The Major Roles of Climate Warming and Ecological Competition in the Small-scale Coastal Fishery in French Guiana

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Abstract

Marine ecosystems, biodiversity, and fisheries are under strain worldwide due to global changes including climate warming and demographic pressure. To address this issue, many scientists and stakeholders advocate the use of an ecosystem approach for fisheries that integrates the numerous ecological and economic complexities at play rather than focusing on the management of individual target species. However, the operationalization of such an ecosystem approach remains challenging, especially from a bio-economic standpoint. Here, to address this issue, we propose a model of intermediate complexity (MICE) relying on multi-species, multi-fleet, and resource-based dynamics. Climate change effects are incorporated through an envelope model for the biological growth of fish species as a function of sea surface temperature. The model is calibrated for the small-scale fishery in French Guiana using a time series of fish landings and fishing effort from 2006 to 2018. From the calibrated model, a predictive fishing effort projection and RCP climate scenarios derived from IPCC, we explore the ecosystem dynamics and the fishery production at the horizon 2100. Our results demonstrate the long-term detrimental impact of both climate change and ecological competition on fish biodiversity. The prognosis is particularly catastrophic under the most pessimistic climate scenario, with a potential collapse of both biomass targeted species and fishing activity by 2100.

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

1 Declarations

1.1 Funding

This study, including data collection and analyzes, was funded by the IFREMER (Institut Français de Recherche pour l'Exploitation de la Mer; english: French Research Institute for Exploitation of the Sea). It also benefited from the CNRS research project entitled ENTROPIC (Ecological-ecoNomic resilience of TROPIcal coastal eCosystem).

1.2 Conflicts of interest/Competing interests

The authors have no financial or proprietary interests in any material discussed in this article.

1.3 Availability of data and material

Data of fishing landings and efforts are available in the website of the IFREMER Fisheries Information System (https://sih.ifremer.fr/). Observed sea surface temperature data (SST) are extracted from the NOAA Earth System Research Laboratory website (https://www.esrl.noaa.gov/).

1.4 Code availability

This study has been performed thanks to the scientific software SCILAB. In particular the calibration was done with "optim_ga" routine. The numerical codes for the calibration and the scenarios are available in the Google drive of codes.enmo.d.20.00261@gmail.com, password: ENMO.D.20.00261. Please contact Hélène Gomes in case of any problem.

1.5 Authors' contributions

All authors contributed to the study conception and design. The model was developed by Abdoul Ahad Cissé, Luc Doyen, Hélène Gomes and Coralie Kersulec. Scenarios for the projections were performed by Luc Doyen and Nicolas Sanz. Analysis were conducted by Fabian Blanchard and Hélène Gomes. The first draft was written by Hélène Gomes and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

2 Introduction

Global changes are exerting significant pressure on marine ecosystems, their biodiversity, and the ecosystem services they provide [8, 41]. In particular, the rapid development of marine and coastal fisheries since the 1950s in order to ensure food and economic security for human populations increased the number of overfished marine stocks by about 20% worldwide between 1975 and 2015 [23]. Climate change introduces new risks, uncertainties, and vulnerabilities and amplifies those already present by altering primary production and fish distribution thus potentially affecting yields [3, 53].

Under these circumstances, designing management tools and public policies that ensure the long-term bio-economic sustainability of marine fisheries has become a pressing challenge. To address this challenge, many scientists and experts advocate the use of ecosystem-based fishery management (EBFM) [25]. The EBFM approach aims to integrate the ecological and socio-economic complexities of fisheries rather than focusing on individual target species [16, 51]. However, the question of how to operationalize EBFM in terms of models, scenarios, quantitative methods, and indicators remains a matter of debate [22, 27, 37, 44, 45, 46, 50]. The general purpose of this article is to contribute to the operationalization of EBFM.

Of the various ecological and socio-economic complexities underlying EBFM, multispecies dynamics play a particularly important role. Ecopath with Ecosim [13] and whole-of-ecosystem (or end-to-end) models, such as Atlantis [26] can provide important insights and numerical tools to simulate these dynamics based on trophic or ecological competition mechanisms. However, whole-ecosystem models have been criticized for their dependence on exhaustive data [45] (although Fulton *et al.* apply a whole-ecosystem model in a data-poor context and suggest that it may be useful in systems that are only slightly fished [27]), while Ecopath is constrained by its assumption of equilibrium and mass balance. Models of intermediate complexity (MICE) [46] represent a methodological alternative to these approaches for EBFM. MICE are context and question-driven and aim to limit complexity by focusing only on the components needed to address the management question under consideration. Although they can integrate complex marine ecosystem dynamics with global change, 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 for easy adaptation and facilitate communication between disciplines. MICE maintain the relative simplicity of models currently supporting fisheries management, can be calibrated through standard statistical methods, while also accounting for broader ecosystem considerations within the scope of certain well-defined management objectives. In particular, important bio-economic factors such as multi-fleet dimensions, technical interactions, and joint production in mixed fisheries can be incorporated into MICE (see Doyen *et al.* [22] and Tromeur & Doyen [58]).

Species competition is an issue of fundamental importance in ecology. In that regard, Tilman [57] has developed a mechanistic model that predicts the outcome of species competition based on the resource requirements of the competing species. He suggests

that the species with the lowest resource requirement at equilibrium will displace all other species. This result is known as the 'exclusion principle' [21]. Examples of species competition and exclusion principle in fisheries can be found in Daan [18] and Botsford [4].

Climate is another crucial component of EBFM as the effects of climate change on marine resource dynamics are of key importance (Stock *et al.* [52], de Lange [34], and Lopes *et al.* [38]). Climate change has been shown to have a major impact on ecological processes such as population distribution and population dynamics [42, 54]. As reproductive success and maturation are temperature-sensitive, climate-related temperature changes have a time-shifted effect on fisheries (depending on growth time to harvest size). This shift is thus tied to the growth rate of the fished species. The best way of integrating this effect in a population dynamics model has been the subject of much debate [10, 61]. For example, Garza-Gil *et al.* [30] incorporate sea surface temperature into several mathematical functions of the natural growth dynamic of sardine biomass as part of a bio-economic model of a European sardine fishery. They then determine the most plausible growth dynamic through statistical testing and calculate projections for future biomass and profits under several climate scenarios. Caballero-Alfonso *et al.* [2] use statistical methods (e.g., Pearson's correlation coefficient, Monte Carlo analysis) to validate a linear relationship between octopus catch and SST in the Canary Islands, highlighting the influence of climate on this fishery. More broadly, Lehodey *et al.* [36] review the current understanding of the impacts of climate variability on fish populations and fisheries, while Brander [5] and Cheung *et al.* [11] argue that, due in large part to their effect on sea temperature, climate change and global warming may be the strongest drivers of stock dynamics and harvest levels in the future. Diop *et al.* [20] and Lagarde *et al.* [33] highlight the bio-economic advantages of fishing strategies that account for climate change. Furthermore, tropical fisheries are facing a particularly challenging situation, since biodiversity is projected to decrease with climate warming in tropical ecosystems [11, 12].

The specific goal of this paper is to account for driving ecological processes in a fished ecosystem on a medium- to long-term time scale in the perspective of EBFM. Particular attention is paid to the impacts of climate change, competition between fish species, and the fishing efforts of different fleets. This goal also aligns closely with the objectives of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) with respect to scenarios of marine biodiversity and ecosystem services [24]. To this end, we propose a multi-species, multi-fleet dynamic MICE that integrates climate change through an envelope model for species growth as a function of sea surface temperature. The model takes into account both ecological and technological complexities, incorporating biology through resource-based stock dynamics and fishing technology through a joint fishing production function. The model is calibrated for the tropical small-scale fishery in French Guiana using time series of fish landings and fishing effort from 2006 to 2018. From the calibrated model, along with RCP climate scenarios derived from the Intergovernmental Panel on Climate Change (IPCC), as well as a predictive fishing intensity at the horizon 2100, we explore possible long-term ecosystem

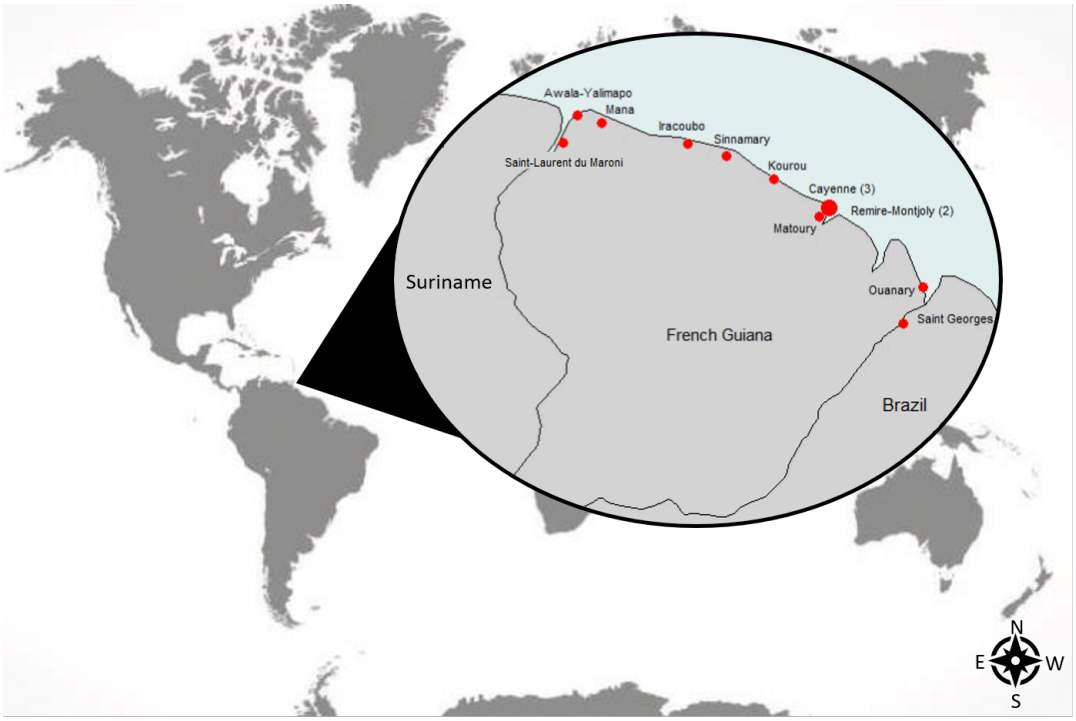


Figure 1: Map of French Guiana with, in red, legal landing points of the coastal fishery.

and fishery trajectories. The IPCC has adopted four climate scenarios, known as Representative Concentration Pathways, based on different greenhouse gas concentration trajectories [47]. Here, we focus on the two extreme scenarios, namely RCP 2.6 and RCP 8.5.

