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# A bio-economic model for the ecosystem-based management of the coastal fishery in French Guiana

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## Un modèle bio-économique de gestion écosystèmique de la pêche côtière en Guyane Française

### Résumé

*Cet article propose une modélisation théorique de gestion éco-systémique appliquée à la pêche côtière en Guyane Française. Un modèle multi-espèces, multi-flottilles intégrant une dynamique de type Lokta-Volterra est développé. Cette pêcherie artisanale, caractérisée par un haut niveau de biodiversité halieutique, des flottilles non sélectives, doit aujourd'hui répondre à une hausse de la demande locale due à la croissance démographique. Le modèle est calibré sur 13 espèces et 4 flottilles à partir de données mensuelles d'effort et de prélèvement entre 2006 et 2009. Plusieurs types de scénarios de prélèvement sont envisagés allant du status quo, à la fermeture, à des stratégies économiques ou de viabilité. Dans chaque cas, les performances en termes de préservation de la biodiversité marine et les performances socio-économiques sont analysées et comparées. Nos résultats montrent que la demande croissante et la profitabilité des flottilles sont soutenables mais qu'une perte significative de biodiversité ne peut pas être évitée.*

**Mots-clés :** pêche artisanale, biodiversité, soutenabilité, profitabilité, sécurité alimentaire, multi-espèces, multi-flottilles

## A bio-economic model for the ecosystem-based management of the coastal fishery in French Guiana

### Abstract

*This paper offers a theoretical and empirical modeling for ecosystem-based fishery management (EBFM). A multi-species and multi-fleets model integrating Lokta-Volterra trophic dynamics and profit functions is developed for the coastal fishery of French Guiana. This small-case fishery constitutes a challenging example with high fish biodiversity, several non selective fleets and a potentially increasing local food demand due to demographic pressure. The dynamic model is calibrated with thirteen species and four fleets using catch and effort data on a monthly basis from 2006 to 2009. Several contrasting fishing scenarios including status quo, total closure, economic and viable strategies are simulated and compared from both biodiversity preservation and socio-economic performance viewpoints. We show that fishing outputs including food supply and profitability of fleets can be sustained although a significant loss of biodiversity cannot be avoided.*

**Keywords:** Small-scale fishery, biodiversity, sustainability, profitability, food security, multi-species, multi-fleets

**JEL: Q22, Q56**

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## 1. Introduction

Marine fishery resources are under extreme pressure worldwide. According to recent studies (FAO, 2004; Garcia and Grainger, 2005), three quarters of fish stocks are maximally exploited or over-exploited. Moreover, the proportion of marine fish stocks which are intensively exploited is growing. Hence sustainability is nowadays a major concern of international agreements and guidelines to fisheries management (FAO, 1999; ICES, 2004). Standard approaches for the sustainable management of fisheries such as MSY (Maximum Sustainable Yield), MEY (Maximum Economic Yield) or ICES (International council for the Exploration of the Sea) precautionary approaches usually address every exploited species separately (Grafton et al., 2007). These kinds of management are apparently not effective enough to avoid loss of biodiversity, over-exploitation and overcapacity worldwide (Hall and Mainprize, 2004). The Ecosystem Approach for Fisheries (EAF) or Ecosystem-Based Fisheries Management (EBFM) advocate an integrated management of marine resources to promote sustainability (FAO, 2003). Such a management requires first to account for the complexity of ecological mechanisms that encompass community dynamics, trophic webs, geographical processes and environmental uncertainties (habitat, climate). Furthermore, by putting emphasis on sustainability, it strives to balance ecological, economic and social objectives for present and future generations and to cope with a large range of goods and services provided by marine ecosystems (Jennings, 2005) including both monetary and non monetary values.

Finding a way to implement the EBFM approach effectively and practically remains unclear and challenging. Regarding such a difficult goal, models, indicators, reference points and adaptive management strategies are essential in implementing the approach. Plaganyi (2007) provides an overview of the main types of modeling approaches and analyses their relative merits for fisheries assessment in an ecosystem context. Modeling approaches and metrics useful for planning, implementing, and evaluating EBFM are also discussed in Marasco et al. (2007), with particular emphasis on management strategy evaluation. For ecosystem indicators, a recent review is proposed by Cury and Christensen (2005) - see also Rice (2000).

