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From fork to fish: The role of consumer preferences on the sustainability of fisheries

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Abstract

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Abstract The increasing consumption of seafood products raises concerns over the sustainability of marine ecosystems. We examine the role of consumer preferences on seafood demand and consequently on the sustainability of fisheries. Our analysis relies on a bio-economic model combining a demand derived from a CES utility depending on different fish species, a mixed fishery supply based on the Schaefer production function, a market equilibrium and a multispecies resource-based dynamics. Using both a steady-state approach and bio-economic viability goals, we identify analytical conditions on consumer preferences making it possible to balance biodiversity conservation with viable profits. We derive policy recommendations in terms of eco-labels for the sustainability of fisheries and the underlying seafood system. We exemplify the analytical results with the coastal fishery in French Guiana.

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Contents

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1 Introduction

Fisheries are facing many pressures endangering their sustainability, like climate change, pollution and overfishing (Halpern et al., 2008; Badjeck et al., 2010; Srinivasan et al., 2010; Hardy et al., 2013; Halpern et al., 2015; Cooley et al., 2022). The livelihoods, nutrition and food security of billions of people depend on the sustainability of these fisheries (Béné et al., 2007; Jacquet and Pauly, 2008; Fao, 2020; Lancker et al., 2019; Loring et al., 2019). In that regard, there is an antagonism between the worldwide growing demand for fish and the need to sustainably manage fisheries in a way that protects ecosystems, but also promotes social and environmental justice (Brunner et al., 2009; Costello et al., 2020). In that context, our article investigates how to foster the sustainability of fisheries through a demand approach and consumer preferences.

Our work relates to the Sustainable Development Goal (SDG) n.12 and the Sustainable Development Goal n.14, which promote "Sustainable consumption and production" and "conserve and sustainably use marine resources for sustainable development" [1]. Indeed, unsustainable consumption leads to strong degradation of ecosystems (Myers and Worm, 2003; Pauly and Maclean, 2003; Brunner et al., 2009). According to the Food and Agricultural Organization (FAO), it is becoming increasingly urgent to implement worldwide dietary transition (Fischer and Garnett, 2016; Tilman and Clark, 2014). For a sustainable diet, the FAO recommends consuming small quantities of seafood products, which should come from certified fisheries (Fischer and Garnett, 2016). Reducing the consumption of animal products in favour of plant-based products is a key for sustainability (Van Dooren et al., 2014; Sabate and Soret, 2014; Aleksandrowicz et al., 2016; Lacour et al., 2018), but fish has a role to play for health and food security at a local but also global level (Van Dooren et al., 2014; Béné et al., 2015). In small-scale fishing communities, fish is most of the time the only source of protein (Loring et al., 2019). As a transition strategy, fish can be used as a meat replacement in high-meat eating countries, because it causes less ecological pressure than meat (Van Dooren et al., 2018; de Boer et al., 2020)

Consumer choices, and in particular that of a more sustainable consumption, are based on a wide variety of motivations, ranging from social responsibility to specific individual needs (Oken et al., 2012; Piligrimienė et al., 2020). Vermeir and Verbeke (2006) shows that more sustainable and ethical food consumption can be stimulated by increasing the involvement of the consumer, i.e. by making him aware that his personal values correspond to more sustainable criteria. Values play an important role in the purchase decision (Holbrook et al., 1999; Sánchez-Fernández and Iniesta-Bonillo, 2006; Gallarza et al., 2011). The PCE (Perceived Consumer Effectiveness) is also an important element: it describes the fact that the consumer is convinced that his individual efforts can contribute to solving the problem (Ellen et al., 1991; Verbeke et al., 2007): for the consumer's behaviour to change, he must be convinced that this will have a real impact (Roberts, 1996). Worldwide, consumers are more and more aware of the necessity of environmental protection [2]. Consumer consumption and purchase of the product studied in this article, fish, depend on a variety of parameters, ranging of course from price and taste qualities (such as flavour, odour and appearance), but also perceived health benefits (or risks, like pollution), childhood

[1] Sustainable development goals: List of the 17 Sustainable Development Goals by 2030, adopted by all United Nations Member States (193 countries) in 2015.

[2] Indeed, sustainable consumption is preferred to other products by more than 70% of consumers, and about 50% of consumers in China are willing to pay 10% more for sustainable products than for classics products (this phenomenon is amplified with millennials) (Wan et al., 2018; Zhang and Wang, 2021)

habits, ease of preparation as well as availability of the product. Other qualities can influence the act of purchase, such as the method of production (wild or farmed) and preservation (fresh, frozen, canned, smoked), the country of origin, the marketing around a product and the presence or absence of a label (Brécard et al., 2009; Carlucci et al., 2015).

In that context, ecolabels (Salladarré et al., 2010; Jonell et al., 2016; Giacomarra et al., 2021) can play a major role for the rise of consumer cognizance about sustainability issues. Indeed, labels allow for a better differentiation of products and thus encourage consumers to buy products that lead to a better sustainability of food systems for instance by distinguishing between labelled and non-labelled products (Roheim and Zhang, 2018). Since their introduction in the late 1990s, fishery sustainability certification have become a major ingredient of marine conservation strategies. Many of these programs emerged largely from increased concerns within civil society that current stock management and policy have failed in ensuring the sustainability of fisheries (Sainsbury, 2010). The key function of these programs is to differentiate fisheries through a set of standards relating to stock status, management practices, and ecosystem impacts. Multi-tier labels (Nadar and Ertürk, 2021) is an alternative that provide a ranking in terms of environmental impact and sustainability.

The specific objectives of this article to contribute to sustainable seafood systems consists in investigating and quantifying the effect of demand through one large retailer's preferences (hereafter called consumer preferences) on the bioeconomic performances of multi-species fisheries. By bio-economic performances, we mean both biodiversity, profitability and consumer utility scores. We here assume that consumer preferences can be modified and controlled through eco-labels and in particular through multi-tier ranking. To quantify these bio-economic effects, we draw on a model articulating a demand derived from a CES utility depending on different fish species, a mixed fishery supply based on the Schaeffer producer function, a market equilibrium and a multispecies resource-based dynamics. Combining a steady-state approach and a bio-economic viability assessment, we exhibit mathematical conditions on consumer preferences making it possible to balance biodiversity conservation with viable catches, profits and consumer utility. Consequently, we suggest policy recommendations based on ecol-labels for the sustainability of fisheries and the seafood systems. The analytical findings are illustrated on the coastal fishery in French Guiana which constitutes an interesting and challenging case study in terms of sustainability and seafood system as it relies on a very rich tropical marine biodiversity, artisanal and non selective fishing activities while the fishing production is consumed only locally.

The paper is organized as follows: Section 2 introduces the bio-economic model; Section 3 details the results with analyses of sustainable preferences and the potential role of eco-label in this context; in Section 4 as an example we apply our model to the case study of small scale fishery in French Guiana . Section 5 offers a conclusion.

2 Bio-economic model

Our analysis relies on a model combining a demand derived from a CES utility depending on different fish species, a fishery supply based on the Schaeffer producer function, a market equilibrium and a multispecies resource-based dynamics.

2.1 Demand

We first focus on the demand side. We assume that the utility of consumers depends on several fish species $i = 1, \dots, n$. Here, we used the Constant Elasticity Substitution (CES) utility function type to capture consumer demand (Sato, 1975; Tohamy and Mixon Jr, 2004; Stoeven, 2014; Quaas et al., 2020):

$$U(Q(t), a) = \left(\sum_{i=1}^{n} a_i Q_i(t)^\sigma \right)^{\frac{1}{\sigma}}, \tag{1}$$

where $Q_i(t)$ stands for the quantity of species i at time t while parameters $a_i > 0$ refers to the consumer preferences. The higher ai is, the higher the consumer appreciates this product.What we consider here as consumer preferences are a set of beliefs that lead to a certain consumption behavior. These preferences can therefore be modified if an external factor changes the beliefs linked to the preferences. The constant elasticity of substitution, $\sigma > 0$, represents to what extent the consumer is ready to replace the quantity of one consumed species with another. When $\sigma < 1$, the products are weakly substitutable, while at the opposite $\sigma > 1$ means that the products are substitutable. The higher σ is, the more substitutable the products are.