The paper is structured as follows: Section 3 introduces the case study and describes the coastal fishery in French Guiana; Section 4 details the model and scenarios used; Section 5 presents the results, including the scenario trajectories, and a comparitive analysis of scenarios. Finally, Section 6 contains a discussion of the results.

3 Case study

French Guiana is located in South America, between Suriname and Brazil. Its coastline measures 350 km, and its exclusive economic zone (EEZ) has an area of 130,000 km2, including 50,000 km2 of continental shelf. The coastal fishery in French Guiana is a small-scale fishery, operating in a 16 km offshore zone with depths ranging from 0 to 20 m. In 2010, there were 14 legal landing points distributed all along the territory's coast, with fishing areas concentrated around these points due to the fishing boats' short range [32] (Figure 1).

As of 2018, the fishery is exploited by 153 boats, mostly built of wood (although some are made of aluminium and plastic) and generally less than 12 meters long. Drift

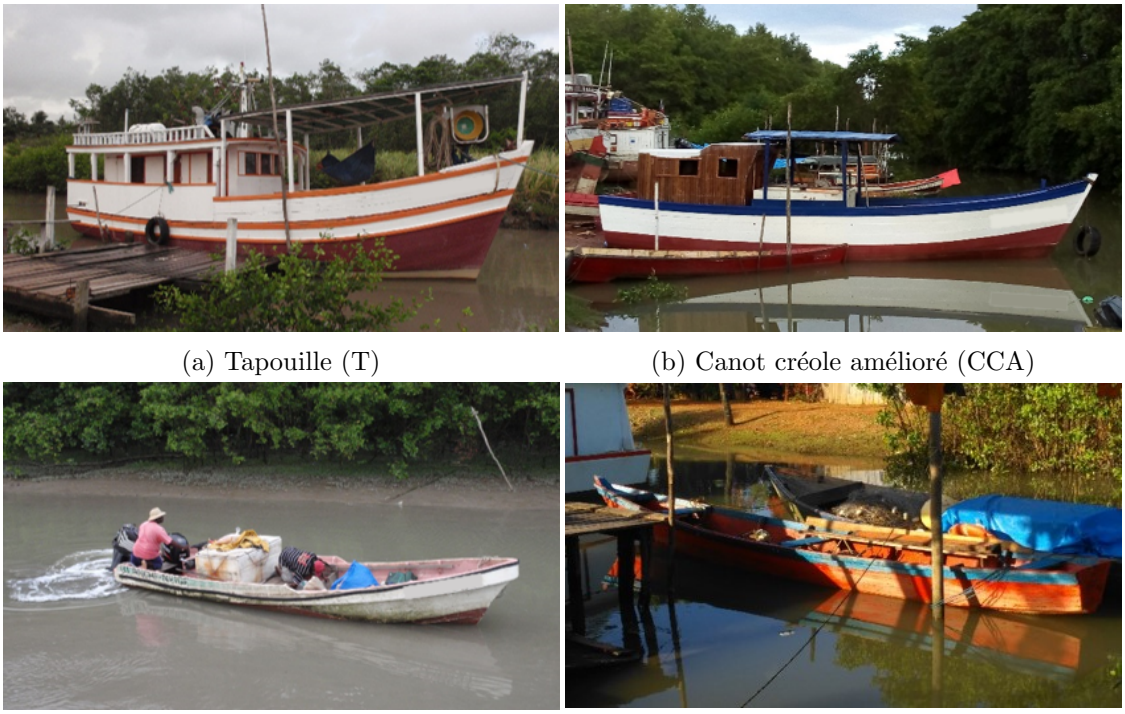
Table 1: Characteristics of each fleet of the coastal fishery in French Guiana

Characteristics	Tapouilles (T)	Canots Créoles Améliorés (CCA)	Canots Créoles (CC)	Pirogues (P)
Width	between 3 and 4 m	≈ 2 m	≈ 1.5 m	≈ 1 m
Number of fishers boarded	≈ 4	3	2	1
Duration of trip (days)	between 8 and 12	between 4 and 8	between 2 and 3	1
Engine	Inboard diesel engine	Outboard gasoline engine	outboard gasoline engine	outboard gasoline engine
% of the total landing	6%	71.2%	22.5%	0.3%
Cooling system	Interior of boat partitioned off to serve as ice hold	≈ 2 custom-built ice holds	Repurposed refrigerator or freezer with ice inside	Repurposed refrigerator or freezer with ice inside, or no cooling system at all

nets are the most commonly used equipment across all of the fleets, though some fixed nets are used as well. There are four categories of boats, illustrated in Figure 2, which are known locally as "pirogues" (hereafter denoted as P), "canots créoles" (CC), "canots créoles améliorés" (CCA) and "tapouilles" (T). These four categories differ in size and operate in different ways, as detailed in Table 1.

Over the last two decades, this coastal fishery in French Guiana has been landing approximately 2,000 tons per year. The fishery is non-selective and exploits more than 30 fish species. The most harvested species is the acoupa weakfish *(Cynoscion acoupa)*, followed by the green weakfish *(Cynoscion virescens)* and the crucifix catfish *(Sciades proops)*, representing an estimated 42%, 18%, and 11%, respectively, of total landings between 2006 and 2018. The French Guiana coastal fishery is particularly important for the territory as it provides employment and contributes to food security.

In the 2010s, the stocks exploited by this small-scale fishery to meet food demand were evaluated as underfished [15, 14]. However, the INSEE (French National Institute of Statistics and Economic Studies) estimates that the Guianese population will double over the next three decades [19], thus increasing future pressure on the coastal ecosystem



(a) Tapouille (T)

(b) Canot créole amélioré (CCA)

(c) Canot créole (CC)

(d) Pirogue (P)

Figure 2: Pictures of the different categories of boats of the coastal fishery in French Guiana.

and fish stocks.

Since 2006, observers from the IFREMER Fisheries Information System have been tracking fishing effort (in days at sea) on a daily basis. They also collected daily fishing landing data from almost all of the landing points between 2006 and 2016, and from two-thirds of the landing points from 2017 onwards.[1]

Observed sea surface temperature data (SST) are extracted from the NOAA Earth System Research Laboratory website [2]. As the coastal fleets operate at a maximum depth of 20 meters, sea temperature can be considered to be homogeneous throughout the water column. Temperature data are extracted at a resolution of 60km x 60km. Five points in total are examined (their geographic coordinates are given in Appendix A.1)), and the SST used in the model is obtained by computing the mean SST value of each point.

In this study, we focus on the period from 2006 to 2018 and on the three species most heavily exploited by the coastal fishery in French Guiana, representing about 71% of the total landings over this period: the acoupa weakfish (AW) and green weakfish (GW), both of which are predators, and the crucifix catfish (CrC), which is at a lower trophic level. We also focus on the three main categories of boats, namely tapouilles (T), canots créoles (CC), and canots créoles améliorés (CCA), and leave aside pirogues (P), as they represent only 0.3% of total landings. As detailed in Section 4 in the Subsection 4.3, we use catch data for these three species and for the three categories of boats as well as effort data for the three categories of boats to calibrate the model.

4 Model and scenarios

The model we developed for the fishery is in line with models of intermediate complexity (MICE ;[22, 46]). As represented in the conceptual model displayed in Figure 3, the model relies on a multi-stock and multi-fleet discrete time dynamics, accounting for climate impact through sea surface temperature (SST). Multi-species dynamics are largely drawn from the resource-based model [57]. Uncertainties are captured by the two climate scenarios. The model is calibrated through a least squares regression of fishery catch data.

4.1 Multi-stock, multi-fleet dynamics

Fished species are denoted by $i = 1, \ldots, N$ while fleets are denoted by $f = 1, \ldots, F$. As under the resource-based model [57], it is assumed that N fished species compete for a common resource (e.g. shrimps and fishes in the case study), denoted by res, and that no direct trophic interactions occur between these fished species; in other words, there

[1] Using data on fish landings for a given effort as well as comprehensive data on fishing effort, IFREMER observers are able to extrapolate landings for all boats and landing points on a quarterly basis using the rule of three. During this period, the fishermen made no technical adaptations and installed no new equipment that would have increased fishing power. Therefore, we can assume that the efficiency of the French Guiana fishery remains constant over time.

