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Viable and ecosystem-based management for tropical small-scale fisheries facing climate change

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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 ecosystem-based fishery management (EBFM). But how such EBFM can be operationalized in ecological-economic terms remains unclear. To address such issues, we propose a model of intermediate complexity (MICE) relying on multi-species, resource-based and multi-fleet dynamics, also taking climate effects into account. The model is calibrated for the small-scale coastal fishery in French Guiana. From the calibrated model, we compare different fishing species in terms of sustainability through to 2070, including a predictive strategy and the normative strategies entitled Multi-species Maximum Sustainable Yield, Multi-species Maximum Economic Yield and Ecoviability. The sustainability assessment of fishing strategies relies here on profitability, food security and biodiversity constraints to be fulfilled over time. The results point overall to the long-term detrimental impact of climate change. The prognosis is particularly catastrophic under the most pessimistic climate scenario (RCP 8.5), with a potential collapse of both biomass of targeted species and fishing activity by 2070, regardless of the fishing strategies. However, under the optimistic scenario (RCP 2.6), our results demonstrate the interest of Ecoviability strategies in order to ensure sustainability and ecosystem-based management of fisheries. Such EVA strategies require a major reallocation of the fleets operating in the fishery.

Keywords: Sustainability; Eco-viability; Climate Change; Ecosystem-based fishery management; Marine biodiversity

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1. Introduction

Marine ecosystems, biodiversity and ecosystem services are under increasing pressures because of global changes [9, 62]. In particular, the development of marine and coastal fisheries to guarantee food and economic security for human populations is resulting worldwide in an increase in overfished marine stocks [35]. Nowadays, new risks, uncertainties, and vulnerabilities for primary production, fish distribution and therefore economic yields are being induced by climate change [2, 76].

Therefore, designing management tools and public policies that ensure the long-term ecological-economic sustainability of marine fisheries constitutes a major challenge [34]. In that context, many scientists and experts advocate use of ecosystem-based fishery management (EBFM) [37]. By contrast with the mono-specific approaches, including Maximum Sustainable Yield (MSY) or Maximum Economic Yield (MEY), EBFM aims to incorporate the ecological and socio-economic complexities of fisheries [38, 73]. How to operationalize such EBFM in ecological-economic terms remains under debate, however. One method for operationalizing EBFM relates to Models of Intermediate Complexity (MICE) [69, 25, 81]. MICEs focus on a limited set of stocks and drivers capturing key ecological, fishing and environmental processes and issues at play. The general purpose of our article is to advance the identification of sustainable and ecosystem-based fishing management facing climate change though quantitative methods and MICE.

Operationalizing the EBFM approach requires new models or the adaptation of existing models. In that respect, the use of monospecific reference points in multi-species fisheries is increasingly criticized [56]. For instance, monospecific maximum sustainable yield (MSY) targets have been shown to alter the structure of harvested ecosystems [84]. Moreover, although maximum economic yield (MEY) favors higher biomasses than MSY policies in single-species fisheries [18, 23], it does not account for potential ecological interactions in mixed fisheries [50]. Instead of single-species reference points, there have been attempts at designing multi-species MSY (MMSY) and MEY (MMEY) policies, in which total catches or total profits are maximized [61, 45]. Such global harvesting policies may however enhance biodiversity losses: while MMSY policies are likely to threaten low-productivity species, MMEY policies induce overexploitation of stocks with low economic value [19, 81, 82].

Beyond MMEY or MMSY, the viability approach to modeling and management strategies is now recognized by a growing number of researchers [51, 20, 77, 52] as a relevant framework for EBFM. Viability analysis investigates the states, controls and thresholds that ensure the safety and good health of a dynamic system, i.e. its ability to meet different constraints over time. Eco-viability analysis (EVA) builds on the viability approach, specifically focusing on Social-Ecological System (SES) management, along with ecological-economic constraints [27, 26]. Over the past decades, EVA has been shown to be adaptable and applicable across a wide range of environmental and ecological contexts, including fishery management [74, 63]. This includes fisheries in Australia [43], Chile [39], Spain [60], the Solomon Islands [47], French Guiana [16] and the Bay of Biscay [42]. Overall, EVA sheds crucial light on the sustainability of an SES by investigating both present and possible future states [3]. Links between EVA and the concept of safe-operating space [72], and more broadly multiple standards such as Basic Needs Poverty Line or precautionary B_{lim} (biodiversity minimal level) and F_{lim} (guaranteed consumption) reference points, have been explored in Doyen *et al.* [26].

Beyond the complexities underlying normative strategies such as MMSY, MMEY and EVA, the integration of climate change is another challenge for realizing EBFM. As highlighted by Stock *et al.* [75], De Lange [54], Lopes *et al.* [58] and Holsman *et al.* [49], exploring the influence of climate change on marine resource dynamics is a key issue. Hence, it is demonstrated that climate change has a huge impact on ecological processes, such as population distributions or population dynamics [64, 78]. However, the way of implementing it in an ecological model of population dynamics remains under debate [12, 87]. Brander [6] and Cheung *et al.* [14] argue that climate change and global warming, in particular through their effects on sea temperature, may be the strongest drivers of stock dynamics and harvest levels in the future. Diop *et al.* [24] and Lagarde *et al.* [53] highlight the bioeconomic benefits of fishing strategies accounting for climate change. In that respect, the case of tropical fisheries is especially challenging, since a decrease in diversity is projected with climate warming [14, 15].

The specific objective of this article is to evaluate the sustainability of several ecosystem-based fishing management strategies including, MMSY, MMEY and EVA, for the coastal fisheries of French Guiana. To achieve this, we rely on a MICE based on multi-species, resource-based and multi-fleet dynamics, which integrates climate change through an envelope model for species growth as a function of sea surface temperature. From the calibrated model, along with RCP climate scenarios derived from the Intergovernmental Panel on Climate Change (IPCC), we compare the

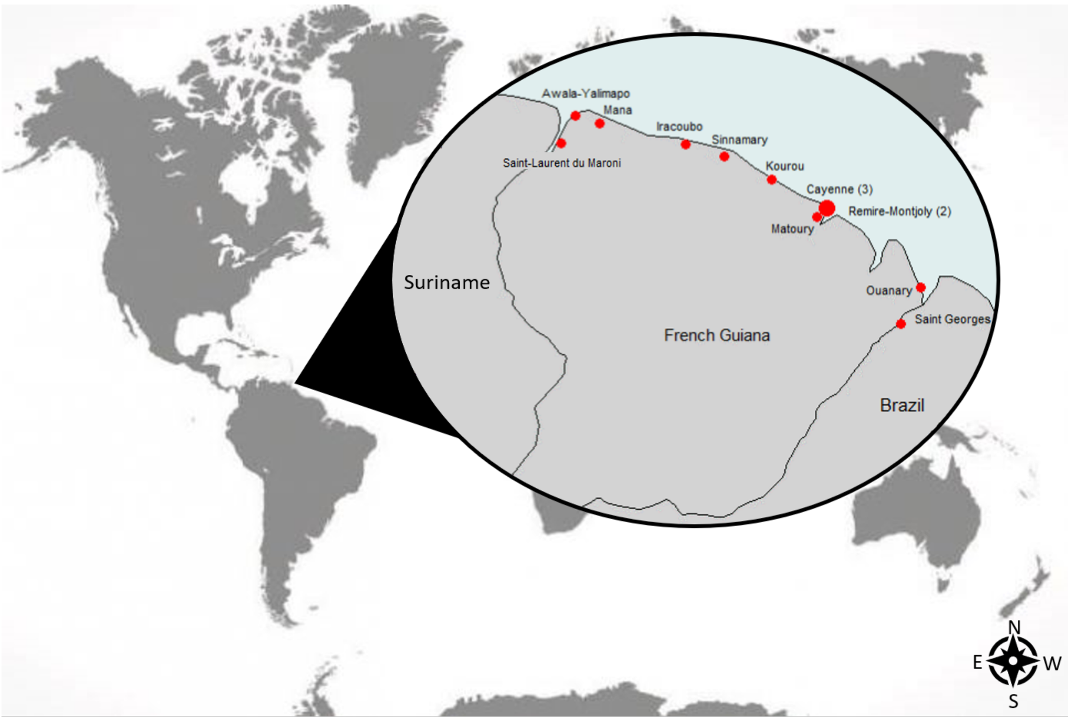


Figure 1: Map of French Guiana with legal landing points in red.

sustainability of the different fishing strategies through to 2070 in terms of profitability, food security and biodiversity conservation thresholds and constraints.

The contribution of the paper is threefold. Firstly it provides a modeling framework for EBFM based on MICE and Ecoviability. Secondly the results stress the long-term detrimental impact of climate change, in particular under the most pessimistic climate scenario (RCP 8.5). Thirdly, under the optimistic scenario (RCP 2.6), an EVA management strategy emerges significantly as a sustainable and ecosystem-based management of the fisheries, bringing about major redistributions of the fleets.

The paper is structured as follows: Section 2 introduces the case study and describes the coastal fisheries in French Guiana; Section 3 details the model and scenarios used; Section 4 presents the results, including ecological, economic and social indicators. Finally, Section 5 contains a discussion of the results.

2. Case Study

French Guiana borders Suriname and Brazil, and is the only French territory in South America. Thanks to its coastline measuring 350km, it benefits from an exclusive economic zone (EEZ) of 130,000 km^2, including 50,000 km^2 of continental shelf. Among the different types of fisheries in the territory, we focus on the small-scale coastal activities. These operate 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 [46] (Figure 1).

The coastal zone is fished by vessels less than 12 meters long, mainly built of wood. Between 2006 and 2018, there were around 100 boats. The boats can be divided into three main categories depending on their size, and their ways of operating: "Canots Créoles", denoted by CC, "Canots Créoles Améliorés", denoted by CCA and "Tapouilles", denoted by T [1]. They represent respectively 6%, 71.2% and 22.5% of the total landing of the Guyanese coastal fishery.

[1]There is a fourth category of boats: the "Pirogues". However, they can be neglected as they only represent 0.3% of total landings of the fishery.