Consumers are here assumed to be myopic and rational. More specifically, they are supposed to maximize with respect to quantities $Q_i(t)$ the difference between their utility arising from $Q_i(t)$ minus their costs of buying $Q_i(t)$ which depend on price $p(t) = (p_1(), \dots, p_n(t))$ as follows: :

$$\max_{Q_1(t),\dots,Q_n(t)} U(Q_1(t), ..., Q_n(t), a) - \sum_i p_i(t) Q_1(t) \tag{2}$$

Applying first order optimality conditions, we obtain the relation:

$$p_i(t) = \frac{\partial U}{\partial Q_i}(Q_i^*, a) = \left(\sum_{j=1}^{n} a_j Q_j^*(t)^\sigma \right)^{\frac{1}{\sigma}-1} a_i Q_i^*(t)^{\sigma-1}, \tag{3}$$

where $Q_i^*(t)$ refers to the optimal quantity of species i at time t. Equation (3) relates to a multispecies inverse demand function as the price emerges as a function of quantities of the different species. The use of this inverse demand allows for an endogenisation of fish prices with respect to consumer preferences a_i and quantities $Q_i(t)$, that is to say dynamic prices (Barten and Bettendorf, 1989; Eales et al., 1997; Holt and Bishop, 2002). From the inverse demand formulation (3), we can also derive an explicit formulation for the preference parameters a_i with respect to Q and p as proved in Appendix B.3. Such a formula is used for the calibration of current preferences in the example and Section 4 with the equation (30).

2.2 Supply and market equilibrium

We now focus on the supply side. For sake of simplicity, we consider that there is only one type of fleet which harvests the different consumed species. We first assume the production is based on Schaefer production functions. Thus, catches of species i reads :

$$H_i(t) = q_i e(t) x_i(t), \tag{4}$$

where $e(t)$ is the fishing effort (typically days at sea or number of boats) at time t, x_i is the state (biomass, abundance, ...) of species i at time t, while q_i corresponds to the catchability for species i.

Profit is defined as the difference between the incomes induced by fishing and cost of operating:

$$\pi(t) = \sum_i p_i(t)H_i(t) - C(e(t)), \tag{5}$$

where $p_i(t)$ is again the price of species i while C is the cost function of fishing effort. We here assumed that the cost function is quadratic as in (Clark et al., 2006; Péreau et al., 2012; Pizarro and Schwartz, 2018)

$$C(e) = c_0 + c_1 e + \frac{c_2}{2}e^2 \tag{6}$$

Above c_0 stands for the fixed cost while c_1 are cost parameters that can relate to fuel or ice consumption for operating. Quadratic cost c_2 can be related to risk aversion (Tromeur et al., 2021)[3].

We now integrate the inverse demand function (3) into the profit (5). We assume a situation of pure competition (Arrow and Debreu, 1954), which implies several conditions in the model. In particular, we consider that the demand for each good depends on the price of the good and that supply and demand coincide on the market. In other words, we assume that the price is such that

$$H_i(t) = Q_i^*(t), \tag{7}$$

where demand $Q_i^*(t)$ is characterized above in (3). We deduce that

$$\begin{aligned} p_i(t)H_i(t) &= p_i(t)Q_i^*(t) && (8)\\ &= \left(\sum_{j=1}^n a_j Q_j^*(t)^\sigma\right)^{\frac{1}{\sigma}-1} a_i Q_i^*(t)^\sigma && (9)\\ &= \left(\sum_{j=1}^n a_j \left(q_j e(t) x_j(t)\right)^\sigma\right)^{\frac{1}{\sigma}-1} a_i (q_j e(t) x_j(t))^\sigma && (10)\\ &= e(t)\left(\sum_{j=1}^n a_j \left(q_j x_j(t)\right)^\sigma\right)^{\frac{1}{\sigma}-1} a_i (q_j x_j(t))^\sigma && (11) \end{aligned}$$

[3] Assuming for instance that the costs of energy c_1 are stochastic and that the expected value of a quadratic utility is considered for the profit in the following sense

$$\mathbb{E}(U(\pi)) = \mathbb{E}(\pi) - a\mathbb{V}ar(\pi) = pH - \overline{c_1}e - a\sigma_1^2 e^2$$

where a is a proxy for risk aversion while $\overline{c_1}$ and σ_1 are the mean and standard deviation of linear costs c_1 respectively.

Therefore we obtain the following formulation for the profit

$$\pi(x(t), e(t)) = e(t) \left(\sum_{j=1}^{n} a_j \left(q_j x_j(t) \right)^{\sigma} \right)^{\frac{1}{\sigma}-1} \sum_{i} a_i (q_j x_j(t))^{\sigma} - C(e(t)) \tag{12}$$

$$= e(t) \left(\sum_{j=1}^{n} a_j \left(q_j x_j(t) \right)^{\sigma} \right)^{\frac{1}{\sigma}} - C(e(t)) \tag{13}$$

$$= e(t) U \Bigg(Cpue(x(t)), a \Bigg) - C(e(t)) \tag{14}$$

where the vector of captures by unit of effort $Cpue(x(t))$ is defined by

$$Cpue_i(x(t)) = q_i x_i(t)$$

Now we consider that, in the fishery, fishers are price-taker, myopic and rational (Péreau et al., 2012). Myopic means that fisher act without considering the consequences of his action on the future. Thus the agents optimize their individual profit as follows:

$$\max_{e(t) \geq 0} \pi(x(t), e(t)). \tag{15}$$

Applying again first order optimality conditions on profit formulation (14) and assuming for now that the optimal effort $e^*(t)$ is positive, we can explicitly determine the optimal effort:

$$e^*(t) = \frac{U\Bigg(Cpue(x(t)), a \Bigg) - c_1}{c_2}. \tag{16}$$

We observe that this optimal effort $e^*(t)$ captures all the bio-economic ingredients as it depends on both consumer features through a and σ and supply features through costs parameter c_1, c_2 and catchability q_i. As expected, it decreases with unit cost of effort c_1 as well as risk aversion proxy c_2. As we focus on the role of consumer preferences a, we hereafter denote the optimal effort by

$$e^*(x, a) = \frac{U\Bigg(Cpue(x), a \Bigg) - c_1}{c_2}. \tag{17}$$

2.3 Multispecies resource-based dynamics

Here, we rely on resource-based dynamics for the different species i in line with resource-based models (Tilman and Sterner, 1984; Tilman, 2020). We thus assume that the n fish species compete for the consumption of a common resource denoted by $y(t)$. For every species i, the state $x_i(t+1)$ at time t+1 depends on the state $x_i(t)$, the state of the resource $y(t)$, and optimal fishing effort $e^*(t)$ (defined in (16)) as follows:

$$x_i(t+1) = x_i(t) \Bigg(1 - m_i + g_i y(t) - q_i e^*(t) \Bigg). \tag{18}$$

In the dynamics (18), m_i stands for the mortality rate of the stock i while g_i is the resource-based per capita growth of species i. As in the Tilman model of mechanistic resource-based species competition (Tilman and Sterner, 1984; Tilman, 2020), the dynamics of the state $y(t)$ of the resource depends on the consumption of the different fish species through the relation:

$$y(t+1) = y(t)\left(1 - \sum_{i=1}^{N} s_i x_i(t)\right) + I \tag{19}$$

where I is the external input (source) for this resource and s_i the consumption rate of the predatior i on the resource. As an alternative to the classical theory of Lotka–Volterra about species competition, Tilman introduced this approach based on a mechanistic resource-based model of competition between species, where the growth of species is restricted by resource availability. A major interest of the resource-based model lies in an exclusion principle. This principle states that, in presence of a multi-species competition for a common resource, the species with the lowest resource requirement in equilibrium will competitively replace all other species after a certain time period. Aarssen (1983) state that two essential conditions must operate for the exclusion principle to take place: "(1) Their resource requirements must overlap beyond a certain critical point; and (2) one of them must be a superior competitor for these common resource requirement". This resource-based species competition is used and recommended to implement the economic management of an ecosystem in (Brock and Xepapadeas, 2002; De Lara and Doyen, 2008; Bøhn et al., 2008; Béné and Doyen, 2008; Gomes et al., 2021).