[2] https://www.esrl.noaa.gov/

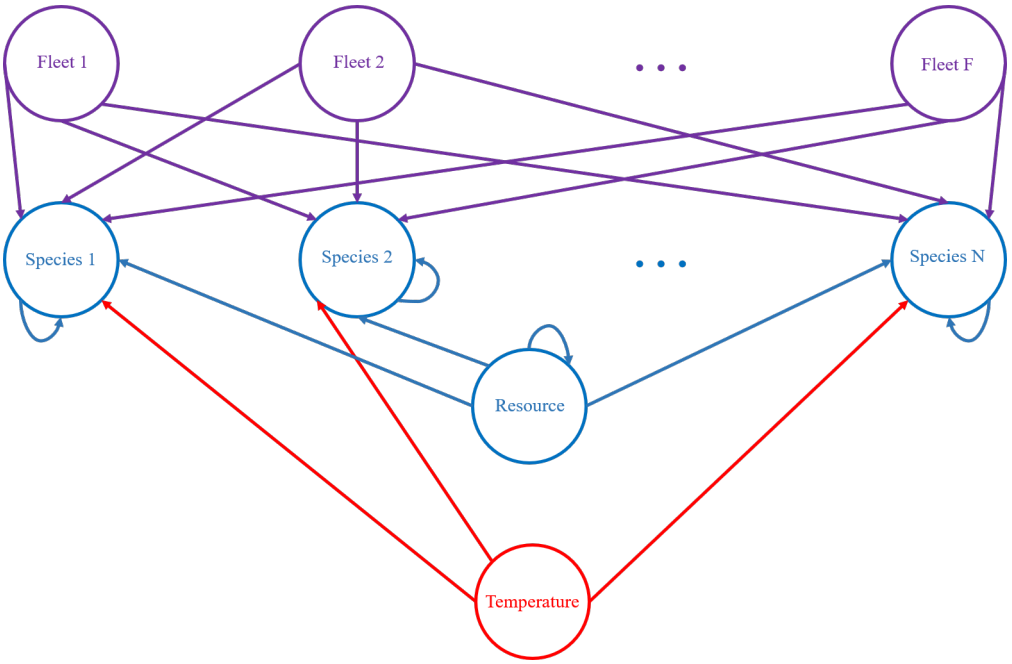


Figure 3: Conceptual model.

are no predator/prey mechanism between the fished species[3]. The growth of each species is also assumed to depend on SST, denoted by θ. Thus, for every species, at each time step t, the biomass $B_i(t+1)$ depends 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:

$$B_i(t+1) = B_i(t)\big(1 - M_i + G_i(t)\big) - H_i(t). \tag{1}$$

with

$$G_i(t) = g_i a_{res,i} B_{res}(t) \gamma_i\big(\theta(t-\tau_i)\big) \tag{2}$$

In equation (1), M_i stands for the mortality rate of fish stock i. In the equation (2), representing the resource consumption by fish species i, parameter g_i stands for the growth efficiency of i and $a_{res,i}$ is the consumption rate of the predator i on the resource, res (in line with Ecosim formulation [60]). The term $\gamma_i(\theta(t-\tau_i))$, based on the species' thermal envelopes together with a time delay τ_i, is specified below in equation (6). This formula captures climate impact on species growth (see Ainsworth *et al.*[1] and Thompson *et al.* [55] regarding time delays).

Catches $H_i(t)$ of the fish species i at time t are derived from the harvests $H_{i,f}(t)$ of

[3]In the model proposed for the French Guiana fishery by Cissé *et al.* [15], trophic interactions turn out to have a weak influence. Here, we have simplified the model by ignoring trophic interactions between fishes in order to focus on the influence of the environment on population dynamics.

the different fleets f:

$$H_i(t) = \sum_{f=1}^{F} H_{i,f}(t). \tag{3}$$

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

$$H_{i,f}(t) = q_{i,f} E_f(t) B_i(t), \tag{4}$$

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

The dynamics of the resource stock $B_{res}(t)$ depends on the consumption of this resource by the different fish species, according to the following equation [7, 35]:

$$B_{res}(t+1) = B_{res}(t)\left(1 - \sum_{i=1}^{N} a_{res,i} B_i(t)\right) + I(t), \tag{5}$$

where $I(t)$ corresponds to the external input (source) for this resource. The impact of climate on the resource is not directly taken into account, but temperature affects the consumption of the resource by its predators.

4.2 Climate impact

The bioclimatic envelope, also known as environmental niche, is the set of physical and biological conditions suitable for a given species [10, 11]. Bioclimatic envelope models calculate species' preference profiles by linking environmental data with maps of relative abundance of the species on a defined size grid. Candela *et al.* [9] use this type of model to create a Half-Degree Species Environmental Envelope table containing ranges of suitable and preferred temperatures. From this temperature table, we define the biological efficiency for each species i, denoted by $\gamma_i(\theta)$, such that efficiency equals 1 when the temperature matches the preferred temperature of the species, while it approaches zero when the temperature is far from this preferred level. The Figure 4 represents the biological efficiency for species i as a function of temperature.In more mathematical terms, the biological efficiency of species i depends on the preferred temperature $\theta_{i,opt}$ as follows:

$$\gamma_i(\theta) = \exp\left(\frac{(\theta - \theta_{i,opt})^2}{\kappa_i^2}\right), \tag{6}$$

where the constant κ_i is defined by:

$$\kappa_i = \frac{\theta_{i,10} - \theta_{i,opt}}{\ln(0.1)^{\frac{1}{2}}}. \tag{7}$$

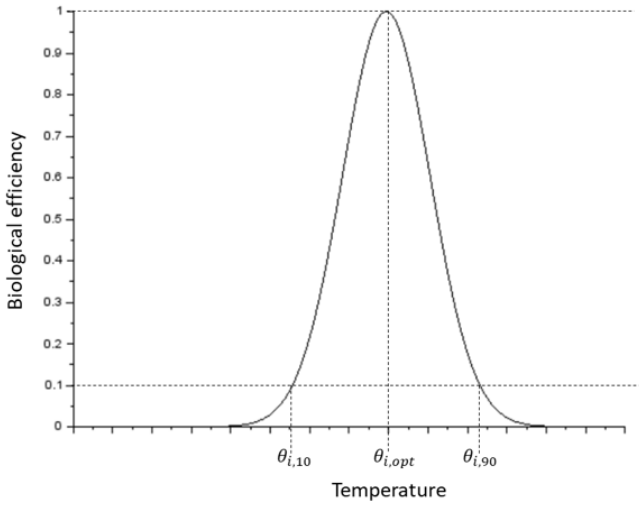


Figure 4: Biological efficiency for species i depending on temperature levels $\theta_{i,10}$, $\theta_{i,opt}$ and $\theta_{i,90}$.

In equation (7), the detrimental temperature $\theta_{i,10}$ is the temperature at which biological efficiency equals 10%:

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

The reference temperatures ($\theta_{i,opt}$, $\theta_{i,10}$ and $\theta_{i,90}$) for each species, obtained from the Aquamaps website, are listed in Appendix A.2.

4.3 Calibration method

The model for the French Guiana case study was calibrated using data and time series from the IFREMER Fisheries Information System on a quarterly basis, from the first quarter of 2006 to the last quarter of 2017. The parameters estimated in the calibration are 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 interaction $a_{i,res}$ between the species and the resource, the growth efficiency g_i of each species, the initial biomass $B_i(t_0)$ of each species, at time $t_0 = 2006$, and the time lag τ_i for each species. The calibration is performed by applying the least squares method to fishery catch data. This method consists of minimizing the mean square error between the quarterly observed catches $H_{i,f}^{data}$ and the catches $H_{i,f}$ simulated by the model, as follows:

$$\min_{M_i;q_{i,f};a_{res,i};g_i;B_i(t_0);\tau_i} \sum_{t=t_0}^{t_1-1} \sum_{i=1}^{N} \sum_{f=1}^{F} (H_{i,f}^{data}(t) - H_{i,f}(t))^2, \tag{8}$$

with $t_1 - 1$ is the last period of data namely the last quarter of 2017.

The nonlinear optimization problem was solved numerically using the scientific software SCILAB. We made particular use of the "optim_ga" routine, which relies on an

evolutionary (or genetic) algorithm. A genetic algorithm is a search heuristic that mimics the process of natural evolution. This heuristic is routinely used to generate solutions to nonlinear optimization problems. Genetic algorithms belong to a larger class of evolutionary algorithms that use techniques inspired by natural evolution, such as inheritance, mutation, selection, and crossover. In our case, the genetic algorithm performed better than the usual optimization and calibration algorithms. This type of numerical method has already been used for bio-economic purposes in Mardle and Pascoe (2000) [40], for instance, and for the small-scale fisheries in French Guiana in particular [15]. The calibration is carried out using both historical fishing catches and effort as inputs; effort data are used as model inputs though equation (4).

4.4 Fishing and climate scenarios

From the calibrated model, we calculate projections from current period $t_1 = 2018$ until $T = 2100$ to explore potential changes in the fishery, in fish biodiversity, and in the marine ecosystem. Projections are made over a relatively long timeframe in order to better compare both climate scenarios, which in the short term differ only slightly in terms of predicted sea surface temperature[4]. We consider a predictive scenario for fishing activity, denoted by PS, and two contrasting climate scenarios, RCP 8.5 and 2.6, drawn from the latest IPCC report [47]. We still assume SST to be constant over the entire coast.

Predictive fishing scenario, denoted by PS: This scenario simulates fishing effort based on the assumption that the fishery and all of its fleets will maintain their current dynamics. Using a first-order approximation of current fishing-effort trends for the various fleets over the period 2006-2018, the PS runs as follows [21]:

$$E_f(t+1) = E_f(t)(1+\delta_f^{hist}), \quad t = t_0, \ldots, T. \tag{9}$$

In equation (9), δ_f^{hist} stands for growth rate of fishing effort based on a regression over the historical data. For the case study, the growth rates δ_f^{hist} of each fleet are detailed in Appendix A.3. We acknowledge that these effort scenarios are somewhat simplified, as they do not rely on a fishing behavioral model [28] and do not fully account for potential adaptive relationships and redistributions of fleet effort with respect to the future state of stocks. Further discussion of the limitations of the fishing projection in that regard is provided in Section 6.4.