This coastal fishery is non-selective, exploiting more than 30 fish species. Over the last two decades, its landings are estimated to have been 2,000 tons per year. The most harvested species is the acoupa weakfish *(Cynoscion acoupa)*, followed by the green weakfish *(Cynoscion virescens)* and crucifix catfish *(Sciades proops)*, representing an estimated 42%, 18%, and 11%, respectively, of total landings between 2006 and 2018. The coastal fishery provides employment and contributes to food security, and thus plays important social and economic roles for the territory.

In this small-scale fishery, although stocks were considered under-exploited during the 2010s [17, 16], implementation of EBFM seems to be necessary in order to face future uncertainties relating to global changes and local anthropogenic pressure. INSEE (French National Institute of Statistics and Economic Studies) hypothesizes that the Guianese population will double over the next three decades [22], thus inducing high pressures on this coastal ecosystem and the fishing sector. Moreover, Gomes *et al.* [41] identify major vulnerabilities of these small-scale fisheries to climate change.

Since 2006, on a daily basis, fishing effort (time spent at sea, expressed in days) and fishing landing data have been collected by observers from the IFREMER Fisheries Information System. Moreover, socio-economic surveys have provided essential economic data, such as selling prices by species, variable and fixed costs for fleets [17].

Observed sea surface temperature data (SST) stems 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 homogeneous throughout the water column.

We focus here on the three most exploited fish species by the coastal fisheries in French Guiana, representing 71% of total landings throughout the 2006-2018 period: the acoupa weakfish (AW), green weakfish (GW) and crucifix catfish (CrC). Regarding fleets, we focus on the three main categories of fleets: tapouilles (T), canots créoles (CC), and canots créoles améliorés (CCA). As detailed in Subsection 4.1, we use catch and effort data from the three fleets, as well as catch data on the three species to calibrate our model.

3. The ecological-economic model

In line with MICEs and EBFM, we follow the general modeling approach portrayed in Doyen [25]. Thus a dynamic, multi-species, resource-based and multi-fleet ecological-economic model is developed and calibrated (Figure 2). Climate change is assumed to impact fish stocks through Sea Surface Temperatures (SST) and two RCP climate scenarios. Five fishing strategies, including a Closure strategy CL, a Predictive strategy PS, as well as normative strategies MMSY, MMEY and EVA, are considered. Ecological-economic indicators are presented to rank these strategies in terms of sustainability.

3.1. Ecological-economic dynamics

The following dynamics of the ecosystem strongly draw on Gomes *et al.* [41]. Fished species are denoted by $i = 1, \dots, N$ while fleets are denoted by $f = 1, \dots, F$. As under the resource-based model [80], it is assumed that N fish species compete for a common resource (e.g. small shrimps and fish in the case study), denoted by res, and that no trophic interactions occur between these targeted species. The growth of each species is also assumed to depend on SST, denoted by θ. Thus, for every fished species, at each step t, the biomass $B_i(t+1)$ depends on the biomass $B_i(t)$ and harvesting $H_i(t)$, as follows:

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

where M_i stands for the natural mortality rate of stock i, while $G_i(t)$ corresponds to the natural growth of stock i. The natural growth rate $G_i(t)$ of every fish species based on resource consumption varies with time because it depends on both the resource state $B_{res}(t)$ and the temperature $\theta(t)$ (with a time lag) as follows:

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

Parameter g_i above 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 [83]). The term $\gamma_i(\theta(t - \tau_i))$, based on the species' thermal envelopes

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

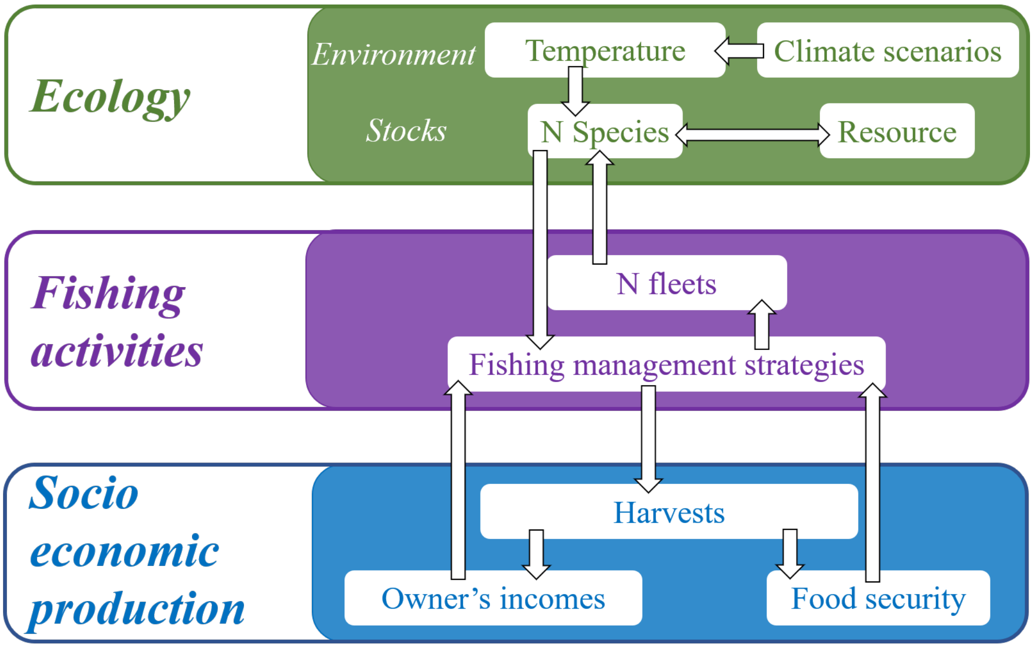


Figure 2: Conceptual model.

together with a time delay τ_i, is specified below in equation (6). This formula captures the climate impact on species growth (see Ainsworth *et al.*[1] and Thompson *et al.* [79] regarding time delays).

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:

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

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 $B_{res}(t)$ depend on the consumption of this resource by the different fish species [7, 55]:

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

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 through relation (2).

The term $\gamma_i(\theta(t-\tau_i))$, induced in the equation (2), relies on the Half-Degree Species Environmental Envelope table, containing ranges of suitable and preferred temperatures [10]. 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, and approaches zero when the temperature is far from this preferred level. Figure 3 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 demonstrated in the following equation:

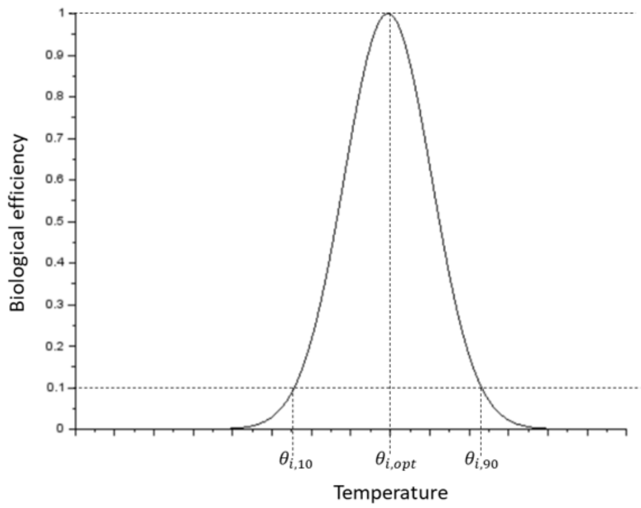


Figure 3: Biological efficiency $\gamma_i(\theta)$ for species i depending on temperature levels $\theta_{i,10}$ and $\theta_{i,opt}$.

$$\gamma_i(\theta) = \exp\left[-\left(\frac{(\theta - \theta_{i,opt})}{\theta_{i,10} - \theta_{i,opt}} \right)^2 ln(10) \right]. \tag{6}$$

In equation (6), 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.1.

3.2. Socio-economic indicators

To examine and evaluate the socio-economic performances of the fishery, we here focus on the landings and profitability of the fleets.

The aggregated harvest, through its capacity to meet the local food demand and contribute to food security, is considered as a social indicator. It reads at follows:

$$H(t) = \sum_{i=1}^{N} H_i(t), \tag{7}$$

where $H_i(t)$ is the catch by species defined by the equation (3).

The profitability of every fleet is derived from the incomes and the costs of these fleets. Thus the profit $\pi_f(t)$ of each fleet f, relies on catches $H_{i,f}(t)$ by species i, the selling price p_i of each species, the fixed costs, variable costs, crew share earnings and number of boats for the fleet f, denoted by c_f^f, c_f^v, β_f and $\text{Nb}_f(t)$ respectively, as follows:

$$\pi_f(t) = (1 - \beta_f) * \left(\alpha_f * \sum_{i=1}^{N} p_i * H_{i,f}(t) - c_f^v * E_f(t) \right) - c_f^f * \text{Nb}_f(t), \tag{8}$$

In equation (8), the fixed parameter α_f stands for the rate of income of fleet f derived from the catches of other species not directly taken into account in the current model [32, 53]. For the case study, selling prices of each species, variable costs, fixed costs and α_f are given by the IFREMER Fisheries Information System and they are assumed to remain unchanged throughout the simulations. They are reported in Appendix A.2. Variable costs include fuel consumption and ice. Equipment depreciation, maintenance and repairs are incorporated in the fixed costs. The crew share earnings represent the salary of the crew. For the CC, the fleet boat owners or members of their family are the crews so $\beta_{CC} = 0$, whereas for the T and CCA fleets $\beta_{T,CCA} = 0.5$ [17]. Throughout the calibration (t_0 (first quarter of 2006) to $t_c - 1$ (last quarter of 2017)) the numbers of boats in each fleet are considered to be equal to the average number of boats in each fleet during this period, and they are assumed to remain unchanged. For the projected period (t_c (first quarter of 2018) to T (last quarter of 2069)) the number of boats in the fleet f at time t depends on the fishing effort of fleet f at time t and the average number of fishing days during one period for fleet f, denoted by $n_f^{d,a}$ through the relation:

$$\mathrm{Nb}_f(t) = \frac{E_f(t)}{n_f^{d,a}}. \tag{9}$$

The average number of fishing days during one period (here one quarter) for each fleet f,$n_f^{d,a}$, includes the duration of the trip, the duration between two trips and the duration of the repairs made on the boats. Values of $\mathrm{Nb}_f(t_0)$ and $n_f^{d,a}$ are reported in Appendix A.2.

