Economic Analysis and Policy
June 2022, Volume 74, Pages 634-656
https://doi.org/10.1016/j.eap.2022.03.016
https://archimer.ifremer.fr/doc/00760/87240/

Resilience management for coastal fisheries facing with global changes and uncertainties

Cuilleret Mathieu [1,*], Doyen Luc [1], Gomes Helene [2], Blanchard Fabian [2]

[1] CNRS, GREThA, University of Bordeaux, Pessac, France
[2] Ifremer, LEEISA (USR 3456, CNRS, Université de Guyane, Ifremer), Cayenne, French Guiana

* Corresponding author : Mathieu Cuilleret, email address : mathieu.cuilleret@u-bordeaux.fr

Abstract :

Operationalizing resilience in fisheries management is a challenging issue in the face of global changes. In this perspective, Grafton et al. (2019) propose a heuristic based on the '3Rs' of resilience, namely resistance, recovery, and robustness. The work presented here applies this generic framework to the coastal fishery of French Guiana, which is under pressure because of both climate change, energy costs and demographic growth. To this end, a dynamic multi-species, resource-based and multi-fleet model accounting for climate and socio-economic uncertainties is developed and calibrated using catch and effort time series. The search for a more resilient management leads us to compare different fishing management strategies and projections including 'Business as usual' (bau), 'Multispecies Maximum Sustainable Yield' (mmsy) and 'Multispecies Maximum Economic Yield' (mmey) strategies. The comparison between the strategies relies on ecological-economic viability goals and thresholds. The two normative strategies mmsy and mmey turn out to provide major gains in terms of the 3Rs and ecological-economic resilience as compared to bau. They both suggest major redistributions in the fishing effort of the different fleets.

Keywords : Resilience, Coastal fishery, Climate warming, Oil price uncertainty, Demographic pressure, Models of intermediate complexity (MICE)

1 Introduction

Resilience considerations influence many decisions and policies, including risk management in the private sector (Sheffi, 2015), development and finance investments (OECD, 2017) and management objectives of influential multilateral and UN agencies (e.g. FAO; World Bank). As a result, resilience is now included in several Sustainable Development Goals (SDG). Resilience was also a foundational concept for the 2005-2015 Hyogo Framework and the 2015-2030 Sendai Framework with respect to international disaster policy (United Nations, 2015).

This rising popularity of resilience contrasts, however, with a lack of clarity over the concept and how to operationalize it in practice (Downes et al., 2013; Quinlan et al., 2016; Béné and Doyen, 2018; Grafton and Little, 2017). Thus, for several decades, leading scientists from various disciplines ranging from ecology, engineering sciences, psychology to economics highlighted the significance of resilience while, also, the need for much better inclusion of resilience management into decision-making (Levin et al., 1998). Recently, Grafton et al. (2019) have made significant progress in the definitions and objectives of resilience-based environmental resource management. However, practical guidance and methodology about how to implement resilience management and policy are still required in particular for fisheries, coastal biodiversity and ecosystems. The case of coastal tropical ecosystems is particularly challenging in that regard because they are facing many threats and uncertainties including climate change and demographic pressure. The overall purpose of our paper is to identify for tropical small-scale fisheries resilience management strategies as proposed in Grafton et al. (2019).

The focus on tropical small-scale fisheries is first justified by the fact this type of fishery plays a major role in the economic development of many countries worldwide as it provides food security, economic value added, employment as well as cultural identity (Bene, 2006; Andrew et al., 2007). Moreover, global changes, notably demographic growth (Rice and Garcia, 2011) are exerting extreme pressure on the tropical marine and coastal ecosystems and consequently on fishing activities (Butchart et al., 2010; Österblom et al., 2015). Climate change (CC) exacerbates and complicates the situation by inducing new - or intensifying existing - ecological and economic risks and vulnerabilities (Sumaila et al., 2011; Cheung et al., 2009; Diop et al., 2018; Lagarde et al., 2018). CC can indeed alter primary production (Cheung et al., 2009), change species interactions (Gomes et al., 2021; Smith et al., 2012) and shift distribution of species to more temperate water (Cheung et al., 2016). Consequently, ensuring the long-term resilience of tropical marine fisheries and in particular of tropical small-scale fisheries while preserving marine biodiversity, ecosystem services and the ecosystems that support them, has become a major issue for regulating agencies as underlined at the international scale by FAO (2018) or IPBES. In that regard, the French Guiana coast constitutes a challenging case study. The small-scale coastal fishery in French Guiana indeed plays a major ecological-economic role because the majority of the Guianese inhabitants live along the Guianese coast. In particular, the production of the coastal fishery is fully consumed locally. Moreover, the coast faces major pressures and risks related to climate change and demographic growth. Thus, promoting resilience management for the fishery coping with the uncertainties and vulnerabilities underlying the coastal social-ecological system is a major objective of Guianese public policies (Cissé et al., 2015; Diop et al., 2019; Gomes et al., 2021).

In that perspective, our paper aims at identifying resilience management strategies for the coastal fishery in French Guiana following in particular the definitions and heuristic proposed in Grafton et al. (2019); More specifically, ecological-economic resilience is considered through the so-called 3Rs of resilience — resistance, recovery and robustness: Resistance refers to the magnitude of shocks and uncertainties that can be withstood; Recovery relates to the time necessary to bounce back to viable or safe states; Robustness (or reliability) refers to the probability to withstand the shocks and uncertainties. Using these 3Rs, we contrast different fishing management strategies over the period 2020-2070. The different strategies correspond to projections over 2020-2070 of a bio-economic model calibrated on historical data (2006-2019) of fishing catches and efforts in French Guiana (Gomes et al., 2021). This model, in line with the Ecosystem Based Fishery Management (EBFM) and Models of Intermediate Complexity (MICE) (Plagányi et al., 2014; Doyen et al., 2017), is a dynamic, multi-species, resource-based and multi-fleet model accounting for climate through Sea surface Temperature (SST). The different fishing strategies that we here focus on include a predictive strategy named 'Business as usual' (BAU) which projects the efforts of the fleets based on their historical trends. More normative strategies include Multi-species Maximum Sustained Yield (MMSY) which aims at maximizing the expected aggregated catches during all future periods and the Multi-species Maximum Economic Yield (MMEY) which maximizes the (expected) net present value induced by fishing across years. An explorative strategy entitled Closure (CLOS) which corresponds to a fishing ban is also considered mainly as an ecological benchmark.

To account for climate change and uncertainties, IPCC projections of the special report entitled "The Ocean and Cryosphere in a Changing Climate" (Pörtner et al., 2019)[1] are considered. We here rely on two contrasted climate scenarios namely RCP 2.6 and 8.5, which corresponds to optimistic and pessimistic scenarios respectively even if they are less likely to occur than the RCP 4.5 as explained in Abadie (2018). We also include 3 scenarios from IEA (2020) to integrate future changes and uncertainties of fuel costs on the economic performances of the fishery.

The general methodology we propose to operationalize the 3Rs articulates MICEs, uncertain scenarios and the viability modeling approach. The use of the viability approach which focuses on dynamic systems under constraints and thresholds is justified by the fact it provides a rigorous and sound basis for the formalization of resilience as already argued in Martin (2004); Deffuant and Gilbert (2011); Hardy et al. (2016); Béné and Doyen (2018); Karacaoglu and Krawczyk (2021). Viability and resilience are indeed both about non-linear dynamic systems and about their persistence in the sense of ability to maintain their identity (Béné et al., 2001; Baumgärtner and Quaas, 2009; Doyen et al., 2019; Schuhbauer and Sumaila, 2016; Oubraham and Zaccour, 2018). The different viability goals and thresholds are here linked to the triple bottom lines of sustainable development and several sustainable development goals (FAO, 2017) related to small-scale fisheries.

The contribution of our paper is threefold. Firstly, it gives important insights into the operationalization of the 3Rs approach and resilience management for fisheries facing global changes through models, metrics, and management strategies. Secondly, the MMSY and MMEY management strategies appear as more resilient in the 3Rs sense as compared to current trends underlying the BAU predictive scenario. Regarding MMEY, such a result confirms the well-known stability of MEY strategies for single species approaches (Clark, 2010; De Lara and Doyen, 2008). The third main contribution of the paper is to identify the major redistributions in the fishing effort of the different fleets in French Guiana induced by both the MMEY and MMSY management strategies and thus by resilience management.

Hereafter, Section 2 describes the ecological, social, and economic context of the case study. Section 3 presents the ecological-economic modeling framework including the ecosystem dynamics, the uncertainty scenarios, the fishing management strategies, the ecological-economic criteria and thresholds as well the 3Rs metrics. Section 4 compares the projections in terms of fishing efforts and ecological-economic resilience.

[1] In the 5th report, the IPCC has adopted four main climatic scenarios. Here we focus on the two extreme scenarios RCP 2.6 and 8.5. Of interest for future works would consist in considering other extreme scenarios such as RCP 1.9 of the newest report of the IPCC Masson-Delmotte et al. (2021).

Finally, these results are discussed in Section 5. Details on the model and the projections are displayed in the appendix.

2 Case study: the coastal fishery in French Guiana

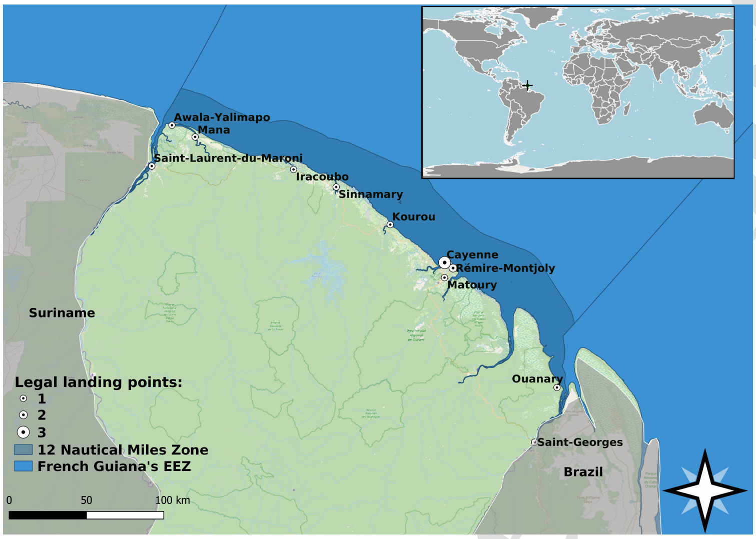

Fig. 1: French Guiana map with the main landing points of the small-scale fishery.

French Guiana, bordering Suriname and Brazil, benefits of an exclusive economic zone (EEZ) of 130,000 km^2, including 50,000 km^2 of continental shelf. The coastal fishery in French Guiana is a small-scale fishery, operating in a 16 km offshore zone with depths from 0 to 15 m. The coastal and small-scale fishery is exploited by about 120 boats (in 2018). The three main categories of boats are 'Canots creoles' (denoted hereafter by CaC), 'Canots creoles ameliorés' (denoted by CaC+) and 'Tapouilles' (denoted by TAP) which differ in size, technological level and fishing areas (Cissé et al., 2015). These fleets use only passive gear such as drift net which is the main fishing gear. They landed an average per year of 2000 tons in the last two decades. This coastal fishery is a non-selective fishery, exploiting more than 30 fish species. The most harvested species are the Acoupa Weakfish (*Cynoscion acoupa*) followed by the Green Weakfish (*Cynoscion virescens*) and the Crucifix Catfish (*Sciades props*), representing around 42%, 18% and 11% respectively of the total landings between 2006 and 2018. The coastal fishery in French Guiana plays a major role for the territory, the local fish industry and local fish market (Cissé et al., 2014) as the production is only consumed locally. Moreover, the INSEE (French National Institute for the Statistical and International Study) projects the doubling of the French Guianese population until 2040 (Demougeot and Baert, 2019) which raises major concerns in terms of fishing pressure, sustainability and resilience.

Since 2006, on a daily basis, fishing effort (time spent at sea, expressed in days), and fishing landing data are collected by the observers from the IFREMER Fisheries Information System. Moreover, socio-economic surveys provide economic data such as selling prices of species, variable and fixed costs for fleets (Cissé et al., 2013). These data and time series are used to calibrate the parameters of the ecological-economic model described below.

The calibration of the model also relies on Observed sea surface temperature data (SST) obtained from the NOAA Earth System Research Laboratory website. We assume that the temperature is homogeneous in the water column exploited by this fishery (0-15m depth) because of the tide currents.

3 The ecological-economic model, scenarios and strategies

The model, scenarios and strategies detailed below are in line with models of intermediate complexity (MICE) as in Hannah et al. (2010); Plagányi et al. (2014); Doyen (2018). As captured by the conceptual model displayed in Figure 2, the model relies on a multi-species, resource-based, and multi-fleet discrete time dynamics, accounting for climate impacts through the sea surface temperature (SST). The calibration of the model for the French Guiana case study strongly draws on Gomes et al. (2021) and the IFREMER Fisheries Information System data between 2006 and 2018.

