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Abstract This work advances the resilience-based management of small-scale fisheries facing both illegal fishing, climate change and cost uncertainties. It focuses on the coastal fishery of French Guiana in South America. Thus a dynamic, multi-species, resource-based and multi-fleet model including the illegal fishing is developed and calibrated using catch and effort time series over 2006-2018. Such model of intermediate complexity (MICE) also accounts for climate and energy costs stochasticities. From the calibrated model, fishing effort projections at the horizon 2050 are compared in terms of bio-economic resilience in the face of uncertainty scenarios. The bio-economic resilience metric is based on probabilistic viability (or reliability or robustness) involving different bio-economic thresholds related to biodiversity conservation, food security and profitability of fleets. It turns out that a massive reduction of the illegal fishing effort significantly improves this bio-economic resilience when compared to 'Business as Usual' (BAU) projections. However such a necessary enforcement approach against illegal fishing needs to be combined with a reallocation of the fishing efforts among the legal fleets to fully strengthen the bio-economic resilience of the whole fishery. Since the resilience-based management induces drastic changes, a 'transition' strategy accounting for the inertia of public policies and behavioral changes is also examined.

Keywords Resilience · Bioeconomics · Coastal fishery · Illegal fishing · Climate change · Uncertainties · Models of intermediate complexity (MICE) · Scenarios · French Guiana

Contents

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1 Introduction

Small-scale fisheries play a key role in the tropics due to their economic, cultural, and food contributions (Bene, 2006; Andrew et al., 2007; Arthur, 2020). These tropical small-scale fisheries and the underlying coastal ecosystems are under pressure worldwide because of global changes and uncertainties including climate change, demographic growth, overfishing and illegal fishing activities (Butchart et al., 2010; Österblom et al., 2015; Sumaila et al., 2011; Cheung et al., 2009). Consequently, promoting the sustainability and resilience of tropical small-scale fisheries is a major challenge for regulatory agencies as underlined at the international scale by FAO (2018) or IPBES (Ferrier et al., 2016). Our paper investigates the resilience-based management of these tropical small-scale fisheries facing these global pressures and uncertainties.

In the face of global changes, pressures, and uncertainties, the popularity of the concept of resilience is rising (Crépin et al., 2012; Troell et al., 2014). For instance, it is included in several Sustainable Development Goals (SDGs): 1 (No Poverty); 2 (Zero Hunger); 13 (Climate Action); and 14 (Life Below Water). This popularity of resilience contrasts, however, with a lack of clarity over the concept across the scientific disciplines and how to operationalize it in terms of decision making and public policy (Derissen et al., 2011; Downes et al., 2013; Quinlan et al., 2016; Grafton and Little, 2017; Béné and Doyen, 2018). Recently, Grafton et al. (2019) and Cuilleret et al. (2022) have made significant progress in the definitions, objectives and quantification of resilience-based management in particular for environmental issues and social-ecological systems (Ostrom, 2009). In particular Grafton et al. (2019) put forward 3 ingredients and metrics (the 3Rs) of resilience, namely recovery, resistance and robustness (or reliability). Here we will focus on robustness to examine the bio-economic resilience of tropical small-scale fisheries. Robustness refers to the probability to withstand the shocks and uncertainties. Such robustness metric is strongly tied to stochastic or probabilistic viability (De Lara and Doyen, 2008; Oubraham and Zaccour, 2018; Doyen et al., 2019; Cuilleret et al., 2022). The viability goals we here consider relates to different bio-economic thresholds in line with the SDGs (FAO, 2017) and the triple bottom line of sustainable development since we deal with both food security, economic viability and biodiversity conservation (Baumgärtner and Quaas, 2009; Hardy et al., 2013; Cissé et al., 2013; Schuhbauer and Sumaila, 2016).

As case-study, we focus on the coastal fishery of French Guiana (FG) in South America which constitutes a particularly interesting example of tropical small-scale fisheries. This coastal fishery of FG plays indeed a key role in terms of food security for the Guinasese inhabitants while it faces numerous pressures and uncertainties including illegal fishing from surrounding countries (Surinam and Brazil) (Kersulec et al., 2024), demographic pressure (doubling of the population over the two next decades) (Cissé et al., 2015), and climate change (Diop et al., 2019; Gomes et al., 2021; Cuilleret et al., 2022). To identify a resilience-based management and fishing strategies for this case study, we first develop a dynamic, multi-species, resource-based and multi-fleet model including the illegal fishing and accounting for uncertainties through Sea surface Temperature (SST) and energy costs stochasticities. Such model of intermediate complexity (MICE) (Plaganyi, 2007; Doyen et al., 2017; Gomes et al., 2021) is calibrated using time series over 2006-2018 of both legal fishing catch and effort (IFREMER, 2018), illegal fishing data from Levrel (2012) as well as SST data from NOAA (2005). From the calibrated model, we contrast three fishing strategies at the horizon 2050. The potential controls of these two strategies are both the fishing efforts of the legal fleets together with the patrol effort of the regional coast guards to deter illegal fishing. The first fishing projection named Business as Usual (BAU) is predictive in the sense that it extrapolates the historical trends of efforts of the different fleets, including the enforcement control. The second strategy we examine is normative and consists in maximizing the resilience via the robustness score or equivalently the viability probability with respect to both biodiversity, food security, profitability and social welfare goals. Social welfare metric takes into account the enforcement cost of illegal fishing. The viability probability depends on both SST and oil price random scenarios. Regarding SST, we rely on two IPCC climate scenarios namely RCP 4.5 and 7.0 while two contrasted scenarios of energy (oil) costs are considered from IEA (2020). A third strategy named 'transition' balances the resilience-based strategy with BAU by accounting for the inertia of public policies and behavioral changes before achieving a resilience-based management.

The results show that the resilience-based management underlying the maximal robustness strategy requires, not surprisingly, a massive reduction of the illegal fishing effort when compared to BAU projections. The magnitude of the mitigation rate of illegal fishing indeed ranges from 60% to 80%. However, this necessary mitigation of illegal activities needs to be articulated with a reallocation of the fishing efforts among legal fleets to fully enhance the bio-economic resilience of the whole fishery in the face of climate and energy costs uncertainties. It turns out that the bioeconomic gains induced by such maximal robustness strategy in terms of balance between food security, economic viability and biodiversity conservation are also massive when compared to BAU. Thus a resilience-based management will induce major changes for the fishery both in terms of bio-economic input (efforts) and outputs. Interestingly, the 'transition' strategy, while still achieving medium and long run bio-economic resilience, does not entail major bio-economic losses when compared to the resilience-based management.

The rest of the paper is organized as follows. We first detail the ecological, social, and economic context of the case study in Section 2. Section 3 outlines the methodology, which includes the description of bio-economic model, its calibration on data, the pressure scenarios and the fishing strategies. Section 4 describes the bioeconomic results. Section 5 discusses the major contributions of this paper while Section 6 finally concludes. An appendix completes the paper with additional information or results.

2 Case study: the coastal fishery in FG

French Guiana, bordering Suriname and Brazil, has an exclusive economic zone (EEZ) of 130,000 km^2, including 50,000 km^2 of continental shelf. The coastal fishery of FG is a small-scale fishery operating in the 12 nautical miles zone with a maximum depth of 20m. The three main types of boats, namely 'Canots Creoles' (CAC), 'Canots Creoles Ameliorés' (CAC+) and 'Tapouilles' (TAP), use gilnet as main gear. These artisanal fleets are nonselective and exploit more than 30 species. Acoupa weakfish (*Cynoscion acoupa*), denoted hereafter by AW, Green weakfish (*Cynoscion virescens*), denoted by GW, and Crucifix catfish (*Sciades props*), denoted by CrC, are the most caught species with more than 70% of the total landings.

This coastal fishery is under four main pressures: climate change, demographic growth, oil price uncertainties and illegal fishing activity. Climate change notably impacts the Guianase coastal fishery through the variations of sea surface temperature (Gomes et al., 2021). Oil price and its underlying uncertainties constitute another major driver of the fishery as a rising oil price may severally alter the profit of the fleets and thus lead to changes in the fishing activity. Moreover, the INSEE (French National Institute for the Statistical and International Study) predicts the doubling of the FG population until 2040 (Demougeot and Baert, 2019) which raises major concerns in terms of future fishing pressure since the production of the coastal fishery is mainly consumed locally. Furthermore, illegal fishing activity is a major issue in FG. Illegal fishing indeed occurs in FG because fish stocks are in better state than in border countries namely Suriname and Brazil. Illegal fishing also results from the difficulty to monitor and control fishing in mangrove areas which constitute the main habitat of the FG coast. This illegal activity lead to excessive fishing time and overexploitation and thus threats food security, profitability of legal fleets and marine biodiversity (Kersulec et al., 2024). A plan (Renaud, 2020) was recently proposed by France to combat and deter this illicit activity by augmenting the number of patrols of coast guards in FG.

Regarding the data of the legal fleets, fishing effort (time spent at sea, expressed in days), and fishing landing data are collected by the observers from the IFREMER Fisheries Information System since 2006, on a daily basis. Moreover, socio-economic surveys provide economic data such as selling prices of species, variable and fixed costs for fleets (Cissé et al., 2013). The quantification of illegal fishing relies on data from the French Armed Forces in FG (Levrel, 2012; Renaud, 2020). The calibration of the model detailed below is also based on sea surface temperature[1] data (SST) obtained from the NOAA Earth System Research Laboratory website.

3 Bio-economic model

The model, scenarios, and strategies detailed below are in line with models of intermediate complexity (MICE) as in Hannah et al. (2010); Plaganyi et al. (2014); Doyen (2018); Gomes et al. (2021). The model relies on multi-species, resource-based, and multi-fleet discrete time dynamics, accounting for climate impacts through the sea surface temperature (SST) and illegal fishing activities. The potential controls of the dynamics are the fishing efforts of the legal fleets together with the patrol intensity of the coast guards to limit illegal fishing.

3.1 Ecological dynamics

Following the resource-based model (Tilman and Sterner, 1984; Brock and Xepapadeas, 2002; De Lara and Doyen, 2008), it is assumed that S fished species compete for a common trophic resource[2]. Thus, for every fished species $s = 1, \dots, S$, the biomass $B_s(t+1)$ at each step $t+1$ depends on the past biomass $B_s(t)$, the natural mortality m_s, the natural growth rate $g_s(t)$, the common resource biomass $B_{res}(t)$ and harvesting $h_s(t)$ as follows:

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

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[1] As the coastal fleets operate at a maximum depth of 20 meters, sea temperature can be considered as homogeneous throughout the water column.

[2] In the case study, the resource is composed of zooplankton, small shrimps and fishes

The natural growth rate $g_s(t)$ of every fish species s is assumed to vary with respect to the environment. Here, the environment corresponds to the SST temperature $\theta(t)$ with a time lag τ_s depending on each species s as in Gomes et al. (2021); Cuilleret et al. (2022):

$$g_s(t) = g_s a_s \gamma_s\big(\theta(t-\tau_s)\big), \tag{2}$$

where the positive parameter g_s stands for growth efficiency of each species while a_s corresponds to the consumption rate on the resource in line with Ecosim formulation (Walters et al., 1997). The biological efficiency $\gamma_s(\theta)$ of species s with respect to the temperature θ, inspired by the Half-Degree Species Environmental Envelope table of Candela et al. (2016), is mathematically defined by

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

This formula is based on Ainsworth et al. (2011) regarding the thermal envelopes and on Thompson and Ollason (2001) for the delays effect. The Gaussian shape of this biological efficiency $\gamma_s(\theta)$ captures the idea that species biological efficiency is maximized and equals one when the SST θ is close to its preferred level, $\theta_{s,opt}$ while it collapses when the temperature is far from this optimal level (Gomes et al., 2021).