3.3. Ecological indicators

In order of examine the ecological performances of the coastal fisheries in French Guiana, several ecological indicators are computed.

The number of viable species $\textsc{sr}(t)$: It informs on the number of viable species in the ecosystem. In line with the ICES precautionary approach and thresholds, it is assumed that the viability of the species i is at stake when its biomass, $B_i(t)$, is lower than a biomass limit, $B_{\mathrm{lim},i}$, which is assumed to be equal to 1% of initial biomass $B_i(t_0)$. In more mathematical terms, the number of species is computed through the relation:

$$\textsc{sr}(t) = \sum_{i=1}^{N} \mathbb{1}_{]0,+\infty[}(B_i(t) - B_{lim,i}), \tag{10}$$

with $\mathbb{1}_{]0,+\infty[}$ represents the characteristic function on positive reals.

The number of functional groups $\textsc{gf}(t)$: It informs on the number of functional groups in the ecosystem. The groups are defined by using several traits (ecological and/or morphological) [67]. In our case study, two groups are defined: one containing the 2 weakfish, another representing the catfish. Mathematically it is expressed as follows:

$$\textsc{gf}(t) = \sum_{X} G_X(t) \tag{11}$$

with X one group and

$$G_X = \begin{cases} 1 & \text{if } \sum_{i=1}^{N_{group}} (\mathbb{1}_{]0,+\infty[}(B_i(t) - B_{lim,i})) > 0 \\ 0 & \text{otherwise} \end{cases} \tag{12}$$

where N_{group} is the number of species i in group X.

The mean trophic level $\textsc{mti}(t)$: This metric informs on the mean trophic level of an ecosystem [65, 66]. The trophic level of one species i, T_i, gives information about the location of this species in a food web. The trophic level varies between 0 for the producers (*e.g.* phytoplankton, plants) and 5 for the top predators. Mathematically, $\textsc{mti}$ reads as follows:

$$\textsc{mti}(t) = \sum_{i=1}^{N} T_i\left(\frac{A_i(t)}{\sum_i^N A_i(t)}\right), \tag{13}$$

with $A_i(t)$ stands for the abundance of the species i and it depends of its biomass, $B_i(t)$, and its common weight (obtained from the Fishbase website and available in the Appendix A.3), w_i, through the relation:

$$A_i(t) = \frac{B_i(t)}{w_i}. \tag{14}$$

The trophic levels for each species, obtained from the Fishbase website, are listed in Appendix A.3.

3.4. Fishing management strategies

From the calibrated model, we make projections from current period t_c (= first quarter of 2018 in the case study) until T (= last quarter of 2069), to explore what could happen in the future for the fishery in terms of ecological and economic scores. In line with Ferrier *et al.* [36] and Doyen [25], we consider a predictive fishing strategy (denoted by PS), a closure strategy (denoted by CL), Multi-species Maximum Sustainable Yield (denoted by MMSY), Multi-species Maximum Economic Yield (denoted by MMEY) and an Ecoviability strategy (denoted by EVA) for the fishing activity. The control variable relating to theses different strategies is the number of boats $\mathrm{Nb}_f(t)$ in each fleet f at time t.

Predictive fishing strategy (PS):

This strategy simulates fishing efforts based on the assumption that the fishery and all of its fleets will maintain their historical dynamics. Using a first-order approximation of historical fishing effort trends for the various fleets over the period 2006-2018, as in Gomes *et al* [41], the PS runs as follows:

$$E_f(t+1) = E_f(t)(1+\delta_f^{hist}), \quad \forall t = t_0, \dots, T. \tag{15}$$

By combining equations (15) and (9), the number of boats, corresponding to the PS strategy for the projection period, can be deduced through the relation:

$$\mathrm{Nb}_f^{\mathrm{PS}}(t+1) = \mathrm{Nb}_f^{\mathrm{PS}}(t)(1+\delta_f^{hist}), \quad \forall t = t_0, \dots, T. \tag{16}$$

In equations (15) and (16), δ_f^{hist} stands for the growth rate of the 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.4.

Closure strategy (CL):

This 'exploratory' strategy assumes a ban in the sense that the fishery will be closed during the projections period (t_c to T):

$$\mathrm{Nb}_f^{\mathrm{CL}}(t) = 0, \quad \forall f = 1, \dots, F \quad \forall t = t_c, \dots, T. \tag{17}$$

Although theoretical, such ban projections provide information on the ecosystem dynamics and viability without fishing pressure. In other words, they represent a benchmark for the ecological scores of the other fishing strategies.

Multi-species Maximum Sustainable Yield (MMSY):

This normative fishing strategy aims at maximizing the aggregated catch over the projected period with respect to the number of boats. Specifically, the objective is to find the number of boats in each fleet f, denoted $\mathrm{Nb}_f^{\mathrm{MMSY}}$, that maximizes the sum of the total catches $H(t)$ over the projection period, namely between t_c and T:

$$\overline{H}(\mathrm{Nb}^{\mathrm{MMSY}}) = \max_{\mathrm{Nb}_f,\ f=1,\dots F} \overline{H}(\mathrm{Nb}). \tag{18}$$

where $\overline{H}(\mathrm{Nb})$ is the average over time of aggregated catches

$$\overline{H}(\mathrm{Nb}) = \frac{1}{T-t_c} \sum_{t=t_c}^{T} H(t). \tag{19}$$

with the total catches $H(t)$ at time t as defined in equation (7), which depends on the effort $E_f(t)$ and thus the number of boats $\mathrm{Nb}_f(t)$ in every fleet f. This strategy MMSY relates to the usual MSY in the case of a single species because, whenever the dynamics are at equilibrium in the long run, it consists in maximizing the (stationary) yield.

Multi-species Maximum Economic Yield (MMEY):

This second normative fishing strategy aims to maximize the net present value over the simulation period, again with respect to the number of boats. Specifically, the objective is to find the number of boats in each fleet, f denoted $\mathrm{Nb}_f^{\mathrm{MMEY}}$, that maximizes the discounted sum of total profit $\pi(t)$ over the projection period, namely between t_c and T:

$$\mathrm{NPV}(\mathrm{Nb}^{\mathrm{MMEY}}) = \max_{\mathrm{Nb}_f,\, f=1,\ldots F} \mathrm{NPV}(\mathrm{Nb}). \tag{20}$$

where the net present value NPV(Nb) is the discounted sum over time of aggregated profits

$$\mathrm{NPV}(\mathrm{Nb}) = \sum_{t=t_c}^{T} (1+r)^{-(t-t_c)} \sum_f \pi_f(t). \tag{21}$$

In (21), r stands for the discount rate, while the profit $\pi_f(t)$ by fleet at time t, as defined in equation (8), also depends on the effort $E_f(t)$ and thus the number of boats $\mathrm{Nb}_f(t)$ in every fleet f. This strategy MMEY relates to the usual MEY in the case of a single species because, whenever the dynamics are at equilibrium in the long run, it consists in maximizing the (stationary) rent. For the case study, we assume that the discount rate is set to $r = 3\%$ as advocated by Weitzman [86] for near-future projects (6 to 25 years). In particular, this discount rate has already been used for our case study by Cissé [17].

Eco-viability (EVA):

This third normative fishing strategy aims to provide a sustainable balance between biodiversity, local food demand and economic performances [25, 27] through functional diversity conservation, food security and profitability constraints to be satisfied over time. Thus, viable numbers of boats in each fleet, denoted by $\mathrm{Nb}_f^{\mathrm{EVA}}$, have to comply with the following ecological-economic constraints:

- A food security constraint: the aggregated catch has to be higher than predicted local food demand.

$$H(t) \geq H(2018) * (1+d)^{t-t_c}, \quad \forall t = t_c, \ldots, T, \tag{22}$$

where d is the quarterly rate of increase in food demand, set to $d = 2.5\%$ [11].

- A profitability constraint: the aggregated profit has to be positive, or equal to 0, throughout the projection period.

$$\pi(t) = \sum_{f=1}^{F} \pi_f(t) \geq 0, \quad \forall t = t_c, \ldots, T. \tag{23}$$

- A functional diversity constraint: the number of functional groups, over the projection period, has to be equal to the number of functional groups over the historical period.

$$\mathrm{GF}(t) = \mathrm{GF}(t_0), \quad \forall t = t_c, \ldots, T. \tag{24}$$

Numerically, the viable numbers of boats $\mathrm{Nb}_f^{\mathrm{EVA}}$ by fleet f for the EVA strategy are obtained by maximizing the following viability function, strongly inspired by the so-called time of crisis function [31]:

,

$$\sum_{t=t_c}^{T} \mathbb{1}_{\mathrm{EVA}}(t) \tag{25}$$

where $\mathbb{1}_{\mathrm{EVA}}$ is a boolean function (or a characteristic function) which equals one when the EVA constraints are fulfilled, while it equals 0 otherwise.

$$\mathbb{1}_{\mathrm{EVA}}(t) = \begin{cases} 1 & \text{if constraints (22), (23) and (24) are satisfied.} \\ 0 & \text{otherwise.} \end{cases} \tag{26}$$

Let us note that several viable solutions can emerge from the computations. Said differently, there is no single EVA solution which can be interesting for management in terms of flexibility and adaptation. In accordance with that, 100 viability solutions Nb_f^{EVA} are computed for this strategy.

For the three normative strategies MMSY, MMEY and EVA, the numbers of boats are assumed to be control strategies that can change each five years. Such dynamic management thus accounts for the inertia underlying decisions and governance, but also makes it possible to modify and adapt the strategies across time.

To compute the optimal solutions for Nb^{MMSY}, Nb^{MMEY} and Nb^{EVA} numerically, we have used the SCILAB software, in particular the routine entitled "optim_ga".

3.5. *Climate and resource scenarios*

In our study, we consider two contrasted climate scenarios, RCP 8.5 and 2.6, relating to the last IPCC report [70]. For both scenarios, the IPCC separates the future into two periods, the near term (2031-2050) and the end-of-century (2081-2100), corresponding to two different rises in sea surface temperature. For each climate 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:

$$\theta_\omega(t+1) = \theta_\omega(t) + \Delta_{\omega,t_f}. \tag{27}$$

In Table 1, 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 1: 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
$\Delta_{\omega,2050}(*10^3)$	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

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.).