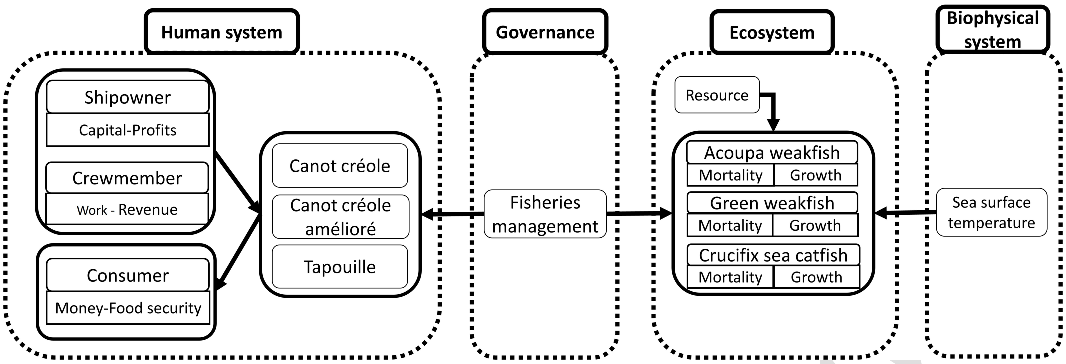

Fig. 2: Conceptual model

3.1 Ecological dynamics

Fished species are denoted by $s = 1, ..., S$ while fleets corresponds to $f = 1, ..., F$. Based on the resource-based model (Tilman and Sterner, 1984), it is assumed that N fished species compete for a common resource (e.g. small shrimps and fishes in the case study), denoted by res, and that no trophic interactions occur between the fished species. For every fished species s, at each step $t+1$, the biomass $B_s(t+1)$ depends on the biomass $B_s(t)$, the natural mortality m_s, the natural growth $g_s(t)$ and harvesting $h_s(t)$ as follows:

$$B_s(t+1) = B_s(t)(1 - m_s + g_s(t)) - h_s(t). \tag{1}$$

Natural growth rate $g_s(t)$ of every fish species s, based on resource consumption, varies with time because it depends on both the resource state $B_{res}(t)$ and the SST temperature $\theta(t)$ (with a time lag) as follows:

$$g_s(t) = g_s a_{res,s} B_{res}(t) \gamma_s\big(\theta(t - \tau_s)\big). \tag{2}$$

In line with Ecosim formulation (Walters et al., 1997), parameter g_s above stands for the growth efficiency of species s while $a_{res,s}$ is the consumption rate of the predator s on the resource. The term $\gamma_s(\theta(t - \tau_s))$, based on the species' thermal envelopes together with a time delay τ_s as in Gomes et al. (2021), is clarified below in equation (3). This formula captures the climate impact on species growth as in Ainsworth et al. (2011) and, regarding time delays, is inspired by Thompson and Ollason (2001). Mathematically, it reads:

$$\gamma_s(\theta(t)) = \exp\left(-\left(\frac{\theta(t) - \theta_{s,opt}}{\sigma}\right)^2\right) \quad \text{where:} \quad \sigma = \frac{\theta_{s,10\%} - \theta_{s,opt}}{\sqrt{\ln(10)}}. \tag{3}$$

Following the Half-Degree Species Environmental Envelope table of Candela et al. (2016), the biological efficiency for every species s, denoted by $\gamma_s(\theta)$, is defined in such a way that the efficiency equals 1 when the temperature level fits with the preferred temperature $\theta_{s,opt}$ of the species while this efficiency is close to zero when the temperature is far from this preferred level. The figure C.1 in Appendix captures the 'Gaussian' shape of this biological efficiency.

The dynamics of the resource stock $B_{res}(t)$ depends on the consumption of this resource by the different fish species (Brock and Xepapadeas, 2002; De Lara and Doyen, 2008):

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

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 results of the calibration of the model from the historical data are detailed in Gomes et al. (2021). To show the quality of the model, we provide in the appendix a comparison of the historical and modeled catches by fleet and fished species within Figure B.1. Table B.1 in the appendix also depicts the values of the calibrated parameters underpinning the model.

3.2 Fishing scores

Fishing effort $E_f(t)$ by fleet f at time t underlying catches $h_s(t)$ by fish s is derived from the number of boats $nb_f(t)$ and the days of the sea $Days_f$ by boat:

$$E_f(t) = nb_f(t)Days_f \tag{5}$$

We assume a stability of the number of $Days_f$ at the sea during all the projections; their values are detailed in Table C.3 of the appendix. The catches $h_{s,f}(t)$ of the species s by the fleet f at the time t are based on the Schaefer production function through the catchability $q_{f,s}$ as follows:

$$h_{s,f}(t) = q_{f,s}E_f(t)B_s(t) \tag{6}$$

The global catches $H(t)$ correspond to the amount of fishes landed every quarter in the coastal fishery. It corresponds to the sum of catches by species and by fleet:

$$H(t) = \sum_{s=1}^{S}\sum_{f=1}^{F} h_{s,f}(t). \tag{7}$$

Income per fleet f depends on harvests $h_{s,f}(t)$, landing prices $p_s(t)$ by species, and other species income $Inc_{Ots}(t)$ as follows:

$$Inc_f(t) = \sum_{s=1}^{S} h_{s,f}(t)p_s(t) + Inc_{Ots}(t), \tag{8}$$

where other species income $Inc_{Ots}(t)$ similarly depends on other species catches[1] $h_{Ots,f}(t)$, historical prices of other species p_{Ots}:

$$Inc_{Ots}(t) = p_{Ots}h_{Ots,f}(t). \tag{9}$$

Prices are based on economic data of IFREMER Fisheries information system.

Variable costs relate to oil price $Coil(t)$ and its consumption $OilCon_f$ and ice cost Ice_f which vary with fleet f as detailed in Table C.3 of the appendix. Fixed costs Fix_f which encompass the costs of maintenance, gears, and equipments are based on the socio-economic data[2] of Cissé et al. (2015). Total costs by fleet f reads:

$$Co_f(t) = E_f(t)\left(OilCon_f\,Coil(t) + Ice_f + Fix_f\right). \tag{10}$$

Total profit of the fishery $\pi(t)$ aggregates the profits by fleet f. It is distributed between boat owner and crew with crew share Bet_f as depicted in Table C.3 of the appendix. Aggregated profit for boat owners depends on fishing income $Inc_f(t)$ and cost $Co_f(t)$ as follows:

$$\pi(t) = \sum_{f=1}^{F}(1 - Bet_f)(Inc_f(t) - Co_f(t)). \tag{11}$$

3.3 Uncertainties and scenarios

From the calibrated model, different projections and scenarios can be considered to investigate the future for the fishery from current period t_c (first quarter of 2018 namely $t_c = t_1^{2018}$ in the case study) until long term horizon T (last quarter of 2069 $T = t_4^{2069}$). We here focus on uncertainties and scenarios relating to both climate warming through SST and oil costs.

Climate change scenarios:

In our study, we consider two contrasted climatic scenarios, RCP 8.5 and 2.6, relating to the IPCC special report entitled "The Ocean and Cryosphere in a Changing Climate" (Pörtner et al., 2019). For both scenarios, the IPCC separate the future in 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 climatic scenario, the

[1] We assume that other species catches per fleet $h_{Ots,f}(t)$ follow a uniform distribution between their extreme historical values: $h_{Ots,f}(t) \sim \mathcal{U}(H_{Ots,f\,low}, H_{Ots,f\,high})$

[2] We assume that fishermen cost on-board like food or individual equipment equal to swim bladders income.

Table 1: Quarterly rise in temperature and initial and midterm conditions for the near term and the end-of-century, for each climatic scenario $\omega \in \{\text{RCP 2.6, RCP 8.5}\}$.
* Each trimester from 2005 and 2050, temperature will increase by 0.00356°C.

Parameters	RCP 2.6	RCP 8.5
$\Delta\theta_\omega(t_1^{2005} < t \leq t_1^{2050})$	3.56×10^{-3}°C *	5.275×10^{-3}°C
$\Delta\theta_\omega(t_1^{2050} < t < t_1^{2100})$	0.45×10^{-3}°C	8.15×10^{-3} °C
$\theta_\omega(t_1^{2005})$	27.41 °C	27.41 °C
$\theta_\omega(t_1^{2050})$	28.05 °C	28.36 °C

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 $\Delta\theta_\omega$, where ω represents the scenario:

$$\theta_\omega(t+1) = \theta_\omega(t) + \Delta\theta_\omega(t), \qquad \forall t = t_c, \ldots, T. \tag{12}$$

Table 1 reports, for the two climate scenarios, the quarterly rise in temperature $\Delta\theta_\omega$ as well as initial and midterm conditions $\theta_\omega(t_1^{2005})$ and $\theta_\omega(t_1^{2050})$ for the near term and the end-of-century, respectively. Hereafter, we assume that each climate scenario has the same probability.

Oil scenarios: For each oil scenario ω, the prices $Coil_\omega(t+1)$ at time $t+1$ depends on prices $Coil_\omega(t)$ at time t, and the rise in temperature over a given time period (per quarter in the case study), denoted by Δc_ω:

$$Coil_\omega(t+1) = Coil_\omega(t) + \Delta c_\omega(t). \tag{13}$$

Three scenarios for oil price future Δc_ω proposed by the international energy agency (IEA, 2020) are considered in our projections. The first scenario entitled "Stated Policies" (TRAD) relates to pre-COVID trends, since it explores the case where economic growth recovers its pre-COVID level in 2021. The second scenario entitled "Delayed Recovery" (DEL) assumes that the COVID-19 crisis alters the global economic growth until 2023. The third scenario, named "Sustainable Development "(SUS) assumes that the carbon energy drops after COVID-19 crisis while renewable energy compensates this decrease and gains influence. Such a situation entails a continuous decrease of oil price during the whole time frame[2]. For every oil scenario, local cost structure is added to the crude oil price, as detailed in Table C.1 of the appendix.

We also assume that every oil price scenario has the same probability and is independent of climate scenarios. In other words, the probability assigned to each combination of oil price and climate scenarios is uniform (1/6).

3.4 Fishing strategies

To investigate the future for the fishery in ecological-economic terms from the calibrated model, different projections of fishing efforts are also considered from current year $tc = t_1^{2018}$ until time horizon $T = t_4^{2069}$. In line with Ferrier et al. (2016) and Doyen (2018), we distinguish between predictive, exploratory and normative strategies. A predictive strategy named 'Business as usual' (BAU) projects the efforts of the fleets based on their historical trends. More normative strategies include here Multi-species Maximum Sustained Yield (MMSY) and the Multi-species Maximum Economic Yield (MMEY). MMSY aims at maximizing the expected aggregated catches during all future periods. Multi-species Maximum Economic Yield (MMEY) maximizes the (expected) net present value induced by fishing across years. An explorative strategy entitled Closure (CLOS) which corresponds to a fishing ban is also considered mainly as an ecological benchmark. For the two normative strategies MMSY and MMEY, we postulate that the fleets will potentially change their fishing effort every five years. The control variable relating to these different (fishing) strategies is the fishing effort $E_f(t)$ defined in (5) (or equivalently the number of boats $nb_f(t)$) of each fleet f at time t.

Business as usual (BAU): 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. (2021), the BAU runs as follows :

[2] Projection period of IEA ends in 2040 while our projection period ends in 2070. In that regard, we postulate that the growth rate declines by 5% each year between 2040 and 2070, as in Wiegman et al. (2018).

$$E_f^{\text{BAU}}(t+1) = E_f^{\text{BAU}}(t)(1+\delta_f^{hist}), \qquad \forall t = t_c, \ldots, T,\ \forall f = 1, \ldots, F. \tag{14}$$

In equations (14), 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 Table C.2 of the appendix.

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

$$E_f^{\text{CLOS}}(t) = 0, \qquad \forall t = t_c, \ldots, T,\ \forall f = 1, \ldots, F. \tag{15}$$

Although theoretical, such a ban projection informs on the ecosystem dynamics and viability without fishing pressure. In other words, it represents 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 expected aggregated catch over the projected period with respect to the fishing effort. Specifically, the objective is to find the effort of each fleet f denoted E_f^{MMSY}, that maximizes the expected value of sum of the total catches $H(t)$ over the projection period namely between t_c and T; the expected value here accounts for both oil and climate uncertainties[3]:

$$H(E^{\text{MMSY}}) = \max_{E_f,\ f=1,\ldots F} \mathbb{E}_{\theta, Coil}[H(E)] \tag{16}$$

where $H(E)$ is the average over time of aggregated catches

$$H(E) = \frac{1}{T - t_c} \sum_{t=t_c}^{T} H(t). \tag{17}$$

The total catches above $H(t)$ at time t, as defined in equation (7), depends on the effort $E_f(t)$ of every fleet f which justifies the notation $H(E)$. Such a strategy MMSY relates to the usual MSY in the single species and deterministic case because, it consists in maximizing the (stationary) yield of this species.

Multi-species Maximum Economic Yield (MMEY): This second normative fishing strategy aims at maximizing, again with respect to the effort, the net present value of the fishery over the simulation period. Specifically, the objective is to find the effort of each fleet f denoted E_f^{MMEY}, that maximizes the expected value of the discounted sum of the total profit $\pi(t)$ over the projection period namely between t_c and T namely

$$\text{NPV}(E^{\text{MMEY}}) = \max_{E_f,\ f=1,\ldots F} \mathbb{E}_{\theta, Coil}[\text{NPV}(E)] \tag{18}$$

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

$$\text{NPV}(E) = \sum_{t=t_c}^{T} (1+r)^{-(t-t_c)} \sum_f \pi_f(t). \tag{19}$$

In formula (19), r stands for the (quartely here) discount rate while the profit $\pi_f(t)$ by fleet at time t, as defined in equation (3.2), also depends on the effort $E_f(t)$ of every fleet f. This strategy MMEY coincides with the usual MEY (Maximum Economic Yield) in the single species case as soon the dynamics is stationary in the long run, as it consists in maximizing the (stationary) rent at equilibrium (Grafton et al., 2012). For the case study, we assume that the quarter discount rate is set to $r = 1.13\%$ as advocated by Quinet (2019) for projects with high uncertainties in France. This rate has already been used for fisheries in Smith (2007).