The dynamics of the common resource stock $B_{res}(t)$ depends on the consumption of this resource by the stocks $B_s(t)$ of the different fish species s at rate a_s together with an external input $I(t)$ (typically zooplankton, phytoplankton):

$$B_{res}(t+1) = B_{res}(t)\left(1-\sum_{s=1}^{S} a_s B_s(t)\right) + I(t). \tag{4}$$

It is assumed that the external input $I(t)$ can potentially fluctuate with time.

3.2 Legal and illegal fishing indicators

The catches $h_{s,f}(t)$ of the species s by the fleet f at the time t are based on a Schaefer production function through fishing effort $E_f(t)$ of the fleet f at period t (here days at sea)[3] and the catchability $q_{s,f}$ of fleet f on species s as follows:

$$h_{s,f}(t) = q_{s,f} E_f(t) B_s(t). \tag{5}$$

Such catches refer to both the F legal fleets[4] and illegal fishing which is considered as an additional fleet denoted by $f = \textsc{Ill}$. The catch $h_s(t)$ by species s introduced in the species dynamics (1) corresponds to the sum of catches of species s by fleet including Ill :

$$h_s(t) = \sum_{f=1}^{F} h_{s,f}(t) + h_{s,\textsc{Ill}}(t). \tag{6}$$

As we hereafter address food security issues, we also consider the per capita contribution of fishing from the legal fleets to seafood production

$$FA(t) = \sum_{f=1}^{F}\sum_{s=1}^{S} \frac{h_{s,f}(t) * prot_s}{D(t)} \tag{7}$$

where $D(t)$ is the local human population level at period t while $prot_s$ stands for proteins rate of each fished species s.

Other important indicators relate to the economic performances of the fishery. The profit $\pi_f(t)$ of legal fleets $f = 1, \ldots, F$ corresponds to the difference between the incomes derived from fishing and fishing costs. Fishing income is proportional to harvests $h_{s,f}(t)$, selling price p_s by species supposed to remain constant, as well as crew share β_f (detailed in Table A.1.4 of the appendix). Costs are proportional to the effort and to oil costs (and other costs detailed in Section 3.3). Thus, the profit $\pi_f(t)$ of legal fleets f reads as follows:

$$\pi_f(t) = (1-\beta_f)\sum_{s=1}^{S} p_s h_{s,f}(t) - c_f(Poil(t))E_f(t) \tag{8}$$

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[3] We assume the number of $Days_f$ at sea to be steady by fleet, as detailed in Table A.1.4 of the appendix.

[4] For the case study, legal fleets include Tap ($f = 1$), Cac ($f = 2$), and Cac+ ($f = 3$).

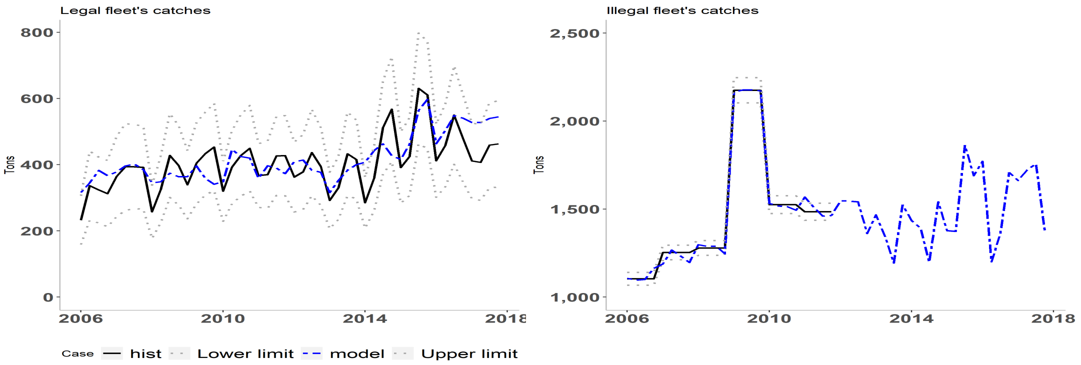

Fig. 1: Comparison of historical ▬ and calibrated ▬ catches together with 95% confidence intervals (▬) for legal (left) and illegal (right) fleets.

where $c_f(Poil(t)) = c_{0,f} + c_{1,f}Poil(t)$. Hereafter, in particular regarding the so-called social welfare, we also use the total profit $\pi(t)$ among legal fleets of the fishery namely

$$\pi(t) = \sum_{f=1}^{F} \pi_f(t). \tag{9}$$

Regarding illegal fishing (Ill), we hereafter focus on its control and mitigation by the public agencies (e.g. coast guard). Our modeling of the illegal activity is based on standard deterrence theory, as described in Kuperan and Sutinen (1998). It suggests that increased risk of detection by coastal patrols reduces Ill activity. We here consider that the intensity of Ill controls is directly related to patrol effort on sea, denoted by $G(t)$ at time t. Thus, the dynamics of the illegal fishing effort reads as follows:

$$E_{\text{Ill}}(t+1) = E_{\text{Ill}}(t) + \varDelta_{\text{Ill}} - q_P G(t) E_{\text{Ill}}(t) \tag{10}$$

where $\varDelta_{\text{Ill}}$ corresponds to the growth of the illegal fleet by period and q_P stands for the arrest rate of illegal boats by the coast guard. The arrest mechanism underlying (10) is in line with works of Bulte and van Kooten (1999); Swanson (1994); Thiault et al. (2020). From the public policy viewpoint, the enforcement cost plays a key role. We assume that the enforcement cost is a linear function of the number of patrol, namely:

$$C_G(t) = c_G G(t). \tag{11}$$

Marginal cost c_G are estimated using the average cost of monitoring in the metropolitan EEZ (Mongruel et al., 2019) and the hours to control from Renaud (2020).

In what follows, and in particular in Subsection 3.5 about strategies and management from the public policy viewpoint, we assume the control of the whole system consists in both fishing efforts $E_f(t)$ of legal fleets $f = 1, \ldots, F$ and the intensity of controls $G(t)$ with respect to the illegal fishing.

3.3 Calibration

The MICE model, previously described in mathematical terms, has been calibrated for the small-scale fishery of FG using first data on the legal fishing from IFREMER Fisheries Information System from $t_0 = 2006$ to 2017 (IFREMER, 2018). These data first include legal fishing efforts $E_f(t)$ for fleets $f = 1, 2, 3$ (Tap, CaC, CaC+) and associated catches $h_{s,f}(t)$ by species $s = 1, 2, 3$ (AW, GW, CrC). Economic data of IFREMER Information System also provide estimations of the costs introduced in equation (8) including oil consumption $c_{1,f}$, fixed costs $c_{0,f}$ of maintenance and other costs (e.g. ice, machine oil, food, market rental, union licensing fees, fishing permits, and gear). They are detailed in Table A.4 of the appendix.

To quantify the illegal activities and dynamics underlying (10), we use data on fishing effort and aggregated catches from 2006 to 2012 from the French Armed Forces of FG. The estimation of the enforcement costs c_G underlying equation (11) which is provided in Table A.1.4 within the appendix is deduced from the efforts of patrol guards (Levrel, 2012) detailed in Fig. A.4. The arrest rate of illegal boat q_P as well as growth of the illegal fleet is $\varDelta_{\text{Ill}}$ are estimated by data from Renaud (2020).

More globally, the calibration of the dynamic model is based on the least squares method, which minimizes the difference between historical catches and catch estimates:

$$\min_{parameters} \sum_{t=t_0}^{2018} \sum_{s=1}^{3} \sum_{f=1}^{3} \left(h_{s,f}^{data}(t) - h_{s,f}(t) \right)^2 + \sum_{t=t_0}^{2012} \sum_{s=1}^{3} \left(h_{s,\mathrm{ILL}}^{data}(t) - h_{s,\mathrm{ILL}}(t) \right)^2, \tag{12}$$

where the parameters to identify are the initial biomass of each species $B_s(t_0 = 2006)$, the natural mortality m_s of the species s, the growth efficiency g_s of each species s, the catchability rate by species and fleet $q_{f,s}$, the illegal fishing effort $E_{\mathrm{ILL}}(t)$ from t_{2012-1} (first quarter of 2012 in the case study) to t_{2018-4} (last quarter of 2018), the interactions a_s between species and the trophic resources $B_{res}(t)$. The calibration also depends on the external input $I(t)$. The time lag τ_s related to the temperature impact and equation (14) for each species has been estimated in Gomes et al. (2021).

The value of the whole set of parameters are detailed in Table A.1 of the appendix. The quality of the calibration is illustrated by Figure 1 where we observe to what extent the calibrated catches of both legal and illegal fleets fit the historical values. Going further, Table A.2 in the appendix details the mean relative errors between the calibrated and modeled catches. It indicates that AW and illegal catches are close to their historical values. Additionally, Table A.2 also offers a comparative analysis of mean relative errors between this study and a previous modeling work for the same fishery neglecting the illegal fishing (Gomes et al., 2021). This comparison points out global gains in the goodness of fit through a decrease in the mean relative error.

We also carried out a sensitivity analysis to evaluate the stability and reliability of our model to marginal changes in parameters. Such analysis consists in assessing the relative changes in terms of catch and biomass induced by variations of parameters ranging from -10% to 10%. Results displayed in the appendices A.1.3 show moderate sensitivities with a variation of biomass or catches smaller than the parameter perturbation.

3.4 Uncertainties and scenarios

To analyze the future of the fishery, several scenarios from the calibrated model can be taken into account from the current period t_1 (here first quarter of 2018 in the case study) to T (final quarter of 2049). In terms of uncertainty, we concentrate on climate change and oil costs stochasticities while the human population growth is assumed to be deterministic.

Demographic growth scenario: The human population $D(t)$ involved in per capita food metric (7) evolves according to a growth rate $\delta D(t)$ as follows:

$$D(t+1) = D(t) \times (1 + \delta D(t)). \tag{13}$$

For the case study, we consider the mean projection of Demougeot and Baert (2019) where $\delta D(t)$ varies from 2.3% before 2020 to 1% in 2050 as detailed in Appendix A.7.

Climate change scenarios: The sea surface temperature $\theta(t)$ of French Guiana is expected to increase in the future due to climate change (Masson-Delmotte et al., 2021). Inter-annual variations caused by atmospheric flux and ocean currents are significant sources of these temperature variations (Sen Gupta et al., 2021). To quantify the effects of climate warming and other atmospheric or current variations, quarterly data are extracted from Copernicus (2023) (CNRM and CMIP models) for the RCP 4.5 and RCP 7.0 scenarios. These scenarios are supplemented by two intermediate scenarios that alternate between these two alternatives (RCP 4.5 and RCP 7.0) in $t_2 = 2033$. In more mathematical terms, the different SST scenarios ι can be represented by the following dynamics:

$$\theta_\iota(t+1) = \theta_\iota(t) + \Delta\theta_\iota(t) \tag{14}$$

where $\Delta\theta_\iota(t)$ represents the change in temperature of scenario ι. To depict $\Delta\theta_\iota(t)$, the table A.8 in Appendix presents key statistics, such as means and standard deviations (SD), for each scenario. It can be observed that, although the RCP 4.5 ($\iota = 1$) and RCP 7.0 ($\iota = 4$) scenarios have close mean variations $\Delta\theta_\iota(t)$ (0.010 versus 0.012) due to their close radiative forcing (4.5 $\mathrm{W/m^2}$ and 6 $\mathrm{W/m^2}$), RCP 4.5 has a larger SD than RCP 7.0, indicating larger potential variations. These scenarios also differ in terms of probability of occurrence as captured by Table 1. To characterize the probability of occurrence of each scenario ι, we rely on Meinshausen et al. (2022); Burgess et al. (2023); Abadie (2018). Furthermore, Abadie (2018) aligned with Burgess et al. (2023), suggests a likelihood of around 50% for the RCP 4.5 scenario, highlighting its plausibility.