4. Results

4.1. *Calibration*

Calibration of the ecological-economic dynamics (1), (2), (4) and (5) for the case study in French Guiana is performed using the data and time series of IFREMER Fisheries Information System at a quarterly rate over the period 2006-2018. The SCILAB scientific software is used for the numerical computations, and in particular the optimization underlying the least square method on fleet and species catches. In this paper, we focus on $N = 3$ fish species (Acoupa Weakfish, Green Weakfish and Crucifix Catfish) and $F = 3$ fleets (Canots créoles, Canots créoles améliorés and Tapouilles). The calibration is carried out using both historical fishing catches and effort as inputs; effort data is used as model inputs though equation (4). As said in the 2 and 3.2 subsections, the economic parameters are given by IFREMER Fisheries Information System and is assumed to remain unchanged throughout the simulations. The estimation of all the parameters, including, for each fished species i, the mortality rate M_i, growth efficiency g_i,

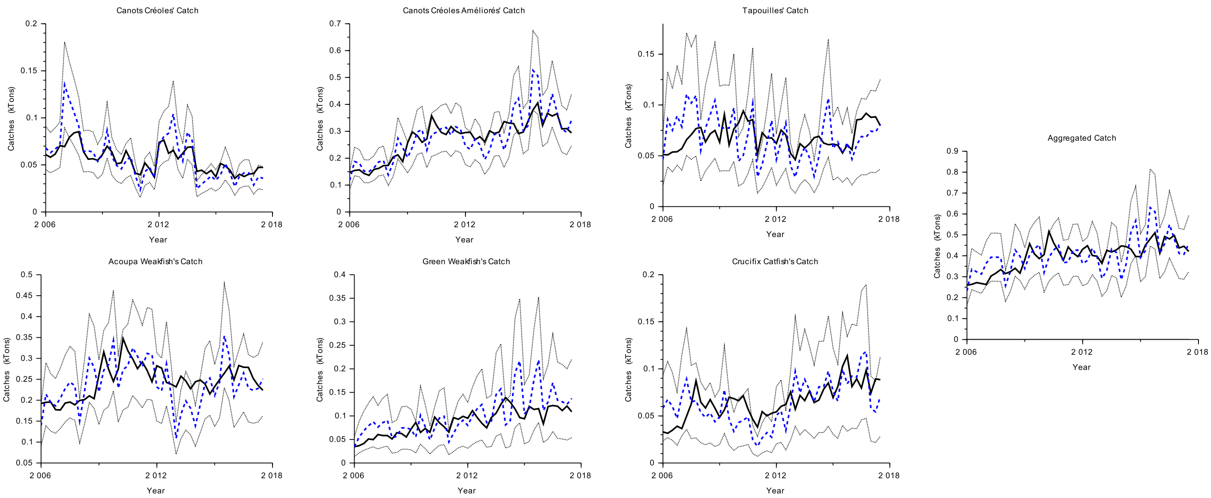


Figure 4: Historical (dark blue points) and calibrated (black line) catch by fleet $H_f(t)$ (first row), by stock $H_i(t)$ (second row), and aggregated $H(t)$ (last graph) with 95% confidence intervals (dotted black lines) from the first quarter of 2006 to the last quarter of 2017.

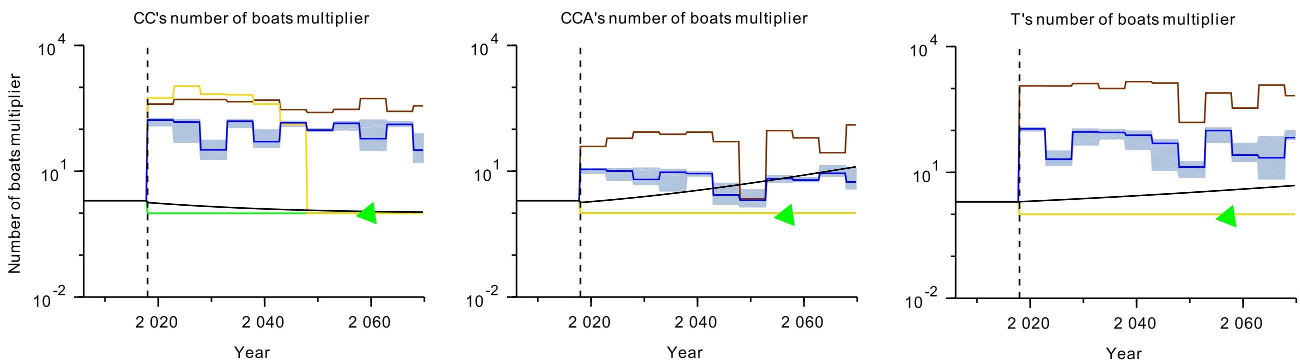


Figure 5: Under climate scenario RCP 8.5, projections over the period [2018 : 2070] of the number of boats multiplier $\frac{\mathrm{Nb}_f(t)}{\mathrm{Nb}_f(t_0)}$ (with a logarithm scale) of the fleets CC, CCA, T by fishing management strategy: CL (green), PS (black), MMSY (brown), MMEY (yellow) and EVA (blue).

initial biomass $B_i(t_0)$ at time $t_0 = 2006$ and climate time lag τ_i, consumption rate $a_{i,res}$ of the resource res, and the catchability $q_{i,f}$ relative to each fleet f are given in the Appendix A.5.

Figure 4 compares the historical and calibrated catches by fleets, stocks and the aggregated catches. We can see in the three cases (fleet catches, stock catches and aggregated catches) that the historical (dark blue points) and calibrated model (black curve) values are close. Even if the historical values show more variability than the estimated ones, the model outputs fit the historical outputs well. More details about the calibration and validation of the model, including relative errors, confidence intervals, sensitivity analysis and comparison between historical and estimated CPUE, are available in Gomes *et al.* [41].

4.2. *Number of boats of the fishing strategies*

Figures 5 and 6 provide information on fishing intensity, namely the number of $\mathrm{Nb}_f(t)$ for each fishing management strategy under the two climate scenarios, RCP 8.5 and RCP 2.6, respectively. To distinguish between the fishing strategies more clearly, we normalize them by plotting the fishing multipliers $\frac{\mathrm{Nb}_f(t)}{\mathrm{Nb}_f(t_0)}$; moreover we rely on a logarithm scale. As expected, during the calibration period (t_0 to $t_c - 1$) the five curves coincide and the number of boats multiplier is equal to 1 for each climate scenario. During the projection period (t_c to T), the multiplier for the closure

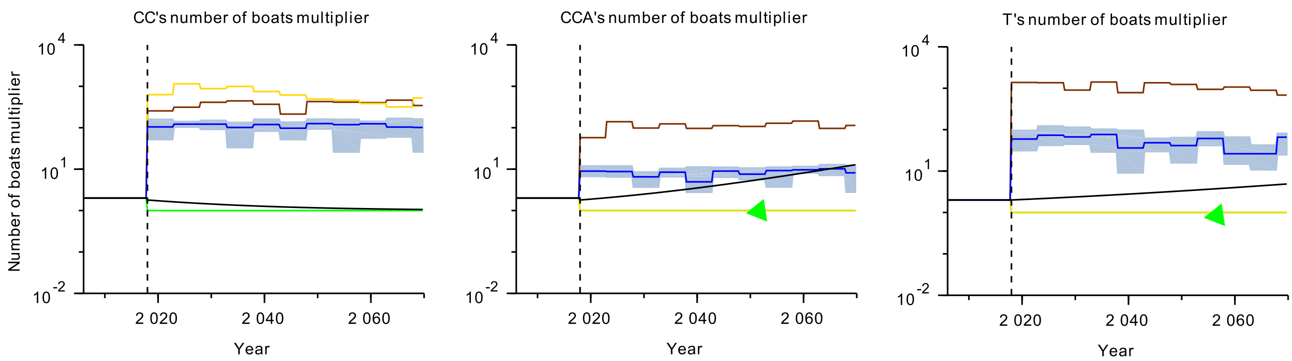


Figure 6: Under climate scenario RCP 2.6, projections over the period [2018 : 2070] of the number of boats multiplier $\frac{\mathrm{Nb}_f(t)}{\mathrm{Nb}_f(t_0)}$ (with a logarithm scale) for each fleet and by fishing management strategy: CL (green), PS (black), MMSY (brown), MMEY (yellow) and EVA (blue).

'strategy' CL (dark blue) is obviously equal to zero[3]. The predictive strategy PS is the same for each climate scenario and it can be noticed that it is positive and increasing during the projection period for fleets CCA and T, whereas it is negative and decreasing during the projection period for fleet CC. These projections stem from the historical trends and in particular the rates g_f^{hist} for the three fleets (Available in the Table A.5 in theAppendix A.4). Regarding the normative strategy MMSY, the number of boats turns out to be the highest for both climate scenarios most if the time. Such an outcome is consistent with the purpose of the MMSY strategy aimed at maximizing the catches. We can also observe that the economic rationalization underpinning the normative strategy MMEY implies stopping fishing activity for T and CCA during the entire simulation period, in both climate scenarios. The MMEY also implies stopping fishing activity for CC from 2048 under the RCP 8.5 scenario. For the ecoviability strategies, the mean of the 100 trajectories is represented by the blue curve, while the blue area represents the 100 trajectories. For these strategies, the numbers of boats for each fleet are in the same order of magnitude for both climate scenarios, even if the results under RCP 8.5 show more variability than under RCP 2.6. For both climate scenarios, the numbers of boats multipliers for CCA are close for the PS and EVA, while the numbers of boats multipliers for CC and T are higher for EVA than for PS. Finally, Figures 6 show some stability over time in terms of number of boats multipliers for most of strategies under RCP 2.6.