The nonlinear optimization solver used to identify the efforts of MMEY and MMSY is the genetic algorithm 'optim_ga' provided by the software SCILAB[4]. This algorithm mimics the process of natural evolution to determine optimal fishing efforts as in Mardle and Pascoe (2000); Cissé et al. (2013).

3.5 Viability goals and thresholds

We here define the ecological-economic viability goals and thresholds to characterize and quantify the 3Rs of resilience (Grafton et al., 2019) as introduced in the next subsection 3.6. Said differently, we draw on

[3] As we assume that the different climate change and oil price scenarios have equal probabilities, it consists in maximizing the mean value over all scenarios.

[4] Scilab is a free software dedicated to scientific calculus: www.scilab.org.

the viability modeling framework and viability goals to address the issue 'resilience with respect to what ?'. More specifically, following ideas of Béné et al. (2001); Pereau et al. (2012); Baumgärtner and Quaas (2009); Doyen et al. (2019); Schuhbauer and Sumaila (2016); Oubraham and Zaccour (2018), the different viability goals are tied to the triple bottom lines of sustainable development and several sustainable development goals FAO (2017): Food security with *Zero hunger goal*, ecological viability with *Life below water*, and economic viability with *Decent work and economic growth*.

Economic viability goal: We consider that economic viability consists in positive profits, notably to incite shipowners to maintain their investments. Thus, we consider the following constraint:

$$\pi(t) \geq 0. \tag{20}$$

Food security goal: Such requirement relates to the key role of small-scale fisheries in the local fish consumption. Thus we consider that the supply derived from the aggregated landings has to be higher than the predicted local food demand:

$$H(t) \geq H(t_c)(1+d)^{t-t_c}, \tag{21}$$

where d is the quarterly rate of increase of food demand, set to $d = 0.38\%$ in line with the human population growth (1.5%/y (Demougeot and Baert, 2019)). We here implicitly assume that demand per capita is stable and that the different fished species are perfect substitutes. Using catch per capita (or food availability) levels $FA(t) = \frac{H(t)}{Pop(t)}$ where $Pop(t)$ stands for the human population level[5], we can rewrite this food security constraint (21) in a more autonomous form:

$$FA(t) \geq FA^{lim}. \tag{22}$$

Social viability goal: We here consider an minimal activity constraint in the sense of a guaranteed effort for the fishery as a whole and to preserve the cultural value underlying fishing. It reads

$$E(t) \geq E^{\text{lim}} \tag{23}$$

where $E(t)$ is the total effort across the fleets, namely $E(t) = \sum_{f=1}^{F} E_f(t)$. For the case study, based on the European fisheries reduction plan (Payne Ian, 2013). [6], we impose to maintain at least 60 boats active namely: $E^{\text{lim}} = 60$.

Ecological viability goal: Viability metric and thresholds here refer to the persistence of the functional groups among the species at play. For our case study, the first functional group relates to weakfish species (AW, GW) which share similar ecological traits while the second group relates to catfishes (CrC) which differ from the other group in terms of morphology and life cycle (Vallée et al., 2019). Moreover, we consider that persistence of species consists in remaining above prescribed conservation limits B_s^{lim} (in line ICES precautionary approach). In mathematical terms, this ecological viability reads as follows:

$$\begin{cases} B_{GW}(t) > B_{GW}^{\text{lim}} \ \textit{or} \ B_{AW}(t) > B_{AW}^{\text{lim}} \\ B_{CrC}(t) > B_{CrC}^{\text{lim}} \end{cases} \tag{24}$$

Biomass viability limits B_s^{lim} of the different species, detailed in Table B.2 of Appendix, are estimated using a closure strategy with the most optimistic climate scenario ICES (2017).

3.6 The 3Rs of resilience

The 3Rs framework of Grafton et al. (2019) combined with the previous viability constraints and thresholds of Section 3.5 allows us to rank the different management strategies introduced in Section 3.4. The 3Rs approach relies on three complementary ingredients of resilience : Recovery, Resistance and Robustness. Recovery highlights the temporal dimension of resilience. Resistance gives insights into on the 'room for manoeuvre' for resilience, while robustness sheds light on the probability of resilience.

In what follows, we consider both global (systemic) resilience scores and scores by type of viability goal (or metrics) k which include food security (inequality (21)), ecological (inequality (24)), social (inequality (23)) and economic viability (inequality (20)).

[5] We have $Pop(t+1) = Pop(t)(1+d)$.
[6] The maximum reduction rate of 40% has been reached in Spain (Payne Ian, 2013)

Resistance refers to the magnitude of shocks and uncertainties that can be withstood (Holling, 1973). Thus, following the ideas of Béné and Doyen (2018); Karacaoglu and Krawczyk (2021), we basically assess the resistance through the distance to the viability thresholds. In other words, we evaluate the viability margins. For instance, the economic resistance is based on the profit itself $\pi(t) - 0$ as soon as it is positive. More generally, for every ecological-economic goal, to account for the dynamics, we compute the distance between the whole trajectories of every indicator and the associated viability threshold. In more mathematical terms, given a strategy of effort $E(.)$, $Resistance_k(E)$ of goal k relates to the distance $\sum_{t=0}^{T}(I_k(E,t) - I_k^{lim})$ between the trajectories of metric $I_k(E,t)$ and the associated viability threshold I_k^{lim}. Accounting for the uncertainties $\theta(t)$ on SST and $Coil(t)$ on oil costs, we assess the expected value of this distance, namely:

$$Resistance_k(E) = \mathbb{E}\left[\sum_{t=0}^{T}(I_k(E,t) - I_k^{lim})^+\right]. \tag{25}$$

Note that we use the function x^+ which corresponds to the positive value of x in the sense that $x^+ = \max(0,x)$. Consequently, the resistance for k is null when the indicator I_k stays below the viability threshold I_k^{lim} across time. By contrast, the resistance is high when the indicator is strictly above the viability threshold during a long period of time. More globally, for every fishing strategy $E(.)$, a systemic (or global) resistance value entitled *Resistance* integrates all the resistances by type $Resistance_k$ in the Euclidean sense as follows:

$$Resistance(E) = \sqrt{\sum_{\text{goals } k} Resistance_k(E)^2} \tag{26}$$

Robustness, also known as reliability, refers to the probability to cope with the viability constraints (Carlson and Doyle, 2002; De Lara and Doyen, 2008; Baumgärtner and Quaas, 2009). Said differently, robustness is the probability to remain above a threshold despite the potential random fluctuations. In that sense, it can be tied to a value of risk. The ecological robustness can be exemplified by the probability of extinction of a species as in the framework of Population Viability Analysis (PVA, (Drake, 2008)). In more mathematical terms, focusing on each ecological-economic goal k, given a strategy of fishing effort $E(.)$, we define $Robustness_k(E)$ as the probability for indicator $I_k(E,t)$ to exceed the threshold I_k^{lim} throughout time:

$$Robustness_k(E) = \mathbb{P}\left[I_k(E,t) - I_k^{lim} \geq 0, \quad \text{for all } t\right] \tag{27}$$

Here again the probability relates to oil and climate uncertainties[7]. Robustness by goal vanishes whenever the indicator remains below its viability threshold for every scenario at least during a period of time. In contrast, robustness is maximal and equals 1 as soon as the viability constraint is satisfied for every scenario and every time; said differently, when there is no risk. A global or systemic robustness metric denoted by *Robustness* integrates the different robustness by goal k and corresponds to the probability of not crossing the different viability thresholds during the projected period:

$$Robustness(E) = \mathbb{P}\left[I_k(E,t) - I_k^{lim} \geq 0 \text{ for all goal } k, \text{ for all } t\right] \tag{30}$$

Recovery relates to the time necessary to bounce back to viable states despite the uncertainties. In other words, recovery coincides with the amount of time spent beyond the threshold. For instance, the ecological recovery time may correspond the required time to restore a fish stock in the sense of reaching again a biomass limit B^{lim} after an adverse shock and a collapse. Such recovery time can be recast in the viability framework through the concept of time of crisis and Boolean functions (Doyen and Saint-Pierre, 1997; Martin, 2004; Hardy et al., 2016) as follows:

$$Recovery_k(E) = \mathbb{E}\left[\sum_t \mathbb{1}_{\mathbb{R}^+}(I_k(E,t) - I_k^{lim})\right] \tag{31}$$

with the Boolean function $\mathbb{1}_{\mathbb{R}^+}(x)$ already defined in (29). Given a fishing strategy $E(.)$, such recovery value counts the expected value of periods where the viability constraint k is fulfilled. Such time of viability is the

[7] Of interest for the numerical estimations of $Robustness_k(E)$ is the equivalent formulation in terms of expected value of Boolean functions as follows

$$Robustness_k(E) = \mathbb{E}\left[\prod_t \mathbb{1}_{\mathbb{R}^+}(I_k(E,t) - I_k^{lim})\right] \tag{28}$$

with the Boolean function

$$\mathbb{1}_{\mathbb{R}^+}(x) = \begin{cases} 1 & x \geq 0 \\ 0 & \text{otherwise.} \end{cases} \tag{29}$$

lowest and equals zero when the constraints are violated at every time and for every uncertain scenario. By contrast, the time of viability is maximal (and equals the number of periods at play) when the constraints are satisfied for all time and all scenarios[8] A systemic or global recovery score to evaluate the system's ability to return above all viability thresholds is derived as follows:

$$Recovery(E) = \mathbb{E}\left[\sum_{t} \prod_{\text{goals } k} \mathbb{1}_{\mathbb{R}^+}(I_k(E,t) - I_k^{lim})\right]. \tag{32}$$

Hereafter, the 3Rs resilience values previously defined are then normalized (with values in $[0,1]$) as explained in equation E of the appendix. This is straightforward for robustness, which is a probability, but it requires some transformations for recovery and resistance. Once normalized, the better the 3Rs values are close to 1, the better the resilience.

4 Results

This section 'Results' provides a comparison of the four management strategies CLOS, BAU, MMSY, MMEY in terms of fishing efforts (Figure 3), of resilience by goal (Figure 4) and of systemic (global or integrated) resilience (Figure 5). More details on the underlying ecological-economic trajectories are displayed in Figures A.1 (species biomass), A.2 (food security) and A.3 (profit) of the appendix.

4.1 Fishing efforts of the strategies

Figure 3 contrasts the trajectories of the efforts by fleet (CaC, CaC+, TAP) and by fishing management strategy. As expected, the efforts of the closure strategy CLOS in green are zero. This figure first highlights that each of the three fleets particularly fits in with a specific fishing strategy. In particular, the top subfigure shows that the CaC+ effort is higher (at least in the long run) with the BAU strategy (in Black) when compared to MMSY and MMEY. This is consistent with the historical trends captured by the historical effort rates δ_f described in Table C.2. For the fleet CaC plotted in the second row of Figure 3, the MMEY strategy in yellow appears well-suited since its efforts globally dominate the others; this points out the economic efficiency of this CaC fleet as compared to others. In contrast, the bottom subfigure focusing on Tapouille (TAP) shows the interest of the MMSY strategy (Brown) in terms of productivity and catch.

[8] Such a very favorable and rare situation refers to the so-called invariance kernel (Aubin and Frankowska, 1991).

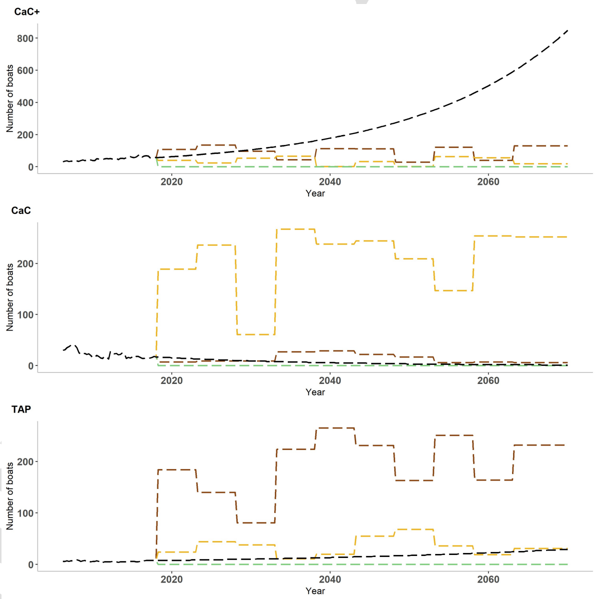

Fig. 3: Dynamics over years 2006-2070 of the efforts $E_f(t)$ by fleet (CaC, CaC+, TAP) and by fishing management strategy: BAU (black), Closure (Green), MMSY (Brown) and MMEY (Yellow). The first period 2006-2018 corresponds to the historical values.

This is consistent with the higher catchability of this last fleet as proved by the catchability coefficients $q_{.,\text{TAP}}$ detailed in Table B.1 of the appendix. In other words, each management strategy strongly relies on a specialization in one fleet depending on its bio-economic features or historical paths.