Climate scenario RCP 8.5: This climate scenario is a pessimistic projection proposed by the IPCC. This scenario assumes a mean increase of about 0.95°C in global SST in the near term (2031-2050) and of 2.58°C towards the end of the century (2081-2100) compared to the recent past (1986-2005).

[4]However we are aware that a longer timeframe introduces significant additional uncertainties to the model.

Climate scenario RCP 2.6: This scenario relies on an optimistic IPCC projection in which global SST increases on average by about 0.64°C in the near term (2031-2050) and by about 0.73°C at the end of the century (2081-2100) compared 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 over a given time period (per quarter in the case study), denoted by Δ_{ω,t_f}, where ω represents the scenario and t_f the final time:

$$\theta_\omega(t+1) = \theta_\omega(t) + \Delta_{\omega,t_f}. \tag{10}$$

In Table 2, we report the quarterly rise in temperature as well as initial and mid-term conditions, represented as $\theta_\omega(2005)$ and $\theta_\omega(2050)$ for the near term and for the end-of-century, respectively:

Table 2: Quarterly rise in temperature and initial and mid-term conditions for the near term and the end-of-century, for each climatic scenario $\omega \in \{\text{RCP 8.5, RCP 2.6}\}$.

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

Resource dynamics: To compute biomass projections for resource $B_{res}(t)$, we assume 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 independently and identically distributed (i.i.d.).

5 Results

5.1 Calibration of the model

For this paper, we focused on $N = 3$ fish species (AW, GW, and CrC) and $F = 3$ fleets (CC, CCA, and T). The estimation of all parameters, including the mortality rate M_i of each species i, the catchability $q_{i,f}$ of each species i relative to each fleet f, the terms of interaction $a_{i,res}$ between the species and the resource, the growth efficiency g_i of each

Table 3: 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	/
$M_i\ (*10)$	0.8	1.4	1.4	/
$g_i\ (*10)$	1.5	0.6	0.6	/
$B_i(2006)\,(tons)$	$14,070$	$25,055$	$12,866$	$282,625$
$\tau_i\,(months)$	12	48	0	/

species, the initial biomass $B_i(t_0)$ of each species i in year $t_0 = 2006$, and the time lag τ_i for each species, are given in Table 3.

The main outputs of the model include calibrated catch by species $H_i(t)$ as defined in equation (3), catch by fleet defined by $H_f(t) = \sum_i H_{i,f}(t)$, the total catch $H(t) = \sum_f H_f(t)$, and the calibrated biomass $B_i(t)$ of each stock i. Figure 5 shows the historical and calibrated catch by fleet and by stock as well as the aggregated catch. We can see in the three cases (catch by fleet, catch by stock, and aggregated catch) that the historical values and the calibrated model values are close. Although the historical values show more variability than the estimated ones, the model outputs fit the historical outputs well, capturing major increasing and decreasing trends. The mean relative error in the catch for each fleet f, each species i, and the aggregated catch are computed through equation (11):

$$\epsilon_k = \frac{1}{t_1 - t_0 - 1} \sum_{t=t_0}^{t_1-1} \left| \frac{H_k^{data}(t) - H_k(t)}{H_k(t)} \right|, \tag{11}$$

with $k = f$ for catch by fleet, $k = i$ for catch by species, and $k = \emptyset$ for the aggregated catch. Table 4 shows the results. From the mean relative errors ϵ_k, 95% confidence intervals, denoted by CI, are computed through the equation:

$$CI_k(t) = [1 - 1.96\epsilon_k, 1 + 1.96\epsilon_k] H_k^{data}(t). \tag{12}$$

Furthermore, Figure 6 compares historical and estimated catch by fleet and by species, as well as aggregated catch, throughout the 2006-2018 time series. The proximity of the crosses to the diagonal demonstrates the goodness of fit for the different catches.

A sensitivity analysis was also carried out to evaluate reliability and contribution to the outputs for each calibrated parameter. The method and results are detailed in

Table 4: Mean relative errors on catches

Parameters	Mean relative errors ϵ_k
CC	0.173
CCA	0.143
T	0.278
AW	0.179
GW	0.310
CrC	0.306
Aggregated	0.149

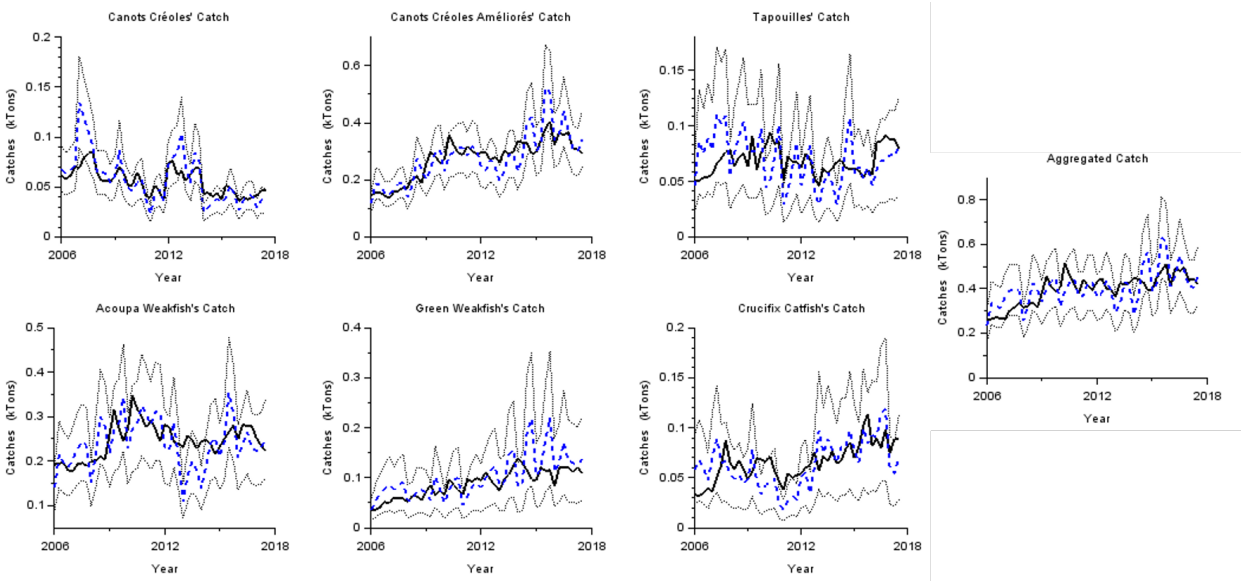


Figure 5: Historical (dark blue points) and calibrated (black line) catch by fleet (first row), by stock (second row), and aggregated (last graph) with 95% confidence intervals (dotted black lines) from the first quarter of 2006 to the last quarter of 2017.

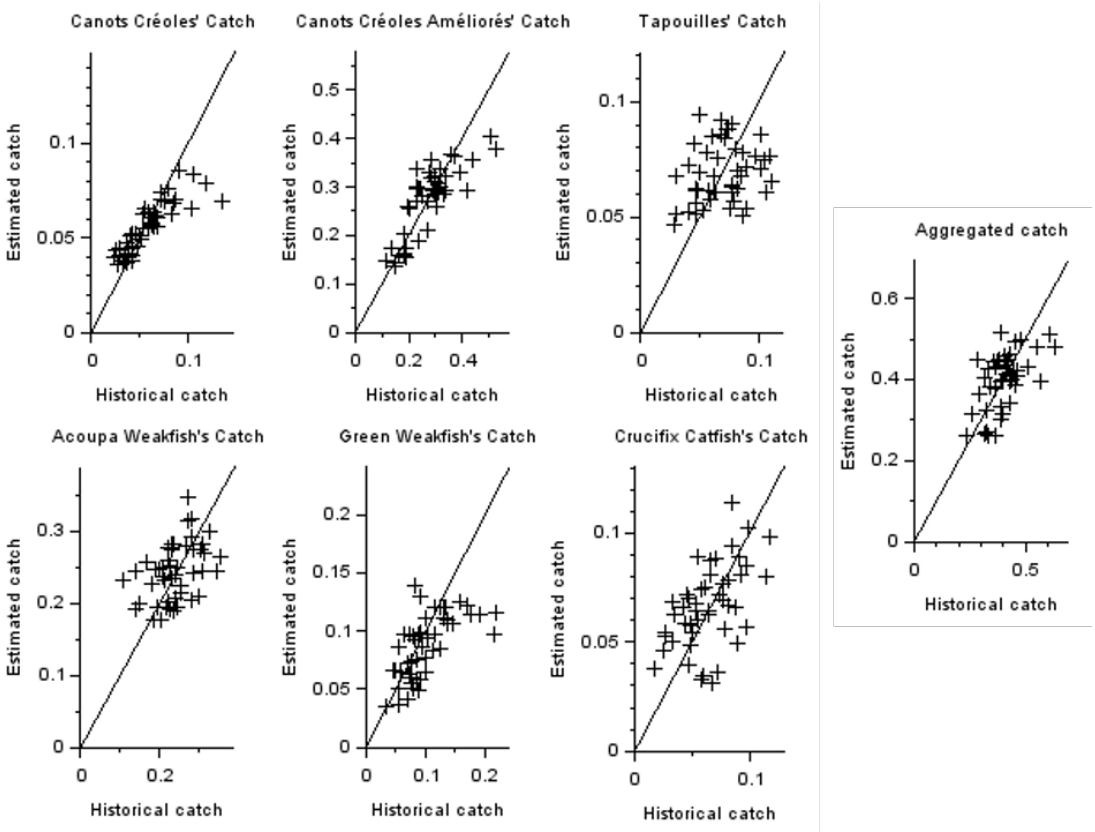


Figure 6: Comparison of historical and estimated catch in the 2006-2018 time series in terms of catch by fleet (first row), catch by species (second row), and aggregated catch (last graph).