In particular, Link (2005) emphasizes the need for a multi-criteria approach to achieve ecological, economic and social objectives.

This article deals with the sustainable management of a multi-species and multi-fleets fishery in an ecosystem based perspective. It especially focuses on the small scale fishery of French Guiana. This case study is challenging with respect to the EBFM approach because of the complexities underlying the ecosystem with a high fish biodiversity (tropical area) together with several non selective fleets impacting such biodiversity and a human local demographic pressure potentially affecting the demand and consequently the production of this fishery. Moreover it is acknowledged that small-scale fisheries are poorly managed because there is a lack of tools adapted to this complexity, while these fisheries are crucial to sustain many communities especially in developing countries (Garcia, 2008).

## 2. Case study

The continental shelf of French Guiana is a tropical ecosystem under the influence of the Amazon estuary, as the whole North Brazil Shelf Large Marine Ecosystem (LME) that contains a high biodiversity (Leopold, 2004). With 350 km of coastline, French Guiana benefits from an 130,000 $km^2$ exclusive economic zone (EEZ) including 50,000 $km^2$ of continental shelf. The coastal fishery operates to 10 miles offshore between 0 and 20 m depths. Several landing points are spread along the coastline and this fishery currently concerns about 200 wooden boats. Bellail and Dintheer (1992) identified four kinds of vessel : "pirogues" (P), "canots créoles" (CC), "canots créoles améliorés" (CCA) and "tapouilles" (T). The "pirogues" are canoes with out-board engine, fishing for periods of a few hours essentially in estuaries and using ice stored in an old fridge. The "canots créoles" are vessels more adapted to sea navigation as compared to "pirogues". The "canots créoles améliorés" have cabins and ice tanks allowing several fishing days. The "tapouilles" are wider boats with cabin desk and in-board gazole engine. The gears used are drifting or fixed nets, mesh sizes between 40 and 100 $mm$. It is to note that the length of gill nets, the number of days spent at sea and the area of fishing activities have an influence on the pressure imposed over the resources, so the quantity of landed fishes differs from a type of fleet to another. On the numerous coastal species, 30 are exploited and about 15 species, including weakfishes, catfishes and sharks, represent more than 90% of the production. The annual landings are estimated around 2,700 tonnes for last years as detailed in the Ifremer[1] Information System (`http://www.ifremer.fr/sih`). The coastal fishery has a great importance for the socio-economic context of all the small cities along the coastline where more than 90% of the population is located. However, the first comprehensive assessment of this fishery really began in 2006 with daily surveys in each landing point to get the fishing effort and production data associated. Economic assessment started in 2009 with a survey on production costs and selling prices carried out on the field.

Coastal fishery in French Guiana remains broadly informal despite 1) the foundation of the cooperative of the fishers of French Guiana (Codepeg) in 1982, 2) the installation of a system of professional licenses in territorial waters by the regional committee of fisheries in 1995, 3) the progressive application of national and European regulations (role of crew, security visits of ships, etc.). There is no quota for catches, and no limitation concerning exploited species and their size. This coastal fishery provides an interesting case study from the perspective of ecosystem management. Since the biodiversity associated with this resource does not seem threatened and the economic activity of this fishery appears stable, the current state is usually postulated as safe. Nevertheless, the sustainability of the fishery can be questioned mainly because of the local fish demand. Indeed, demographic projections suggest a 100% increase of the local population over 30 years. Consequently, the demand for local fish could increase as the fishing pressure. Therefore arises the question whether both the marine ecosystem and the fishing sector can cope with such changes in fishing demand and food security.