	Oil price change $\Delta Poil_\nu(t)$				Climate change $\Delta\theta_\iota(t)$			
Scenario	$\nu = 1$	$\nu = 2$	$\nu = 3$	$\nu = 4$	$\iota = 1$	$\iota = 2$	$\iota = 3$	$\iota = 4$
Acronym	SUS	SUS-TRAD	TRAD-SUS	TRAD	RCP 4.5	RCP 4.5-7.0	RCP 7.0-4.5	RCP 7.0
$\Delta(t)$ **Period** $t_1 - t_2$	0.0001	0.0001	0.0013	0.0013	0.010	0.010	0.012	0.012
$\Delta(t)$ **Period** $t_2 - T$	0.0001	0.0013	0.0001	0.0013	0.010	0.012	0.010	0.012
Probability (%)	11	22	22	44	44	22	22	11

Table 1: Characteristics and probability of occurrence $\mathbb{P}(\nu)$ or $\mathbb{P}(\iota)$ for each oil price scenario Δ_ν and each climatic scenario Δ_ι.

Oil price scenarios: Oil price *Poil*(t) is an important variable for the economic performance of fleets. Hereafter, its quarterly fluctuations, referred to as $\Delta Poil_\nu(t)$ for scenario ν, rely on projection data provided by the International Energy Agency (IEA, 2020). These projections, designed by connecting future global energy supply and demand scenarios, include two plausible trajectories on oil price called SUS (Sustainable Use Scenario, $\nu = 1$) and TRAD (Energy Transition Scenario, $\nu = 4$). Additionally, we examine two intermediate scenarios $\nu = 2, 3$ that correspond to transitions between SUS (Sustainable Use Scenario) and TRAD (Energy Transition Scenario) in $t_2 = 2033$. The oil price variations in every scenario ν are modeled by the following equation :

$$Poil_\nu(t+1) = Poil_\nu(t) + \Delta Poil_\nu(t). \tag{15}$$

Table A.8 in Appendix provides means and standard deviations of oil price variations for each scenario. To characterize the probability of occurrence of each scenario ν, we adopt the same methodology than for climate but using now the International Energy Agency's scenarios. Last row of Table A.8 specifies these probabilities of oil price scenarios. This approach suggests that the Traditional (TRAD) oil price scenario together with RCP 4.5 are the most likely.

Moreover, globally, it is assumed that the climate and energy scenarios are independent meaning that

$$\mathbb{P}(\nu, \iota) = \mathbb{P}(\nu)\mathbb{P}(\iota).$$

Such (joint) probabilities will be used in the following section for the computation of the resilience strategy.

3.5 Legal fishing effort and ILL control strategies

To investigate the future for the fishery in ecological-economic terms from the calibrated model, beyond the pressure scenarios previously introduced, different projections of both legal fishing efforts $E_f(t)$ ($f = 1, \ldots, F$) and patrol guards effort $G(t)$ are also considered from current year $t_1 = 2018$ until year $T = 2050$. Here we consider 3 contrasted strategies: a business as usual projection denoted by BAU, a normative strategy denoted by ROB* aiming at maximizing the bioeconomic resilience and a strategy of transition between BAU and ROB*. What is meant by bioeconomic resilience is clarified below.

Business As Usual (BAU) : For this projection, regarding the legal fleets, it is assumed that the fishing efforts follows the historical trends $\Delta_{E_f}^{hist}$ detailed for the case study in Appendix A.9 and in Gomes et al. (2021). For the control by guard boats of illegal boats, projections BAU also relies on the historical mean rate, namely Δ_G^{hist}:

$$\begin{cases} E_f(t+1) = E_f(t) + \Delta_{E_f}^{hist} \\ G(t+1) \ = \ G(t) + \Delta_G^{hist} \end{cases} \tag{16}$$

Resilience strategy (ROB*) : The second strategy we examine is normative and corresponds to maximizing the resilience via the robustness score or equivalently the viability probability as in Gourguet et al. (2014); Doyen (2018); Cuilleret et al. (2022). This strategy aims at balancing food security, economic performances and ecological conservation throughout time in terms of probability. Such robustness and viability probability depends on both SST and oil price uncertain scenarios defined in previous Subsection 3.4. We now formulate mathematically these bio-economic constraints or goals.

- *Food security goal* relates to the key role of small-scale fisheries in the local protein consumption. Thus, we consider that the proteins intake $FA(t)$ of fish per capita defined in (7) has to be larger than the historical minimal level, namely $FA^{\lim} = 2.54$ g/day/person. This constraint is thus defined by:

$$FA(t) \geq FA^{\lim}. \tag{17}$$

- *Economic viability goal* is considered through the positivity of profits of every legal fleets. In more mathematical terms, this reads:

$$\pi_f(t) \geq 0, \text{ for every legal fleet } f = 1, \dots, F. \tag{18}$$

- *A social welfare (IUU depending) goal* is to ensure that the enforcement cost to control illegal fishing (say ILL fleet) in the fishery through patrol effort $G(t)$ is balanced by the economic benefit induced by the legal fleet, as in Mangin et al. (2018). Such social welfare viewpoint relates to the benefit-cost analysis as shown by Naidoo et al. (2006); Hilborn et al. (2006); Balmford et al. (2003). In mathematical terms, this constraint corresponds to:

$$\pi(t) \geq C_G((t), \tag{19}$$

where enforcement cost $C_G(t)$ is defined in equation (11) while profit $\pi(t)$ corresponds to equation (3.2).

- *Ecological conservation* goal refers to the persistence[5] of the functional groups among the species. In our case study, theses functional groups include weakfishes (AW,GW) and catfishes (CRC) (Vallée et al., 2019). In mathematical terms, the ecological viability thus reads as follows:

$$\begin{cases} B_{GW}(t) > B_{GW}^{\lim} \ \textit{or} \ B_{AW}(t) > B_{AW}^{\lim} \\ \\ B_{CrC}(t) > B_{CrC}^{\lim} \end{cases} \tag{20}$$

Given these different bio-economic viability constraints, the optimal robustness associated with the strategy ROB* is obtained by maximizing the probability to fulfill the constraints (17), (18), (19), and (20). The robustness metric for a given strategy (E, G) is thus defined by

$$\text{ROB}(E, G) = \mathbb{P}_{\theta, Poil}(\textit{Constraints } (17), (18), (19), (20) \textit{ are fulfilled}) \tag{21}$$

where the probability $\mathbb{P}_{\theta,Poil}$ arises from the randomness of the climate $\theta_\iota(t)$ and oil scenarios $Poil_\nu(t)$. Consequently the optimal robustness strategy ROB* refers to the optimization problem:

$$\text{ROB}(E^*, G^*) = \max_{E_f(t),\ f=1,\dots,F;\ G(t)} \text{ROB}(E, G). \tag{22}$$

At this stage, we have to pay attention to the class of controls to optimize when facing uncertainties (De Lara and Doyen, 2008). In terms of strategy, we here focus on feedback and adaptive controls, which are known to be well-suited to cope with uncertainties and stochasticities. More specifically, here, feedback is taken into account by considering two 15 year periods, with the decision process on fishing and patrol efforts at the beginning of the first period $(E(t_1), G(t_1))$ depending on the initial state information, and a second decision $(E(t_2), G(t_2))$ made to adapt efforts to the uncertain state of the system in period t_2. The underlying mathematical formulation, both of the associated criteria and of the optimization is inspired from Shapiro et al. (2014); Doyen et al. (2017) and detailed in the Appendix A.5.2.

Transition strategy (TRANS) :

The transition strategy denoted by TRANS consists in minimizing the gap between the current effort underlying BAU and the targeted effort of the maximal resilience ROB* with an additional transition constraint. To account for the rigidity and inertia in the fishery, we impose the relative variation of the legal fishing efforts to be smaller than a global prescribed threshold denoted by δE at every period t as follows:

$$\left| \frac{E_f(t+1) - E_f(t)}{E_f(t)} \right| \leq \delta E, \qquad f = 1, \dots, F \tag{23}$$

The rigidity, set to $\delta E = 6\%$ for each time step t in the case study, aligns to ICES (2018) and corresponds to an annual variation of 20%. Below, we detail the dynamics of this strategy $E_f^{\text{TRANS}}(t)$. First, at the time step t_1 where the projections start, fishing effort for every fleet f corresponds to the initial value namely:

$$E_f^{\text{TRANS}}(t_1) = E_f(t_1).$$

Furthermore, between periods t_1 and t_2, we consider that the transition efforts $E_f^{\text{TRANS}}(t)$ are characterized by the following dynamics:

$$E_f^{\text{TRANS}}(t+1) = E_f^{\text{TRANS}}(t) + \delta 1_f^{\text{TRANS}}(t) * E_f^{\text{TRANS}}(t) \text{ with } \delta 1_f^{\text{TRANS}}(t) = \min\left(\delta E, \frac{E_f^*(t_1) - E_f(t_1)}{(t_2 - t_1) E_f^{\text{TRANS}}(t)}\right) \tag{24}$$

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[5] Persistence means that species biomass are above conservation limits, $B_s^{\lim}$ depicts in Appendix A.5

Such a fishing effort strategy minimizes the distance between the maximal resilience strategy $E_f^*(t) = E_f^*(t_1)$ while accounting for the transition[6] constraint (23). Between periods t_2 and T, we proceed similarly. Thus the fishing efforts of every fleet f are characterized by the dynamics:

$$E_f^{\mathrm{TRANS}}(t+1) = E_f^{\mathrm{TRANS}}(t) + \delta 2_f^{\mathrm{TRANS}}(t) E_f^{\mathrm{TRANS}}(t) \quad \text{where} \quad \delta 2_f^{\mathrm{TRANS}}(t) = \min\left(\delta E, \frac{E_f^*(t_2) - E_f^{\mathrm{TRANS}}(t_2)}{(T - t_2) E_f^{\mathrm{TRANS}}(t)}\right) \tag{27}$$

Again, whenever maximal resilience effort $E_f^*(t_2)$ is close to the effort of the transition strategy $E_f^{\mathrm{TRANS}}(t_2)$ at time t_2 when compared to δE, transition and resilience-based efforts coincide in the long run in the sense that $E_f^{\mathrm{TRANS}}(T) = E_f^*(T)$.

Similarly, we use the δE rate to take into account the inertia of change for the patrols control in the TRANS strategy. Such a control effort strategy minimizes the distance between the maximal resilience strategy $G^*(t)$ while accounting for a rigidity constraint similar[7] to (23). Such transition strategy for enforcement actions is detailed mathematically in Appendix A.5.3.

4 Results

In this section, we compare the three strategies BAU, ROB and TRANS in terms of fishing efforts, biomass, catch, profit and social welfare including the enforcement costs of illegal fishing.

4.1 Projections of fishing efforts and control of illegal fishing

Figure 2 informs over the period $t_1 = 2018$ - $T = 2050$ on both patrol guard controls $G(t)$ (subfigure a) and the fishing intensities of the different fleets across the three fishing strategies namely Business as usual BAU (in black), maximal resilience ROB (in blue) and transition TRANS (in purple). The fleets include the three legal fleets $f = 1$ (CaC+, subfigure c), $f = 2$ (CaC, subfigure d)), $f = 3$ (Tap, subfigure e) and the illegal 'fleet 'Ill (subfigure b). The different plots stand for effort multipliers with respect to year $t = 2017$ namely $\frac{E_f(t)}{E_f(2017)}$ per fleet f and time t. The historical period corresponds to black plots from years $t_0 = 2006$ to $t_1 = 2018$. The blue and violet envelope and uncertainties of ROB and TRANS efforts from $t_2 = 2033$ arise from the climate and oil price uncertainties and stochasticities along with the adaptive (feedback) efforts underlying such resilience-based strategies. The envelopes correspond to the 90% confident intervals of the projections.