Hereafter, we examine to what extent some consumer preferences a could relax the exclusion principle and entail more sustainability for biodiversity, catches and profits.

2.4 Sustainability goals

By sustainable states, we here mean that the optimal effort is positive

$$e^*(x,a) = \frac{U\big(Cpue(x), a\big) - c_1}{c_2} \geq 0. \tag{20}$$

and the biodiversity is large enough in the sense of species richness

$$Bio(x) \geq 2, \tag{21}$$

where species richness of the ecosystem state x is defined by $Bio(x) = \sum_{i=1}^{n} 1_{\mathbb{R}_*^+}(x_i)$ where $1_{\mathbb{R}_*^+}(.)$ is the characteristic (boolean) function of non negative reals $\mathbb{R}^+$. Of interest is that such effort positivity requirement entails positivity of both optimal catches through equation (4) as well as profit. This occurs because such a effort constraint implies a positive gross or quasi-rent (revenue minus variable cost)[4].

[4] As the optimum of a quadratic function, quasi-rent indeed simplifies to

$$\pi^* + c_0 = \frac{c_2}{2}(e^*)^2$$

To address the compatibility of the bio-economic constraints (20), (21) with the dynamics (18) and (19) of the ecosystem, we rely on the mathematical concept of viability kernel (Aubin, 1991; Béné et al., 2001; De Lara and Doyen, 2008; Oubraham and Zaccour, 2018):

$$\mathbb{V}iab(a) = \{(x_1(0), \ldots, x_n(0), y(0)) \mid (18),\ (19),\ (20),\ (21) \text{ hold true for any time } t \geq 0\} \quad (22)$$

Hereafter, we aim at identifying consumer preferences a such that $Viab(a)$ is non empty.

3 Analytical results

3.1 Sustainable consumer preferences

Our main analytical result exhibits below conditions for consumer preferences a_i balancing biodiversity and economic viability throughout time in the sense of the viability kernel (22). At this stage, we need to introduce key values y^* and e^* as follows:

$$\begin{cases} y^* = \min_{i,j} \frac{m_i * q_j - m_j * q_i}{g_i * q_j - g_j * q_i} = \frac{m_{i^*} q_{j^*} - m_{j^*} q_{i^*}}{g_{i^*} q_{j^*} - g_{j^*} q_{i^*}} \\ e^* = \frac{g_{i^*} y^* - m_{i^*}}{q_{i^*}} \end{cases} \quad (23)$$

We then obtain conditions for the non-emptiness of the viability kernel.

Proposition 1 *Assume that parameters (q, m, g) are such that y^* and e^* are strictly positive. Then there exists consumer preferences a^* such that $\mathbb{V}iab(a^*) \neq \emptyset$. Sufficient bio-economic conditions for sustainable consumer preferences $a^* = (a^*_1, a^*_2, \ldots, a^*_n)$ are:*

$$a^*_{i^*} q^\sigma_{i^*} + a^*_{j^*} q^\sigma_{j^*} = \left(\frac{y^*(s_{i^*} + s_{j^*})(c_2 e^* + c_1)}{I} \right)^\sigma \quad (24)$$

In particular, in that case, the state (X^*, y^*) such

$$X^*_{i^*} = X^*_{j^*} = \frac{I}{y^*(s_{i^*} + s_{j^*})}, \quad X^*_i = 0 \ \forall i \neq i^*, j^* \quad (25)$$

satisfies $(X^*, y^*) \in \mathbb{V}iab(a^*)$.

The Proof of Proposition 1 is detailed in Section B.1 of the Appendix. This proposition thus provides conditions for consumer preferences a_i promoting the sustainability of the fishery since it favors biodiversity with at least two viable species while also sustaining the profitability, activity and production of the fishery. The equality between two species states $X^*_{i^*} = X^*_{j^*}$ underlying the proposition can be relaxed as in the Proposition 2 below. However, such equality is of interest in terms of biodiversity metrics as it also guarantees a score of 2 for the Simpson index[5] which is a key indicator of biodiversity assessing the evenness among the different species.

[5] The Simpson index is defined by

$$Simpson(x) = \left(\sum_j^n \left(\frac{x_j}{\sum_l x_l} \right)^2 \right)^{-1}. \quad (26)$$

It is optimal and equals n in the case of equi-repartition $x_1 = x_2 = \ldots = x_n$.

We can also go further and delineate consumer preferences sustainable in the sense of Proposition 1, whenever we assume that the sum of preferences a_i is equal to 1 as in Quaas et al. (2020). At this stage; it is convenient to introduce the notation

$$x^* = \frac{I}{y^*(s_{i^*} + s_{j^*})}.$$

We then obtain an explicit formula for sustainable preferences.

Corollary 1 *Assume conditions of Proposition 1 on parameters* (q, m, g). *If the sum of* a_i *is equal to 1, sustainable consumer preferences are characterized by the following explicit formula:*

$$\begin{cases} a^*_{i^*} = 1 - a^*_{j^*} \\ a^*_{j^*} = \dfrac{(c_2 e^* + c_1)^\sigma - q_i^\sigma (x^*)^\sigma}{(x^*)^\sigma \left(q^\sigma_{j^*} - q^\sigma_{i^*}\right)} \\ a^*_i = 0, \ \forall i \neq i^*, j^* \end{cases}$$

The Proof of Corollary 1 is detailed in Section B.1.1 of the Appendix.

Proposition 2 *Assume conditions of Proposition 1 on parameters* (q, m, g) *and condition* (24) *on consumer preferences* a^*. *The viability kernel* $\mathbb{V}iab(a^*)$ *includes states* (X^*, y^*) *such that*

$$a^*_{i^*}(q_{i^*} X^*_{i^*})^\sigma + a^*_{j^*}(q_{j^*} X^*_{j^*})^\sigma = (c_2 e^* + c_1)^\sigma, \quad X^*_i = 0 \ \forall i \neq i^*, j^* \tag{27}$$

The Proof of proposition 2 is detailed in Section B.2 of the Appendix.

3.2 Labeling policies for sustainable mixed fisheries

The previous analytical results, together with their application to the case study in the following section 4, shows that consumer preferences a_i for the different species can be used to promote a bio-economic sustainability by preserving biodiversity while maintaining the economic activity through fishing profitability. Such finding highlights that it is possible to regulate fishing activities and manage biodiversity by the consumer side through market-based mechanisms. At this stage, we can wonder to what extent regulating agencies can apply such results. Based on results of section 3.1, the objective would consist in moving from current preferences denoted hereafter by a_i^{BAU} to sustainable preferences a_i^* defined in Proposition 1 or Corollary 1.