To deal with such issues, this paper proposes a theoretical and empirical modeling, related to an ecosystem-based fishery management (EBFM). A multi-species and multi-fleets model

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[1] French Research Institute for Exploration of the Sea.

integrating Lokta-Volterra trophic dynamics and profit functions is used. The dynamic model is calibrated on a monthly basis with thirteen species and four fleets (“P”, “CC”, “CCA”, “T”) through catch and effort data from 2006 to 2009 derived from the Ifremer fishery information system. The ecological and economic performances of contrasting fishing scenarios including “status quo”, “total closure”, “economic” and “viable” strategies are examined. The paper is structured as follows. Section 3 is devoted to the description of the ecosystem-based model, bio-economic indicators and scenarios. Section 4 provides the results related to the fishing scenarios with respect to biodiversity and socio-economic indicators. Results are discussed in terms of sustainability, EBFM and management tool in section 5. The last section concludes.

## 3. Methods

The numerical implementations of the model are realized with the scientific software SCILAB 5.2.2 [2].

### 3.1. The ecosystem-based model

Among the thirty exploited species, thirteen are selected for the model as shown in table (1). These species represent 88% of the total landing for years 2006 to 2009. Is added a virtual fourteenth species which stands for all the other marine producers. A potential trophic web displayed in figure (1) is built with these selected species, according to their diet (Leopold, 2004) and their trophic level (table 1).

The ecosystem-based model is a multi-species, multi-fleets dynamic model described in discrete time with a monthly step. The states of the species in the ecosystem-based model are supposed to be governed by a complex dynamic system based on Lotka-Volterra trophic interactions and fishing efforts from the different fleets which play the role of controls in the system. Thus, at each step $t$, the biomass $B_i(t+1)$ $(kg)$ of species $i$ at time $t+1$ depends

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[2] SCILAB (`http://www.scilab.org`) is an open-source software dedicated to scientific calculus.

on other stocks $B_j(t)$ and fishing efforts $e_k(t)$ of fleet $k$ (time spent in sea, in hour) through the relation:

$$B_i(t+1) = B_i(t)\left(1 + r_i + \sum_{\textit{species}\ j=1}^{14} S_{i,j} B_j(t) - \sum_{\textit{fleets}\ k=1}^{4} q_{i,k} e_k(t)\right)$$

Here $r_i$ stands for the intrinsic growth rate of the population $i$ and $S_{i,j}$ the trophic effect of species $j$ on species $i$ (positive if $j$ is a prey of $i$ and negative if $j$ is a predator of $i$). The parameter $q_{i,k}$ measures the catchability of species $i$ by fleet $k$. It corresponds to the probability that a biomass unit of species $i$ is caught by a boat of fleet $k$ during one fishing effort unit. The fleet $k = 1$ is associated with "canots creoles", $k = 2$ with "canots créoles améliorés", $k = 3$ with "pirogues" and $k = 4$ with "tapouilles".

The catches $h_{i,k}$ of species $i$ by fleet $k$ at time $t$ are thus given by the Schaefer production function:

$$h_{i,k}(t) = q_{i,k} e_k(t) B_i(t) \tag{1}$$

*3.2. Model and calibration inputs*

Values used to define the model parameters come from different sources. Daily observations (catches and fishing efforts) from the landing points all along the coast are available from January 2006 up to December 2009. The literature (Leopold (2004), Fishbase[3]) provides qualitative trophic interactions and intrinsic growth rates to start the calibration. Initial stocks, catchabilities, trophic intensities and refined intrinsic growth rates values of this ecosystem have been estimated by a least square method. This method consists of minimizing the error between the monthly observed catches $h_{i,k}^{\text{data}}$ and the one $h_{i,k}$ simulated by the model as defined in equation (1):

$$\min_{B_0;\ S;\ q;\ r} \sum_{t=2006}^{2009} \sum_{i=1}^{13} \sum_{k}^{4} \left(h_{i,k}^{\text{data}}(t) - h_{i,k}(t)\right)^2$$

Here $(B_0;\ S;\ q;\ r)$ is the set of parameters to be identified. $B_0$ is the vector $(14 \times 1)$ of initial stocks (December 2005), $S$ the matrix $(14 \times 14)$ of trophic interactions, $q$ the matrix

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[3] `http://www.fishbase.org`

$(14 \times 4)$ of catchabilities and $r$ a vector $(14 \times 1)$ of intrinsic growth rates.