The projections of the resilience-based strategy ROB* until $T = 2050$ show major changes when compared to BAU strategy as well as historical fishing efforts. We first observe a massive reduction of the illegal fishing activity (subfigure 2 (b)) when implementing the resilience-based strategies ROB* and TRANS. This reduction is particularly pronounced at the beginning of the projection period in $t_1 = 2018$, with illegal fishing efforts decreasing to about 20% of the historical level. To reach such a drastic reduction of illegal fishing, enforcement and patrol guard efforts have to be increased by four in comparison to their average historical values as shown in the subfigure 2 (a) on control rate $G(t)$. Interestingly, from year $t_2 = 2033$, the control of illegal fishing can be slightly relaxed. Such result is due to the economic gains in terms of both the profit of legal fleets and the social welfare (19) induced by the higher enforcement in the first period of decision and the mitigation of the illegal fishing. Such somehow counter-intuitive finding regarding the second period is scrutinized and discussed in Section 5.

Beyond the massive reduction of illegal fishing, it turns out that the resilience-based management ROB* and TRANS also suggest an important reallocation in the future between the different legal fleets CaC, CaC+ and Tap. For the BAU strategy, we can indeed observe a major growth of the CaC+ fleet based

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[6] In particular, whenever the gap between $E_f^*(t_1)$ and $E_f(t_1)$ is small when compared to δE, dynamics (24) simplifies to

$$E_f^{\mathrm{TRANS}}(t+1) = E_f^{\mathrm{TRANS}}(t) + \frac{E_f^*(t_1) - E_f(t_1)}{t_2 - t_1} \tag{25}$$

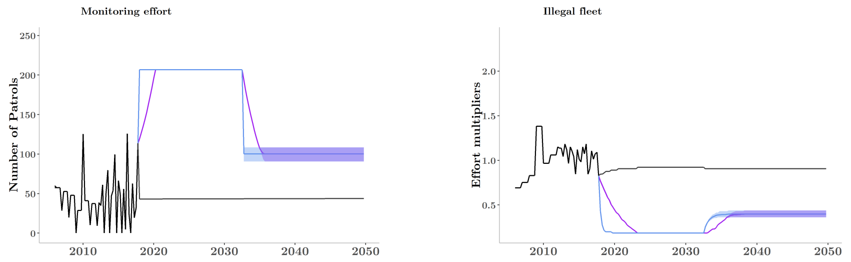
which implies $E_f^{\mathrm{TRANS}}(t_2) = E_f^*(t_1)$. By contrast, whenever the gap between $E_f^*(t_1)$ and $E_f(t_1)$ is large when compared to δE, dynamics (24) simplifies to

$$E_f^{\mathrm{TRANS}}(t+1) = E_f^{\mathrm{TRANS}}(t)(1 + \delta E) \tag{26}$$

where the inertia constraint (23) binds at every period.

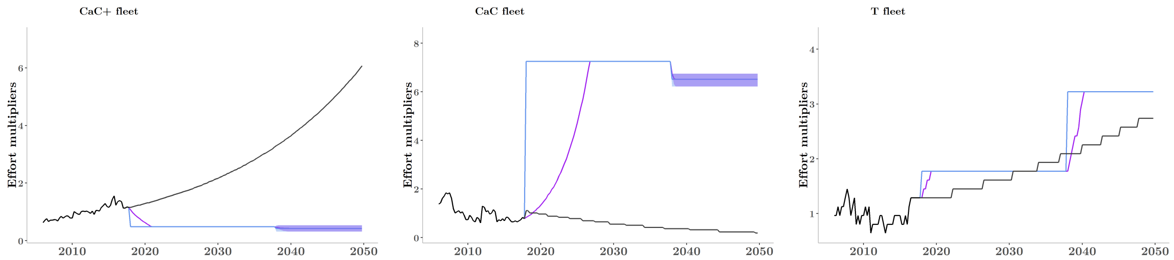
[7] namely

$$\left|\frac{G(t+1) - G(t)}{G(t)}\right| \le \delta E.$$



(a) Patrol guard effort $G(t)$ of illegal fishing

(b) Illegal fleet Ill



(c) Fleet CaC+

(d) Fleet CaC

(e) Fleet Tap

Fig. 2: Effort Trajectories from $t_0 = 2006$ to $T = 2050$ across the 3 strategies BAU (■), ROB* (🟦), and TRANS (🟪) for (a) Patrol Guard Effort $G(t)$, (b) Illegal Fleet Effort Multiplier, (c) Effort Multiplier for CaC+, (d) Effort Multiplier for CaC, and (e) Effort Multiplier for Tap. Solid lines represent the means, while the envelopes are the 90% confidence intervals. Historical values correspond to plots from $t_0 = 2006$ to $t_1 = 2018$.

on historical trends (subfigure 2 (c)). The magnitude of this CaC+ growth is about six at the time horizon 2050. By contrast, when adopting the resilience-based strategies ROB* and TRANS, both the CaC (top - left) and Tap (bottom - left) fishing efforts have to be significantly increased while the CaC+ has to be reduced in particular when compared to BAU. The growth of both CaC and Tap to promote the bioeconomic resilience is around seven times the current level by 2050 for ROB* and TRANS strategies. Furthermore, the adaptations of resilience-based efforts from $t_2 = 2033$ confirm the global trends although some adjustments with respect to $t_1 = 2018$ decisions are required: a slight decrease of CaC effort and an increase in Tap effort. Because of the inertia constraint (19), fishing effort of the transition strategy TRANS requires time to reach the resilience targets underpinning ROB*. This occurs particularly in the first period for CaC. However such transitions do not strongly affect the long run efforts of resilience-based management ROB* as expected.

To summarize, to foster the bioeconomic resilience of the fishery, beyond the necessary and intuitive massive mitigation of illegal fishing, the growth of both CaC and Tap fishing efforts is needed at the expense of the CaC+ fleet. Such last result about the redistribution of legal fleets is fully in line with findings of Cuilleret et al. (2022) for the case study.

4.2 Projections of fish biomasses

Figure 3 contrasts the biomass of the three fished species GW (a) AW (b) and CRC (c) across the three fishing strategies BAU (in black), ROB (in blue) and TRANS (in purple) over the period $2018 - 2050$. We can first note that few differences emerge between ROB* and TRANS strategies. Said differently, the inertia constraint affects only marginally the ecological and biodiversity projections. Consequently, we hereafter focus on the comparison between BAU and ROB*. It turns out the difference between the fishing strategies for biomass trajectories is only pronounced for the AW and CRC species. With the BAU fishing, we indeed observe the collapse of these two species and thus a significant biodiversity crisis at the horizon $T = 2050$. In contrast, with the resilience-based strategy ROB*, these two species survive and a species richness of 3 is maintained. These major ecological differences between the strategies mainly stem from the massive reduction of illegal fishing underlying the resilience strategy ROB* when compared to BAU fishing. In particular, as detailed in Table A.1 within the appendix, the catchabilities $(*10^{-6})$ of the illegal fishing $q_{AW,\text{Ill}} \approx 14$ on AW and $q_{CRC,\text{Ill}} \approx 12$ on CRC are almost ten times stronger than the catchability on GW namely $q_{GW,\text{Ill}} \approx 1.6$. However, we can remark that the ecological viability for GW and CRC due to the mitigation of illegal fishing in ROB* occur at lower biomass levels when compared to the historical values. The decline or the extinction of both the AW and CRC benefits to the GW species for every strategy. This

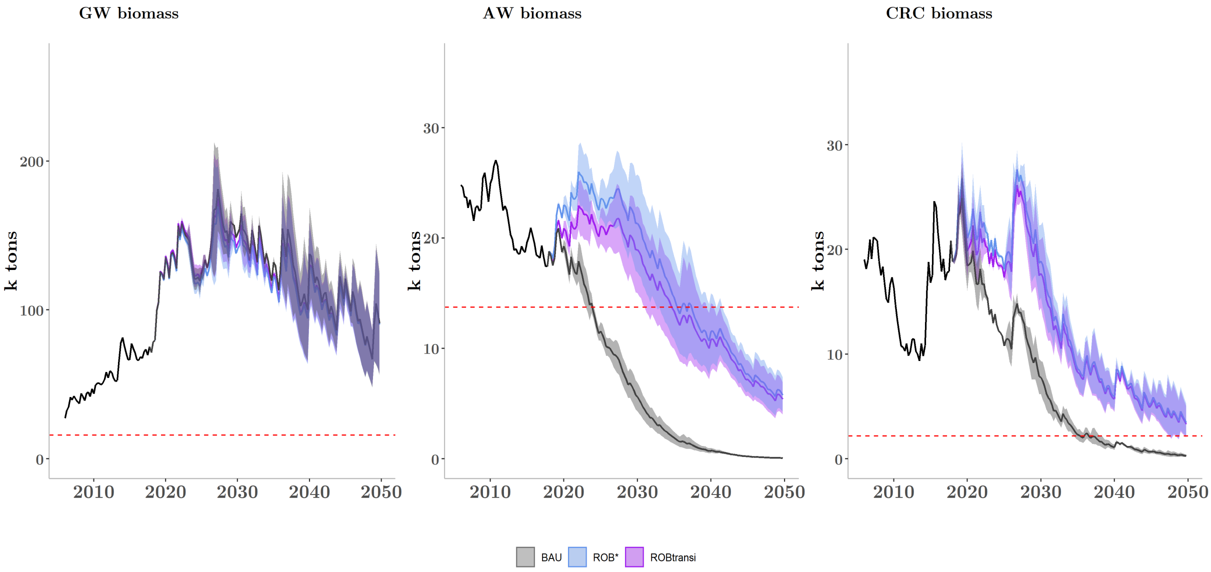


Fig. 3: Trajectories of biomass $B_s(t)$ from 2006 to 2050 across the 3 strategies: BAU (■), ROB* (🟦), and TRANS (🟪) —Threshold B^{lim} (····) for species GW (left), AW (center), and CrC (right). Solid lines denote the means, while the envelopes are the 90% confidence intervals. Historical values correspond to plots from $t_0 = 2006$ to $t_1 = 2018$.

result mainly arises from the exclusion principle underpinning the resource-based dynamics (1) where the most ‘effective’ species (here GW) displaces the others and becomes dominant (Tilman, 1982).

Figure 3 also depicts a general decline in biomass across the species and strategies from the long-term viewpoint. It turns out that such global biomass decrease in the long run is due to climate change and biological efficiency $\gamma_s(\theta(t))$ with respect to SST $\theta(t)$, a key input of the growth function in species dynamics (1), (2) and (3). Figure A.7 in the appendix shows that the efficiencies by species, depending on the difference between sea temperature and the species' optimal temperature, decline with time through the increase of temperature $\theta(t)$. Such global erosion of tropical marine biodiversity due to climate change is in line with findings of Gomes et al. (2021); Cuilleret et al. (2022); Cheung et al. (2009).

4.3 Projections of food supply

Figure 4 compares the per capita food supply $FA(t)$ as defined in (7) across the three fishing strategies BAU (in black), ROB (in blue) and TRANS (in purple) over the period $2018 - 2050$. Such seafood supply depends on the catches $h_{s,f}(t)$ over the species s and legal fleets f as well as the population growth $D(t)$. The red dotted line stands for the food security threshold $FA^{\text{lim}} = 2.54$ also introduced in (7).