It can also be observed that both the MMSY and MMEY efforts strongly fluctuate in particular in the first periods of projections after 2018. These important variations stem from the dynamics of the fished stocks as depicted in Figure A.1 of the appendix. The smoother efforts observed in the long run, associated with more steady fish stocks, relate to 'usual' MEY or MSY levels (in the sense of maximizing strategies at equilibrium). In that regard, it can be emphasized that these MEY or MSY effort levels are larger that the current effort levels (2018) of the fleets. This finding stresses that the fishery is currently under-exploited, both biologically and economically.

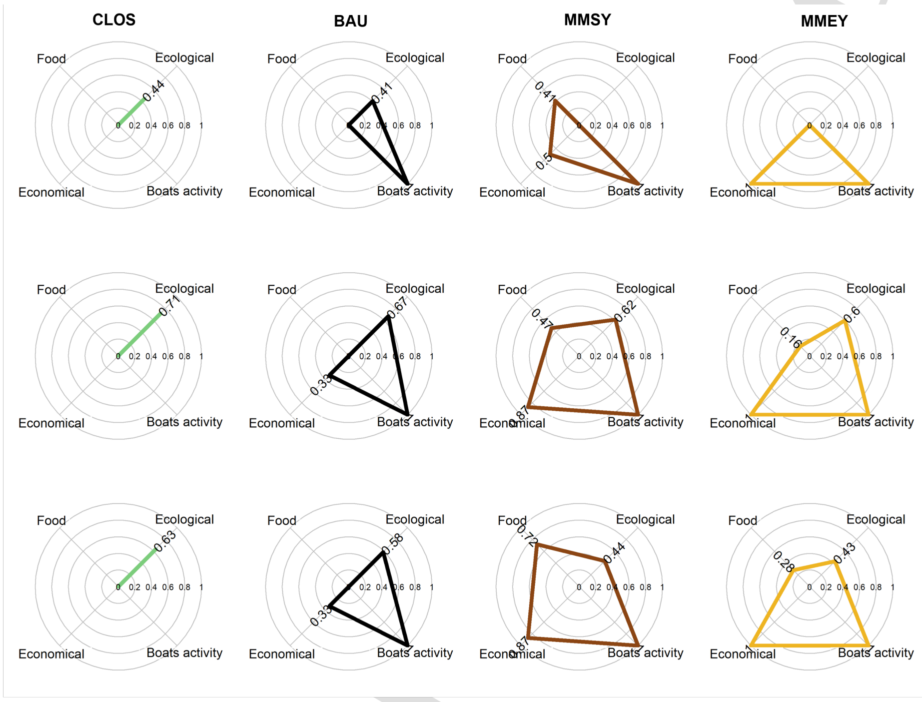

Fig. 4: Spider plots of each resilience components- recovery-resistance-robustness- of the 3Rs framework as defined in subsection 3.6 with respect to the 4 management strategies CLOS, BAU, MMSY and MMEY and to every goal k: economic, ecological, social, food security. Numbers in spider plot shows the normalized indicator value.

4.2 Closure strategy: a good ecological resilience

As shown by the first column of Figure 4, the closure scenario CLOS performs well for the ecological resilience, as expected. This holds true in particular for resistance (second row, 71%) and robustness (third row, 63%). By contrast, not surprisingly, such strategy induces null outcomes for the other goals and criteria related to fishing and including activity, food supply and economic profitability. Going further regarding the ecological resilience, Figure A.1 in the appendix shows that this CLOS strategy is sufficient to maintain the ecological viability with the two fished species, GW and CrC, above their viability thresholds in the optimistic climate scenario RCP 2.6 but is not sufficient to withstand the worth climate situation involved in RCP 8.5. Taking the mean of ecological scores through the expected value with respect to these two extreme climate scenarios explains the intermediary values of resistance (71%) and robustness (63%). The low value of ecological recovery arises from the inability for the fish species to recover from the continuous climate warming underpinning RCP 8.5.

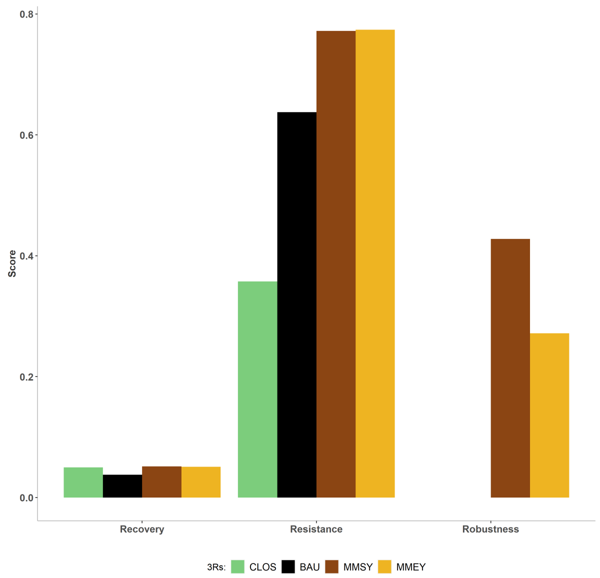

Fig. 5: *Barplot of the systemic 3Rs – Recovery, Resistance, Robustness - across different fishing management strategies:* BAU *(black),* CLOS *(green),* MMSY *(brown),* MMEY *(yellow)*

4.3 BAU: good resilience for the fishing activity

The second column of the figure 4 together with Figure 5 display the 3Rs of the predictive strategy BAU in black. The 3Rs scores turn out to be globally rather low as captured in Figure 5 by the value of systemic robustness which equals 0% or low systemic recovery. These bad global performances derive from bad scores for food security and profitability of the fishery in this predictive strategy. Figure A.2 indeed shows a continuous crisis regarding food supply for the black trajectory. Said differently, this predictive scenario does not account for the human demographic growth and the induced rise of the food demand for the fishery. Similarly, Figure A.3 shows a profitability in crisis during most of the simulation period. Even in the optimistic scenario where oil price declines and climate slowly warms (RCP 2.6), food production and profit are below their viability thresholds.

By contrast, the resilience scores are satisfying for both ecological and activity goals. The increasing fishing effort due to CaC+ (see Figure 3) indeed entails a viable score in terms of activity and the social goal. Ecological resilience metrics are also rather tolerable, as the 2 functional groups are maintained with RCP 2.6. However, with RCP 8.5, BAU fishing pressure is too high to maintain the 2 functional groups (Figure A.1).

Altogether, the 3Rs scores for BAU highlight the vulnerabilities of the current trend of the fishery with respect to demographic, climate and oil price pressures. They point to the need to adjust the fishing efforts to be more resilient to pressures and uncertainties, in particular with respect to economic goals including profit and production.

4.4 MMSY strategy: better resilience for food security

The MMSY normative strategy aims at maximizing the aggregated catches of the fishery in a sustainable way. Its resilience is depicted in brown in the 3rd column of Figure 4 together with Figure 5 for global resilience scores. When compared to BAU, such strategy globally performs better for food security as expected. The gains clearly emerge for robustness and resistance. They stems from an important increase of the fishing effort mainly for the TAP fleet as captured by Figure 3 and already pointed out in Subsection 4.1. This increase of TAP effort benefits to catches and consequently to fish availability. Interestingly, such an improvement of food production and security does not occur at the expense of ecological or social (fishing activity) resilience as compared to BAU. Such viable outcomes are confirmed by the brown trajectories of the figure A.2. The gain of MMSY with respect to current trends and dynamics of BAU is also captured by the systemic values for resistance and robustness in Figure 5.

However, the bad systemic recovery score (0%, on top) alarms on difficulties underlying this MMSY and mainly related to profitability. The figure A.3 indeed shows a long crisis for profitability for this MMSY strategy.

4.5 MMEY resilience: better economic resilience

The detailed outcomes by goals in terms of resilience of the MMEY strategy are plotted in the fourth column of the figure 4. Not surprisingly, when compared to BAU and MMSY, such strategy, which consists in maximizing the expected net present value, globally performs better for profitability. The economic gains hold true for all the 3Rs namely recovery, robustness, resistance. This stems from a rationalization of the fishing efforts relying on an important increase for the CaC fleet along with a reduction of both CaC+ and TAP fleets as captured by Figure 3 and already pointed out in Subsection 4.1. Such redistribution of efforts among fleets, which strongly differs from those of both the BAU and MMSY, globally improves the rents and consequently the global profitability by promoting the most efficient fleet namely CaC. Of interest is that these better economic outputs do not strongly alter the ecological or social (fishing activity) resistance and robustness as compared to BAU and MMSY. Regarding the ecological performance, this result confirms the well-known benefit of MEY for single species in terms of conservation of fished stocks. Such viable ecological results are highlighted by the yellow trajectories in Figure A.1. Less intuitive is the satisfying performance for fishing activity and the underlying social viability because the MMEY strategy induces a global reduction of the efforts through a rationalization of the fishery. Such satisfying performance here arises from the low viability threshold $E_{\lim}$ relating to the standard imposed by the European agency (see the equation (23)).

By contrast, the reduction of efforts derived from the MMEY strategy induces a reduction of catches as compared to MMSY which alters the viability and resilience for food security and fish availability. Figure A.2 indeed exhibits major crisis for food supply with yellow trajectories below the viability threshold whatever the climate scenario. Indeed, maximizing the rent induces catch levels below the maximum sustainable yield because it consists in balancing the incomes derived from catches and the cost of efforts.

The overall gains of MMEY with respect to BAU are also captured by the systemic values for resistance and robustness in Figure 5 .

5 Discussion:

5.1 Operationalization of the 3Rs

Our paper is a step toward the operationalization of the 3Rs approach -recovery-resistance-robustness- as proposed in Grafton et al. (2019) through models, metrics and management strategies for fisheries. It indeed provides a quantitative modeling methodology about how to implement resilience management and policy, in particular for small-scale and coastal fisheries. The proposed methodology articulates ecosystem-based management models, viability approach together with the 3Rs.

By ecosystem-based models is meant the idea to take into account different ecological-economic complexities at play in fisheries, in particular in small-scale fisheries. In that perspective, our model relies on a multi-species, resource-based, and multi-fleet dynamics in discrete time, accounting for climate and oil price uncertainties. The management of the ecosystem relating to the fishing effort of the different fleets contributes to the complexity, in particular because these fleets are not selective across the fished species. Globally, our approach is in line with MICEs as in Hannah et al. (2010); Plagányi et al. (2014); Doyen (2018). As opposed to End-to-End (or whole-ecosystem) modeling which intends to integrate all the components of the system under consideration, MICEs focus only on the ecological-economic components and interactions necessary to address a management question.

The use of the viability approach to implement the 3Rs is justified by the fact it provides a rigorous and sound basis for the formalization of resilience as already argued in Martin (2004); Deffuant and Gilbert (2011); Hardy et al. (2016); Béné and Doyen (2018); Karacaoglu and Krawczyk (2021). First, resilience and viability modeling approach are both about dynamic systems, including the possible existence of feedbacks, nonlinear trajectories, and thresholds effects. Second, both resilience and viability refer to a tension within a system between its dynamics and its persistence, namely its ability to maintain its identity. The aim of the viability approach (Aubin and Frankowska, 1991) indeed consists in analyzing the compatibility between the (possibly uncertain) dynamics of a system and a series of goals, constraints and thresholds and in determining controls, actions, or management that allow the (eco-)system to stay within the safe or sustainable zone defined by the thresholds (Béné et al., 2001; Baumgärtner and Quaas, 2009; Doyen et al., 2019; Schuhbauer and Sumaila, 2016; Oubraham and Zaccour, 2018). The different viability goals we propose to consider here arise from the triple bottom lines of sustainable development and several SDGs including food security, biodiversity conservation and economic viability through profitability. In that regard, the term Ecoviability has been recently coined in Cissé et al. (2015); Doyen et al. (2017, 2019) to address ecological-economic viability issues. We think that such a multi-criteria viewpoint is strongly relevant to deal with both ecological-economic resilience and ecosystem-based management.

Furthermore, some of the tools developed around the viability approach are specifically designed to explore the recovery processes. We here refer to the concept of 'minimal time of crisis' which corresponds to the time it takes for the system to come back into its viability space, once it has been 'pushed out' of that viability space, generally under the impact of a shock (Béné et al., 2001; Doyen and Saint-Pierre, 1997; Martin, 2004; Doyen and Saint-Pierre, 1997). The metric entitled 'recovery' defined in (31) in our paper is strongly inspired by this minimal time of crisis. Regarding resistance and the magnitude of shocks to withstand, mathematical tools relating to the size of the so-called viability kernel turn out particularly well suited (Béné and Doyen, 2018; Karacaoglu and Krawczyk, 2021). This is the way we choose here with the metric entitled 'resistance' based on equation (25) and the distance between the viability thresholds and the states of the system. Regarding robustness or reliability and the probability to cope with adverse events and shocks, we draw on the so-called probabilistic (or stochastic) viability developed in De Lara et al. (2007); Doyen et al. (2017); Doyen (2018); Hardy et al. (2017) with the metric entitled 'robustness' based on equation (27) and the probability to comply with the thresholds throughout time. Such quantitative tool gives key insights into the management of multidimensional and systemic risks.

5.2 Normative MMEY and MMSY management strategies improve the 3Rs

The overall ecological-economic gains of strategies MMEY and MMSY as compared to the predictive strategy BAU are put forward by the systemic values for resistance and robustness of Figure 5. These gains stem first from the fact that these strategies are normative in the sense that they are based on the optimization of specific intertemporal criteria (catch or profit). These gains also derive from the account for uncertainties in the objectives through the expected value of the intertemporal criteria with respect to climate and oil price scenarios. In that sense, MMEY and MMSY are more adaptive and thus foster the resilience. In other words, this result points out important margins of improvements for the fishery in terms of risk mitigation. Of interest is also the important reallocation of fleet efforts induced by the normative strategies MMSY or MMEY when compared to the current situation underlying BAU. This point is elaborated in the following subsection dealing with policy recommendations for the French Guiana case study.