4.3. Ecological scores of the fishing strategies

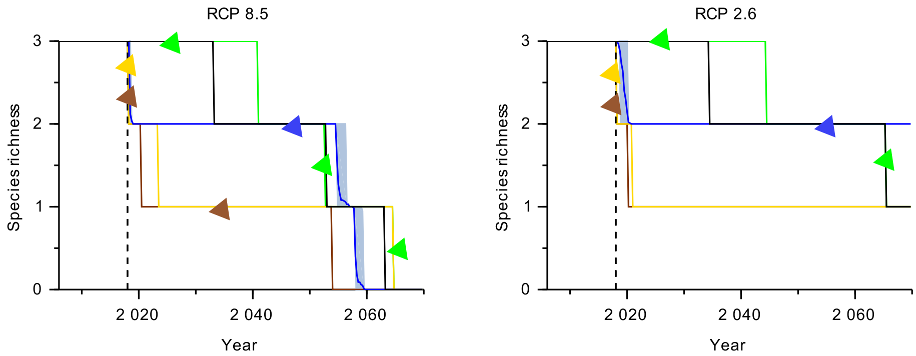
The projections over the period [2018 : 2070] are plotted by fishing management strategies and climate scenarios in Figure 7 in terms of viable numbers of species (7a), number of functional groups (7b) and mean trophic levels (7c).

RCP 8.5: Under the RCP 8.5 scenario, it first appears in Figure 7a that, whatever the fishing management strategy, the three fished species will be extinct in the long-run ($SR(t = 2070) = 0$). As such a negative result includes the ban case, it points to the detrimental effect of climate warning.

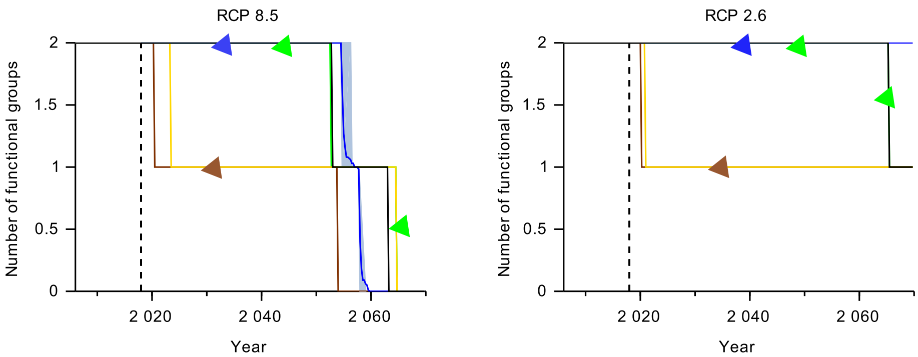
Focusing on the MMSY and MMEY normative strategies, we observe that the first losses of biodiversity occur in 2018 (Figure 7a). However it can be noticed that these losses of biodiversity do not induce losses of one functional group (Figure 7b), meaning that the first species to be extinct is a weakfish. The second loss of biodiversity occurs around 2021 for MMSY and around 2024 for MMEY (Figure 7a). The mean trophic level in Figure 7c shows that the jeopardized species differ between these two normative management strategies, as the MTI(t) falls significantly for MMEY, while it rises with MMSY. Regarding the values of trophic levels of each species in the Appendix A.3, it turns out that the CrC remains in the ecosystem for MMSY, as the MTI is equal to 4.4, whereas the GW remains in the ecosystem for MMEY, as the MTI is equal to 4. Finally the results show that these two latter species will be extinct in 2054 and 2065 for both MMSY and MMEY respectively (Figure 7a), obviously inducing a number of function groups $GF(t)$ equal to 0 (Figure 7b).

For the EVA strategy, the first loss of biodiversity occurs around 2018 (Figure 7a). As for MMSY and MMEY, this loss does not induce a loss of one functional group (Figure 7b), meaning that the first species to be extinct is a weakfish.

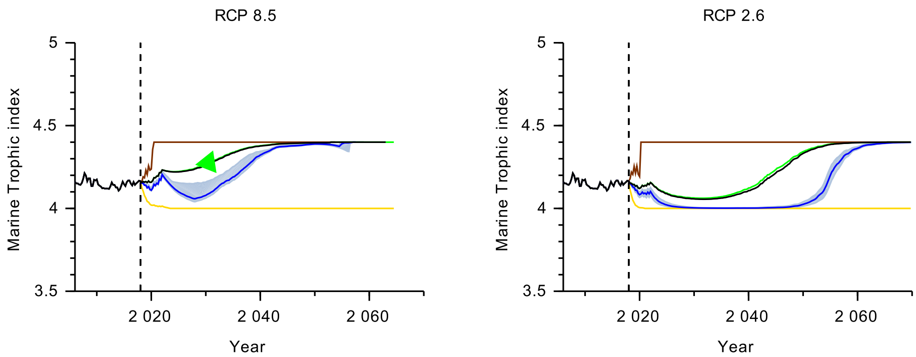
[3]When one curve is not visible in the graphs, because several curves also coincide, a marker of the color of the curve has been added.



(a) Number of viable species SR(t).



(b) Number of functional groups GF(t).



(c) Mean trophic levels MTI(t).

Figure 7: Ecological indicators for each fishing management strategy: CL (green), PS (black), MMSY (brown), MMEY (yellow) and EVA (blue). The first row (a) shows the number of viable species, SR(t), the second row (b) shows the number of functional groups, GF(t), and the third row (c) shows mean trophic levels, MTI(t). The graphs on the left show the results under RCP 8.5, while the graphs on the right show the results under RCP 2.6. The line of black dashes represents the separation between the calibrated and projected trajectories.

The second loss of biodiversity occurs around 2054, inducing a loss of one functional group. Regarding Figure 7c, it can be seen that the mean MTI varies from 4 to 4.4 between 2020 and 2054. These results show that the two species in the ecosystem are the GW and CrC (See trophic levels in Appendix A.3), first with a predominance of GW and after a predominance of CrC in the ecosystem. However the upper trajectory of this indicator emphasizes possibilities that the fish community might remain rather steady between 2020 and 2036. The location of the mean EVA trajectory within the interval of viable trajectories indicates that these situations are rare. After 2054, the MTI is equal to 4.4, showing that the latest species in the ecosystem is the CrC. Finally, the CrC is extinct around 2058 (Figure 7a).

Regarding the CL and PS trajectories, the first loss of biodiversity occurs in 2041 and 2033 respectively (Figure 7a). Once more, these losses of biodiversity do not induce a loss of one functional group (Figure 7b), meaning that the species that is extinct is a weakfish. As the mean trophic levels (Figure 7c) between 2033 and 2041 of the CL and PS are close, we can deduce that the first extinct species in both cases coincides. The second loss of biodiversity occurs in 2053 for both CL and PS (Figure 7a), inducing the loss of one functional group (Figure 7b). Again, the similarities of the mean trophic levels (Figure 7c) indicate that the same species is at stake. From 2053, as the value of mean trophic level is equal to 4.4, it can be concluded that the remaining viable species is the CrC for both strategies (Figure 7c and Appendix A.3). Finally, the CrC collapses from 2063 and from 2065 for the PS and CL strategies respectively (Figure 7a).

Altogether, under RCP 8.5, there is no fishing management strategy that can comply with the biodiversity constraint defined by the equation (24), as the GF falls to 0 whatever the strategy (Figure 7b).

RCP 2.6: Regarding the RCP 2.6, first it appears that, for four fishing management strategies (CL, PS, MMSY, MMEY), two species will be extinct in the long-run term ($SR(t = 2070) = 1$, Figure 7a).

For the MMSY and MMEY, the first loss of biodiversity occurs in 2018 (Figure 7a). Once more, this loss of biodiversity does not induce a loss of GF (Figure 7b), showing the extinction of one weakfish. The second loss of biodiversity occurs around 2020 for MMSY and around 2021 for MMEY (Figure 7a), inducing the loss of one functional group (Figure 7b). As under RCP 8.5, the mean trophic level in Figure 7c shows that the jeopardized species differs between these two normative management strategies, as the MTI(t) falls significantly for MMEY, while it rises with the MMSY. Regarding the values of trophic levels of each species in the Appendix A.3, it turns out that the CrC remains in the ecosystem for MMSY, as the MTI is equal to 4.4, whereas the GW remains in the ecosystem for MMEY, as the MTI is equal to 4.

For the EVA strategy, first it can be noticed that for the three indicators, the interval defined by the 100 trajectories is small. The first loss of biodiversity occurs around 2018. Once more, this loss of biodiversity does not imply a loss of one functional group (Figure 7b), showing the extinction of one weakfish. Regarding Figure 7c, it can be seen that the mean MTI varies from 4 to 4.4 between 2020 and 2070. These results show that the two species in the ecosystem are the GW and the CrC (See trophic levels in Appendix A.3), first with a predominance of GW until 2055, and after a predominance of CrC in the ecosystem.

For the CL and PS strategies, the first loss of biodiversity occurs in 2044 and 2034 respectively (Figure 7a). As the mean trophic levels (Figure 7c) between 2033 and 2041 of the CL and PS are close, we can deduce that the first extinct species in both cases coincides. Once more, this loss of biodiversity does not imply a loss of one functional group (Figure 7b), showing the extinction of one weakfish. The second loss of biodiversity occurs in 2065 for both fishing strategies (Figure 7a), implying a loss of one functional group (Figure 7b). Again, the similarities of the mean trophic level (Figure 7c) indicate that the same species is at stake. From 2065, as the value of mean trophic level is equal to 4.4, it can be concluded that the remaining viable species is the CrC for both strategies (Figure 7c and Appendix A.3).

In conclusion, under RCP 2.6, the only fishing management strategy that can fulfill the biodiversity constraint defined by the equation (24) is EVA, as the GF remains constant over the projection period.

4.4. Aggregated catch of the fishing strategies

The socio-economic performances and sustainability of the different fishing strategies are first examined through the production of the coastal fishery. Figure 8 shows the aggregated catch for each fishing management strategy under both climate scenarios. The projected local food demand defined in equation (22) is plotted in the red dotted curve. The graph is displayed with a logarithmic scale.