We first observe that the food security is ensured over the whole temporal horizon with a very high probability regardless the management strategies. Important tensions about food security only occur in the long run namely from year 2046. The contrast between BAU, ROB* and TRANS is strongly pronounced in the first periods of projections (and decisions) namely years 2018-2033. We can clearly see here to what extent strategy TRANS is a transition between BAU and ROB* as it switches progressively from levels close to BAU to higher levels aligned to ROB*. Going further, we now need to unravel the important difference, of about 200% on average, between BAU and ROB* in this first period. Such gap of magnitude in terms of per capita food supply between BAU and ROB* mainly stems from the major difference of efforts already discussed in Section 4.1 and Figure 2. In particular, it is explained by the major growth of fishing efforts of both CAC ($\approx \times 9$) and TAP ($\approx \times 2$) fleets when compared to BAU and the moderate growth of CAC+ ($\approx \times 1.5$) on the first periods ($t < t_2 = 2033$).

In the long run (say from 2040), such differences between BAU and ROB* are progressively smoothed and vanished mainly because of the global decline of biomass discussed in previous Subsection 4.2. The global erosion of fish biomasses indeed entails a relative stagnation of catches through the Schaefer production functions (5) and consequently of the per capita food supply. These catches are detailed by species in Figure A.8 of the appendix. The demographic growth $D(t)$ in FG characterized in (13) also shrinks in the long run the per capita food supply $FA(t)$ as well as its differences across the strategies.

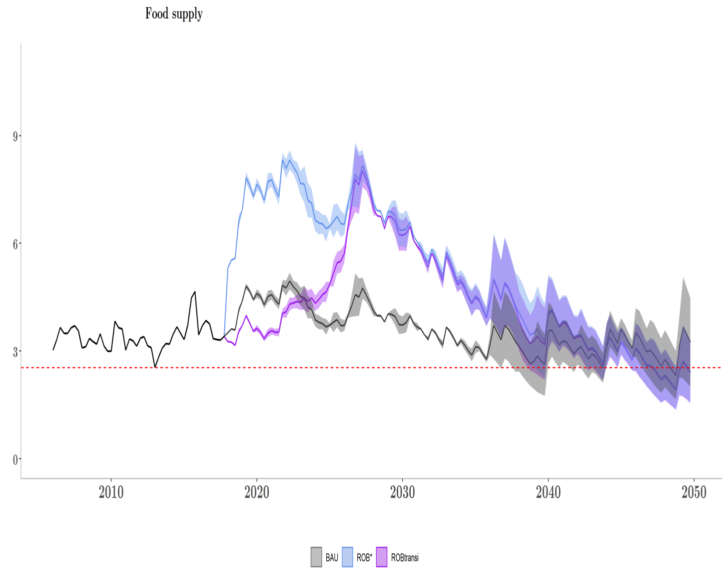


Fig. 4: Trajectories of food supply $FA(t)$ from 2006 to 2050 across the 3 strategies: BAU (■), ROB* (🟦), and TRANS (🟪) — Threshold FA^{lim} 3.5 (····). Solid lines denote the means, while the envelopes are the 90% confidence intervals. Historical values correspond to plots from $t_0 = 2006$ to $t_1 = 2018$.

4.4 Projections of profits of legal fleets

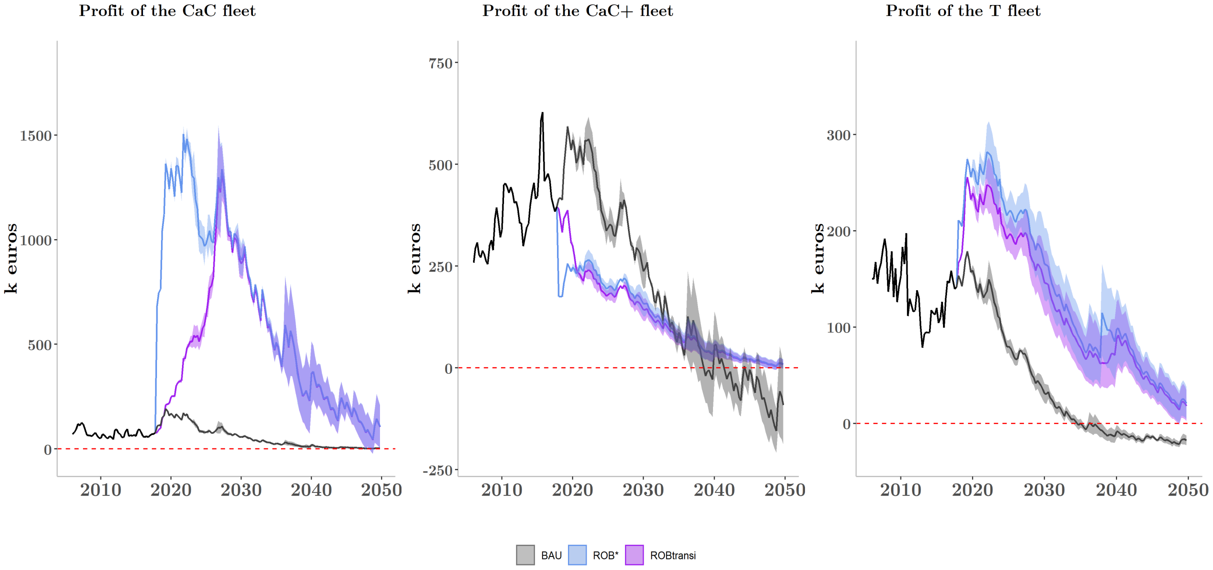


Fig. 5: Trajectories of profit $\pi_f(t)$ by legal fleet f from $t_0 = 2006$ to $T = 2050$ across the three strategies: BAU (■), ROB* (🟦), and TRANS (🟪). Viability thresholds $\pi^{\text{lim}} = 0$ are the red dot lines. Legal fleets are CaC (left), CaC+ (center) and Tap (right). Solid lines denote the means, while the envelopes represent the 90% confidence intervals. Historical values correspond to plots from $t_0 = 2006$ to $t_1 = 2018$.

Figure 5 contrasts the profits of the three legal fleets CaC (left-hand side), CaC+ (center) and Tap (right-hand side) across the three fishing strategies BAU (in black), ROB (in blue) and TRANS (in purple) over the period $2018 - 2050$. We can first point out that the BAU strategy is not sustainable from the economic profitability viewpoint as, in the long run (say from year $t = 2040$), the profits of every fleet become non positive, in particular for fleets CaC+ and Tap. By contrast, the resilience-based strategies, including both ROB* and TRANS are economically viable despite the uncertainties since for every fleet the profits remain strictly positive throughout years $2018 - 2050$. However, again, tensions occur in terms of sustainability at the end of the projection for ROB* in particular for the CaC+ fleet. More globally, the decline of the profits for every fleet after 2035 is strongly aligned with the global decline of species biomasses as previously stressed in subsection 4.2. The profitability gains observed in the first periods of projections,

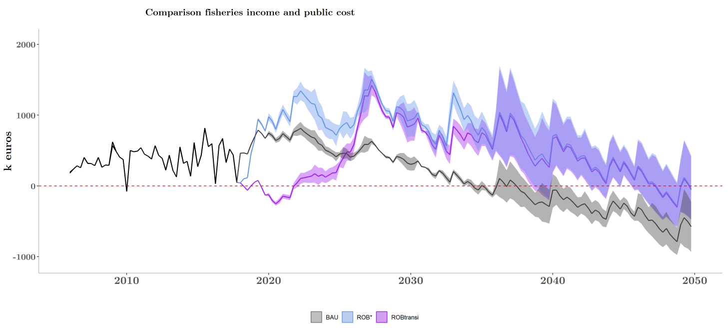


Fig. 6: Trajectories of social welfare $\pi(t) - C_G(t)$ from 2006 to 2050 across the 3 strategies: BAU (■), ROB* (🟦), and TRANS (🟪). Viability threshold is in red. Solid lines stands for the means, while the envelopes correspond to the 90% confidence intervals.

say from 2018 to 2035, arise from the increase of the fishing efforts of the fleets already put forward in subsection 3.5 namely: an increase of CAC and TAP efforts for the resilience-based strategies ROB* and TRANS; an increase of CAC+ for BAU. The role and originality of the transition strategy TRANS emerge in the first periods in particular for the CAC fleet but remains limited in the long run.

4.5 Projections of social welfare, including enforcement costs

Figure 6 shows the difference between the aggregated profit $\pi(t)$ of legal fleets introduced in equation (3.2) and the enforcement costs of illegal fishing $C_G(t)$ as defined in (19). Such difference corresponds to a social (monetary) welfare from the public viewpoint, as it accounts both for the economic gains induced by the legal fleets and the enforcement costs of controlling the illegal fishing. We first observe that the resilience-based strategy ROB* again performs better than BAU throughout the period of projection. This result confirms the benefits of massively mitigating illegal fishing. However, at this stage, we need again to distinguish between the first and second decision periods. In the first years of projection, the good scores of ROB* strategy arise from the legal profits gains mentioned above in subsection 4.4 which are more than enough to compensate the major increase of the enforcement costs of illegal fishing $C_G(t)$. In contrast, in the long run, the gains of the resilience-based strategy are more limited since profits are also reduced because of species biomass declines (see previous subsection 4.4) while, in parallel, the enforcement costs of illegal fishing remain high. Interestingly, in this long run period, the BAU strategy strongly deteriorates because of the important profitability crisis already emphasized in previous subsection 4.4.

In the case of the TRANS strategy, the outcome is more complex. The small loss in social welfare in the first years of the projection is due to the loss in profit of the CAC fleet in the first years of the transition. Such profitability loss induced by the transition for the CAC fleet is implied by the major change of effort illustrated in Figure 2 for the resilience-based strategy ROB* with an effort multiplier of magnitude seven until year 2035.

4.6 Robustness

The figure 7 compares the robustness scores for strategies ROB*, TRANS and BAU. The radar plot refines the global robustness score of (21) with respect to the different goals namely biodiversity, food supply, profit and social welfare using the metrics

$$Rob_k(E, G) = \mathbb{P}\left[I_k(E(t), G(t)) - I_k^{\lim} \geq 0, \quad \text{for all } t\right]. \tag{28}$$

Here $I_k(E(t), G(t))$ refers to the specific metric underlying goal k and depending on strategies of legal efforts $E(t)$ and patrol control intensities $G(t)$ throughout time while $I_k^{\lim}$ stands for the viability thresholds of goal k. For instance, food supply goal relates to the constraint (17).