Although they both provide important resilience benefits with respect to BAU, each normative strategy differs and especially promotes the resilience of one goal: a social goal with food security resilience as regards MMSY; an economic goal with profitability resilience regarding MMEY. In that respect, difficulties with MMEY are that it depends on many key economic parameters such as selling prices and costs whose fluctuations may threaten the economic resilience of the fishery, as explained in Grafton et al. (2012). The level of the discount rate as described in Dichmont et al. (2010) is a similar issue. Another threat which occurs in multispecies management is that a change in the management can modify the behavior of fishermen from a non-target species activity to a specialized activity (Pascoe et al., 2020).

The use of more adaptive management in the sense of feedback controls instead of open-loop should also improve the resilience of MMEY. Feedback controls mean that management accounts for the uncertainty through the different possible states underlying the stochastic dynamics (Shapiro et al., 2009; De Lara and Doyen, 2008)). In that respect, we also think that the account for risk aversion in that MMEY strategy could significantly enhance its ecological-economic resilience as suggested recently by Tromeur et al. (2021). Such potential ecological-economic benefits relates to a portfolio approach and the diversification of risks as explained in Edwards et al. (2004); Sanchirico et al. (2008). Going further in that vein to limit risks, we postulate that considering ecoviability strategies to optimize the global robustness through the maximization of the ecoviability probability as in Cissé et al. (2015) (French Guiana), Gourguet et al. (2016) (Australia), Doyen et al. (2017) (Bay of Biscay) would shed major light on the ecosystem-based and ecological-economic resilience management of fisheries.

5.3 Policy recommendations

The application of our quantitative 3Rs framework to the resilience management of tropical small-scale fisheries is justified by the fact this type of fishery plays a major role for the economic development of many countries worldwide in terms of food security, economic value added, employment as well as cultural identity (Bene, 2006; Andrew et al., 2007). Moreover, global changes, notably climate change (Sumaila et al., 2011; Cheung et al., 2009; Diop et al., 2018; Lagarde et al., 2018) and demographic growth, (Rice and Garcia, 2011) are exerting extreme pressure on the tropical marine and coastal ecosystems and consequently on fishing activities (Butchart et al., 2010; Österblom et al., 2015) by inducing new – or intensifying existing – ecological and economic risks and vulnerabilities. In that perspective, by evaluating in terms of the 3Rs different and contrasted strategies for the coastal fishery in French Guiana, our paper provides key guidelines about how to implement resilience management and policy facing global changes. The account for climate change and uncertainties though two extreme and contrasted climate scenarios namely RCP 2.6 and 8.5 together with scenarios on fuel price strengthens the relevance of the application.

In the 2010s, the small-scale fishery of French Guiana was evaluated as viable (Cissé et al., 2013). However, the demographic growth raises concerns about the sustainability and resilience 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 (Demougeot and Baert, 2019), thus implying a 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 (Garcia, 2008). The present study also stresses major vulnerabilities relating both to climate change and oil price. Of particular interest for the Guianese case study, is the major redistributions of fleets efforts suggested by the normative strategies MMSY or MMEY to mitigate these vulnerabilities. The findings of Subsection 4.1 which tie each strategy with a specific fleet indeed suggest to move from a dominance of the CaC+ fleet observed in BAU to foster CaC and/or TAP fleets. Said differently, the CaC+ fleet emerges as the most vulnerable fleet facing global changes. In that perspective, a regulation of the fishery through licence quotas by fleet promoting CaC and TAP at the expense of CaC+ would constitute a relevant policy.

The positive role of marine protected areas to promote the resilience and recovery of marine ecosystems and fisheries has been pointed out in (Grafton et al., 2009; Doyen et al., 2007; Bates et al., 2019) in particular for small-scale fisheries. In that regard, of interest for French Guiana would be the extension of the "Reserve Naturelle du Grand Connétable" which is a no fishing zone where large adults of exploited species are protected). Another possibility to reinforce the resilience for the coastal fishery would consist in protecting estuarine mangroves areas where larvae and juveniles of the exploited species are observed (Rousseau et al., 2017). The development of aquaculture could also complement such policy to face both the food security, climate and energy costs stakes.

6 Conclusion

Our paper sheds important light on the operationalization of resilience management for fisheries facing global changes through models, metrics, scenarios and fishing strategies. In particular, it shows the interest of combining models of intermediate complexity (MICEs, Plagányi et al. (2014)), (Eco)viability approach (Doyen et al., 2019) and the 3Rs framework as proposed in Grafton et al. (2019). The MICEs make it possible to account for key ecological-economic complexities. The eco-viability modeling framework stresses the pivotal role of both dynamics, controls, thresholds and multi-criteria viewpoints for a resilience analysis. The three ingredients involved in the 3Rs, namely recovery (time), resistance (state-flows), robustness (probability) also complement the evaluation of resilience management.

The application of this generic framework to the coastal fishery of French Guiana is also informative because this small-scale fishery is under pressure from both population growth, energy costs and climate change as numerous tropical and artisanal fisheries worldwide. In particular, the work exhibits important gains in terms of ecological-economic resilience of normative management strategies such as MMSY and MMEY as compared to a predictive scenario BAU. Regarding MMEY, such a result confirms the well-known stability of MEY strategies as compared to MSY for single species approaches (Clark, 2010; De Lara and Doyen, 2008). Another main contribution of the paper is to identify major redistributions in the fishing effort of the different fleets for the small-scale fishery in French Guiana entailed by both the MMSY and MMEY management strategy and thus by resilience management. Policy recommendations to regulate the licenses of the different fleets are thus deduced from the findings.

More globally, our work paves the road for the design of more resilient management strategies based on the mitigation of multi-criteria risks beyond the too restrictive approaches maximizing the expected value of a single criterion such as MMEY or MMSY strategies.

Declarations:

Conflicts of interest:

The authors declare that they have no property or financial interest in the subject discussed in this article.

Author Contributions:

All authors contributed to the study conception and design. The model was calibrated by Hélène Gomes and Mathieu Cuilleret. Mathieu Cuilleret and Luc Doyen carried out the implementation of the 3Rs framework and performed the calculations. Analysis of the results was conducted by Mathieu Cuilleret, Fabian Blanchard and Luc Doyen. The first draft was written by Mathieu Cuilleret, and all authors commented on previous versions of the manuscript. Fabian Blanchard and Luc Doyen conceived the study and were in charge of overall direction and planning.

Funding Information:

This study, including data collection, modeling, management strategies and scenarios as well as interpretations, was funded by the CNRS research project entitled ENTROPIC (Ecological-ecoNomic resilience of TROPIcal coastal eCosystem) in collaboration with IFREMER and the University of French Guiana.

Data availability :

The Scilab codes used for the different fishing strategies and the quantifying of resilience are available in: https://github.com/mcuilleret/Entropic.

References

L. M. Abadie. Sea level damage risk with probabilistic weighting of IPCC scenarios: An application to major coastal cities. *Journal of Cleaner Production*, 175:582–598, Feb. 2018. ISSN 09596526. doi: 10.1016/j.jclepro.2017.11.069. URL https://linkinghub.elsevier.com/retrieve/pii/S0959652617327270.

C. H. Ainsworth, J. F. Samhouri, D. S. Busch, W. W. L. Cheung, J. Dunne, and T. A. Okey. Potential impacts of climate change on Northeast Pacific marine foodwebs and fisheries. *ICES Journal of Marine Science*, 68(6):1217–1229, July 2011. ISSN 1095-9289, 1054-3139. doi: 10.1093/icesjms/fsr043. URL https://academic.oup.com/icesjms/article/68/6/1217/707044.

N. L. Andrew, C. Béné, S. J. Hall, E. H. Allison, S. Heck, and B. D. Ratner. Diagnosis and management of small-scale fisheries in developing countries. *Fish and Fisheries*, 8(3):227–240, Sept. 2007. ISSN 1467-2960, 1467-2979. doi: 10.1111/j.1467-2679.2007.00252.x. URL https://onlinelibrary.wiley.com/doi/10.1111/j.1467-2679.2007.00252.x.

J.-P. Aubin and H. Frankowska. Viability kernel of control systems. In *Nonlinear synthesis*, pages 12–33. Springer, 1991.

A. E. Bates, R. S. Cooke, M. I. Duncan, G. J. Edgar, J. F. Bruno, L. Benedetti-Cecchi, I. M. Côté, J. S. Lefcheck, M. J. Costello, N. Barrett, T. J. Bird, P. B. Fenberg, and R. D. Stuart-Smith. Climate resilience in marine protected areas and the 'Protection Paradox'. *Biological Conservation*, 236:305–314, Aug. 2019. ISSN 00063207. doi: 10.1016/j.biocon.2019.05.005. URL https://linkinghub.elsevier.com/retrieve/pii/S0006320718308346.

S. Baumgärtner and M. F. Quaas. Ecological-economic viability as a criterion of strong sustainability under uncertainty. *Ecological Economics*, 68(7):2008–2020, 2009. Publisher: Elsevier.

C. Bene. *Small-scale Fisheries: Assessing Their Contribution to Rural Livelihoods in Developing Countries*. Food & Agriculture Org., 2006.

C. Béné and L. Doyen. From Resistance to Transformation: A Generic Metric of Resilience Through Viability. *Earth's Future*, 6(7):979–996, July 2018. ISSN 23284277. doi: 10.1002/2017EF000660. URL http://doi.wiley.com/10.1002/2017EF000660.

C. Béné, L. Doyen, and D. Gabay. A viability analysis for a bio-economic model. *Ecological economics*, 36 (3):385–396, 2001. Publisher: Elsevier.

W. Brock and A. Xepapadeas. Optimal Ecosystem Management When Species Compete for Limiting Resources. *Journal of Environmental Economics and Management*, 44:189–220, Sept. 2002. doi: 10.1006/jeem.2001.1206.

S. H. M. Butchart, M. Walpole, B. Collen, A. van Strien, J. P. W. Scharlemann, R. E. A. Almond, J. E. M. Baillie, B. Bomhard, C. Brown, J. Bruno, K. E. Carpenter, G. M. Carr, J. Chanson, A. M. Chenery, J. Csirke, N. C. Davidson, F. Dentener, M. Foster, A. Galli, J. N. Galloway, P. Genovesi, R. D. Gregory, M. Hockings, V. Kapos, J.-F. Lamarque, F. Leverington, J. Loh, M. A. McGeoch, L. McRae, A. Minasyan, M. H. Morcillo, T. E. E. Oldfield, D. Pauly, S. Quader, C. Revenga, J. R. Sauer, B. Skolnik, D. Spear, D. Stanwell-Smith, S. N. Stuart, A. Symes, M. Tierney, T. D. Tyrrell, J.-C. Vie, and R. Watson. Global Biodiversity: Indicators of Recent Declines. *Science*, 328(5982):1164–1168, May 2010. ISSN 0036-8075, 1095-9203. doi: 10.1126/science.1187512. URL https://www.sciencemag.org/lookup/doi/10.1126/science.1187512.

L. Candela, D. Castelli, G. Coro, P. Pagano, and F. Sinibaldi. Species distribution modeling in the cloud:. *Concurrency and Computation: Practice and Experience*, 28(4):1056–1079, Mar. 2016. ISSN 15320626. doi: 10.1002/cpe.3030. URL http://doi.wiley.com/10.1002/cpe.3030.

J. M. Carlson and J. Doyle. Complexity and robustness. *PNAS- COLLOQUE*, page 8, 2002.

W. W. Cheung, V. W. Lam, J. L. Sarmiento, K. Kearney, R. Watson, and D. Pauly. Projecting global marine biodiversity impacts under climate change scenarios. *Fish and Fisheries*, 10(3):235–251, Sept. 2009. ISSN 14672960, 14672979. doi: 10.1111/j.1467-2979.2008.00315.x. URL http://doi.wiley.com/10.1111/j.1467-2979.2008.00315.x.

W. W. L. Cheung, G. Reygondeau, and T. L. Frölicher. Large benefits to marine fisheries of meeting the 1.5°C global warming target. *Science*, 354(6319):1591–1594, Dec. 2016. ISSN 0036-8075, 1095-9203. doi: 10.1126/science.aag2331. URL https://www.sciencemag.org/lookup/doi/10.1126/science.aag2331.

A. Cissé, S. Gourguet, L. Doyen, F. Blanchard, and J.-C. Péreau. A bio-economic model for the ecosystem-based management of the coastal fishery in French Guiana. *Environment and Development Economics*, 18(03):245–269, 2013. Publisher: Cambridge Univ Press.

A. Cissé, L. Doyen, F. Blanchard, C. Béné, and J.-C. Péreau. Ecoviability for small-scale fisheries in the context of food security constraints. *Ecological Economics*, 119:39–52, Nov. 2015. ISSN 09218009. doi: 10.1016/j.ecolecon.2015.02.005. URL https://linkinghub.elsevier.com/retrieve/pii/S0921800915000440.

A. A. Cissé, F. Blanchard, and O. Guyader. Sustainability of tropical small-scale fisheries: Integrated assessment in French Guiana. *Marine Policy*, 44:397–405, Feb. 2014. ISSN 0308597X. doi: 10.1016/j.marpol.2013.10.003. URL https://linkinghub.elsevier.com/retrieve/pii/S0308597X13002285.