We here assume that the regulating agency targets sustainable preferences a_i^* in an inertial way, namely by limiting the changes in preferences of consumer with respect to the current situation a_i^{BAU}. Such a strategy reads:

$$\min_{a^* \text{ satisfying (24)}} ||a^* - a^{BAU}||^2 = \sum_i \left(a^*_i - a^{BAU}_i\right)^2, \tag{28}$$

where (24) refers to sustainability conditions for consumer preferences. The linear-quadratic problem (28) has an explicit unique solution[6] that is given by

$$\begin{cases} a^*_{i^*} = a^{BAU}_{i^*} + q^{\sigma}_{i^*}\left(q^{2\sigma}_{i^*} + q^{2\sigma}_{j^*}\right)^{-1}\lambda \\ a^*_{j^*} = a^{BAU}_{j^*} + q^{\sigma}_{j^*}\left(q^{2\sigma}_{i^*} + q^{2\sigma}_{j^*}\right)^{-1}\lambda \\ a^*_i = a^{BAU}_i & \text{if } i \neq i^*, j^* \end{cases} \tag{29}$$

with $\lambda = \left(\frac{c_2 e^* + c_1}{x^*}\right)^{\sigma} - q^{\sigma}_{i^*} a^{BAU}_{i^*} - q^{\sigma}_{j^*} a^{BAU}_{j^*}$. When regulating the demand-side with a sustainability purpose, key instruments are eco-labels (Wessells et al., 1999; Mason, 2006). Eco-labels support a demand-based approach to manage environmental problems. These eco-labels would lessen information asymmetry (Ward and Phillips, 2008) between producers and consumers on the sustainability of the underlying fishery, value chain and food system. The decision-maker could here choose a multi-tier design (Nadar and Ertürk, 2021).This multi-tier label system has been used on various occasions, in particular to inform about the nutritional quality of a food, for example via the Nutri-Score, which has been successfully applied in several European countries (Julia et al., 2018; Szabo de Edelenyi et al., 2019), or to classify products according to their environmental impact, such as the Planet-score label or the Eco-score label , both of which have been developed by the ADEME. Multi-tier labels can provide a ranking of sustainability and therefore assess the bio-economic performances of the fishery. The aim is to encourage or discourage the consumption of some species. Here one could figure out a 3-level colour scale depending on the comparison between a^{BAU}_i and $a^*_{i^*}$ as follows:

- **Green (sustainable) label**: $a^*_i > a^{BAU}_i$;
- **Red (at risk) label**: $a^*_i < a^{BAU}_i$;
- **White label** : $a^*_i = a^{BAU}_i$.

From optimal characterization (29), we can note that the sustainability tier and label strongly depend on the sign of the index λ. In particular, whenever $\lambda > 0$, both species i^* and j^* should be colored green. In contrast, whenever $\lambda < 0$, both species i^* and j^* should be colored red and considered at risk. Of interest is the fact that the sign of λ relies on the sustainability of the current consumer preferences a^{BAU} in the sense of equality (24).

Accounting for both the multi-species labelling, species interactions underlying the CES utility function in (3), the supply side and the market equilibrium, the combined effects of sustainability labels across the species prices can turn out complex. The example below illustrates such a complexity.

4 Example: the coastal fishery in French Guiana

To study the impact of consumer preferences on the sustainability of fisheries, we apply our bio-economic model and analytical results of Section 3 to the coastal fishery in French Guiana (South America) which has been already studied in Cissé et al. (2015); Gomes et al. (2021);

[6] We can use for instance the Lagrangian defined by

$$L(a,\mu) = \left(a^*_i - a^{BAU}_i\right)^2 + \mu\left(\left(\frac{c_2 e^* + c_1}{x^*}\right)^{\sigma} - q^{\sigma}_{i^*} a_{i^*} - q^{\sigma}_{j^*} a_{j^*}\right),$$

to derive first order optimality conditions.

Table 1: Parameters of the bioeconomic model for the case study in French Guiana.

Parameters	Unit	Species $i = 1$ AW	Species $i = 2$ GW	Species $i = 3$ CsC
Interaction species - resource $s_i * 10^6$		2.5	7.6	7.0
Catchability $q_i * 10^6$		3.4	0.7	0.6
Natural mortality $m_i * 10$		0.9	1.4	1.6
Growth efficiency $g_i * 10$		5.5	1.15	5.5
Initial stock $x_i(t_0 = 2006)$	Tons	21 394	34 695	59 212
Initial catches $Q_i(t_0 = 2006)$	Tons	156	50	75
Initial Prices $p_i(t_0 = 2006)$	(€/Kilo)	3.4	1.9	1.6
Initial Resource $y(t_0)$	Tons	282 625		
Resource input I	Tons	318 931		
Utility elasticity σ		1.4		
Risk aversion proxy c_2		0.109		
Variable costs c_1	(€/$Days_f$)	95		
Fixed costs c_0	(€/Quarter)	1640		

Cuilleret et al. (2022). This small-scale fishery is a multi-species and multi-fleet fishery landing about 3 000 tonnes of fish per year, worth € 9 million (US$ 9.78 million). The fishery harvests approximately 30 species in a non selective way. The fishery plays a key socio-economic role for the local population, both in terms of livelihoods and food security since the fish production is consumed only locally. The management of the fishery is currently based on the regulation of fishing effort, through a system of fishing licenses.

4.1 Sustainable consumer preferences, labels and scenarios

We draw on models from Gomes et al. (2021); Cuilleret et al. (2022) and data given by IFREMER Fisheries Information System (SIH) on catches and fishing effort from 2006 to 2017 as well as on selling prices of each species, variable costs, fixed costs. We here focus on three species: Crucifix Sea Catfish (CsC, *sciades proops*), Acoupa Weakfish (AW, *Cynoscion acoupa*) and Green Weakfish (GW, *Cynoscion virescens*). We also simplify the problem by aggregating the effort, catch and profit of the different fleets. Estimated parameters are detailed in Table 1.

To investigate the role of consumer preferences on the sustainability of this fishery, we contrast the trajectories of biomass, effort, catch, price and profit of three scenarios. The first scenario named 'Business as usual' (BAU, in black in Figures 1, 2 and 3) relies on current (estimated) consumer preferences a_i^{BAU}. The second scenario named sustainable (in blue) stems from Proposition 1 on sustainable preferences a_i^* along with the inertial strategy (29). A third intermediary scenario (in green) accounts for a progressive change of preferences between the BAU and sustainable preferences. Below we specified the mathematics and numerics underlying these three scenarios.

From the inverse demand formulation (3), we first derive an estimation for the current preference parameters a_i^{BAU}. We rely on mean prices[7] $p_i(t_0)$ and catches $Q_i(t_0)$ at year $t_0 = 2006$

[7] Such prices turn out to remain rather steady from this period as emphasized in Kersulec et al. (2021) from IFREMER Fisheries Information System

Table 2: BAU consumer preferences a_i^{BAU} and the sustainable preferences a_i^*.

	Acoupa Weakfish	Green Weakfish	Crucifix sea Catfish
BAU scenario a_i^{BAU}	100755	88464	63645
Sustainable scenario a_{i*}^*	5462	78503	63645
Sustainability Label color	Red	Red	White

detailed in Table 1. As proved in Appendix B.3, we can indeed write:

$$a_i^{BAU} = p_i(t_0)Q_i(t_0)^{1-\sigma}\left(\sum_{j=1}^{n} p_j(t_0)Q_j(t_0)^{\sigma-1}\right) \tag{30}$$

Table 2 displays the estimated values a_i^{BAU} for the three species AW, GW and CsC.

Regarding the computation of the optimal consumer preferences a_i^* underlying the second scenario (blue), we need to first determine the values y^*, i^*, j^*, e^* and x^*. We obtain $y^* = 337603$ tons, $i^* = AW$, $j^* = GW$, $e^* = 1638$ fishing days at sea per quarter and $x^* = 88966$ tons. We deduce the sustainable preferences a_i^* displayed in Table 2. Comparing a_i^* and $_i^{bau}$, we obtain red labels for AW and GW while CSC is white.

The third scenario assumes that changing consumer behavior takes time, as it is embedded in the consumer's habits (Amel et al., 2017; White et al., 2019). To take into account a progressive transition in the consumer's purchasing behavior towards a more sustainable consumption shape and therefore towards a_i^*, the 'progressive sustainable' scenario (green in the figures) relies on a constant change Δ ($\Delta < 0$ in the example) applied at each period t as follows:

$$a_i(t+1) = a_i(t) + \Delta \ with \ \Delta = \frac{(a_i^* - a_i^{bau})}{(T - t_1)} \tag{31}$$

Here we have t_1, first quarter of 2018, T=2100 and $a_i(t_1) = a_i^{bau}$, so at the end of the scenario $a_i(T) = a_i^*$. In Figures 1, 2 and 3, we compare the three scenarios and examine the ecological, economic and social effects of the reduction in consumer preferences underpinning a^* or $a(t)$ and potentially induced by a policy of sustainability labeling.