Figure 7 clearly shows the resilience gains of ROB* and TRANS when compared to BAU. As expected, the maximal resilience-based strategy ROB* performs better as its very definition consists in maximizing the global robustness. Furthermore, the probabilities by goals of ROB* are all close to one meaning its strong bioeconomic robustness. More specifically, ROB* almost doubles the robustness scores of BAU for the economic, ecological goals and social welfare including illegal fishing control costs. However, we can observe that the robustness scores of ROB* and BAU about food supply coincide. This holds true because,

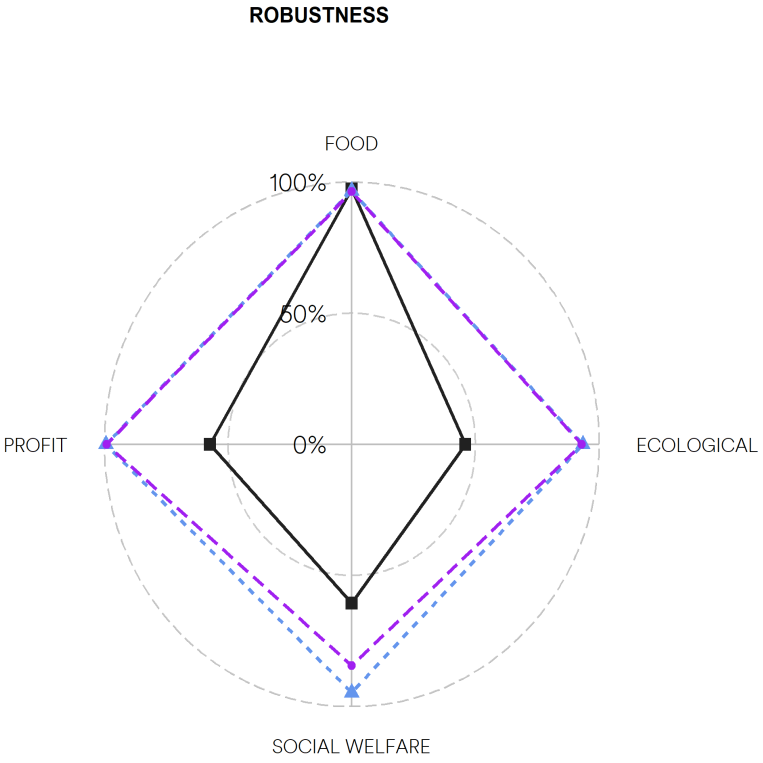


Fig. 7: Robustness scores $\mathrm{ROB}_k(E,G)$ by goals k across strategies : ROB^* (▲), TRANS (●) and BAU (■) for biodiversity, food supply, profits and social welfare accounting for illegal fishing enforcement costs.

as already said in subsection 4.3, both BAU and ROB^* strategies comply with the food security goal with a similar and high probability.

Interestingly, Figure 7 also shows few discrepancies between ROB^* and TRANS strategies in terms of robustness performances. Both ROB^* and TRANS indeed exhibit similar levels of biodiversity, food security and profitability robustness. The main discrepancy involves the social welfare. The small loss in social welfare robustness of TRANS is explained by the important loss in profit of the CaC fleet in the first years of the transition as captured by the left hand side of Figure 5. Such profitability loss with respect to ROB^* regarding the CaC fleet is a consequence of its drastic increase of effort of the resilience-based strategy ROB^* with an effort multiplier of magnitude 7 until year 2035.

5 Discussion

We here propose a transversal analysis of the results detailed in the previous Section. More specifically, we focus below on (i) the need to strongly mitigate illegal fishing; (ii) the need to redistribute the fishing effort across the legal fleets; (iii) the feasibility of a transition for these changes to achieve a resilience-based management and; (iv) the interest of the robustness approach to promote a bio-economic resilience-based management.

5.1 Mitigating illegal fishing is necessary for bio-economic resilience

The important bioeconomic gains resulting from the resilience-based strategy ROB^*, summarized by Figure 7 and detailed in previous subsections 4.2, 4.3, 4.4, require a massive mitigation of illegal fishing with respect to BAU efforts as shown by the first row in Figure 2. Such a mitigation of illegal fishing is obtained by increasing the enforcement intensity of the regulating agency through patrol controls.

The ecological gains implied by the massive reduction of illegal fishing underlying the ROB^* strategy include the viability of two fish (over three) species, namely the Acoupa Weakfish and the Crucifix Sea Catfish, when compared to BAU as displayed by Figure 3. Such an ecological benefit is consistent with the findings of Camaclang et al. (2017) about the negative impact of illegal fishing on the probability of extinction, on marine biodiversity and, more globally, on marine ecosystems.

The economic gains of ROB* generated by the reduction of illegal fishing include major profitability benefits for legal fleets, in particular for fleets CAC+ and TAP, as captured by Figure 5. Illegal fishing indeed results in loss of income for legal fleets due to illegal catches of high-value species such as Acoupa Weakfish which confirms the findings of Kersulec et al. (2024) in the FG case study. Similar issues have been highlighted in many other fisheries worldwide by Agnew et al. (2009). This economic loss is also exacerbated by the fact that illegal fishing is not subject to the same regulations and restrictions as legal fishing, giving illegal fleets an unfair competitive advantage as stressed by Long et al. (2020).

Of interest in that economic regard, is also the social welfare metric estimated in subsection 4.5. This social welfare score indeed points out that, the reduction of illegal fishing underlying the resilience-based policy ROB* appears to be economically relevant despite its important enforcement costs, because of the intertemporal economic gains for the legal fleets (Mangin et al., 2018; Doumbouya et al., 2017). Moreover, the monetary gain considered in our study is underestimated as it does not include the potential gains of tax revenue, which can be substantial as emphasized in Sumaila et al. (2020). Furthermore, it can noted that the social welfare metric does not directly take into account other (non monetary) benefits of reducing illegal fishing, such as the enforcement of state sovereignty in these areas as well as the fight against drug and human trafficking (Benoît, 2020). It can also be put forward that the social welfare results suggest that it is not efficient to fully eliminate the illegal activity in the EEZ because the costs of doing so are too high when compared to the induced benefits for legal fishing. In line with such a finding, we could even argue that it would be likely impossible, in practise, to totally prevent illegal fishing at least in the FG case-study.

5.2 Mitigating illegal fishing is not sufficient for bio-economic resilience

The results, in particular Figure 2, also highlight that, although the mitigation of the illegal fishing is necessary, it is not sufficient to promote the whole bioeconomic resilience of the fishery. The management of the legal fleets turns out to be also necessary. The resilience strategy ROB* indeed suggests increasing the fishing efforts of CAC and TAP fleets while drastically reducing the share of CAC+ fishing. This contrasts with BAU trajectories where this last fleet CAC+ massively should increase and dominate the fishery in the long run. This reallocation and diversification of efforts among legal fleets is fully aligned with the findings of Cuilleret et al. (2022) who point out that profits (through MEY strategy) are favored by the CAC fleets while catches (through MSY strategy) are promoted by the TAP fleet. Such redistribution of effort occurs because these legal fleets differ in terms of both catchabilities and costs.

Said differently, since the resilience-based strategy ROB* aims at sustainably balancing both biodiversity, productive and monetary performances facing both climate and cost uncertainties, the diversification of efforts across the legal fleets makes sense by taking advantage of the specific bioeconomic performances of these fleets (Cissé et al., 2015). Moreover, it is well known that in the face of uncertainties and risks, diversification is a relevant strategy (Markowitz, 2010; Sanchirico et al., 2008; Ay et al., 2014; Eide, 2016; Tromeur et al., 2021). In the case-study, diversification is however complicated by the fact that the various vessels are artisanal and not selective with respect to the fished species (Kasperski and Holland, 2013). Furthermore, diversification is also complexified here by the fact that the uncertainty is multifaceted, since they relate to both climate change and energy costs. Table A.3, which details the revenue generated per unit of oil for each fleet, notably shows that fleets CAC and TAP outperform CAC+ in terms of revenue per unit of oil. Such diversification in the face of energy cost uncertainties has to be balanced with the diversification with respect to climate uncertainty which strongly impacts fish species dynamics as stressed in subsection 4.2.

5.3 The interest of a transition towards bioeconomic resilience

We here focus on the strategy called TRANS which corresponds to a progressive transition from the current situation and trends (BAU) towards the resilience-based management ROB*. Such TRANS strategy accounts for rigidity and inertia in the management, decisions and anthropogenic changes as in Béné et al. (2001); Eide (2016); Beckensteiner et al. (2023). Here such rigidity is captured by limits on the adjustment of fishing efforts of each legal fleet as well as the enforcement intensity via patrol boats. In our study, we limit the relative adjustment to 20% of the legal fleets per year, in line with the principle of relative stability of the European Common Fisheries Policy (CFP) (Sobrino and Sobrido, 2017). Imposing such rigidity makes a lot of sense in our study because Figure 2 shows that the effort multiplier (with respect to year 2017) required by the resilience-based management ROB* are very important, in particular higher than 2 for

CaC and Tap fleets. Lluch-Cota et al. (2023) explains to what extent such large changes could alter the acceptability of the strategy and thus impede its potential implementation.

Interestingly, our results, synthesized in the radar-plot of Figure 7, show that the transition TRANS (in violet) occur without a significant loss in robustness and thus in resilience when compared to strategy ROB* (blue) since the two curves almost coincide. It means that the gains with respect to the BAU (black) are still huge with a magnitude of order 2 for profitability and biodiversity despite the rigidity on efforts underlying TRANS. This small social welfare loss for TRANS is due to the profit loss of the CaC fleet during the transition, resulting from a significant change in effort required until 2035.

Thus, more globally, the loss in terms of bioeconomic resilience of the transition is limited making TRANS an interesting transition path. The implementation of the transition constraints makes these changes in fishing effort trajectories more socially acceptable and realistic, in line with previous research on social acceptability by van Hoof et al. (2020); Rotmans et al. (2001).

5.4 A methodology for operationalizing resilience

In more methodological terms, our paper is a step toward the operationalization of resilience for fisheries (Hardy et al., 2016; Béné and Doyen, 2018; Grafton et al., 2019) through models, metrics and management strategies. It indeed provides a quantitative modeling framework about how to implement resilience-based management, scenarios and policy, in particular for small-scale and coastal fisheries facing several pressures such as climate change and illegal fishing. The proposed methodology articulates ecosystem-based management models, viability approach together with the 3Rs of resilience.

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, accounting for the illegal fishing pressure as well as climate and oil price uncertainties. The competition for a resource between the fish species is part of the ecological complexity together with the non linear role of climate through SST and climate envelopes. 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); Plaganyi et al. (2014); Doyen (2018) since it only focuses on the ecological-economic components and interactions necessary to address a management question.

The use of the viability approach to realizing resilience is justified by the fact it provides a rigorous and sound basis for the quantification 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 sustain its identity. 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. We think that such a multi-criteria viewpoint is strongly relevant to address bio-economics and resilience-based management, in particular for fisheries.

Regarding resilience quantification, we here 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 (21) and the probability to comply with the thresholds throughout time. Such quantitative tool gives key insights into the management of multidimensional and systemic risks which are key challenges of our paper. Finally, the feedback controls (efforts of legal fleets and of patrol guards) introduced in subsection 3.5 for the normative strategy ROB* points out the adaptive content (Walters and Hilborn, 1976) of the resilience-based management adopted in our paper. Such an adaptive management and feedback controls are known to be pivotal ingredients when facing uncertainties and stochasticities (De Lara and Doyen, 2008). In that respect, expanding the adaptive content of the resilience-based management ROB* by using more than two periods of decisions would make a lot of sense. However, such feedback strategies turn out to very costly in numerical terms.

6 Conclusion

The coastal fishery of French Guiana, as many small-scale fisheries in the tropics, faces numerous complexities and numerous pressures which question its bioeconomic resilience. Complexities relate to the rich tropical marine biodiversity together with the non-selective fishing techniques of the artisanal fleets. Pressures include illegal fishing, climate change, and oil prices. To explore and quantify the ways to improve the bioeconomic resilience of the coastal fishery in French Guiana, we have developed and calibrated a multi-species, multi-fleet model accounting for illegal fishing, using data from 2006 to 2018. From the calibrated model, we compared bioeconomic projections at the horizon 2050 for three strategies: business-as-usual, maximal robustness, and maximal robustness with transition. These projections are constrasted in terms of bio-economic resilience in the face of stochastic scenarios, including climate scenarios (Masson-Delmotte et al., 2021) and energy cost scenarios (IEA, 2020). Robustness is the indicator of resilience used in this study (Grafton et al., 2019; Cuilleret et al., 2022). It is based on probabilistic viability, which here involves different thresholds in terms of biodiversity, food supply, profitability and social welfare. In particular, such social welfare accounts for enforcement costs of illegal fishing as in Wedathanthirige (2019).