Appendix A.4. Figure 11 shows limited variation in the aggregated catch, ranging from -10% to 10%. The parameters with the greatest impact were found to be catchability, mortality, growth efficiency, and the value of resource input I. As aggregated catch varies little, we can conclude that the model is stable and the parameters are reliable.

In Appendix A.5, goodness of fit is also assessed in terms of abundance using Catch Per Unit Effort (by fleet), denoted by CPUE, suggesting a satisfactory goodness-of-fit for every biomass. Figure 12 in particular confirms the quality of the calibration.

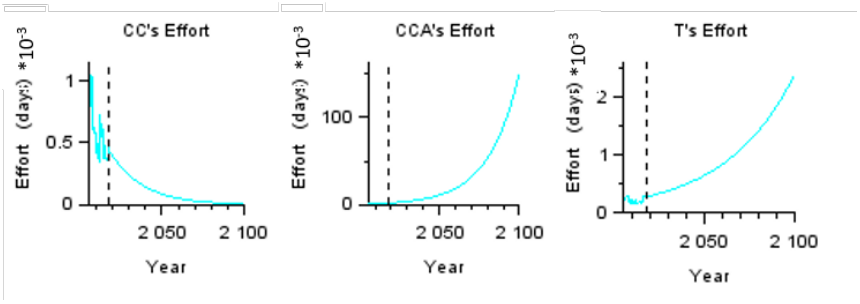
5.2 Projections and scenario outcomes

As explained in Section 4.4, we apply two contrasting climate scenarios for the horizon $T = 2100$ to the predictive scenario for fishing. The outcomes of the scenarios are measured in both catch and species biomass. Regarding species state, we assume that a species is extinct when its biomass falls below a viability threshold set at 1% of the initial state.

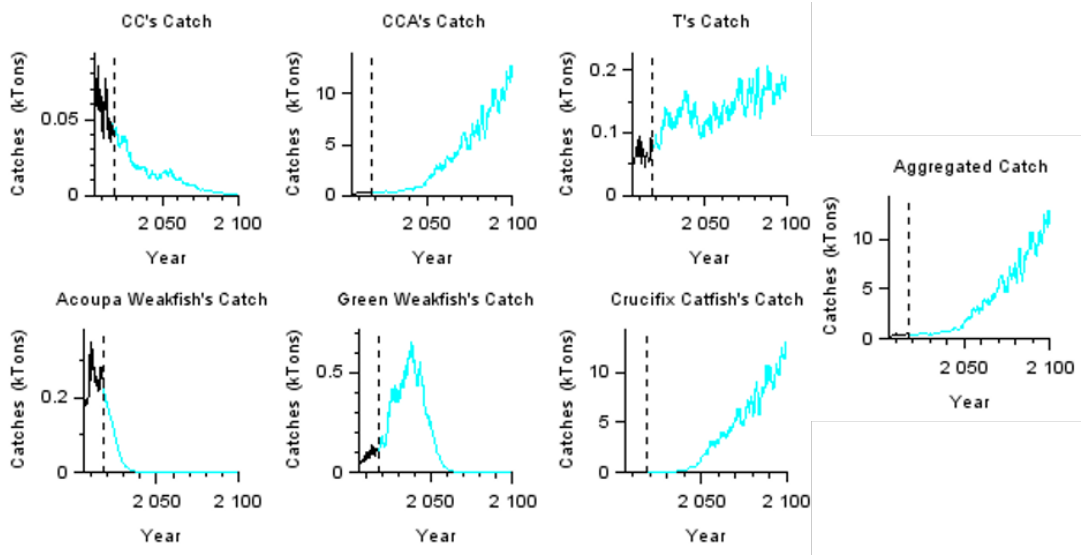
RCP 2.6: In the optimistic RCP 2.6 scenario (Figure 7), we can observe that two species become extinct in the long run, namely the AW around year 2034 and the GW around year 2065, in contrast to the third species, CrC, whose biomass remains at high levels until 2100 (Figure 7c). The two species extinctions entail the collapse of AW and GW catch. Consequently, CrC accounts for all catch from 2065 onward (Figure 7b, second row). The growth of CrC fishing leads to a reduction in CrC biomass in the long run (Figure 7, third column). It should also be noted that harvesting by CCA and T increases during the projection period, whereas CC catch decreases (Figure 7b, first row). This is consistent with projected effort (Figure 7a), since the CC effort growth rate δ_{CC}^{hist} is negative, whereas the growth rates for the effort of other fleets (δ_{CCA}^{hist} and δ_{T}^{hist}) are positive (Appendix A.3). The increase in CCA and T catch despite reduced CrC biomass can be explained by high growth in CCA and T fishing efforts. Finally, it can be seen that the development of CCA and T catch allows for a major increase in the overall harvest of the fishery over the period of the projection (Figure 7b right).

RCP 8.5: In the pessimistic climate scenario RCP 8.5, displayed in Figure 8, we can observe a collapse of fish species and harvest in the long run. The collapse of species biomass highlights that an erosion of fish biodiversity may occur. Figure 8b shows extinction of all the three fish species in the long run: in year 2033 for the AW, 2053 for the GW, and 2063 for the CrC. Hence, the catch for each targeted stock as well as the aggregated catch also fall to 0 in the long run (Figure 8a). In this scenario, as captured by Figure 8b (right hand side), resource biomass begins to grow exponentially from 2050 onward because it is no longer consumed by the fish species AW,GW and CrC.

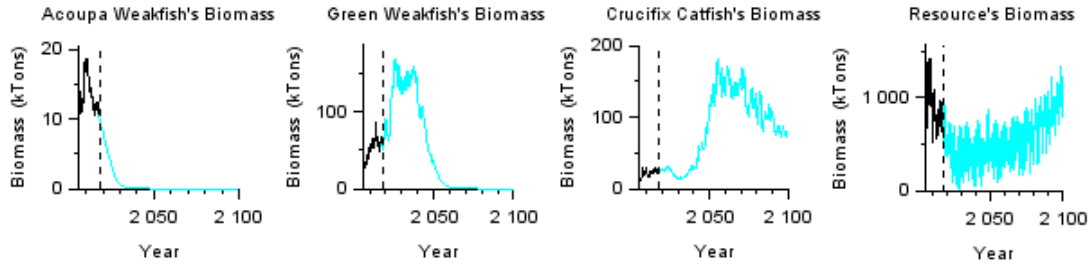
Comparison between RCP 2.6 and RCP 8.5: In order to evaluate the impact of climate change, biomass and catch trajectories are compared for each of the two climate scenarios. Figures 9 and 10 show respectively species richness (i.e., the estimated number



(a)



(b)



(c)

Figure 7: Scenario PS for fishing under RCP 2.6: calibrated (black) and projected (blue) trajectories. The first row (a) shows fishing effort by fleet. The second row of (b) shows catch by fleet and the third row of (b) catch by stock, while aggregated catch is displayed at the end of these two rows; the last row (c) represents biomass. The line of black dashes represents the separation between the calibrated and projected trajectories.

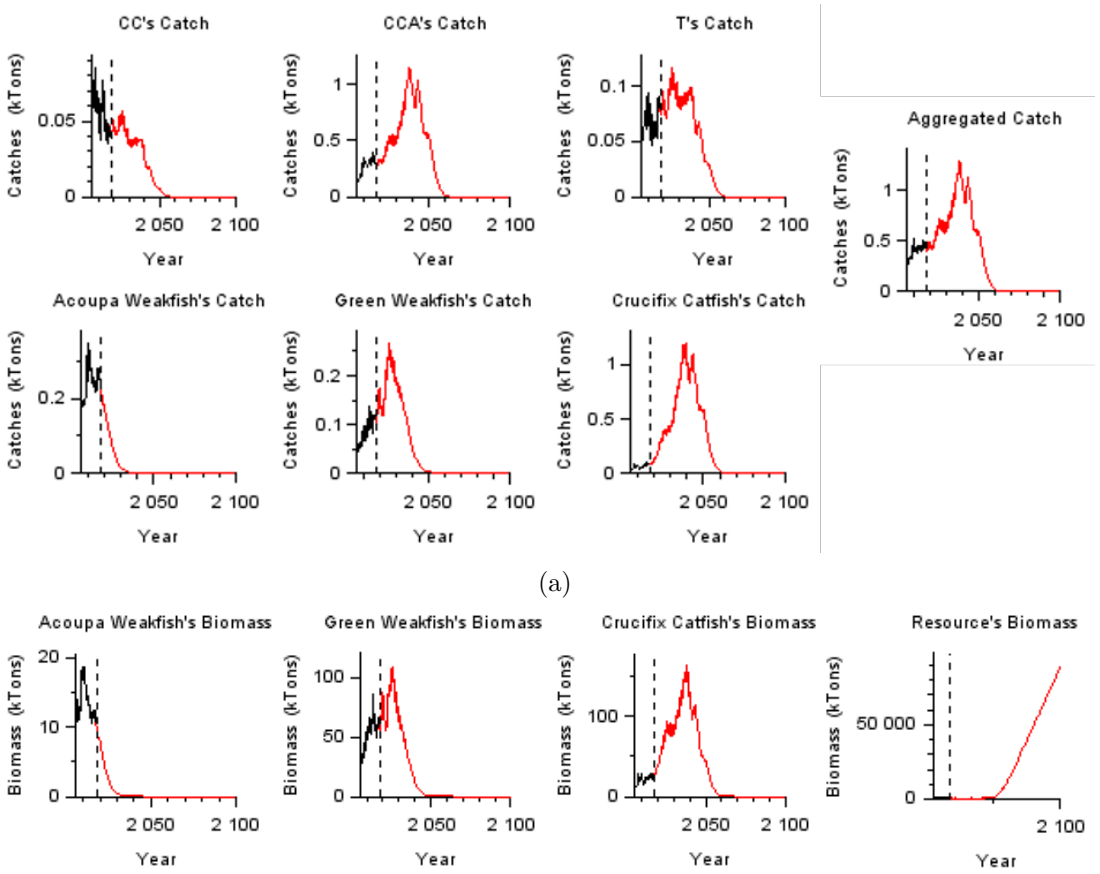


Figure 8: Scenario PS for fishing under RCP 8.5: calibrated (black) and projected (blue) trajectories. The first row of (a) shows catch by fleet and the second row of (a) catch by stock, while aggregated catch is displayed at the end of these two rows; the last row (b) represents biomass. The line of black dashes represents the separation between the calibrated and projected trajectories.