4.2 Ecological effects

The biomass trajectories of Figure 1 show, as expected, that the two scenarios related to sustainable preferences a^*, green or blue, promote the diversity of species in the ecosystem as compared to the BAU scenario. The viability of both the AW and CsC species is indeed at stake in the long run for BAU while only the CsC collapses for the two 'sustainable' scenarios. The three scenarios mainly differ in terms of AW biomass. In particular, we can note that, on average over the projection period from 2018 to 2100, the state of the AW with the sustainable projection based on consumer preferences a^* in blue is 2.5 times higher than in the case of a_i^{BAU} and 1.22 times higher with the progressive sustainable scenario $a(t)$ in green. By contrast, in every scenario, the CSC collapses and is extinct from 2050. Such an outcome arises from the exclusion principle underlying the resource-based dynamics and the highest resource requirement of this species

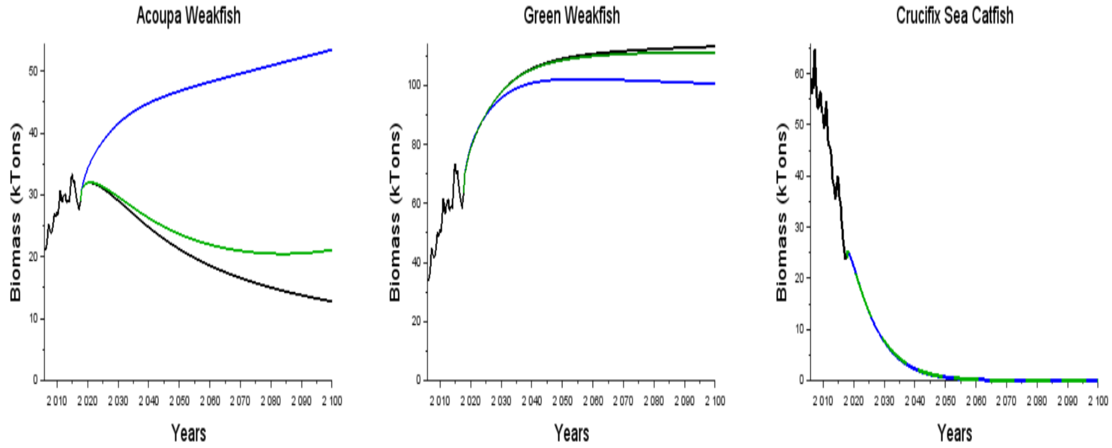

Fig. 1: Biomass trajectories $x_i(t)$ for the three species AW, GW and CSC from 2006 to 2100 across three scenarios depending on consumer preferences a_i. The black curve represents the historical period (2006-2018) and from 2018, the projections of BAU scenario (based on consumer preference a^{BAU}). The blue trajectories represents the stocks with the scenario based on sustainable preferences a^*. The green curve represents the species stocks for the progressive sustainable scenario $a_i(t)$ as defined in equation (31).

as compared to the two others [8]. As regards the GW species, its biomass projections turn out slightly lower in the case of sustainable scenarios and in particular for the sustainable scenario a^*. More globally, the qualitative patterns of GW are opposite to those of AW. This is due again to the ecological competition (for the resource y) between the species and the resource-based dynamics. Said differently, the increase of AW in the case of the sustainable scenario (blue) leads to a lower availability of the resource $y(t)$ for the GW which alters its growth. Moreover, when the long run equilibrium is reached, after 2100, the two viable species are equally distributed, as captured by equation (25).

Our results are in line with the perspective implementing a sustainable diet recommended by the FAO (Fischer and Garnett, 2016): a decrease in preferences for these fish species, leads to a decrease of their consumption which entails their ecological viability.

4.3 Economic and social effects

Of interest for food security and the sustainability of the seafood system is the long term gain of catches displayed by Figure 2 (second column) for the sustainable preferences (blue) as compared

[8] The resource requirement of species, noted $y_i(t)$, is expressed according to the following equation:

$$y_i(t) = \frac{m_i + q_i e^*(t)}{g_i} \tag{32}$$

Over the whole period from 2006 to 2100, in the BAU scenario, $y_{i=CsC}(t)$ is on average 23% higher than that of the GW, the $y_{i=AW}(t)$ is on average 4% higher than that of the GW. In sustainable scenarios at equilibrium $y_{i=AW} = y_{i=GW} < y_{i=CsC}$. See the Appendix D for the evolution of the resource requirements of the different species in the BAU scenario .

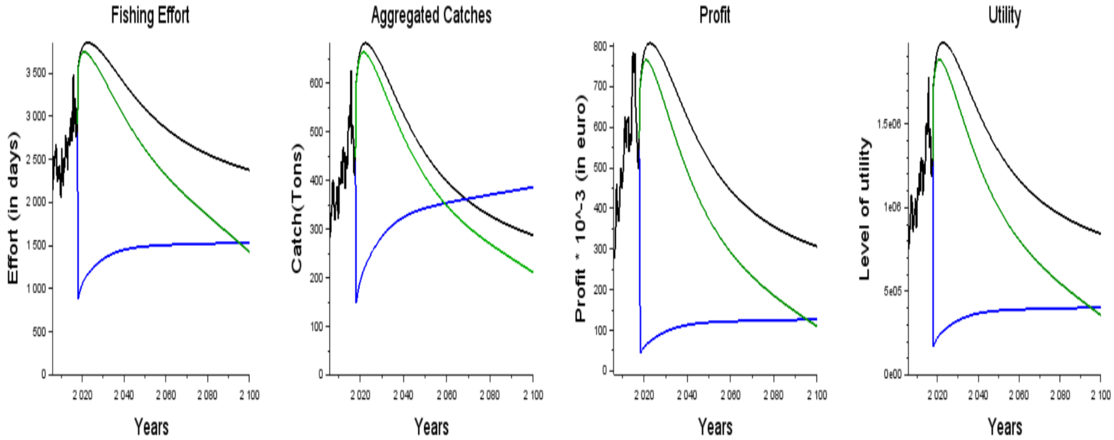

Fig. 2: Trajectories of fishing effort, aggregated catches (over species), profit and utility from 2006 to 2100 across three scenarios depending on consumer preferences a_i. The black line represents the historical period and, from 2018, the economic scores with the preferences a_i^{BAU} underpinning BAU scenario. The blue line represents the scenario with the sustainable consumer preferences a^*. The green line represents the scenario with the progressive sustainable consumer preferences $a(t)$.

to BAU (black). Such gains occur from about 2070 and continue to increase after. These long term gains for food production stems from the gains in terms of biodiversity and in particular the viability of the AW species. However the sustainable scenario (blue) implies a major decrease in fishing effort in the first periods when compared to BAU scenario (black). The blue fishing effort is indeed, on average over the projection period, about 50% lower than BAU effort. In that respect, the progressive sustainable fishing effort (green) represents an interesting transition and intermediary strategy for effort toward sustainability with a reduction of effort limited to only 20 % with respect to BAU on average over the projection period. Figure 2 (third column) shows that the scenario a^* yields also a major decrease of profits in the first years aligned with the reduction of fishing effort. However, as expected by the analytical results and the underlying viability goals, these profits remain viable (positive) over time. In addition, after the first period of abrupt reduction, the profits start to grow as opposed to the decrease of profits in the BAU scenario after 2030. The progressive sustainable (green) scenario leads to a more gradual decrease in effort and profit. At this stage we can postulate that a transition in consumer preference exists where both long and short term bio-economic performances can be balanced.