The important resilience gains identified between the business-as-usual and maximal robustness highlight two important ingredients allowing to enhance the bioeconomic resilience: (i) drastically reducing illicit fishing and (ii) reallocating the fishing effort among the legal fleets. The first ingredient (i) entails, in particular, major gains in the medium and long run in terms of both biodiversity and profitability of legal fleets. The second ingredient (ii), inspired by the portfolio strategy (Markowitz, 2010), relies on the diversification of efforts among legal fleets facing climate and energy costs uncertainties. Moreover, the third strategy ‘maximal robustness with transition’ shows that global bio-economic resilience could be achieved progressively from the current situation to the resilient situation with limited bioeconomic losses. Thus the acceptability of the changes needed for a bioeconomic resilience and the implied adaptation could be taken into account while still fostering the resilience in the medium and long run.

More globally, beyond the case-study, our article suggests bioeconomic, robust, and adaptive management strategies for small-scale fisheries affected by illegal fishing and climate changes. Such management strategies clearly account for biodiversity, food supply, and profitability outcomes and uncertainties in both the short and long run. This is an important contribution because small-scale fisheries play a key role in the tropics due to their ecological, economic, cultural, and food contributions and because they are under pressure worldwide (Bene, 2006; Andrew et al., 2007; Arthur, 2020; FAO, 2018; Sumaila et al., 2020).

Declarations:

Conflicts of interest:

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

Author Contributions:

Each author made a contribution to the study’s idea and design. Mathieu Cuilleret performed the calibration of the model. Both the predictions and the robustness implementation were completed by Mathieu Cuilleret. The fishing strategies were designed by Luc Doyen and Mathieu Cuilleret. Analysis of the results was conducted by Mathieu Cuilleret, Fabian Blanchard and Luc Doyen. Mathieu Cuilleret wrote the original draft of the manuscript, and all other authors have provided feedback on it.

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A Appendix

A.1 Calibration of the model

A.1.1 Value of parameters

Parameters	AW	GW	CsC
$a_s \times 10^{-6}$	2,50	7,79	6,8
$q_{s,\mathrm{CaC}} \times 10^{-6}$	1,06	0,98	1,6
$q_{s,\mathrm{CaC}+} \times 10^{-6}$	4,28	0,66	1,4
$q_{s,\mathrm{Tap}} \times 10^{-6}$	12,18	0,58	0,7
$q_{s,\mathrm{Ill}} \times 10^{-6}$	14,52	1,66	12,0
$m_s \times 10^{-2}$	2,13	6,07	5,9
$g_s \times 10^{-2}$	19,37	5,74	6,3
B_s (2006)	24793	27238	18589
τ_s	12	48	0
B_{res} (2006)	590 970		
$\min(E_{\mathrm{Ill}})$ (days)	2 011		
$\max(E_{\mathrm{Ill}})$ (days)	2 855		

Table A.1: Calibrated parameters

A.1.2 Goodness of fit of the calibration

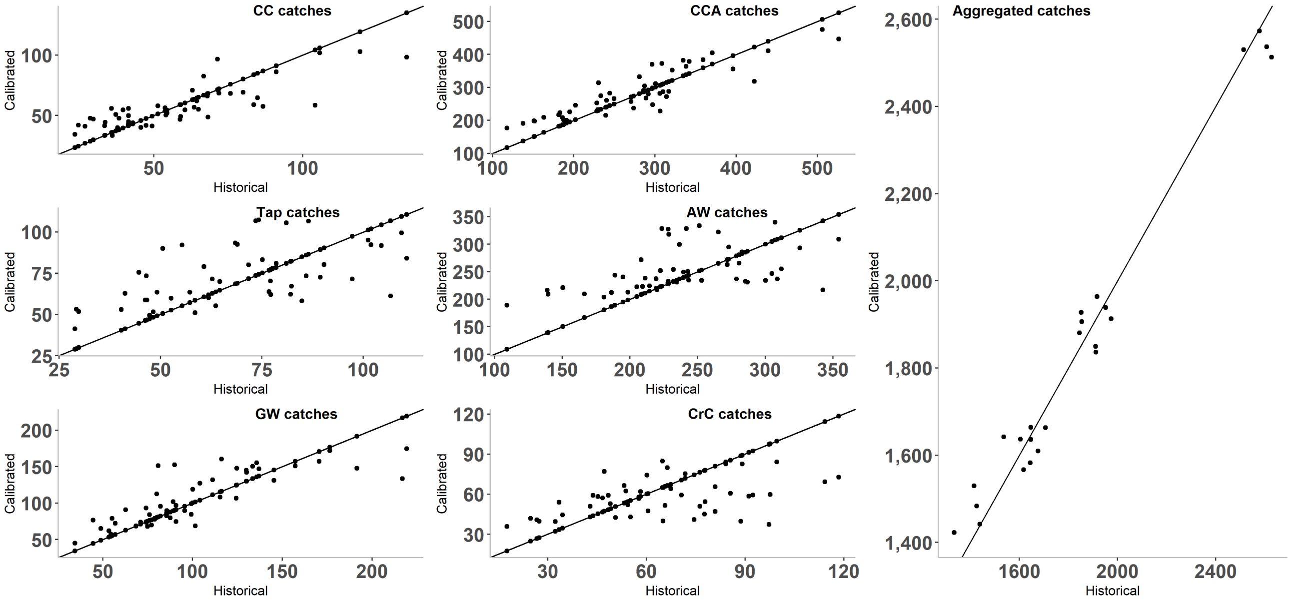

Fig. A.1: Comparison of historical and estimated catch in the in terms of catch by fleet (first row), catch by species (second row), and aggregated catch (3rd columns)

	Mean relative errors of this study	Mean relative errors with climate change Gomes et al. (2021)	Comparative gains
CaC	20%	17%	-3%
CaC+	12%	14%	2%
Tap	20%	28%	8%
AW	13%	18%	4%
GW	17%	31%	14%
CrC	31%	31%	0%
Aggregated	3%	15%	12%

Table A.2: Comparison of mean relative errors by fleets and species $\epsilon_k = \frac{1}{t_1-t_0-1}\sum_{t=t_0}^{t1-1}\left|\frac{H_k^{data}(t)-H_k^{calib}(t)}{H_k^{calib}(t)}\right|$.

A.1.3 Sensitivity analysis of the calibration

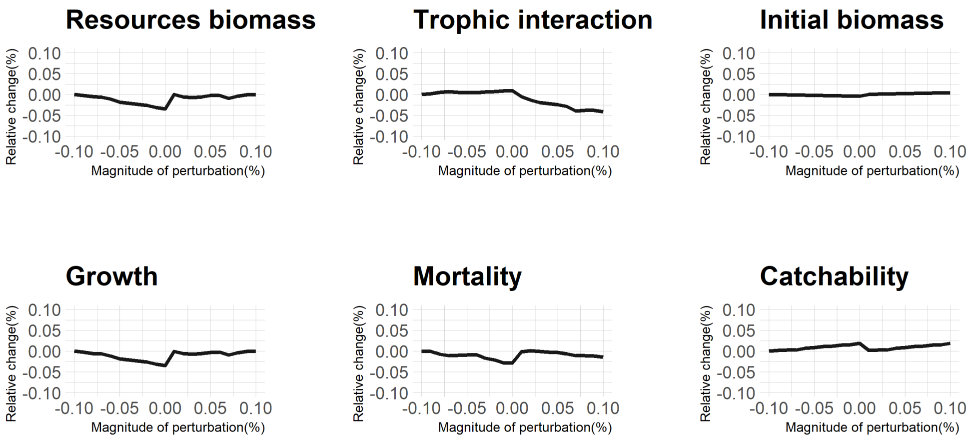

Fig. A.2: Sensitivity analysis for biomass

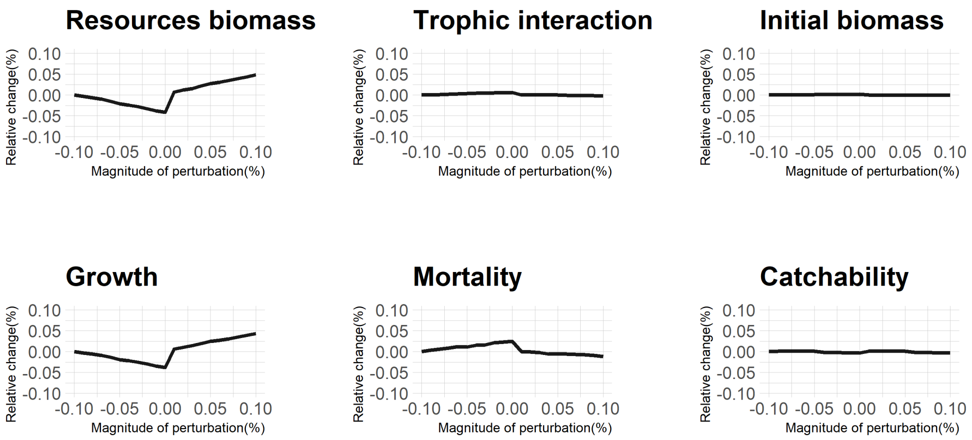

Fig. A.3: Sensitivity analysis for catch

A.1.4 Other parameters of the bio-economic model

$\frac{p_s \times q_{s,f}}{OilCons_f}$	GW	AW	CRC	Total	Efficiency ratio
CaC (x 10^{-6})	2.499	5.724	2.56	10.783	0,03
CaC+ (x 10^{-6})	0.8415	23.112	2.24	26.1935	0,01
Tap (x 10^{-6})	1.479	65.772	1.12	68.371	0.02

Table A.3: Efficiency of price and catchabilities with the oil consumption

Sensitivity of the previous table shows the comparison between the revenue per unit of effort with the oil consumption. It shows the economic vulnerability of each fleet. The CaC+ is the most sensitive fleet to the oil consumption.

Table A.4: Annual cost for each fleet

	CaC	CaC+	Tap
Oil consumption $c_{1,f}$ (L)	16346	24729	37791
Other costs $c_{0,f}$ (€)	1404	7373	10979

Species	GW	AW	CrC
(a) Price p_s (€/kg)	2.55	5.4	1.6
(b) Protein $prot_s$ [8] (g/100g)	17.5	18.3	17.1
(c) Biomass limit $B_s^{\lim}$ [9]	15943	13751	2218

Table A.5: Additional information: (a) price per species, (b) proteins per species and (c) biomass limit

Average Cost of One Hour of Patrol Mongruel et al. (2019)	**Minimum Duration of a Patrol Renaud (2020)**	**Cost of a Patrol** c_G
€829/h	6 hours	€4974

Table A.6: Monitoring costs.

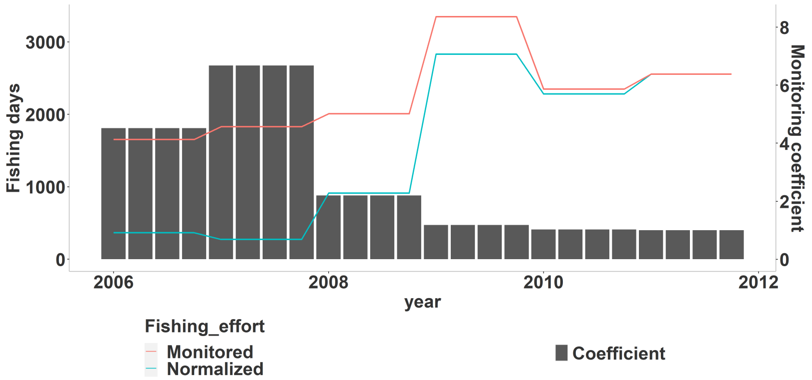

Fig. A.4: Reconstructing illegal fishing activity with monitoring effort, normalized rate in blue and monitored in red.