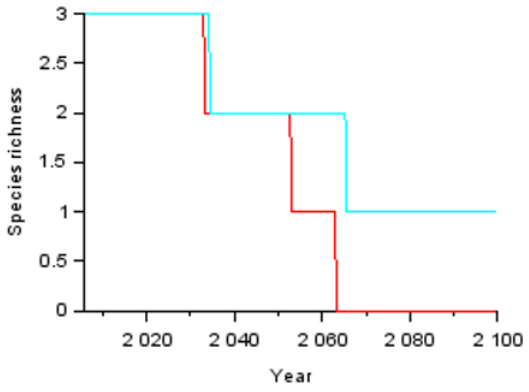


Figure 9: Estimated number of non extinct species among the three species taken into account for RCP 8.5 (red) and RCP 2.6 (blue) under the PS fishing scenario.

of non extinct species among the three species taken into account) and the aggregated catch on a logarithmic scale for both climate scenarios under the PS.

With respect to species state, the largest difference between the two scenarios is predicted for the CrC, which is projected to go extinct under the pessimistic scenario while remaining viable until 2100 under the optimistic scenario. For the two other species, AW and GW, we can observe that the extinctions occur earlier in the pessimistic case than in the optimistic case. Thus, the collapse of fished species under RCP 8.5 is more severe than under RCP 2.6, suggesting a major loss of fish biodiversity under RCP 8.5 as compared to RCP 2.6.

The two extreme climate scenarios also predict vastly different outcomes for fishing production. In the pessimistic scenario, the species extinctions result in a complete collapse of landings and production; whereas, in the optimistic case, fishery production overall persists and even grows thanks to rising of CrC catch.

5.3 Analysis in terms of ecological competition and Tilman exclusion

As represented by equation (5) in Section 4.1, the fish species compete for a common resource entitled 'res'; this is a situation involving multi-species competition for a limiting factor. Tilman *et al.* [56, 57] investigated this type of ecosystem dynamic and proposed an 'exclusion principle' [35] under which the stock with the lowest resource requirement at equilibrium, denoted by $B^*_{res,i}$, displaces all other stocks. In Table 5, we compute resource stock equilibrium in the long run for each stock i under the RCP 2.6 scenario and given PS fishing effort[5].

[5]We used the level of the resource stock at equilibrium in year 2085 to obtain $B^*_{res,i}$

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

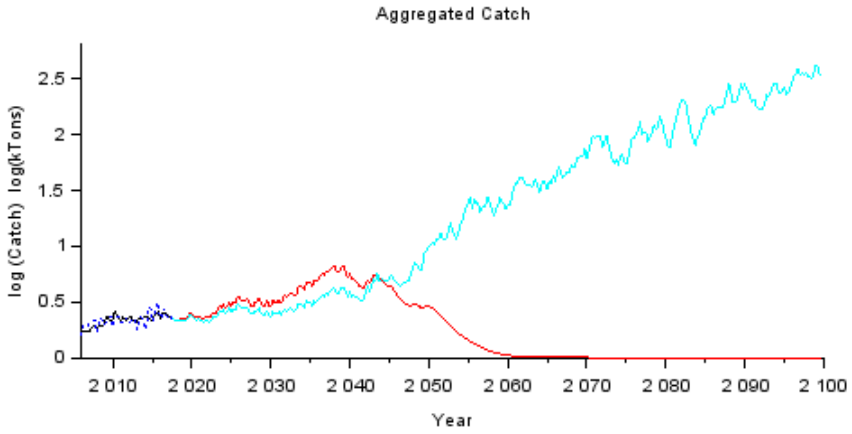


Figure 10: Aggregated catch on a logarithmic scale for RCP 8.5 (red) and RCP 2.6 (blue) under the PS fishing scenario.

Table 5: Resource requirement in equilibrium, $B^*_{res,i}(t)$ (ktons), for each stock i in 2085

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

Table 5 shows that CrC is the species with the lowest resource requirement in 2085. This result is consistent with the trajectories predicted by the model and scenario (PS - RCP 2.6) and plotted in Figure 7c, where the CrC has the highest biomass in 2085 while the two other species are extinct. The finding confirms that the model results are consistent with what would be expected form the exclusion principle. However, it is important to note that this exclusion mechanism depends on 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 for the CrC, than to $\theta_{i,opt}$ temperatures for either the AW ($\theta_{AW,opt} = 25.94°C$) or the GW ($\theta_{GW,opt} = 27.59°C$) (see Appendix A.2). In other words, SST in year 2085 favors CrC dynamics due to its higher biological efficiency $\gamma(\theta)$ at that temperature. Therefore, it is the interplay of climate and exclusion mechanisms that accounts for the extinctions of the AW and GW under climate scenario 2.6.

Different mechanisms may be in play in other parts of the marine environment of French Guiana. For example, Vallée *et al.* apply the Pecuchet method [43] to the continental shelf of French Guiana at a depth of between 20 and 50 meters in order to study the relationship between species richness and functional diversity. Using this method,

with t_{2085} corresponding to the value of the first quarter of the year 2085. The choice of the year 2085 is rather arbitrary. The idea is to consider a relatively distant year in which two species would already be extinct.

they describe how the ecosystem is influenced by environmental filtering and competitive exclusion and show that, based on comparisons of functional and taxonomic fish diversity, environmental filtering is a more important driver than competitive exclusion in this region. High ecosystem productivity and the large surface area of the shelf - the two resource dimensions laid out under niche theory [59] - are the main factors explaining why competition is less important in this system. By contrast, in the coastal area relevant to our study of the coastal fishery, the fish community is more tolerant of large environmental variations, including high fluctuations in salinity from the estuaries. In other words, competition is the most important process in the coastal ecosystem, while environmental filtering is more important on the continental shelf. It would be interesting to investigate the taxonomic and functional diversity of the coastal fish community using the Pecuchet method [43] in order to confirm this interpretation.

5.4 Interpretation of climate time lags

In this Subsection, we focus on species climate time lags (τ_i), which play a role in ecosystem dynamics (1) through the thermal envelope defined in equation (6). These time lag parameters are closely related to the 'resilience' parameter in FishBase [6]. This resilience value, denoted here as t_i^{*2}, is equal to the minimum time necessary to double the biomass of each species i, and thus indicates species' time to maturity and growth rate. In other words, a low t^{*2} means fast growth and a low age at maturity. The 'resilience' values for the three species considered in our case study are reported in Table 6 and compared to time lags τ_i.

Table 6: 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

As reproductive success and maturation are temperature-sensitive processes, climate change has a time-shifted effect on fisheries, with the magnitude of the delay dependent on growth time to harvest size. This delay is thus tied to the growth rate. Here, $t_{*2,i}$ and τ_i represent different values, but are correlated. Accordingly, we can see that the parameters given by FishBase are consistent with the time lags τ_i identified by the model, since they have the same ranking. In particular, the growth rate of the CrC is higher than that of the AW and GW, and age at maturity is lower for the CrC than for the AW and GW. Consequently, climate change affects the population state of the CrC almost immediately, while it has a delayed impact on the two weakfish species. These

[6] https://www.fishbase.se

results suggest that our model captures the age-structured processes underlying species dynamics. In other words, it paves the way for age-structured models [49].

6 Discussion

As shown in the previous section, through two model-based scenarios in line with MICE, this paper mainly contributes to the identification of long term harvesting and ecological leading processes for the coastal fishery in French Guiana. By doing this, it gives insights into the EBFM, in particular for tropical coastal fisheries. In this section, we discuss several points relating to the model and results of the paper, namely: the advantages of models of intermediate complexity (MICE) in subsection 6.1; the impact of environmental changes on ecosystem dynamics in subsection 6.2; recommendations for improving the sustainability of the coastal fishery in French Guiana in subsection 6.3; and finally the limitations of the model in subsection 6.4.

6.1 The advantages of models of intermediate complexity (MICE)

To operationalize the EBFM, many researchers advocate the use of whole-ecosystem or end-to-end models such as Atlantis [28]. Such models integrate many ecological complexities including trophic web dynamics, climate change together with the economic processes underlying marine fisheries. By contrast, models of intermediate complexity aim to limit complexity. MICEs instead focus only on the components and interactions necessary to address the main effects of the management question under consideration. Plagànyi *et al.* [46] advocate using MICE for ecosystem modeling and present principles for their application. MICE help to explain the underlying ecological processes for a limited group of populations (typically <10) subject to fishing and anthropogenic pressure, and include at least one explicit representation of an ecological process. Our paper follows this approach toward MICE, as in Cissé *et al.* and Doyen *et al.* [15, 22], to develop a model integrating the dynamics of three fished stocks and a resource along with competition interactions, the impact of three fleets harvesting the fish species, and the impact of global warming.

As emphasized in Section 5.1 on calibration results, our model accurately represents the complex multi-species, multi-fleet dynamics that we intend to manage through harvesting strategies. Our MICE contributes to EBFM in several ways: it provides important insights into the role of interspecies competition within the ecosystem, as described in Section 5.3; it captures the detrimental impact of global warming on catch, as detailed in Section 6.2; and, as the species modeled represent around 71% of the total landing, the MICE provides major insights into the sustainability of the coastal fishery in French Guiana.