Figure 3 illustrates the dynamic prices as a function of a_i^{BAU} and a_{i*}^*. These dynamic prices are obtained from the inverse demand of equation (3). Because of the form of the inverse demand which involves crossed and substitution effects between species, it is difficult to determine a direct link between the preferences of a species i and the price of a species i. In particular, with the abrupt scenario a^* (blue), although consumer preferences a_1^* and a_2^* are both lower than current preferences a_1^{BAU} and a_2^{BAU}, the prices of AW and GW have opposite dynamics in the first periods. Indeed, AW price increases while GW price increases. In the long run (after 2070), the lower preferences a^* for the two species AW and GW entail lower prices than those of

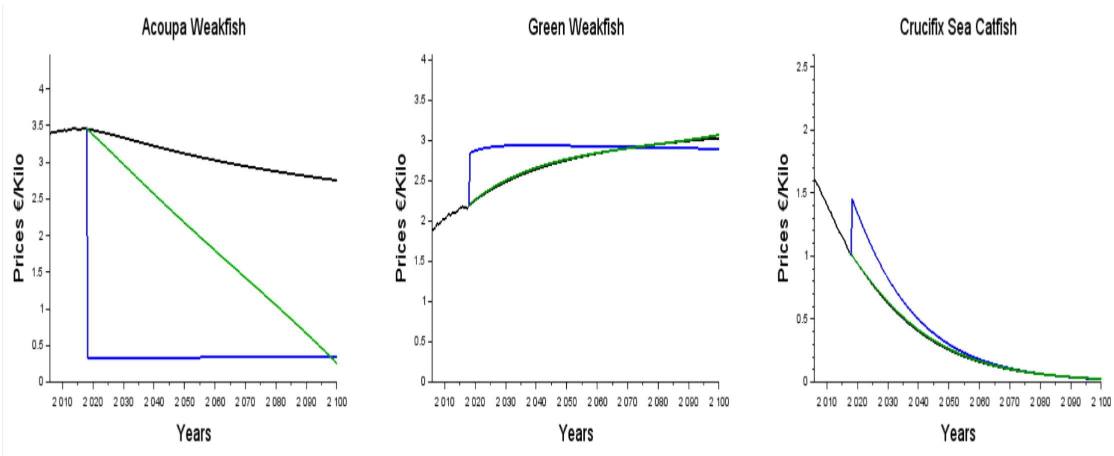

Fig. 3: Trajectories of prices of fished species AW, GW and CSC (in €/ Kilo) from 2006 to 2100 across three scenarios depending on consumer preferences a_i. The black line represents the historical period and from 2018 profit, effort and aggregated catches with the a_i^{BAU} : BAU scenario. The blue line represents the scenario with the sustainable consumer preferences a^*. The green line represents the scenario with the progressive sustainable consumer preferences $a(t)$

BAU scenario. Such result on prices is more intuitive and arises from the convergence towards equilibrium values in the long run. As regards the green (progressive) sustainable scenario, not surprisingly, the price decline is more gradual and represents on average a decrease of 37 % compared to the BAU scenario price. Figure 2 represents the level of consumer utility related with each of the scenarios. The implementation of the sustainable scenario implies here a decrease in the level of preferences, as $a_i^* < a_i^{BAU}$, and a decrease in the level of consumer utility associated with the consumption of these species.

5 Conclusion and perspectives

This article provides analytical results on whether consumer preferences are sustainable or not in the context of mixed fisheries where one fleet harvests several fish species. The analysis relies on a bio-economic model articulating a demand derived from the optimization of a CES utility with several fish species, a mixed fishery supply based on the maximisation of the rent of fishing activities, a market equilibrium along with a multispecies resource-based dynamics. Using a steady-state approach, we identify analytically conditions on consumer preferences making it possible to balance biodiversity conservation with viable catches and profits. We deduce bio-economic policies in terms of or eco-labels (or sustainability labels) for the fisheries.

By integrating consumer, fishermen and fish mechanisms within the bio-economic model, the work relates to 'fish to fork' viewpoint and food systems (Belchior et al., 2016) which justifies the title of the paper. The concept of food system has gained prominence in recent years amongst both academics and policy-makers. Experts from diverse disciplines have in particular discussed the nature and origin of the “unsustainability” of our modern food systems (Béné et al., 2019) We contribute to this field of research by designing market-based sustainability strategies for seafood systems.

Our work also contributes to seafood certification and ecolabeling as sustainability pathways (Swartz et al., 2017). Since their introduction in the late 1990s, fishery sustainability certification have become a major ingredient of marine conservation strategies. Many of these programs emerged largely from increased concerns within civil society that current stock management and policy have failed in ensuring the sustainability of fisheries (Sainsbury, 2010). The key function of these programs is to differentiate fisheries through a set of standards relating to stock status, management practices, and ecosystem impacts. The eco-labeling strategy we propose in our paper differs from these programs by focusing on species rather than on fleets or fisheries. We indeed suggest to color species on the market as green (sustainable) or red (at risk) depending on the viability of current consumer preferences. In other words, the policy consists in encouraging (or discouraging) the consumption and demand of fished species to increase (or decrease) the supply of these species through the optimal (myopic) fishing effort and market-based mechanisms.

Another originality of the paper is to address sustainability goals with a viability modelling approach and bio-economic thresholds (Béné et al., 2001; De Lara and Doyen, 2008; Schuhbauer and Sumaila, 2016; Doyen et al., 2017; Oubraham and Zaccour, 2018; Doyen et al., 2019). Here bio-economic viability goals relate both to biodiversity conservation and strictly positive efforts and profits. The novelty arises from the use of this viability approach on a food system integrating consumers, producers and the ecosystem in line with the 'fork to fish' viewpoint. However, we must confess that the viability analysis is not complete since it does not identify so far the viability kernel (viable states) as a whole nor all viable controls. Here the focus is on the viability of steady states which paves the road for a more extensive viability study and more viable policies in particular regarding consumer preferences and eco-labels.

Another contribution of the paper is to apply the model and the analytical findings to the French Guiana coastal fishery. In particular, the account of the demand side and consummer preferences represent a key improvement with respect to the previous bio-economic works and scenarios of Cissé et al. (2015); Gomes et al. (2021); Cuilleret et al. (2022). Our results show that consumer preferences have a great impact on the viability of two Acoupa Weakfish, a keystone species of the ecosystem and of the fishing economy of French Guiana. With the current consumer preferences, our projections highlights the un-sustainability of this species. Consequently, we propose eco-labels, red (at risk) for Acoupa Weakfish and also Green Weakfish, to recover the viability of AW and more globally of the coastal fishery in French Guiana. Therefore, we argue that it is possible to foster biodiversity together with profits for this tropical fishery, in particular with market-based mechanisms.

Of course numerous improvements of the current work are possible. At the theoretical stage, key improvements of the current work include modification of the utility function. We can refine the shape of the utility function by considering various important points in sustainable consumption like "warm-glow" effect, "cold prickle" effect or social norm (Andreoni, 1990, 1995; Grolleau et al., 2012). Different refinements of utility functions are elaborated in Van't Veld (2020) depending on the consumer attitude one wishes to consider. Also, we suggest to decision-maker the use of eco-label to promote some product, but label are not perfect. Consumer must remain vigilant in the label because sometimes labels are used for marketing purposes and label industrial fisheries that are unsustainable or practice mislabelling (Sumaila et al., 2017; Le Manach et al., 2020), hence the importance of educating consumers to avoid greenwashing practices (Brécard et al., 2012). Integrating retailers within the supply chain is another challenge for our bio-economic model and analysis. At the level of the case study, it would be interesting to add to our model other dimensions that have a strong impact on the Guianese case study: global warming (Diop et al., 2018; Gomes et al., 2021), illegal fishing and swim bladder trade (Kersulec et al., 2021). Regarding variable costs relating mainly on the oil price, more dynamic and/or uncertain features should be taken into account. More globally, paying more attention to food security and catch viability goals is another key challenge in particular for tropical small-scale fisheries and seafood systems (Béné et al., 2007; Arthur et al., 2022).