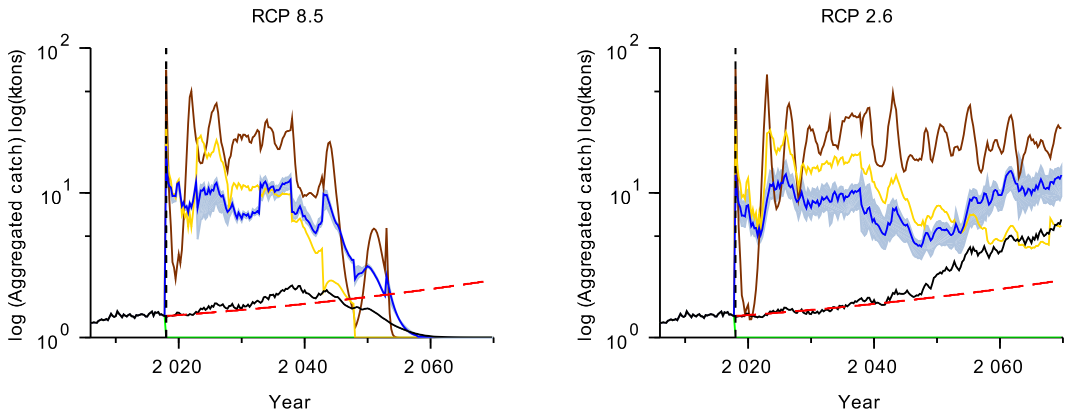


Figure 8: Aggregated catch $H(t)$ on a logarithmic scale together with local food demand (red dotted curve) for each fishing management strategy: CL (green), PS (black), MMSY (brown), MMEY (yellow) and EVA (blue). The graph on the left shows the results under RCP 8.5, while the graph on the right shows the results under RCP 2.6. The line of black dashes represents the separation between the calibrated and projected trajectories.

RCP 8.5: Overall, it turns out that, in the long run, none of the strategies satisfies the food security constraint, defined by the equation (23). Figure 8 indicates that, whatever the fishing management strategy, the aggregated catch falls to 0 for RCP 8.5. This is consistent with the previous comments in subsection 4.3 on ecological scores, since the three species are extinct in the long-run. Such results raise major concerns as to the sustainability of the fisheries under a pessimistic climate scenario.

Despite this alarming outcome, the transients before the collapses are informative. The highest aggregated catch is for the MMSY strategy, while the aggregated catch equals 0 for the closure strategy, as expected. For MMSY, the aggregated catch is higher than local food demand until 2047, lower between 2047 and 2049, higher between 2049 and 2053, and finally lower from 2053. The aggregated catches for the MMEY and EVA strategies are close and generally decrease during the projection period (t_c to T). The aggregated catches exceed local food demand from 2047 and 2054 for MMEY and the mean EVA, respectively. It can be noticed that the interval between EVA trajectories is small, and decreases during the projection period. The aggregated supply for the PS complies, most of the time, with food demand until 2045.

RCP 2.6: By contrast to the previous case, we first point out that, in the long run, all the fishing strategies (excluding of course CL) are, most of the time, viable in the sense of food security and equation (22). Moreover, it can be noticed that, again as expected, MMSY induces the highest aggregated supply. However it can be stressed that, at the beginning of the projection period, the aggregated catch for the MMSY does not meet local food demand. The aggregated catches for the MMEY and EVA strategies are again close, which is of interest regarding the economic content underlying the EVA. The aggregated catch decreases during the projection period (t_c to T) for MMEY, while it remains rather stable for EVA. Regarding the PS strategy, the aggregated catch is close to local food demand until 2042, while after this date it exceeds local food demand. Until 2042, the aggregated catch under PS does not always meet local food demand. In that sense, MMEY and EVA are the only strategies which clearly fulfill the food security constraint defined by the inequality (22).

The results obtained for MMSY for both climate change scenarios show large potential development of the coastal fishery, suggesting that, actually, the stocks are biologically under-exploited. Furthermore, the similarities of the aggregated catch for the PS with food demand until 2045 for both climate scenarios suggests that the current dynamic of the coastal fishery relies on local food demand. Until 2045, even if the aggregated catch for the PS is not always higher than local food demand, it can be assumed that this strategy is viable. Indeed, as the landings vary around the food demand, storage can be used by the fishermen as a buffer to try to dampen these gaps between landings and demand [4]. In accordance with that, it can be noticed that, whatever the climate scenario, the aggregated supply for the PS complies with local food demand until 2045, emphasizing the viability of the 'status quo' in the short temporal

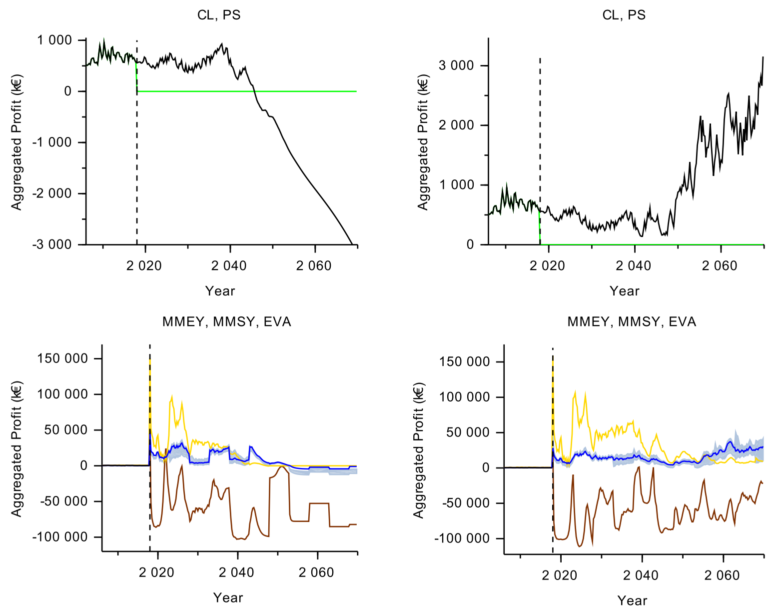


Figure 9: Aggregated profits $\pi(t)$ for each fishing management strategy: CL (green) and PS (black) first row, MMSY (brown), MMEY (yellow) and EVA (blue) in the second row. The graphs on the left show the results under RCP 8.5, while the graphs on the right show the results under RCP 2.6. The line of black dashes represents the separation between the calibrated and projected trajectories.

horizon.

4.5. Profits of the fishing strategies

Dynamics of aggregated profits for scenarios RCP 8.5 and RCP 2.6 are plotted[4] in Figure 9.

RCP 8.5: Figure 9 shows that MMEY and CL are the only strategies in which the aggregated profits are positive or equal to 0 throughout the projection period. CL induces profits equal to 0 during the projection period, as expected. Even if it is viable considering the constraint defined by the equation (23), in reality this strategy is not socially viable. Owners do not just need to cover the costs, they need to receive salaries. The aggregated profits for MMSY are negative during all the projection period, while they are positive until 2046 and 2052 for PS and EVA respectively. Once more, the interval of EVA trajectories is small. Regarding MMEY, it can be noticed that the aggregated profits are equal to the CC's profits (as $\mathrm{Nb}_{CCA}^{MMEY} = 0$ and $\mathrm{Nb}_{T}^{MMEY} = 0$, see Figure 5, the CCA's and T's profits are equal to 0). As said in 3.4 part, the aim of this strategy is to maximize the NPV. In order to compare the economic performances of the fleet, equation (8) is rewritten as follows:

$$\pi_f(t) = \mathrm{Nb}_f(t)\underbrace{\left((1-\beta_f)(\alpha_f\sum_{i=1}^{N}B_i p_i q_{i,f} n_f^{d,a} - c_f^v n_f^{d,a}) - c_f^f\right)}_{A} \tag{28}$$

Considering the long-run biomass for each species, the term denoted by A for each fleet can be computed for each climate scenario and each fishing management strategy. The results are available in Table A.7 in Appendix A.6. It can be noticed that for each fishing management strategy, the A for CC is higher than the A for CCA and for T[5]. In that sense, it seems consistent thatMMEY suggests closing the CCA and T fisheries. Even if it seems viable in terms of profitability, in reality it is not socially viable. The profits are not distributed between the different fleets, with the CC owners being favored over CCA and T owners.

[4]Due to high differences in terms of values of profits, the CL and PS strategies are plotted together in the graphs at the top, while MMSY, MMEY and EVA are plotted together in the graphs at the bottom.

[5]As under RCP 8.5, all the strategies have the same biological results in the long-run, the results for A are the same.

RCP 2.6: Regarding Figure 9, it can be noticed that MMSY is the only strategy in which the aggregated profits are negative. As for RCP 8.5, the CL induces profits equal to 0 during the projection period. Consequently, once more, this strategy is not economically or socially viable. For MMSY, the aggregated profits are negative. Regarding the Appendix A.7, in which the profits of each fleet are available, it can be underlined that, even if the number of boats in CC and CCA are close (respectively 7206 and 8110), the CC's profits are positive most of the time, whereas the CCA's profits are negative. This is due to high differences in the economic parameters (see paragraph above and Appendix A.2 Table A.3). The PS and EVA trajectories seem economically viable throughout the projection period. However it can be noticed that not all the fleets are profitable throughout the projection period (T for PS and T and CCA for EVA, See Figure A.12 in Appendix A.7), and in that sense these strategies are not socially viable (see paragraph above). For PS, from 2047 it is visible that the aggregated profits increase considerably, with this increase being induced by the increase in aggregated catch (Subsection 4.4). For MMEY, the aggregated profits are positive, and their sum during the projection period is the highest, as expected. As for the RCP 8.5, the CCA and T fisheries are closed due to the values of the economics parameters, inducing social issues (see paragraph above).

5. Discussion

5.1. EVA as a step towards EBFM

EBFM is defined by a set of principles and criteria [85, 68, 27]. They can be summarised as:

- Maintaining the natural structure and function of ecosystems, including the biodiversity and productivity of natural systems and identified important species, is the focus of management.
- Human use and values of ecosystems are central to establishing objectives for use and management of natural resources.
- Ecosystems are dynamic; their attributes and boundaries are constantly changing and consequently interactions with human uses also are dynamic.
- Natural resources are best managed within a management system based on a shared vision and set of objectives developed amongst stakeholders.
- Successful management is adaptive and based on scientific knowledge, continual learning and embedded monitoring processes.