6.2 Environmental changes as a major driver of ecosystem dynamics

As highlighted in the Subsection 5.2, RCP 2.6 entails better performances than RCP 8.5. Indeed, under RCP 2.6, in the long-run, one species remains viable, supporting

the fishery, whereas the three species and the global fishing collapse under RCP 8.5. However, it can be noticed that the temporal ranking of species decline is the same for both climate scenario. This collapse in term of species biomass can be in large part explained by the fish species' thermal envelopes and preferred temperatures ($\theta_{i,opt}$), which vary between species as detailed in Appendix A.2. Indeed, Table 8 shows that the CrC benefits more from high temperatures than do the other two species. In particular, the $\theta_{i,opt}$ and $\theta_{i,90}$ temperature thresholds are both higher for the CrC. Furthermore, as quantified by $\theta_{i,opt}$ in Table 8 of Appendix A.2, the ranking of the species in term of optimal temperature (i.e., $\theta_{AW,opt} < \theta_{GW,opt} < \theta_{CrC,opt}$) matches the sequence of species declines: AW collapses first, followed by GW and then by CrC.

However, although preferred temperature $\theta_{i,opt}$ may be the main driver of species extinctions, it is not the only one. The projected SST at the extinction dates, indicated in Appendix A.6, is lower than $\theta_{i,90}$ for the GW in the optimistic climate scenario and for the AW in both climate scenarios, whereas SST is higher than the $\theta_{i,90}$ for the GW and CrC in the pessimistic case. These observations can be explained by the available biomass of the resource. In the climate optimistic case, the biomass of the resource is low, whereas in the pessimistic case resource biomass is high, entailing high food availability for the species in the ecosystem and thus fostering species growth.

These findings illustrate that environmental changes, in this case climate warming, are a major driver of ecosystem dynamics and ecosystem services in the coastal area of the French Guiana. In this region, climate change has a negative impact on both biodiversity and the provisioning ecosystem service (seafood) underpinning fishing activities. This result is consistent with the conclusions of Cheung *et al.* [12], who suggest that an increase in SST in the equatorial area significantly reduces maximum catch potential. In French Guiana, Diop *et al.* [20] also highlight similar very detrimental impacts of climate warming on the shrimp fishery.

6.3 Policy recommendations for French Guiana fishery

The major challenges of this fishery are to meet sustainably the local food demand and to ensure economic security of the territory while preserving the coastal biodiversity. Our study globally emphasizes the interest to operationalize the EBFM to address the challenges, complexities and vulnerabilities of this small-scale fishery [37].

In the 2010s, the small-scale fishery of French Guiana was evaluated as viable [14, 15]. However, increasing demographic pressure raises concerns about the sustainability of this fishery, as the INSEE (French National Institute of Statistics and Economic Studies) estimates that the Guianese population will double over the next three decades [19], placing great strain on marine and coastal resources. Other vulnerabilities for this coastal fishery, as for many other small-scale tropical fisheries, include insufficient data and the lack of effective policies to manage fishery access [29]. The present study also points to major vulnerabilities relating to climate change. The results of the pessimistic climate scenario (RCP 8.5) indicate that the coastal fishery could be jeopardized by around 2070, while in the optimistic climatic scenario (RCP 2.6), the coastal fishery would be entirely dependent on one species (the crucifix catfish) from 2080 onward. It should be

noted that in the latter scenario, crucifix catfish biomass begins to decrease in 2050, thus questioning the viability of this species after 2100. This highlights a major threat to the long-term viability of the French Guiana coastal fishery as a whole; said differently, the fishery's sustainability seems weak in the face of climate change. The implementation of aquaculture could be a pillar of the policy to address the challenges and vulnerabilities of this coastal fishery by supporting the local seafood production and mitigating the pressure on the coastal fishery. However, in order to have a sustainable aquaculture, the territory has to prepare itself now, by identifying species and areas compatible with aquaculture or training the futures generations for example. The present paper points out that climate change should be strongly integrated in the design of such economic marine activities to be viable.

Furthermore, our paper highlights the key role played by the resource consumed by the fishes species including small fishes and shrimps. In that sense, it is necessary to support the preservation of this resource for instance by limiting the shrimp fishery operating in French Guiana or increasing the minimal mesh size of the coastal fishery to reinforce the selectivity and preserve the small fishes. Moreover, as the resource depends of the state of the environment, it is necessary to preserve the coastal ecosystem as a whole. In that sense all the policies established by the Water Framework Directive have to be applied [17]. In particular, in French Guiana, the mangrove is a major resource's habitat and plays a key role of nursery for fish stocks. Thus, the study of its dynamic and policies protecting it in line with EBFM would improve the sustainability of the coastal fishery.

Moreover, our paper shows to what extent environmental change are visible with time lags. In that respect, the design of multi-year management plan could improve the sustainability of this fishery. Thus the management of the coastal fishery based on licenses currently allocated each year by the Fisheries Committee should be adapted. One way to establish multi-year management consists in of developing ecological-economic and EBFM policies based on multi-species Maximum Sustainable Yield (MMSY) [33, 58], eco-viability [6, 22] or resilience management [31]. These last strategies potentially coping with several constraints (food demand, economic, ecologic, etc) and complex dynamic systems are clearly in line with the EBFM and the challenges of the Guianese coastal fishery. The merits of the different ecological-economic instruments that could be derived from such strategies, including limited numbers of licensed boats, catch quotas or subsidies to foster categories of fleet should be discussed with the local stakeholders.

6.4 Limitations of the model

The present paper is a step forward in our understanding of leading processes for the ecosystem and harvesting dynamics of the French Guiana coastal fishery and more globally tropical coastal fisheries. However, many future improvements are of course possible.

The refinement of resource dynamics and the incorporation of trophic interactions between species constitute major potential ecological improvements. The resource variable includes shrimps and other fish species. It would be interesting to decompose this global aggregated resource stock into more detailed stocks. Following Cissé *et al.* [15]

who suggest that trophic interactions between the main fished species have only a limited impact, we have chosen so far to exclude them from our model. However, a next step of the modeling work could be to account for these trophic interactions for the sake of a more realistic model.

Furthermore, the model in its current form does not allow for other species in the ecosystem to play a more important role in the fishery over the course of the projection period. As we assume that no technical adaptations will be made nor new equipment installed to increase fishing power, we can also assume that the exploitation of a given species will vary with its biomass, itself a function of the species' thermal affinity. Figure 13 in the Appendix A.7 shows biological efficiency for the 13 most-fished species in the coastal fishery in French Guiana, representing around 90% of the total landings. We can observe that the suitable temperature curves of the species included in the model (in red) are similar to those of the other species (in black), suggesting that the species not taken into account in the current model should also be strongly altered by climate warming over the projection period. In other words, these species are not good candidates to replace in term of future catches the three main species we focused on.

With regard to fishing activity, the predictive scenario PS is essentially illustrative. The model assumes that there is no adaptive relationship between future biomass and effort by the fleets of the coastal fishery, and that the fishery will maintain its current dynamics throughout the projection period. This paper is a first step towards a bio-economic model exploring leading processes for ecosystems under fishing pressure. Going forward, it would be interesting to apply economic scenarios incorporating an adaptive relationship between future biomass and effort; such scenarios would be more accurate and better model the economic performance of the fishery.

Even if the model takes into account the uncertainty through the two climate scenarios, many other uncertainties including observation uncertainty, parameter uncertainty and model structural uncertainty are here neglected. Ongoing works expanding the model and the analysis by accounting for other uncertainties in the framework of 'decision under uncertainty' and 'resilience management' as in Doyen [21] or Grafton *et al.* [31] should reinforce the relevance and reliability of the model and the scenarios. Furthermore, our choice of a long temporal horizon ($T = 2100$) is also open to adjustment. Such a lengthy timeframe clearly compounds the uncertainties underlying ecosystem and fishery dynamics. There may be a need to explicitly account for uncertainties in the model and scenarios through stochastic approaches, as in Doyen [21].

7 Conclusion

This paper illustrates leading processes for the ecosystem and harvesting dynamics of the coastal fishery in French Guiana and for tropical small-scale fisheries in general. Our work contributes in particular to EBFM through two model-based scenarios. These two model-based scenarios combine IPCC climatic scenarios and a predictive fishing strategy with a MICE. Such MICE integrates resource-based multi-species and multi-fleet components, in which the fish species' growth function depends on climate through

SST. The model is validated using time series data over the period 2006-2018.

The projections show alarming outcomes for the future of the fishery. Under the pessimistic climate scenario, the fishery outcome seems catastrophic, as both fish diversity and catch are severely altered. Under the optimistic scenario, the fishery seems to persist by specializing in one species (CrC). These results highlight the importance of limiting the rise in SST and thus the emissions of greenhouse gases. As our model incorporates climate change only in the form of increased SST, and does not consider other effects such as ocean acidification, changes in primary productivity, etc., the impact of climate change could be greater in reality.

Lastly, the paper identifies the exclusion principle as one of the leading biological processes affecting population dynamics in the fishery. Our results show that both the exclusion principle and environmental filtering as a result of climate change are major drivers of population dynamics. Finally the paper underlines the importance of adapting the fishery in order to improve its sustainability. To identify sustainable fishing management, a number of different integrated strategies, such as MMSY (Multi-species Maximum Sustainable Yield) [58], MMEY (Multi-species Maximum Economic Yield) [48] or Eco-viability, should be applied to the model. Moreover, it may be helpful to expand the model to include other stocks of the marine ecosystem.

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A Appendix

A.1 Geographic coordinates of the points used for the SST

See Table 7.