C. W. Clark. *Mathematical bioeconomics: the mathematics of conservation*, volume 91. John Wiley & Sons, 2010.

M. De Lara and L. Doyen. *Sustainable management of natural resources: mathematical models and methods*. Springer Science & Business Media, 2008.

M. De Lara, L. Doyen, T. Guilbaud, and M.-J. Rochet. Is a management framework based on spawning-stock biomass indicators sustainable? A viability approach. *ICES Journal of Marine Science*, 64(4):761–767, May 2007. ISSN 1095-9289, 1054-3139. doi: 10.1093/icesjms/fsm024. URL https://academic.oup.com/icesjms/article/64/4/761/641082.

G. Deffuant and N. Gilbert. *Viability and resilience of complex systems: concepts, methods and case studies from ecology and society*. Springer Science & Business Media, 2011.

L. Demougeot and X. Baert. La population guyanaise à l'horizon 2050 : vers un doublement de la population ?, Mar. 2019. URL https://www.insee.fr/fr/statistiques/3902223.

C. Dichmont, S. Pascoe, T. Kompas, A. E. Punt, and R. Deng. On implementing maximum economic yield in commercial fisheries. *Proceedings of the National Academy of Sciences*, 107(1):16–21, 2010. Publisher: National Acad Sciences.

B. Diop, F. Blanchard, and N. Sanz. Mangrove increases resiliency of the French Guiana shrimp fishery facing global warming. *Ecological Modelling*, 387:27–37, Nov. 2018. ISSN 03043800. doi: 10.1016/j.ecolmodel.2018.08.014. URL https://linkinghub.elsevier.com/retrieve/pii/S0304380018302837.

B. Diop, N. Sanz, F. Blanchard, R. Walcker, and A. Gardel. The role of mangrove in the French Guiana shrimp fishery. *Journal of Environmental Economics and Policy*, 8(2):147–158, Apr. 2019. ISSN 2160-6544, 2160-6552. doi: 10.1080/21606544.2018.1522601. URL https://www.tandfonline.com/doi/full/10.1080/21606544.2018.1522601.

B. J. Downes, F. Miller, J. Barnett, A. Glaister, and H. Ellemor. How do we know about resilience? An analysis of empirical research on resilience, and implications for interdisciplinary praxis. *Environmental Research Letters*, 8(1):014041, Mar. 2013. ISSN 1748-9326. doi: 10.1088/1748-9326/8/1/014041. URL https://iopscience.iop.org/article/10.1088/1748-9326/8/1/014041.

L. Doyen. Mathematics for Scenarios of Biodiversity and Ecosystem Services. *Environmental Modeling & Assessment*, 23(6):729–742, 2018. Publisher: Springer.

L. Doyen and P. Saint-Pierre. Scale of Viability and Minimal Time of Crisis. *Set-Valued Analysis*, 5:227–246, Sept. 1997. doi: 10.1023/A:1008610123440.

L. Doyen, M. De Lara, J. Ferraris, and D. Pelletier. Sustainability of exploited marine ecosystems through protected areas: a viability model and a coral reef case study. *Ecological Modelling*, 208(2):353–366, 2007. Publisher: Elsevier.

L. Doyen, C. Béné, M. Bertignac, F. Blanchard, A. A. Cissé, C. Dichmont, S. Gourguet, O. Guyader, P.-Y. Hardy, S. Jennings, L. R. Little, C. Macher, D. J. Mills, A. Noussair, S. Pascoe, J.-C. Pereau, N. Sanz, A.-M. Schwarz, T. Smith, and O. Thébaud. Ecoviability for ecosystem-based fisheries management. *Fish and Fisheries*, 18(6):1056–1072, Nov. 2017. ISSN 14672960. doi: 10.1111/faf.12224. URL http://doi.wiley.com/10.1111/faf.12224.

L. Doyen, C. Armstrong, S. Baumgärtner, C. Béné, F. Blanchard, A. Cissé, R. Cooper, L. Dutra, A. Eide, D. Freitas, and others. From no whinge scenarios to viability tree. *Ecological Economics*, 163:183–188, 2019. Publisher: Elsevier.

J. M. Drake. Population Viability Analysis. In S. E. Jørgensen and B. D. Fath, editors, *Encyclopedia of Ecology*, pages 2901–2907. Academic Press, Oxford, Jan. 2008. ISBN 978-0-08-045405-4. doi: 10.1016/B978-008045405-4.00654-6. URL https://www.sciencedirect.com/science/article/pii/B9780080454054006546.

S. F. Edwards, J. S. Link, and B. P. Rountree. Portfolio management of wild fish stocks. *Ecological Economics*, 49(3):317–329, July 2004. ISSN 09218009. doi: 10.1016/j.ecolecon.2004.04.002. URL https://linkinghub.elsevier.com/retrieve/pii/S092180090400148X.

FAO. FAO and the SDGs. Indicators: Measuring Up to the 2030 Agenda for Sustainable Development |Policy Support and Governance| Food and Agriculture Organization of the United Nations, 2017. URL https://www.fao.org/policy-support/tools-and-publications/resources-details/fr/c/854006/.

FAO. *The State of World Fisheries and Aquaculture 2018: Meeting the sustainable development goals*. Number 2018 in La situation mondiale des pêches et de l'aquaculture (SOFIA). FAO, Rome, Italy, 2018. ISBN 978-92-5-130562-1. URL http://www.fao.org/documents/card/fr/c/I9540EN/.

S. Ferrier, K. Ninan, P. Leadley, R. Alkemade, L. Acosta, H. R. Akcakaya, L. Brotons, W. Cheung, V. Christensen, K. A. Harhash, J. Kabubo-Mariara, C. Lundquist, M. Obersteiner, H. Pereira, G. Peterson, R. Pichs-Madruga, N. Ravindranath, C. Rondinini, and B. Wintle. *IPBES (2016): Summary for policy-makers of the methodological assessment of scenarios and models of biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. Secretariat of the Intergovernmental Platform for Biodiversity and Ecosystem Services: Bonn, Germany. IPBES, Jan. 2016.

S. Garcia, editor. *Towards integrated assessment and advice in small-scale fisheries: principles and processes*. Number 515 in FAO fisheries technical paper. Food and Agriculture Organization of the United Nations, Rome, 2008. ISBN 978-92-5-106064-3.

H. Gomes, C. Kersulec, L. Doyen, F. Blanchard, A. A. Cisse, and N. Sanz. The Major Roles of Climate Warming and Ecological Competition in the Small-scale Coastal Fishery in French Guiana. *Environmental Modeling & Assessment*, May 2021. ISSN 1420-2026, 1573-2967. doi: 10.1007/s10666-021-09772-8. URL https://link.springer.com/10.1007/s10666-021-09772-8.

S. Gourguet, O. Thébaud, S. Jennings, L. R. Little, C. M. Dichmont, S. Pascoe, R. A. Deng, and L. Doyen. The Cost of Co-viability in the Australian Northern Prawn Fishery. *Environmental Modeling & Assessment*, 21(3):371–389, June 2016. ISSN 1420-2026, 1573-2967. doi: 10.1007/s10666-015-9486-y. URL http://link.springer.com/10.1007/s10666-015-9486-y.

Q. R. Grafton, T. Kompas, T. N. Che, L. Chu, and R. Hilborn. BMEY as a fisheries management target. *Fish and Fisheries*, 13(3):303–312, 2012. Publisher: Wiley Online Library.

R. Q. Grafton and L. R. Little. Risks, resilience, and natural resource management: Lessons from selected findings. *Natural Resource Modeling*, 30(1):91–111, Feb. 2017. ISSN 08908575. doi: 10.1111/nrm.12104. URL http://doi.wiley.com/10.1111/nrm.12104.

R. Q. Grafton, T. Kompas, and P. Van Ha. Cod Today and None Tomorrow: The Economic Value of a Marine Reserve. *Land Economics*, 85(3):454–469, Aug. 2009. ISSN 0023-7639, 1543-8325. doi: 10.3368/le.85.3.454. URL http://le.uwpress.org/cgi/doi/10.3368/le.85.3.454.

R. Q. Grafton, L. Doyen, C. Béné, E. Borgomeo, K. Brooks, L. Chu, G. S. Cumming, J. Dixon, S. Dovers, D. Garrick, A. Helfgott, Q. Jiang, P. Katic, T. Kompas, L. R. Little, N. Matthews, C. Ringler, D. Squires, S. I. Steinshamn, S. Villasante, S. Wheeler, J. Williams, and P. R. Wyrwoll. Realizing resilience for decision-making. *Nature Sustainability*, 2(10):907–913, Oct. 2019. ISSN 2398-9629. doi: 10.1038/s41893-019-0376-1. URL http://www.nature.com/articles/s41893-019-0376-1.

C. Hannah, A. Vezina, and M. S. John. The case for marine ecosystem models of intermediate complexity. *Progress in Oceanography*, 84(1-2):121–128, Jan. 2010. ISSN 00796611. doi: 10.1016/j.pocean.2009.09.015. URL https://linkinghub.elsevier.com/retrieve/pii/S0079661109001487.

P.-Y. Hardy, C. Béné, L. Doyen, J. Pereau, and D. Mills. Viability and resilience of small-scale fisheries through cooperative arrangements. *Environment and Development Economics*, 21(6):713–741, Dec. 2016. ISSN 1355-770X, 1469-4395. doi: 10.1017/S1355770X16000152. URL https://www.cambridge.org/core/product/identifier/S1355770X16000152/type/journal_article.

P.-Y. Hardy, C. Béné, L. Doyen, and D. Mills. Strengthening the resilience of small-scale fisheries: A modeling approach to explore the use of in-shore pelagic resources in Melanesia. *Environmental Modelling & Software*, 96:291–304, Oct. 2017. ISSN 13648152. doi: 10.1016/j.envsoft.2017.06.001. URL https://linkinghub.elsevier.com/retrieve/pii/S1364815217306515.

C. S. Holling. Resilience and stability of ecological systems. *Annual review of ecology and systematics*, 4(1): 1–23, 1973. Publisher: Annual Reviews 4139 El Camino Way, PO Box 10139, Palo Alto, CA 94303-0139, USA.

ICES. Technical Guidelines - ICES fisheries management reference points for category 1 and 2 stocks. *ICES library - ices.dk*, 2017. doi: 10.17895/ICES.PUB.3036. URL http://www.ices.dk/sites/pub/PublicationReports/Forms/DispForm.aspx?ID=32751. Publisher: ICES.

IEA. *World Energy Outlook 2020*. IEA, iea edition, 2020.

G. Karacaoglu and J. B. Krawczyk. Public policy, systemic resilience and viability theory. *Metroeconomica*, page meca.12349, Aug. 2021. ISSN 0026-1386, 1467-999X. doi: 10.1111/meca.12349. URL https://onlinelibrary.wiley.com/doi/10.1111/meca.12349.

A. Lagarde, L. Doyen, A. Ahad-Cissé, N. Caill-Milly, S. Gourguet, O. L. Pape, C. Macher, G. Morandeau, and O. Thébaud. How Does MMEY Mitigate the Bioeconomic Effects of Climate Change for Mixed Fisheries. *Ecological Economics*, 154:317–332, Dec. 2018. ISSN 09218009. doi: 10.1016/j.ecolecon.2018.07.001. URL https://linkinghub.elsevier.com/retrieve/pii/S0921800917317688.

S. A. Levin, S. Barrett, S. Aniyar, W. Baumol, C. Bliss, B. Bolin, P. Dasgupta, P. Ehrlich, C. Folke, and I.-M. Gren. Resilience in natural and socioeconomic systems. *Environment and development economics*, 3(2):222–235, 1998. Publisher: JSTOR.

S. Mardle and S. Pascoe. Use of evolutionary methods for bioeconomic optimization models: an application to Fisheries. *Agricultural Systems*, page 17, 2000.

S. Martin. The cost of restoration as a way of defining resilience: a viability approach applied to a model of lake eutrophication. *Ecology and Society*, 9(2), 2004. Publisher: JSTOR.

V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, Ö. Yelekçi, R. Yu, and B. Zhou, editors. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, 2021.

OECD. *Development Co-operation Report 2017: Data for Development.* Organisation for Economic Co-operation and Development, Paris, 2017. ISBN 978-92-64-27450-1. URL https://www.oecd-ilibrary.org/fr/development/development-co-operation-report-2017_dcr-2017-en.

H. Österblom, J.-B. Jouffray, C. Folke, B. Crona, M. Troell, A. Merrie, and J. Rockström. Transnational Corporations as 'Keystone Actors' in Marine Ecosystems. *PLOS ONE*, 10(5):e0127533, May 2015. ISSN 1932-6203. doi: 10.1371/journal.pone.0127533. URL https://dx.plos.org/10.1371/journal.pone.0127533.

A. Oubraham and G. Zaccour. A survey of applications of viability theory to the sustainable exploitation of renewable resources. *Ecological economics*, 145:346–367, 2018. Publisher: Elsevier.

S. Pascoe, T. Hutton, E. Hoshino, M. Sporcic, S. Yamasaki, and T. Kompas. Effectiveness of harvest strategies in achieving multiple management objectives in a multispecies fishery. *Australian Journal of Agricultural and Resource Economics*, 64(3):700–723, July 2020. ISSN 1364-985X, 1467-8489. doi: 10.1111/1467-8489.12369. URL https://onlinelibrary.wiley.com/doi/10.1111/1467-8489.12369.

