fisheries. To achieve this, IPCC climatic scenarios and a business as usual fishing strategy are assessed using a MICE integrating dynamic multi-species, at various trophic levels, and multi-fleet ingredients in which the fish species growth function depends on climate through SST. The model is validated using times series over the period 2006-2018. Our work contributes to ecosystem-based fishery management through two model-based scenarios. The projections show a largely pessimistic result for the future of the fisheries under the pessimistic climate scenario, but they can rely on the Crucifix Catfish fishery under the optimistic scenario. This result highlights the importance of limiting the increase of the SST and therefore the emissions of greenhouse gases. As we consider only the increase of the SST in the impact of the climate change, and not all the others parameters like the acidification of the ocean, the primary productivity changes etc, we can assume that the impact of the climate change will be in reality higher. Moreover, the paper identifies one of the leading biological processes on the populations' dynamics which is the exclusion principle. All this results show that both exclusion principle and environmental filtering, through climate change, are major drivers-effects on the populations' dynamics. Finally the paper underlines the importance of adapting the fishery in order to improve its sustainability. To determine how to improve it, several fishing strategies, like co-viability or MSY for example, have to be applied to the model. Moreover, it can be interesting to add other stocks of the marine ecosystem to the model as these other stocks could benefit from warmer temperatures through higher thermal efficiency.

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A Appendix

A.1 Temperatures $\theta_{i,10}$, $\theta_{i,opt}$, $\theta_{i,90}$ used for climate change modelling

Table 4: Temperatures $\theta_{i,10}$, $\theta_{i,opt}$, $\theta_{i,90}$ for each stock i

Temperature (°C)	Acoupa Weakfish (AW)	Green Weakfish (GW)	Crucifix Catfish (CrC)
$\theta_{i,10}$	23.56 °C	26.9 °C	27.38 °C
$\theta_{i,opt}$	25.94 °C	27.59 °C	27.9 °C
$\theta_{i,90}$	28.32 °C	28.28 °C	28.42 °C

A.2 Rate δ_f^{hist} used for projected efforts

Table 5: Rate δ_f^{hist} for each fleet

δ_f^{hist}	Canots Créoles Améliorés (CCA)	Canots Créoles (CC)	Tapouilles (T)
δ_f^{hist}	-0.012	0.013	0.007

A.3 Calibrated parameters

Table 6: Parameters obtained by the calibration

Parameters	Acoupa Weakfish (AW)	Green Weakfish (GW)	Crucifix Catfish (CrC)	Resource (Res)
$a_{res,i}\,(*10^6)$	2.5	7.6	6.8	/
$q_{i,CC}\,(*10^6)\,(day^{-1})$	3.3	0.5	1.4	/
$q_{i,CCA}\,\ (*10^6)\,(day^{-1})$	7.3	0.5	1.1	/
$q_{i,T}\,\ (*10^6)\,(day^{-1})$	13.2	2	1	/
M_i	0.08	0.139	0.137	/
g_i	0.153	0.06	0.066	/
$B_i(2006)\,(tons)$	$14,070$	$25,055$	$12,866$	$28,2625$
$\tau_i\,(months)$	12	48	0	/

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