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A Appendix

B Analytical results

B.1 Proof of Proposition 1

Consider y^*, x^*, e^* defined in equation (23) and assume for sake of simplicity that the species i are ranked in such a way that the max underlying y^* is realized for species $i^* = 1$, $j^* = 2$ in the sense that

$$\begin{cases} y^* = \min_{i,j} \frac{m_i * q_j - m_j * q_i}{g_i * q_j - g_j * q_i} = \frac{m_1 * q_2 - m_2 * q_1}{g_1 * q_2 - g_2 * q_1} \\ x^* = \frac{I}{y^*(s_1+s_2)} \\ e^* = \frac{g_1 y^* - m_1}{q_1} \end{cases} \tag{33}$$

Assume now that parameters (q, m, g) are such that y^* and e^* are strictly positive.

Consider now consumer preferences a_i such that

$$a_1 q_1^\sigma + a_2 q_2^\sigma = \left(\frac{y^*(s_1+s_2)(c_2 e^* + c_1)}{I} \right)^\sigma \tag{34}$$

Let us now prove that the state (X^*, y^*) such $X^* = (x^*, x^*, 0, \ldots, 0)$ satisfies $(X^*, y^*) \in \mathbb{V}iab(a)$. From (34), we first have

$$U(Cpue(X^*), a)^\sigma = a_1(q_1 x^*)^\sigma + a_2(q_2 x^*)^\sigma = (x^*)^\sigma \left(a_1 q_1^\sigma + a_2 q_2^\sigma\right) = (x^*)^\sigma \left(\frac{y^*(s_1+s_2)(c_2 e^* + c_1)}{I} \right)^\sigma = (c_2 e^* + c_1)^\sigma \tag{35}$$

Consequently $e^*(X^*, a) \geq e^* > 0$.

Furthermore, since $X_1^* = X_2^* = x^* > 0$, the species richness of X^* is such that

$$Bio(X^*) \geq 2.$$

Furthermore, from the very definition of e^* in (23), we have

$$-m_1 + g_1 y^* - q_1 e^* = 0,$$

Moreover, from the definition of y^* in (23), we also have

$$e^* = \frac{g_1 y^* - m_1}{q_1} = \frac{g_2 y^* - m_2}{q_2}$$

Thus, we can deduce that

$$-m_2 + g_2 y^* - q_2 e^* = 0,$$

From the definition of x^*, we also see that (X^*, y^*) is an equilibrium of the resource dynamics (19) since:

$$y^* = y^*(1 - x^*(s_1+s_2)) + I.$$

Therefore (X^*, y^*) is a steady state of both dynamics (18) and (19). As (X^*, y^*) satisfies also the constraints 20) and (21) for any time $t \geq 0$, it is a viable state and belongs to the viability kernel namely $(X^*, y^*) \in \mathbb{V}iab(a)$ (De Lara and Doyen, 2008; Aubin, 1991).

B.1.1 Proof of Corollary 1

We have

$$U(cpue(x), a) = e^* * c_2 + c_1 \tag{36}$$

and

$$U(cpue(t), a) = \Big(\sum_{j=1}^{n} a_j q_j^\sigma x_j(t)^\sigma\Big)^{\frac{1}{\sigma}} \tag{37}$$

So:

$$(e^* * c_2 + c_1)^\sigma = \sum_{j=1}^{n} a_j q_j^\sigma x_j(t)^\sigma \tag{38}$$

So at equilibrium, with *species richness* $= 2, x_{j^*}^* = x_{i^*}^*$ and $\sum_{a_i} = 1$:

$$(e^* * c_2 + c_1)^\sigma = a_j q_j^\sigma x_j(t)^\sigma - (1 - a_j) q_j^\sigma x_j(t)^\sigma = a_j q_j^\sigma x^*(t)^\sigma - (1 - a_j) q_j^\sigma x^*(t)^\sigma \tag{39}$$

Therefore :

$$a_{j^*}^* = \frac{(c_2 e^* + c_1)^\sigma - q_i^\sigma (x^*)^\sigma}{(x^*)^\sigma \left(q_{j^*}^\sigma - q_{i^*}^\sigma\right)} \tag{40}$$

B.2 Proof of Proposition 2

By definition,

$$U\Big(Cpue(x), a\Big) = \left(\sum_{j=1}^{n} a_j \left(q_j x_j(t)\right)^\sigma\right)^{\frac{1}{\sigma}} \tag{41}$$

and according to Equation 17

$$U\Big(Cpue(x), a\Big) = e^* * c_2 + c_1 \tag{42}$$

So

$$\left(\sum_{j=1}^{n} a_j \left(q_j x_j(t)\right)^\sigma\right)^{\frac{1}{\sigma}} = e^* * c_2 + c_1 \tag{43}$$

Therefore,

$$a_{i^*}^* (q_{i^*} x_{i^*})^\sigma + a_{j^*}^* (q_{j^*} x_{j^*})^\sigma = (c_2 e^* + c_1)^\sigma \tag{44}$$

At equilibrium

$$s_i x_i^* + s_j x_j^* = \frac{I}{y^*} \tag{45}$$

From this definition 45, we see that (x_i^*, x_j^*, y^*) is an equilibrium of the resource dynamics (19) since:

$$y^* = y^*(1 - (s_i x_i^* + s_j x_j^*)) + I.$$

Moreover, from the definition of y^* in (23), we also have

$$e^* = \frac{g_1 y^* - m_1}{q_1} = \frac{g_2 y^* - m_2}{q_2}$$

Thus, we can deduce that

$$-m_2 + g_2 y^* - q_2 e^* = 0,$$

Therefore (x_i^*, x_j^*, y^*) is a steady state of both dynamics (18) and (19).

B.3 Consumer preferences for business as usual scenario

From section Demand 2.1, we obtain an explicit equation for the preference parameter a_i for (Q_j, Q_i, p_i, p_j)

$$a_i(Q) = p_i Q_i^{1-\sigma} (\sum_{j=1}^{n} p_j Q_j)^{\sigma - 1} = p_i Q_i^{1-\sigma} (p_i Q_i + \sum_{j=1}^{n-1} p_j Q_j)^{\sigma - 1} \tag{46}$$

Proof of Equation 46 is developed below We have the consumer program (CP) :

$$CP = U(Q(t), a) - \sum_{j=1}^{n} p_j Q_j \tag{47}$$

So,

$$\frac{\partial CP}{\partial Q_i} = 0 \iff \frac{1}{\sigma}\left(\sum_{j=1}^{n} a_j Q_j^{\sigma}\right)^{\frac{1}{\sigma}-1} a_i \sigma Q_i^{\sigma-1} = p_i \tag{48}$$

$$a_i Q_i^{\sigma}\left(\sum_{j=1}^{n} a_j Q_j^{\sigma}\right)^{\frac{1}{\sigma}-1} = p_i Q_i \tag{49}$$

$$\sum_{i=1}^{n} a_i Q_i^{\sigma}\left(\sum_{j=1}^{n} a_j Q_j^{\sigma}\right)^{\frac{1}{\sigma}-1} = \sum_{i=1}^{n} p_i Q_i \tag{50}$$

Furthermore, as $\sum\limits_{j=1}^{n} a_j Q_j = \sum\limits_{i=1}^{n} a_i Q_i$ we can deduce that

$$\sum_{j=1}^{n} a_j Q_j^{\sigma}\left(\sum_{j=1}^{n} a_j Q_j^{\sigma}\right)^{\frac{1}{\sigma}-1} = \sum_{i=1}^{n} p_i Q_i \tag{51}$$

$$\left(\left(\sum_{j=1}^{n} a_j Q_j^{\sigma}\right)^{\frac{1}{\sigma}}\right)^{\sigma} = (\sum_{j=1}^{n} p_j Q_j)^{\sigma} \tag{52}$$