Payne Ian. Retrospective Evaluation of Scrapping and Temporary Cessation Measures in the EFF. Lot 2: Retrospective and prospective evaluations on the common fisheries policy, excluding its international dimension, European Commission, Nov. 2013.

J.-C. Pereau, L. Doyen, L. Little, and O. Thebaud. The triple bottom line: Meeting ecological, economic and social goals with individual transferable quotas. *Journal of Environmental Economics and Management*, 63(3):419–434, 2012. Publisher: Elsevier.

É. E. Plagányi, A. E. Punt, R. Hillary, E. B. Morello, O. Thébaud, T. Hutton, R. D. Pillans, J. T. Thorson, E. A. Fulton, A. D. Smith, and others. Multispecies fisheries management and conservation: tactical applications using models of intermediate complexity. *Fish and Fisheries*, 15(1):1–22, 2014. Publisher: Wiley Online Library.

H.-O. Pörtner, D. Roberts, and V. Masson-Delmotte. IPCC (2019): Special Report on the Ocean and Cryosphere in a Changing Climate. Rationale Reference, June 2019.

. Préfecture de la Guyane. Arrété préfectoral relatif au prix maximum de certains produits pétroliers et du gaz domestique, July 2020.

A. Quinet. La valeur de l'action pour le climat. Technical report, France Stratégie, 2019.

A. E. Quinlan, M. Berbés-Blázquez, L. J. Haider, and G. D. Peterson. Measuring and assessing resilience: broadening understanding through multiple disciplinary perspectives. *Journal of Applied Ecology*, 53(3): 677–687, June 2016. ISSN 00218901. doi: 10.1111/1365-2664.12550. URL http://doi.wiley.com/10.1111/1365-2664.12550.

J. C. Rice and S. M. Garcia. Fisheries, food security, climate change, and biodiversity: characteristics of the sector and perspectives on emerging issues. *ICES Journal of Marine Science*, 68(6):1343–1353, July 2011. ISSN 1095-9289, 1054-3139. doi: 10.1093/icesjms/fsr041. URL https://academic.oup.com/icesjms/article/68/6/1343/704758.

Y. Rousseau, F. Blanchard, and A. Gardel. Spatiotemporal dynamics of larval fish in a tropical estuarine mangrove: example of the Mahury River Estuary (French Guiana)1. *Canadian Journal of Fisheries and Aquatic Sciences*, May 2017. doi: 10.1139/cjfas-2016-0267. URL https://cdnsciencepub.com/doi/abs/10.1139/cjfas-2016-0267. Publisher: NRC Research Press.

J. N. Sanchirico, M. D. Smith, and D. W. Lipton. An empirical approach to ecosystem-based fishery management. *Ecological Economics*, 64(3):586–596, 2008. Publisher: Elsevier.

A. Schuhbauer and U. R. Sumaila. Economic viability and small-scale fisheries?A review. *Ecological Economics*, 124:69–75, 2016. URL http://ac.els-cdn.com/S092180091630132X/1-s2.0-S092180091630132X-main.pdf?_tid=b3a751dc-b18c-11e6-9133-00000aab0f02&acdnat=1479913035_05838483be6bc12fe950da520adb8f40. Publisher: Elsevier.

A. Shapiro, D. Dentcheva, and A. Ruszczyński. *Lectures on stochastic programming: modeling and theory.* SIAM, 2009.

Y. Sheffi. *The power of resilience: How the best companies manage the unexpected.* mit Press, 2015.

C. R. Smith, L. J. Grange, D. L. Honig, L. Naudts, B. Huber, L. Guidi, and E. Domack. A large population of king crabs in Palmer Deep on the west Antarctic Peninsula shelf and potential invasive impacts. *Proceedings of the Royal Society B: Biological Sciences*, 279(1730):1017–1026, Mar. 2012. ISSN 0962-8452, 1471-2954. doi: 10.1098/rspb.2011.1496. URL https://royalsocietypublishing.org/doi/10.1098/rspb.2011.1496.

M. Smith. Generating Value in Habitat-Dependent Fisheries: The Importance of Fishery Management Institutions. *Land Economics*, 83:59–73, Feb. 2007. doi: 10.3368/le.83.1.59.

U. R. Sumaila, W. W. Cheung, V. W. Lam, D. Pauly, and S. Herrick. Climate change impacts on the biophysics and economics of world fisheries. *Nature climate change*, 1(9):449–456, 2011. Publisher: Nature Publishing Group.

P. M. Thompson and J. C. Ollason. Lagged effects of ocean climate change on fulmar population dynamics. *Nature*, 413(6854):417–420, Sept. 2001. ISSN 0028-0836, 1476-4687. doi: 10.1038/35096558. URL http://www.nature.com/articles/35096558.

D. Tilman and R. W. Sterner. Invasions of equilibria: tests of resource competition using two species of algae. *Oecologia*, 61:4, 1984.

E. Tromeur, L. Doyen, V. Tarizzo, L. R. Little, S. Jennings, and O. Thébaud. Risk averse policies foster bio-economic sustainability in mixed fisheries. *Ecological Economics*, 190:107178, Dec. 2021. ISSN 09218009. doi: 10.1016/j.ecolecon.2021.107178. URL https://linkinghub.elsevier.com/retrieve/pii/S0921800921002366.

United Nations. Transforming our world: The 2030 agenda for sustainable development. *Online - https://www.un.org/*, 2015.

V. Vallée, M. Villanueva, and F. Blanchard. Functional richness and turnover patterns reveal assembly rules structuring marine fish communities on the continental shelf of French Guiana. *Marine Ecology Progress Series*, 630:183–195, Nov. 2019. ISSN 0171-8630, 1616-1599. doi: 10.3354/meps13129. URL https://www.int-res.com/abstracts/meps/v630/p183-195/.

C. Walters, V. Christensen, and D. Pauly. Structuring dynamic models of exploited ecosystems from trophic mass-balance assessments. *Reviews in Fish Biology and Fisheries*, 7(2):139–172, June 1997. ISSN 1573-5184. doi: 10.1023/A:1018479526149. URL https://doi.org/10.1023/A:1018479526149.

A. R. Wiegman, J. W. Day, C. F. D'Elia, J. S. Rutherford, J. T. Morris, E. D. Roy, R. R. Lane, D. E. Dismukes, and B. F. Snyder. Modeling impacts of sea-level rise, oil price, and management strategy on the costs of sustaining Mississippi delta marshes with hydraulic dredging. *Science of The Total Environment*, 618:1547–1559, Mar. 2018. ISSN 00489697. doi: 10.1016/j.scitotenv.2017.09.314. URL https://linkinghub.elsevier.com/retrieve/pii/S0048969717326621.

Appendices:

A Projections across the management strategies and climate scenarios

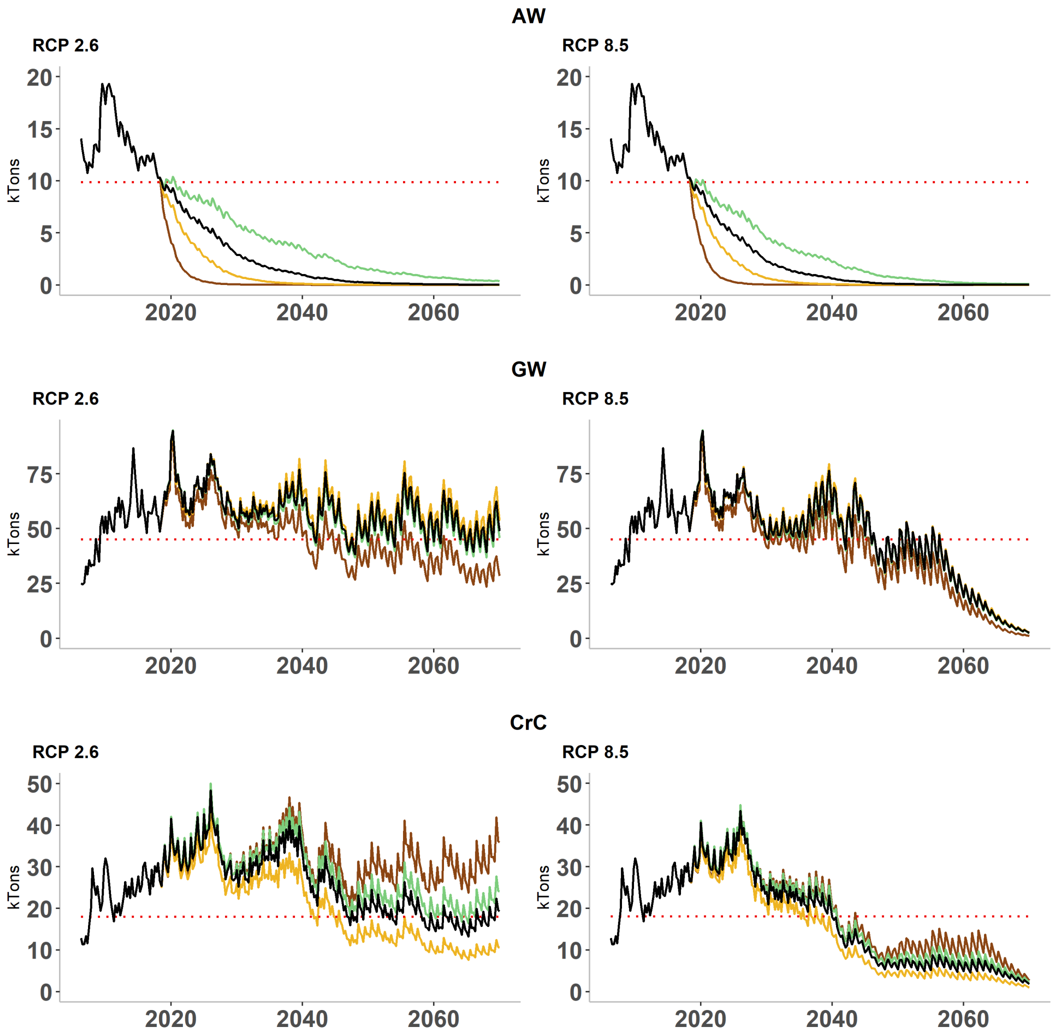

Fig. A.1: Biomass trajectories $B_s(t)$ of fished species under the different management strategies BAU (black), CLOS (green), MMSY (brown), MMEY (yellow) and with respect to the two climate scenarios RCP2.6 (left) and RCP 8.5 (right). Red dotted line is the viability limit B^{lim}. (top) Acoupa Weakfish (AW); (middle) Green Weakfish (GW) and (bottom) Crucifix Sea Catfish (CSC).

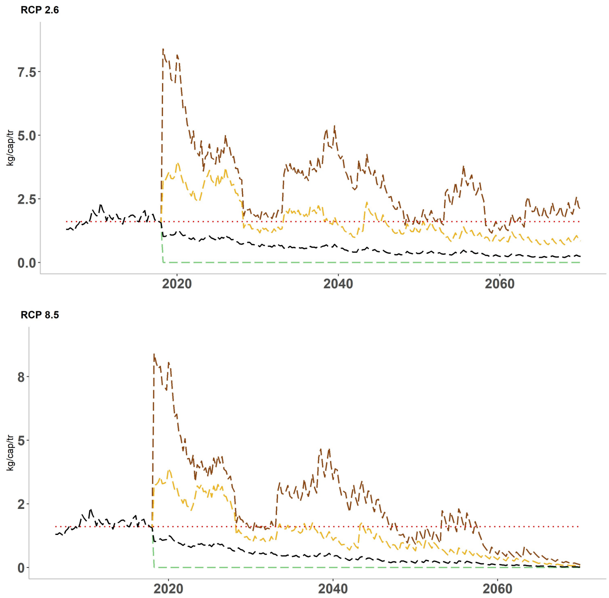

Fig. A.2: Trajectories of fish availability $FA(t)$ under different fishing strategies: BAU (black), CLOS (green), MMSY (brown), MMEY (yellow). Red dotted line corresponds to the viability threshold FA^{lim} which is the amount of fish per capita of 2017.

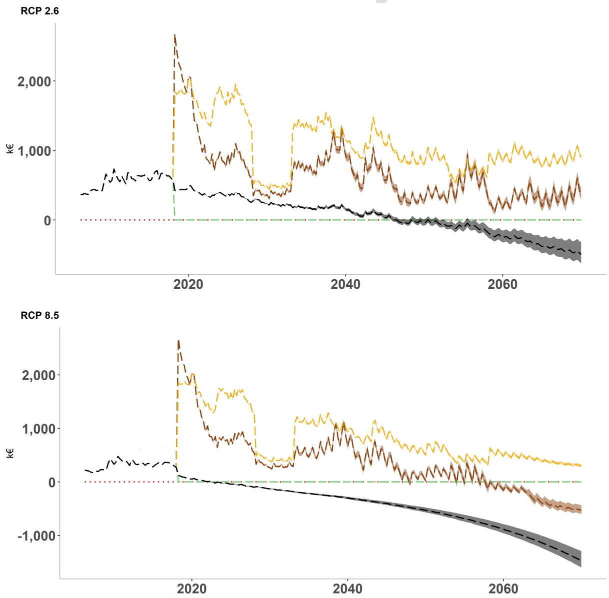

Fig. A.3: Profits evolution $\pi(t)$ by climate scenario under different fishing management strategies : BAU (black), CLOS (green), MMSY (brown), MMEY (yellow); Profit constraint (0) in red.