Table 7: Geographic coordinates of each point

Point	Latitude	Longitude
1	5.625	-53.625
2	5.375	-52.875
3	5.125	-52.375
4	4.875	-52.125
5	4.375	-51.625

A.2 Temperatures $\theta_{i,10}$, $\theta_{i,opt}$, $\theta_{i,90}$ used for climate change modelling

See Table 8

Table 8: 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.3 Rate δ_f^{hist} used for projected efforts

See Table 9.

Table 9: Rate δ_f^{hist} for each fleet

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

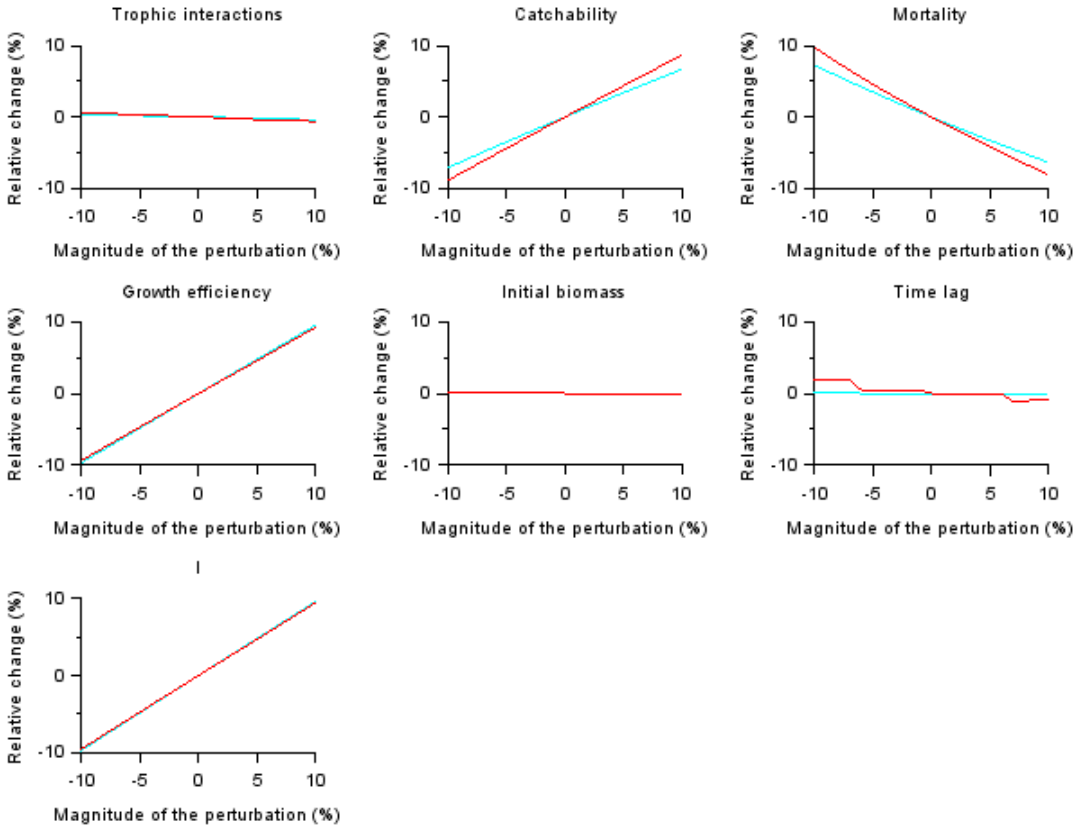

Figure 11: Relative change in average catch per quarter $\bar{H}$ for scenarios RCP 8.5 (red) and RCP 2.6 (blue) as a function of variations in input parameters by 1% increments from -10% to +10%. The baseline is the predictive scenario.

A.4 Sensitivity analysis

A sensitivity analysis was carried out to evaluate reliability and contribution to the outputs for each calibrated parameter. To this end, additional simulations were run based on the PS, RCP 2.6, and RCP 8.5 scenarios. Due to the large number of parameters, we simplified the sensitivity analysis for each climate scenario by simultaneously perturbing all of the calibrated parameters of the same category. There were seven categories in total: trophic interactions, catchability, mortality rate, growth efficiency, initial biomass, time lag, and values of I. For each category of parameters, a level of noise ranging from -10% to +10% of the calibrated values was added. Relative differences in average catch per quarter $\bar{H} = \frac{1}{t_f - t_1} \sum_{t=t_1}^{t_f} \sum_{f=1}^{F} \sum_{i=1}^{N} H_{i,f}(t)$ were computed for each climate scenario.

Figure 11 displays the sensitivity results for both climate scenarios. These results show that the parameters with the greatest impact, in both cases, are catchability, mortality, growth efficiency, and values of I. With the exception of the time-lag parameter,

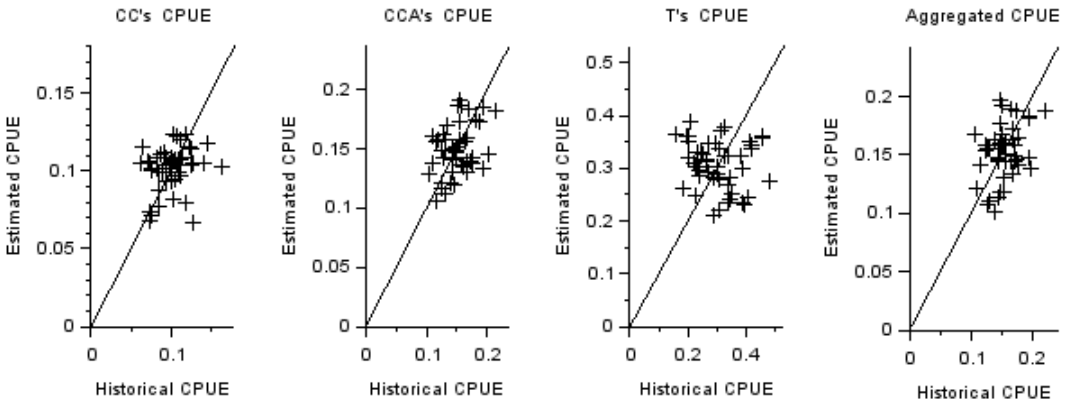

Figure 12: Comparison between historical and estimated CPUE in the 2006-2018 time series for CC, CCA, T and aggregated catches.

the relative change in average catch appears to vary more or less linearly with the magnitude of the perturbations, with the absolute value of the slopes ranging from 0.008 to 0.97, indicating the bounds of the marginal effects of the parameters. Since the relative changes are smaller than the magnitude of the perturbations for these parameters, it appears that the effects of these parameters are small. We can see that the impact of the perturbations on trophic interactions, growth efficiency, initial biomass, and parameter I is similar for both climate scenarios: the red and blue lines practically coincide. For the perturbations of the time lag, the graph of the relative change in catch is stepped; time lag is an integer value, so the magnitude of the perturbation has an impact when its value is higher than 1. Finally, we can see that the time lag has a greater effect on relative change in average catch in the RCP 8.5 scenario than in the RCP 2.6 scenario. This is because the temperature increase Δ_{ω,t_f} is higher under RCP 8.5 than under RCP 2.6.

A.5 Comparison of historical and estimated CPUE

As the efficiency of the fishing time of the French Guiana coastal fishery is assumed to be constant between 2006 and 2018, the catch per unit effort (CPUE) can be considered a proxy for abundance [39]. Since ours is a multi-species, multi-fleet model, we cannot calculate the CPUE for each species. However, we can compute the CPUE for each fleet and for the aggregated catch. Figure 12 compares historical CPUE with the estimated CPUE. The position of the crosses on the diagonal suggests a satisfactory goodness-of-fit for every biomass.

A.6 Sea surface temperatures at extinctions dates of each species for both climate scenario

See Table 10.

Table 10: Sea surface temperatures at extinctions dates of each species for both climate scenario

Species	RCP 2.6	RCP 8.5
AW	$t_{extinction}$ = 2034; SST=27.83°C	$t_{extinction}$ = 2033; SST=27.98°C
GW	$t_{extinction}$ = 2065; SST=28.08°C	$t_{extinction}$ = 2053; SST=28.46 °C
CrC	/	$t_{extinction}$ = 2063; SST=28.79°C

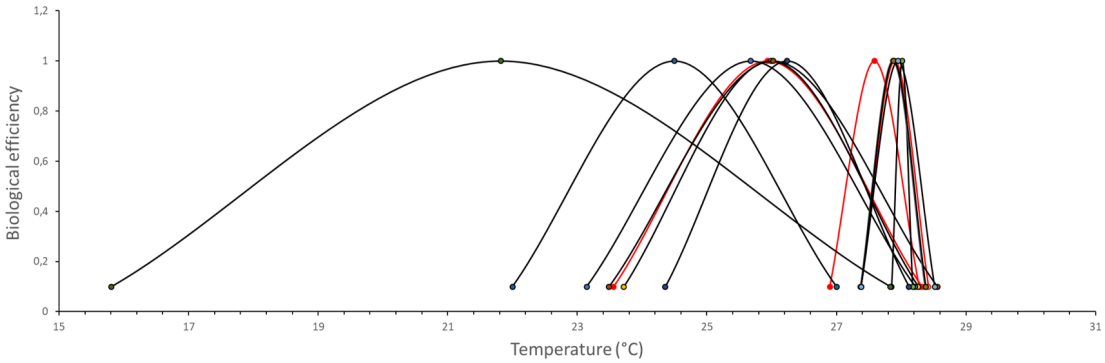

Figure 13: Biological efficiency for the 13 most-fished species in the coastal fishery in French Guiana. The species included in the model are represented by red curves, while the others are represented by black curves.

A.7 Biological efficiency for the 13 most-fished species in the coastal fishery in French Guiana.

See Figure 13