In such purpose, the combination of MICEs with EVA appears as a well-suited modeling framework for EBFM [27]. Indeed, it aims to conserve the natural structure and function of ecosystems through the establishment of the constraint (24), with social and economic objectives relative to human uses (constraints (22), (23)). By relying on these acceptable bio-economic thresholds and precautionary points, the eco-viability approach incorporates the social, economic and cultural context of the fishery. Furthermore this approach supposes that ecosystems are complex, dynamic, that their attributes and boundaries are constantly changing, in particular as they relate to the interactions with human uses [27]. Moreover, through the establishment of the three constraints, this approach is based on a shared vision and set of objectives developed amongst stakeholders (See Subsection 5.4). More generally, the constraints reflect national and international goals, objectives and constraints relating to both conservation and sustainable use. Finally, the eco-viability approach relies on the knowledge of utilized species through calibrated and dynamic models, here in the vein of MICE. Thus the resource management system is based on reliable data and scientific knowledge.

5.2. The detrimental impact of climate warming

All the results of the subsections 4.3, 4.4 and 4.5 highlight the negative impact of climate change on biodiversity, fishing landings and economic performances of the coastal fisheries in French Guiana. Such alarming results expand the findings of Gomes *et al.* [41] who focused on PS and CL explorative fishing strategies in French Guiana, because they show the detrimental impact of climate warming whatever the applied fishing strategy under a pessimistic climate scenario such as RCP 8.5. These results are consistent with the works of Cheung *et al.* [15, 13] who proved that the increase of the SST in the equatorial area significantly and negatively alters the maximum catch potential. For French

Guiana, Diop *et al.* [24] also pointed out similar detrimental ecological-economic impacts of climate warming for the shrimp fishery.

Regarding the number of species (Figure 7a, Subsection 4.3), under RCP 2.6, at least one species remains in the ecosystem for each fishing management strategy, while they are all extinct under RCP 8.5, whatever the fishing management strategy. More particularly, the largest difference and gain is for EVA, as there is no second loss in biodiversity for RCP 2.6, whereas there is one for the RCP 8.5.

The two climate scenarios also induce large differences in terms of productivity during the projection period. Obviously, for RCP 8.5, the species extinctions result in a complete collapse of the coastal fishery. For the MMSY, PS, MMEY and EVA, the sums of the aggregated catches, during the projection period, are respectively 2226 ktons, 244 ktons, 939 ktons and 581 ktons higher for RCP 2.6 than for RCP 8.5.

Regarding the sum of the aggregated profits during the projection period, the difference between the two climate scenarios is also considerable. For MMEY, PS and EVA, the sums of the aggregated profits are respectively 2981,079 k€, 287,957 k€ and 2265,812 k€ higher for RCP 2.6 than for RCP 8.5. MMSY is the only strategy in which the sum of the aggregated profits is higher for RCP 8.5 than for RCP 2.6 (-12514,839 k€ and -12604,210 k€ respectively).

5.3. The fishery as a regulator of species competition

Fisheries impact ecosystems, inducing changes in their composition. In particular, fishing of one species in an ecosystem under competition mechanisms can favor other species [5]. The effect is specially shown in the case of sardine-anchovy in California and Peru/Chile [5]. Indeed, a correlation has been shown between the decrease in the biomass of one species, caused by fishing, and the increase in the biomass of the other species [21]. Examining the Figure 7b for RCP 2.6, it can be highlighted that EVA has better biological performances than CL, as $\text{GF}_{\text{EVA}}(t = 2070) = 2$ while $\text{GF}_{\text{CL}}(t = 2070) = 1$. This result suggests that the fishing activity regulates competition between the fished species, which was shown as a major driver of dynamics of the ecosystem in Gomes *et al.* [41]. More specifically, fishing contributes to balancing the competition for resources between species. This result is in line with the studies by Ripple *et al.* [71], Estes *et al.* [33] or Doyen *et al.* [28]. They assert that the conservation of top-predators is essential, as they are often able to exert strong regulatory effects on ecosystems. Considering the harvesting by humans in marine ecosystems and the fact that they do not have predators in this ecosystem, humans can be considered as a top-predator in marine ecosystems.

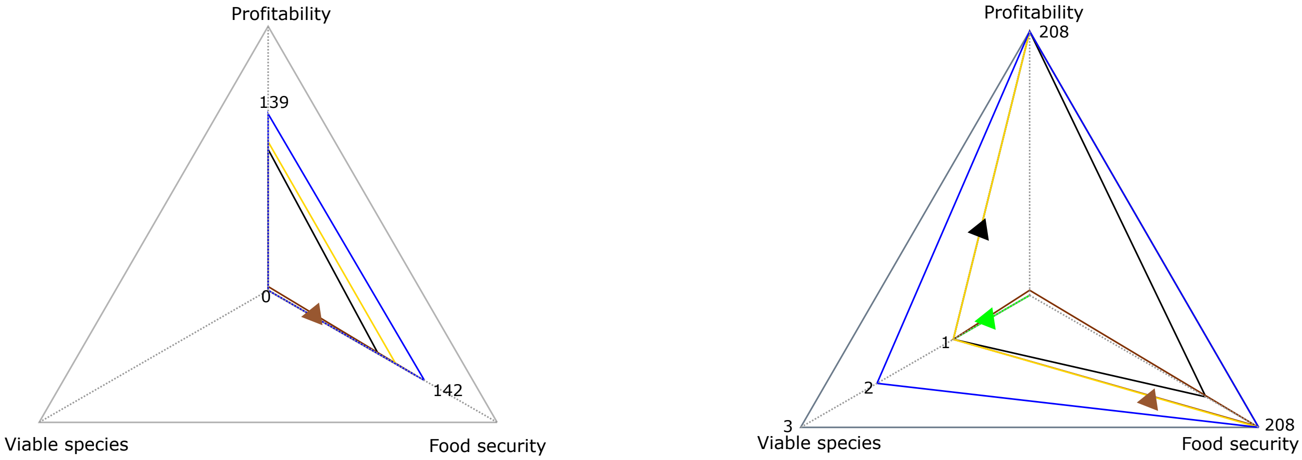
5.4. EVA strategy as a step towards sustainability

Figure 10 synthesizes the ecological-economic performances of each fishing management strategy under RCP 8.5 (Figure 10a) and RCP 2.6 (Figure 10b). The axis of the radar includes the number of viable species in the long-run, the number of quarters during the projection period in which the aggregated catch is higher than local food demand, denoted by food security, and the number of quarters during the projection period in which the profits are positive, denoted by profitability.

We can compare the areas of the radar plots for each strategy in order to rank them in terms of these ecological-economic scores:

$$\text{CL} \Big\langle \text{MMSY} \Big\langle \begin{matrix}\text{PS}\\ \text{MMEY}\end{matrix} \Big\langle \text{EVA}$$

As highlighted in the Subsection 4.4, the aggregated catch under PS can in reality meet local food demand. In accordance with that, we can rank PS together with MMEY. Such findings reinforce previous works on small scale fisheries in French Guiana [16] (see below for more details). This result is also consistent with the general literature on sustainability. Brundtland *et al.* defined sustainable development as a development "that meets the needs of the present without compromising the ability of future generations to meet their own needs" [8]. As emphasized in Martinet & Doyen [59, 30] and in Doyen & Gajardo [29], the viability modeling framework is closely related to intergenerational equity. Moreover, by adopting a multi-criteria approach, viability brings major insights and quantitative methods to strong sustainability [3, 26]. Such a multi-criteria viewpoint is crucial for the sustainability of fisheries, since many distinct stakeholders are involved in fisheries (fishermen, recreational fishermen, environmentalists, economists, biologists, public decision makers, etc), and each one of them has its favorable outcomes from fisheries, which may be undesirable for another group. In that sense, considering just one point of view for fishery management of an ecosystem can deteriorate its sustainability. In accordance with that, a multi-criteria approach seems a better option



(a) Radarplot under RCP 8.5.

(b) Radar plot under RCP 2.6.

Figure 10: Radar plot under both climate scenarios, RCP 8.5 on the left (a) and RCP 2.6 on the right (b), for each fishing management strategy: CL (green), PS (black), MMSY (brown), MMEY (yellow) and EVA (blue). The three criteria considered are: the number of viable species in the long-run, $SR(T)$, the number of quarters, during the projection period, in which the aggregated catch, $H(t)$, is higher than local food demand, the food security and the number of quarters, during the projection period, in which the aggregated profits, $\pi(t)$ are positive, the profitability.

for fishery management, to ensure sustainability from economic, environmental and social viewpoints. EVA has been shown to be adaptable and applicable across a wide range of diverse contexts [74, 63]. These include fisheries in Australia [43], Chile [39], Spain [60], the Solomon Islands [47], French Guiana [16] and the Bay of Biscay [42, 53].

5.5. *Policy recommendations for French Guiana fishery*

In the 2010s, the small-scale fishery of French Guiana was evaluated as viable [16, 17]. However, increasing demographic pressure raises concerns about its sustainability, as the INSEE (French National Institute of Statistics and Economic Studies) estimates that the Guianese population will double over the next three decades [22], placing great pressure 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, although these fisheries are crucial to sustaining many communities especially in developing or underdeveloped countries [40]. The present study also points to major vulnerabilities relating to climate change. Whatever the fishing management strategy, the results of the pessimistic climate scenario (RCP 8.5) indicate that coastal fishery could be jeopardized in the long-run, while in the optimistic case (RCP 2.6) it could be maintained. This highlights a major threat to the long-term viability of the coastal fishery of French Guiana as a whole. In other words, the fishery's sustainability seems weak in the face of climate change. The major challenges of this fishery are to meet local food demand and ensure economic security of the territory. The implementation of aquaculture could support these two challenges. In order to have efficient aquaculture in the future, the territory has to prepare itself now, by identifying species and areas compatible with aquaculture or training the future generations, for example.

Moreover, the results show that Ecoviability seems the best fishing management strategy to ensure the sustainability of French Guiana coastal fishery, whatever the climate scenario. The numbers of boats vectors for each fleet give information about how many licenses can be delivered to reach sustainability. This strategy suggests that the CC fleet has to be promoted, compared to CCA and T fleets. On the contrary, the current dynamic, represented by the PS strategy, induces the development of CCA and T fleets and a reduction in CC fleet. Incentives could thus be provided to CCA and T owners to help them change their boats. Moreover it can be noticed that, for both climate scenarios, the EVA strategy induces negative profits for T and CCA in some quarters. Considering that, subsidies could be provided to T and CCA owners.