B Calibration of the model

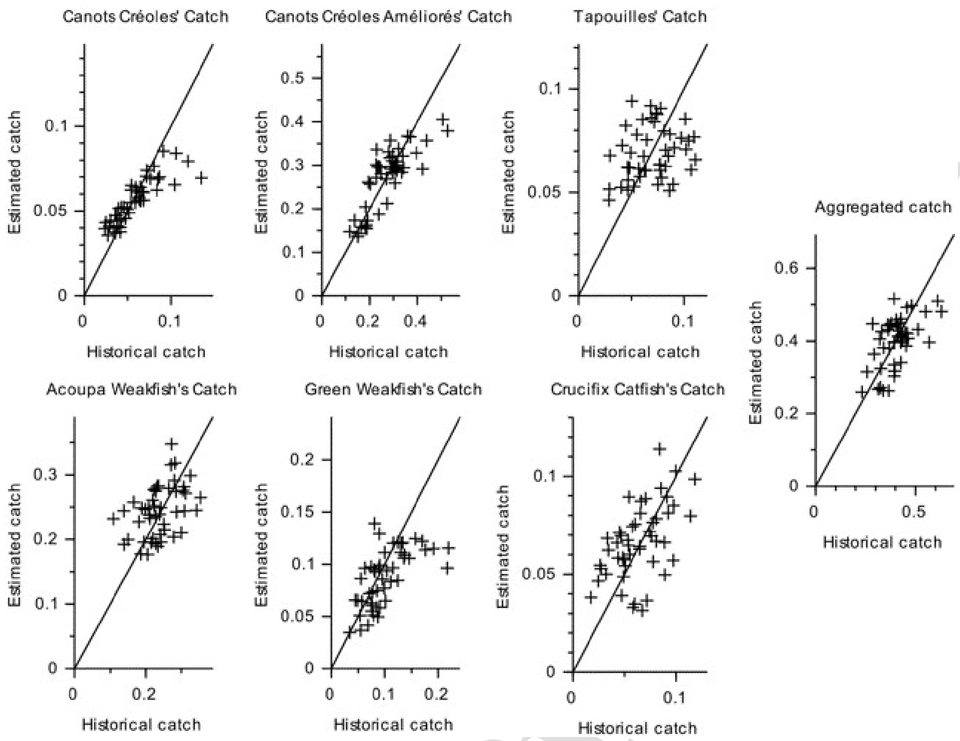

Fig. B.1: Comparison of historical and estimated (modeled) catches $H(t)$ obtained in Gomes et al. (2021) over the 2006–2018 time series in terms of catch by fleet (1st row), catch by species (2nd row), and aggregated catch (3rd row). The estimated parameters of the model in Gomes et al. (2021) are based on a least squares method.

Table B.1: Parameters obtained with the calibration of Gomes et al. (2021) based on the least squares method.

Parameters	Unit	Acoupa Weakfish (AW)	Green Weakfish (GW)	Crucifix Catfish (CrC)	Resource (Res)
$a_{res,s}$	/	2.5×10^{-6}	7.6×10^{-6}	6.8×10^{-6}	/
$q_{s,CaC}$	day^{-1}	3.3×10^{-6}	0.5×10^{-6}	1.4×10^{-6}	/
$q_{s,CaC+}$	day^{-1}	7.3×10^{-6}	0.5×10^{-6}	1.1×10^{-6}	/
$q_{s,T}$	day^{-1}	13.2×10^{-6}	2×10^{-6}	1×10^{-6}	/
m_s	/	0.08	0.14	0.14	/
g_s	/	0.15	0.06	0.06	/
$B_s(2006)$	tons	14 070	25 055	12 866	282 625
τ_s	months	12	48	0	/

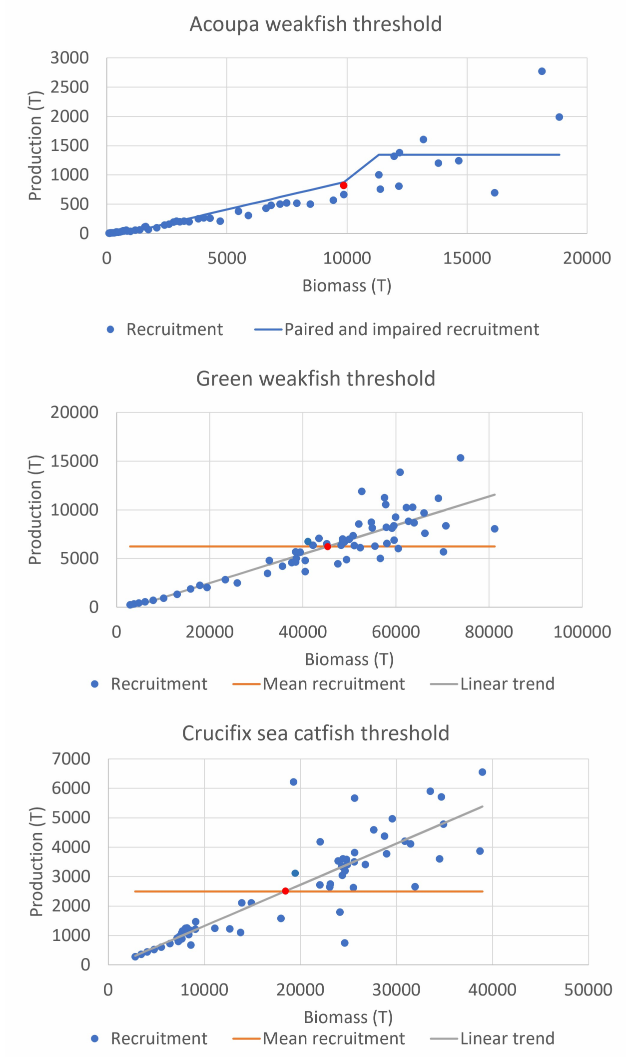

Fig. B.2: Ecological threshold (red dot) B_s^{lim} for the different species s: Acoupa weakfish, Green weakfish,and Crucifix sea catfish.

Biomass limit is set with the evolution of stocks and recruitment obtained in a CLOS strategy with a RCP 2.6 scenario. We identify a correlation between stock and recruitment for Acoupa weakfish. For other species, we establish the threshold at the intersection between mean recruitment and linear trend as explained in ICES (2017).

Table B.2: Biomass viability limit per species

Species s	AW	GW	CrC
Biomass limit B_s^{lim}(Tons)	9867	45369	18360

C Details of the model

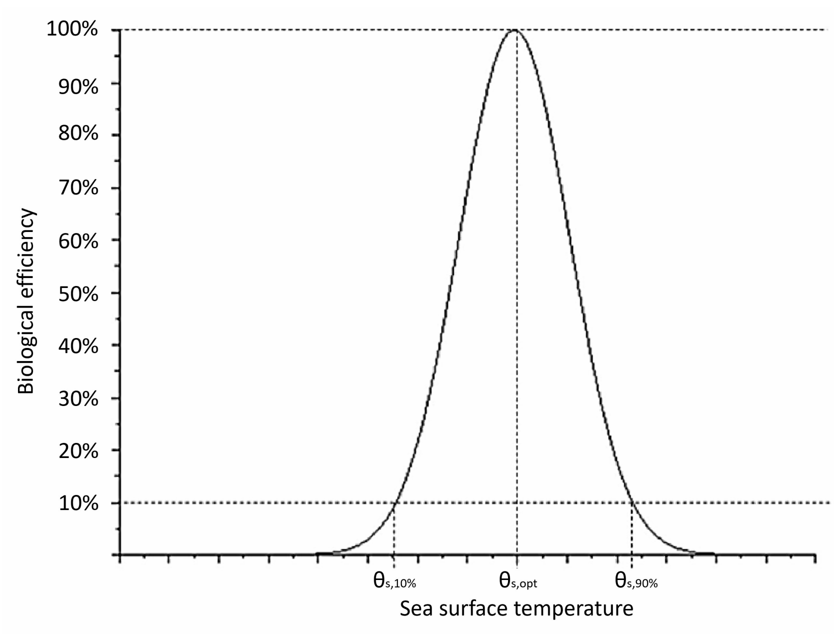

Fig. C.1: Biological efficiency $\gamma_s(\theta)$ for species s depending on SST θ. The Gaussian shape varies with preferred temperature $\theta_{s,opt}$ and detrimental temperature $\theta_{s,10\%}$ where the efficiency equals 10%. For the three species AW, GW and CrC considered in the study, optimal values $\theta_{s,opt}$ correspond to $\theta_{AW,opt} = 25.94°C$, $\theta_{GW,opt} = 27.59°C$ and, $\theta_{CrC,opt} = 27.9°C$
.

Table C.1: Cost structure of oil $Coil(t)$
This table aims to explain how we obtain refined oil price with IEA prediction of crude oil price. It is based on Préfecture de la Guyane (2020).

Cause	**€ or %**	Example with crude oil price at 0.4€/L
Crude oil price	IEA price €/L	0.4
Refined cost	0.37 €/L	0.77
Regional Import taxes	2%	0.78
Wholesaler margin	0.09085 €/L	0.87
Interprofessional agreement	0.0064 €/L	0.88
Retailer margin	0.1104 €/L	0.99
Refined oil price at the gas station	$Coil(\mathbf{t})$ €/L	0.99€/L

Each component of this price is assumed stable throughout the simulation.

Table C.2: Fleet's evolution in the BAU scenario

Fleet	CaC	CaC+	TAP
δ_f^{hist}	0.98	1.013	1.007

Table C.3: Fleet characteristics:

Fleet	CC	CCA	TAP
Oil consumption ($OilCon_f$) (L/quarter)	13.7	49.8	74.2
Ice price per day (Ice_f) (€/$Days_f$)	18.7	19.8	70.4
Fixed cost (Fix_f) (€/$Days_f$)	32.7	44.1	93.8
Average number of fishing days during one period ($Days_f$)	26	37	37
Crew share (Bet_f)	0	0.5	0.5

Table C.4: Fish availability FA^{lim} in French Guiana

This table aims to explain how we obtain the fish availability limit with the landing of 2017.

Variable	Unit	Value
Total catches of TAP in 2017	Tons	322
Model species catches by TAP	Tons	229
Total catches of CAC in 2017	Tons	278
Model species catches by CAC	Tons	128.44
Total catches of CAC+ in 2017	Tons	1730
Model species catches by CAC+	Tons	1404.76
Total model species catches	Tons	1762.2
French guiana's population in 2017	Persons	268011
Model species availability: year	Kg/hab	6.58
Model species availability: trimester (FA^{lim})	Kg/hab	1.64

D Pressures and uncertainties

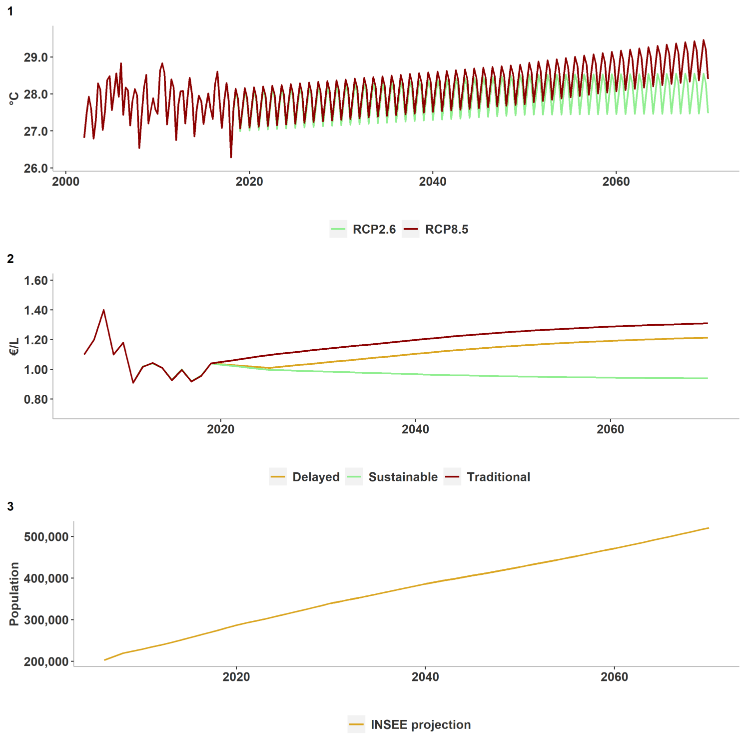

Fig. D.1: Evolution of Pressures

1: Historical trajectories of SST in French Guiana from 2006 to 2018 and projection of SST according to IPCC climate scenario: RCP 2.6 the optimistic, and RCP 8.5 the pessimistic. Seasonal variation is also included.

2: Historical variation from 2006 and 2018 and projection of oil price according to IEA scenarios: Traditional, Delayed and Sustainable. Delayed is the scenario where global oil demand is impacted by COVID crisis during the beginning but increase after. Sustainable is the scenario where global oil demand decrease and induces a continuous decrease of the price. Traditional is the scenario where COVID doesn't play a role in oil price and continuously increase. To this global oil price, the cost structure depicted in the next appendices is applied.

3: Guianese population growth according to INSEE projection. It predicts a growth rate of 1.5%.

E Normalisation of resilience metrics

x(t) corresponds to the value to be normalized between [0;1].

$$|| \text{ Recovery } ||= \frac{1}{\frac{x(t)}{T}+1}$$

$$|| \text{ Resistance } ||= 1-\exp^{-(\max(0;x(t)))}$$