A.2 Pressures and uncertainties

A.3 Demographic growth

t	2013-2020	2020-2030	2030-2040	2040-2050
δD	2,3%	1,7%	1,3%	1

Table A.7: Statistics on quarterly growth in population based on Demougeot and Baert (2019)

A.4 Stochasticities on climate and oil prices

	Oil price scenarios $\Delta Poil_\nu(t)$				Climate scenarios $\Delta\theta_\iota(t)$			
Scenarios	$\nu = 1$	$\nu = 2$	$\nu = 3$	$\nu = 4$	$\iota = 1$	$\iota = 2$	$\iota = 3$	$\iota = 4$
Mean	0.0001	0.0004	-0.0006	0.0013	0.010	0.010	0.011	0.012
Standard Deviation	0.0645	0.0686	0.0546	0.0593	0.671	0.674	0.570	0.572

Table A.8: Statistics on quarterly changes in (left) price $\Delta Poil_\nu$ for each oil price scenario ν (for example $\nu = 1$ corresponds to SUS scenario) and (right) temperature $\Delta\theta_\iota(t)$ for each climatic scenario ι (for example $\iota = 1$ corresponds to RCP 4.5 scenario).

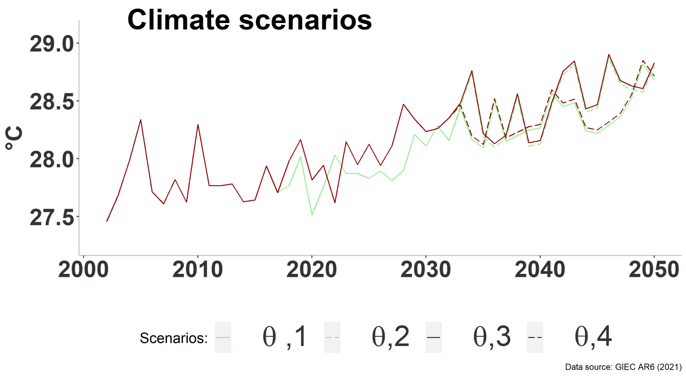

Fig. A.5: Historical trajectories of SST in French Guiana from 2006 to 2018 and projection of SST according to IPCC climate scenario: RCP 2.6 the optimistic, and RCP 8.5 the pessimistic. Seasonal variation is also included.It adds information on 3.4.

Historical trajectories of SST in French Guiana from 2006 to 2018 and projection of SST according to IPCC climate scenario: $\Delta\theta_1$, $\Delta\theta_2$,$\Delta\theta_3$, $\Delta\theta_4$

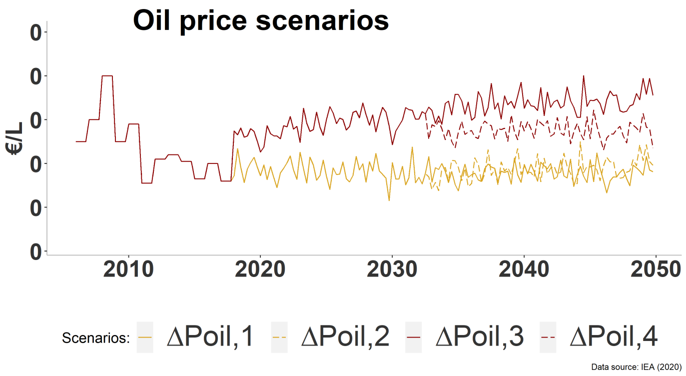

Fig. A.6: Historical variation from 2006 and 2018 and projection of oil price according to IEA scenarios: $\Delta Poil_1$, $\Delta Poil_2$,$\Delta Poil_3$, $\Delta Poil_4$

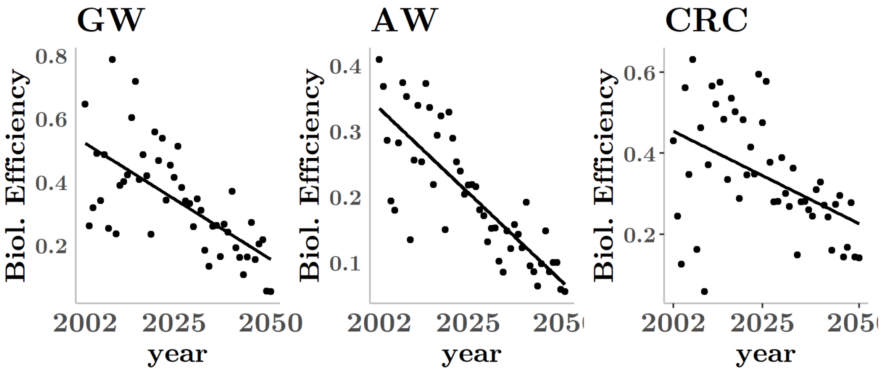

Fig. A.7: Average value per year of biological efficiency $\gamma_s(\theta(t))$, Green weakfish (left), Acoupa weakfish (center), Crucifix sea catfish (right)

A.5 Details on strategies

A.5.1 BAU *strategy*

$\Delta_{E_f}^{hist}$	CAC	CAC+	TAP	G
	-0.012	0.013	0.007	0.005

Table A.9: Evolution of fishing effort for BAU

A.5.2 Numerical computation of ROB* *strategy:*

This appendix details the computational approach for feedback efforts under the ROB strategy, which involves solving a closed-loop optimization problem. This closed-loop optimization problem is inspired from Bellman equation (dynamic programming) and more specifically Shapiro et al. (2014); Cissé et al. (2013); Doyen et al. (2017).

For sake of simplicity and clarity, we hereafter denote by

- $u(t)$ the controls of the system at time namely the efforts of three legal fleets $E_f(t)$ together with patrol guard effort $G(t)$. Thus
$$u(t) = (E_1(t), E_2(t), E_3(t), G(t))$$
- $\omega(t)$ the uncertainties (here stochasticities) of the system relating to climate and energy scenarios
$$\omega(t) = (\theta_\iota(t), Poil_\nu(t))$$
- $B(t)$ the state at time t of the whole dynamic system including species biomass and the common consumed resource namely
$$B(t) = (B_1(t), B_2(t), B_3(t), B_{res}(t))$$
Since $B(t)$ depends on strategies u and scenarios ω, we also use the notation $B(t, u, \omega)$.
- $I_k(B, u)$ the instantaneous indicator of the goal k depending on both the state and the control of the system.

We remind that the probability of viability underlying robustness criteria is defined by

$$\mathrm{ROB}(u) = \mathbb{P}_\omega\,(\text{Constraints } (17), (18), (19), (20) \text{ holds } \forall t) = \mathbb{E}_\omega\left[\prod_t \prod_k \mathbb{1}_{\mathbb{R}_+}(I_k(B(t,u,\omega), u(t)) - I_k^{\lim})\right]$$

with $I_k^{\lim}$ the tipping thresholds of goal k.

More specifically, for the two decision periods t_1 and t_2, the ROB* strategy consists in following stochastic optimization problem with respect to decisions $u(t)$ under uncertainties $\omega(t)$:

$$\max_{u(t_1)} \mathbb{E}_{\omega_1}\left[\prod_{t=t_1}^{t_2-1}\prod_k \mathbb{1}_{\mathbb{R}_+}(I_k(u(t_1), B(t, u(t_1), \omega_1)) - I_k^{\lim}) \max_{u(t_2,\omega_1)} \mathbb{E}_{\omega_2}\left[\prod_{t=t_2}^{T}\prod_k \mathbb{1}_{\mathbb{R}_+}(I_k(u(t_2,\omega_1), B(t, u(t_1), u(t_2), \omega_1, \omega_2)) - I_k^{\lim})\right]\right] \tag{A.2}$$

where $B(t, u(t_1), \omega_1)$ means the states (biomasses) of the dynamic system at time t for a scenario ω_1 over the period $t_1 - t_2$ while $B(t, u(t_1), u(t_2), \omega_1, \omega_2)$ means the states (biomasses) of the system at time t for a scenario (ω_1, ω_2) over the whole projection period $t_1 - T$. Using the very definition of expected value $\mathbb{E}$, we obtain

$$\max_{u(t_1)} \sum_{\omega_1} \mathbb{P}(\omega_1)\left[\prod_{t=t_1}^{t_2-1}\prod_k \mathbb{1}_{\mathbb{R}_+}(I_k(u(t_1), B(t, u(t_1), \omega_1)) - I_k^{\lim}) \max_{u(t_2,\omega_1)} \sum_{\omega_2} \mathbb{P}(\omega_2)\left[\prod_{t=t_2}^{T}\prod_k \mathbb{1}_{\mathbb{R}_+}(I_k(u(t_2,\omega_1), B(t, u(t_1), u(t_2,\omega_1), \omega_1, \omega_2)) - I_k^{\lim})\right]\right] \tag{A.3}$$

The optimal control problem outlined above is then transformed into a more conventional mathematical optimization problem.

$$\max_{u(t_1)} \max_{\substack{u(t_2,\omega_{1,1})\\ u(t_2,\omega_{1,2})\\ \dots\\ u(t_2,\omega_{1,K_1})}} \sum_{i=1}^{K_1}\sum_{\omega_2} \mathbb{P}(\omega_{1,i})\mathbb{P}(\omega_2) \prod_{t=t_1}^{t_2-1}\prod_k \mathbb{1}_{\mathbb{R}_+}(I_k(u(t_1), B(t, u(t_1), \omega_1)) - I_k^{\lim}) \\ \prod_{t=t_2}^{T}\prod_k \mathbb{1}_{\mathbb{R}_+}(I_k(u(t_2,\omega_{1,i}), B(t, u(t_1), u(t_2,\omega_{1,i}), \omega_{1,i}, \omega_2)) - I_k^{\lim}) \tag{A.4}$$

In this formulation, the number of unknown variables equals the number of controls u (4) multiplied by the number of scenarios (4) + 1. To approximate this optimal value (a viability probability) and determine the optimal control (efforts), we rely on the optimization function 'optim-ga' in the scientific software SCILAB.

Fig. A.8: Share of the different species GW (green) AW in (yellow) and CRC (brown) in the catches across strategies ROB and BAU.

A.5.3 Additional information on the transition strategy for enforcement control

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Patrol efforts for the transition strategy are equal to their initial value at first time t_1 of projections, namely $G^{\text{TRANS}}(t_1) = G(t_1)$ while, between periods t_1 and t_2, they read :

$$G^{\text{TRANS}}(t+1) = G^{\text{TRANS}}(t) + \delta 1_G^{\text{TRANS}}(t) G^{\text{TRANS}}(t) \; with \; \delta 1_G^{\text{TRANS}}(t) = \min\left(\delta E, \frac{G^*(t_1) - G(t_1)}{(t_2 - t_1) G^{\text{TRANS}}(t)}\right) \tag{A.5}$$

Between last periods t_2 and T, we also impose the following dynamics

$$G^{\text{TRANS}}(t+1) = G^{\text{TRANS}}(t) + \delta 2_G^{\text{TRANS}}(t) G^{\text{TRANS}}(t) \quad \text{where} \quad \delta 2_G^{\text{TRANS}}(t) = \min\left(\delta E, \frac{G^*(t_2) - G^{\text{TRANS}}(t_2)}{(T - t_2) G^{\text{TRANS}}(t)}\right) \tag{A.6}$$

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