With (52) and (48), we obtain:

$$p_i = a_i Q_i^{\sigma-1}\left(\left(\sum_{j=1}^{n} p_j Q_j\right)^{\sigma}\right)^{\frac{1}{\sigma}-1} \tag{53}$$

Thus, we can conclude that

$$a_i = p_i Q_i^{1-\sigma}\left(\sum_{j=1}^{n} p_j Q_j\right)^{\sigma-1} = p_i Q_i^{1-\sigma}\left(p_i Q_i + \sum_{j=1}^{n-1} p_j Q_j\right)^{\sigma-1} \tag{54}$$

C Calibration for the case study of French Guiana

The calibration of this resource based model is realised by applying a least squares method in order to minimize the distance between historical catches and the catches estimated by our model. This reads as follows:

$$\min_{\text{Parameters}} \sum_{t=t_0}^{t_1} \sum_{i=1}^{N=3} \left(H_i^{data}(t) - H_i(t)\right)^2. \tag{55}$$

and to obtain the value of the sigma coefficient and c_2, we apply a least squares method in order to minimize the distance between historical effort and the effort estimated by our model, according to Equation 16, from 2006 to 2017 :

$$\min_{\sigma\ c_2} \sum_{t=t_0}^{t_1} \sum_{i=1}^{N=3} \left(E^{data}(t) - E(t)^*\right)^2 \tag{56}$$

In line with Cissé et al. (2015); Gomes et al. (2021), the model described previously has been calibrated using quarterly data and time series of landing and fishing effort from the IFREMER Fisheries Information System for fleets of the small scale fishery in French Guiana[9]. The period of calibration we use here to estimate the parameters of the model goes from $t_0 = 2006$ to $t_1 = 2018$ (decomposed in quarters). We consider a single fleet and our fishing effort and landings correspond to the fishing effort and landings aggregated by fleet type.

The parameters (Table 1) to be identified in Equation (18) are the natural mortality rate m_i of each species i, the catchability q_i of each species, the terms of interaction s_i between the species and the resource,g_i the resource-based per capita growth of species, the initial biomass $x_i(t_0)$ of each species, as well as the external input of the resource I(t). Moreover, since we here consider a quarterly time step, periods t_0 and t_1 corresponds to the first quarter of 2006 and the last quarter of 2017 respectively. Furthermore, we used a genetic algorithm from the Scilab software[10] to solve numerically the minimization problem 55 and 56.

Figure 4 compares aggregated catches. We see that theses historical and estimated catches are close and follow the same trends.

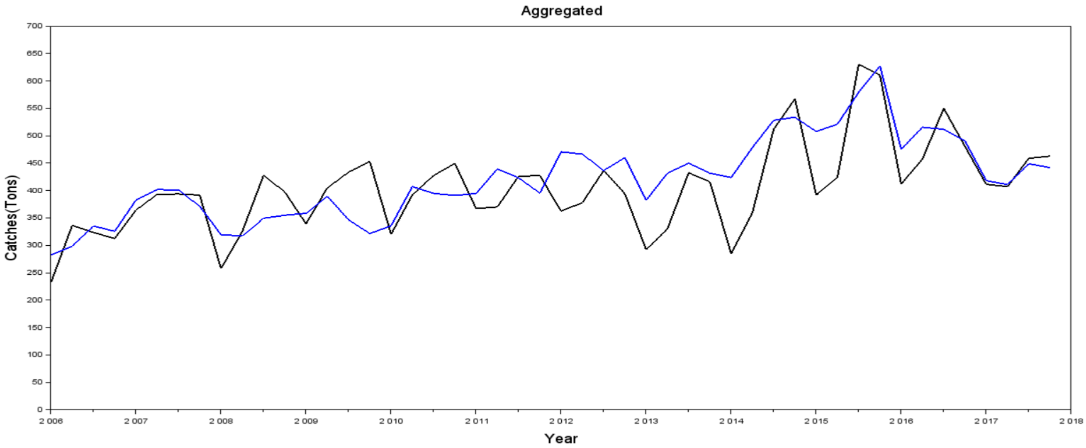

Fig. 4: Comparison of aggregated catches from the first quarter of 2006 to the last quarter of 2017. The blue line represents the catches, $H(t)$, derived from the model. The black line represents the historical data, $H_{data}(t)$.

Figure 5 compares historical effort with estimated effort from Equation 16 according to the minimization problem 56.

[9] Since 2006, IFREMER observers reconstruct the proceedings of the trip with legal fishers on a daily basis (type of vessel, fishing technology used, fishing effort, landings by species and associated costs). To estimate fishing effort, the SIH uses the monthly activity calendars and counts the number of days spent at sea per vessel. From the landing data for a given effort, IFREMER observers determine the quarterly landings for the different types of fleets and landing points using the rule of three (Weiss et al., 2018).

[10] See https://www.scilab.org

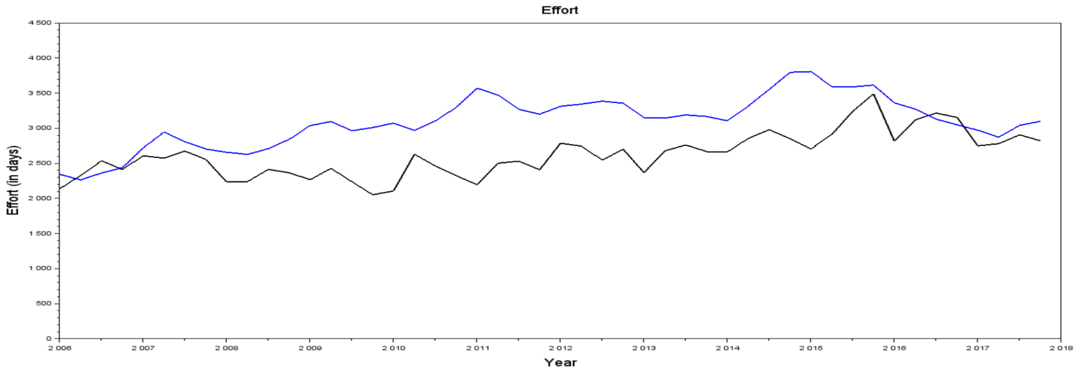

Fig. 5: The blue line represents the effort, $E(t)$, derived from the model. The black line represents the historical effort, $E_{data}(t)$.

To simplify, we consider here that there is only one form of preference a_i which varies with the sigma according to Equation 46 [11].

D Resource requirement

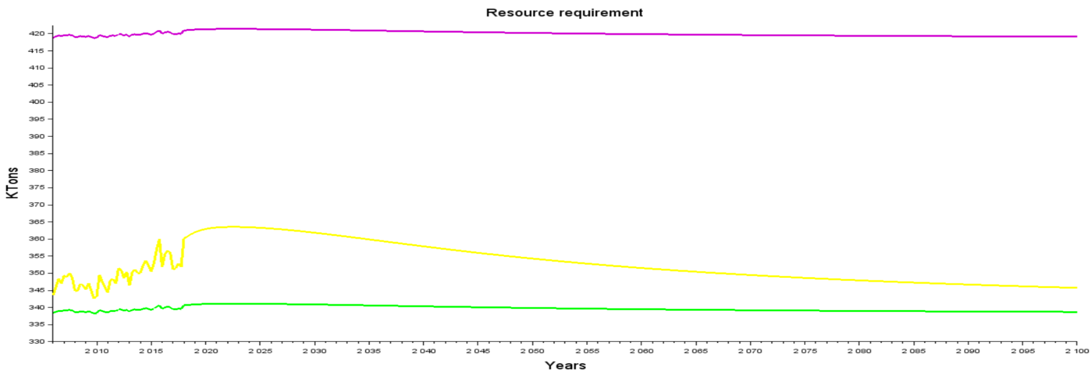

Fig. 6: Resource requirement for the BAU scenario. The purple line represents the CsC resource requirement. The yellow line represents the AW resource requirement. The green line represents the GW resource requirement.

[11] View value of consumer preferences in Table 2

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