5.6. Limitations of the model

The present paper presents a comparative analysis of several fishing management strategies for tropical fisheries facing climate change. However, many future improvements are of course possible.

The refinement of resource dynamics and incorporation of trophic interactions between species constitute potential ecological improvements. The resource variable includes shrimps and other fish species. It would be interesting to break down this global aggregated resource stock into more detailed stocks. Following Cissé *et al.* [17], 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 in 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 for the historical period, 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. As the suitable temperature curves of the species included in the model (in red) are similar to those of the other species (in black) (Figure A.11 in the Appendix A.1), we can consider that the species not taken into account in the current model should also be significantly altered by climate warming over the projection period. In other words, these species are not good candidates to replace the three main species we focused on in term of future catches.

With regard to climate scenarios, the sea surface temperature is assumed to follow a linear growth dynamic, in line with the IPCC climate scenarios. However, Hilsenroth *et al.* [48] show that the consideration of seasonality in climate scenarios induces changes in economic results. As the seasons in French Guiana are based on a succession between dry and rainy seasons, the establishment of new climate scenarios, including seasonality, would be more accurate and model the environmental parameters of the ecosystem more effectively.

The profitability constraint, defined by the equation (23), consider the aggregated profits. Consequently, as shown in the subsection 4.5, this constraint can be fulfilled even if the profits are not shared between all the fleets, inducing social issues. In that sense, sustainability of the coastal fishery could be increased by considering others criteria, based on the well-being of the owners, or the fishermen for example, as put forward in Link *et al.* [57], Schuhbaueur & Sumaila [74] and Doyen *et al.* [26]. Moreover, the model in its current form does not include endogenization of the prices. A next step could be to account for this endogenization for the sake of more realistic projections.

Even if the model does take uncertainty into account through the two climate scenarios, many other uncertainties, including observation uncertainty, parameter uncertainty and model structural uncertainty are neglected here. 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 [25] or Grafton *et al.* [44] should reinforce the relevance and reliability of the model and scenarios. Furthermore, our choice of a long temporal horizon ($T = 2070$) 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, strategies and scenarios through stochastic approaches, as in Doyen [25].

6. Conclusion

This paper provides an ecological-economic model and analysis for the coastal fisheries in French Guiana. This model is a MICE relying on resource-based multi-stock and multi-fleet discrete time dynamics, accounting for climate impact through sea surface temperature (SST). The model is validated using time series data, provided by the IFREMER Information System, over the period 2006-2018. Ecological and economic performances of fishing management strategies, including CL, PS, MMSY , MMEY and EVA strategies are compared, along with climate scenarios.

The projections under the pessimistic climate scenario show alarming outcomes for the future of the fisheries. Whatever the fishing management strategy, both biomass of fished species and fishery are expected to collapse in the long-run. Under the optimistic climate scenario, fishing enables the potentially increasing food demand to be met, inducing positive profits, except for MMSY. 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.

The paper also highlights the impact of fishery in species competition. Indeed, under the optimistic climate scenario, the ecological results under EVA are better than under closure, suggesting that the fishery contributes to balancing competition for resources between species.

Another contribution of this study is to advocate the use of Ecoviability approaches as a relevant modeling framework for EBFM and sustainability issues. On the one hand, the eco-viability approach is identified as a well-suited modeling framework for EBFM, while on the other hand, by balancing ecological and economic goals with production and food security objectives over several decades, the ecoviability approach perfomrs well to addressing sustainability. For the case study in French Guiana, the ecoviability approach allows to derive policy recommendations in terms of number of boats in each fleet. The underlying reallocation of fishing efforts turns out to be major.

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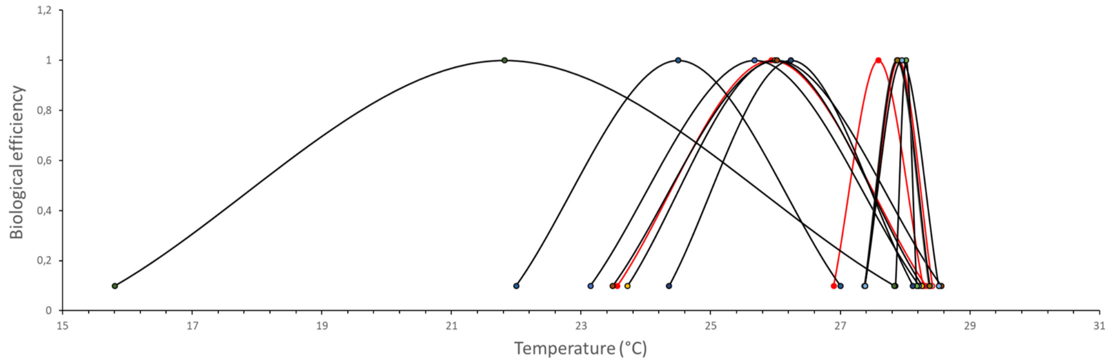

Figure A.11: Biological efficiency $\gamma_i(\theta)$ for the 13 most-fished species in the coastal fishery in French Guiana. The species included in the model are represented by red curves, while the others are represented by black curves.

Appendix A. Appendix

Appendix A.1. Temperatures $\theta_{i,10}$, $\theta_{i,opt}$, $\theta_{i,90}$ used for climate change modeling and biological efficiency for the 13 most-fished species in the coastal fishery in French Guiana.

See Table A.2 and Figure A.11.

Table A.2: 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

Appendix A.2. Economic parameters

See Table A.3.

Appendix A.3. Biological parameters of each species

See Table A.4.

Appendix A.4. Rate g_f^{hist} used for projected efforts

See Table A.5.

Appendix A.5. Calibrated parameters

See Table A.6.

Appendix A.6. Term A (equation (28)) for each fleet under each climate scenario and each fishing management strategy

See Table A.7.

Appendix A.7. Profits by fleet under RCP 2.6 for each fishing mangament strategy

See Figure A.12.

Table A.3: Economic parameters

Parameters	Canots Créoles	Canots Créoles Améliorés	Tapouilles
Number of boats for t_0, $\mathrm{Nb}_f(t_0)$	21	72	7.6
Variable cost, c_f^v (€/ fishing day)	27.43	98.26	222.75
Fixed cost, c_f^f (€/boat.year)	3398	6530	13880
Selling prices p_i (€/kg)			
Acoupa Weakfish	2.92	2.92	2.92
Green Weakfish	1.99	1.99	1.99
Crucifix Catfish	1.53	1.53	1.53
Average number of fishing days during one period (here one quarter) ,$n_f^{d,a}$ (day)	26	37	37
α_f	2.77	1.49	1.16

Table A.4: Biological parameters of each species

Parameters	Acoupa Weakfish	Green Weakfish	Crucifix Catfish
ω_i (kg)	4	3	2
T_i	4.1	4	4.4

Table A.5: Rate g_f^{hist} for each fleet

g_f^{hist}	Canots Créoles	Canots Créoles Améliorés	Tapouilles
g_f^{hist}	-0.012	0.013	0.007

Table A.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	/
$B_i(2006)\,(tons)$	$14,070$	$25,055$	$12,866$	$282,625$
$\tau_i\,(months)$	12	48	0	/
$max\,I$	/	/	/	$776,371$
$min\,I$	/	/	/	$166,603$

Table A.7: Term A (equation (28)) for each fleet under each climate scenario and each fishing management strategy

	Canots Créoles	Canots Créoles Améliorés	Tapouilles
RCP 8.5			
CL	-1563	-3450	-7591
PS	-1563	-3450	-7591
MMSY	-1563	-3450	-7591
MMEY	-1563	-3450	-7591
EVA	-1563	-3450	-7591
RCP 2.6			
CL	27,814	5,403	-1,313
PS	22,405	3,773	-2,469
MMSY	3,727	-1,856	-6,461
MMEY	909	-2,502	-4,635
EVA	14,995	1,541	-4,032

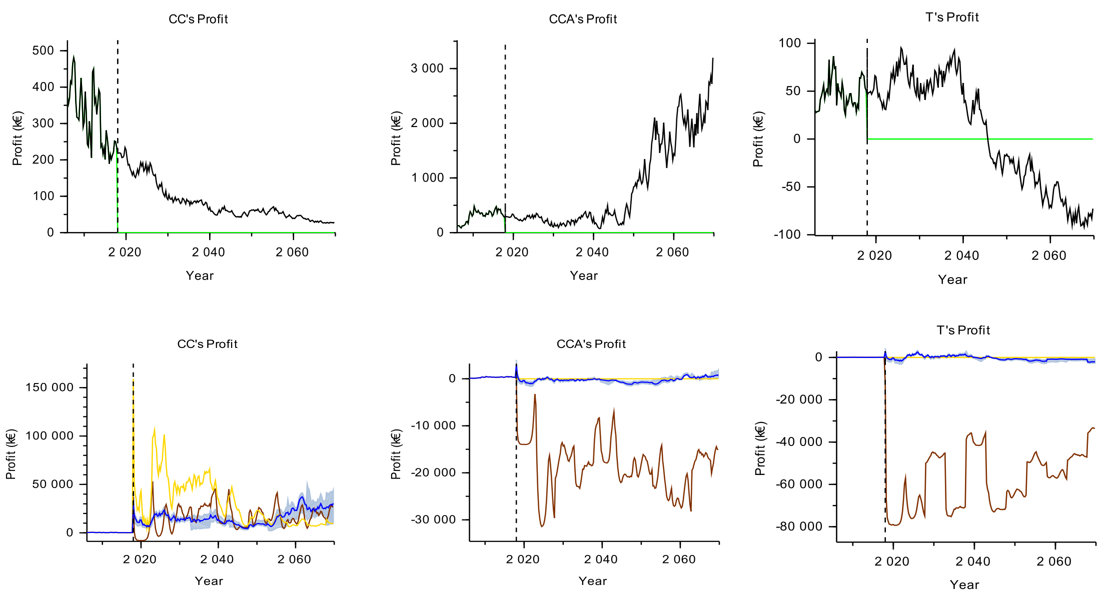

Figure A.12: Profits $\pi_f(t)$ by fleet for each fishing management strategy: CL (green) and PS (black) first row, MMSY (brown), MMEY (yellow) and EVA (blue) in the second row under RCP 2.6. The line of black dashes represents the separation between the calibrated and projected trajectories.

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