### *3.3. Model outputs : ecological indicators*

After the calibration, ecological and economic indicators are computed to assess the performance of both the ecosystem and the fishery. We first focus on biodiversity index. Although the choice of a biodiversity metric remains controversial as pointed out in Magurran (2007), we selected the species richness, Simpson and marine trophic indexes.

**Species richness.** The species richness (SR) gives the estimated number of species represented in the ecosystem. It is measured by an indicator function depending on the abundances $N_i(t)$ computed as the ratio between the biomass $B_i(t)$ and the common weight $w_i$ of each species, derived from the Fishbase information system:

$$\mathrm{SR}(t) = \sum_i \mathbf{1}_{\mathbb{R}_+^*}(N_i(t)), \quad \text{with} \quad N_i(t) = \frac{B_i(t)}{w_i}$$

where the set $\mathbb{R}_+^*$ is defined by $\mathbb{R}_+^* = \{N_i \mid N_i > 0\}$, the function $\mathbf{1}_{\mathbb{R}_+^*}$ corresponds to the characteristic function[4] of the set $\mathbb{R}_+^*$. Through the constraint in $\mathbb{R}_+^*$, it is assumed that a species vanishes whenever its abundance falls to zero (Worm et al., 2006). It has to be noted that rare species have a huge impact in the species richness index.

**Simpson's diversity.** The Simpson index (SI) is expressed as:

$$\mathrm{SI}(t) = 1 - \sum_i f_i^2(t), \quad \text{with} \quad f_i(t) = \frac{N_i(t)}{N(t)} \tag{2}$$

where $N(t) = \sum_i N_i(t)$. The index SI measures the probability that two individuals belong to the same species. The index varies between 0 and 1. A perfectly homogeneous community would have a Simpson diversity index score of 1. Such a metric gives more weight to the more abundant species. The addition of rare species causes only small changes in the value.

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[4] $\mathbf{1}_{\mathbb{R}_+^*}(x) = \left\{ \begin{array}{ll} 1 & \text{if } x > 0 \\ 0 & \text{otherwise} \end{array} \right\}$

**Marine trophic index.** Trophic level measures the position of a species in a food web, starting with producers (eg phytoplankton, plants) at level 0, and moving through primary consumers that eat primary producers (level 1) and secondary consumers that eat primary consumers (level 2), and so on. In marine fishes, the trophic levels vary from two to five (top predators). The marine trophic index (MTI) of the ecosystem is computed from the trophic level of each species $T_i$ (table 1) and their relative abundances $f_i$ (equation 2), (Pauly et al., 1998; Pauly and Watson, 2005):

$$\mathrm{MTI}(t) = \sum_{i=1} f_i(t) T_i$$

### 3.4. Model outputs : economic indicators

We now turn to the assessment of the fishing sector through productive and profitability values of the fishery.

**Food supply.** We first consider the total catches ($H(t)$) within the fishery which play the role of the food supply:

$$H(t) = \sum_k \sum_i h_{i,k}(t)$$

The supply of seafood has to be compared with the food demand which is predicted to increase at a significant rate for the years to come with population growth.

**Profits.** The profit ($\pi_k(t)$) of each fleet $k$ is derived from the landings of each species, fixed costs ($cf_k$) and variable costs ($cv_k$) as follows:

$$\pi_k(t) = (1 - \beta_k)\left(\sum_i p_{i,k} h_{i,k}(t) - cv_k e_k(t)\right) - cf_k$$

where $\beta_k$ stands for the crew share earnings and $p_{i,k}$ the price of species $i$ landed by fleet $k$. Share contract is the salary system commonly used in this fishery for "canots créoles améliorés" (fleet k=2) and "tapouilles" (fleet k=4) . Crews are remunerated as a part of the landing value lessened by the variable costs. "Canots créoles" (fleet k=1) and "pirogues" (fleet k=3) crews are mostly made up of boat owners sometimes assisted by a family member. If there is a pay system for these fleets, it differs from one owner to another. To simplify, wages are not computed or deducted in the profit calculus for “canots créoles” and “pirogues” ($\beta_k = 0\%$ ). We assume $\beta_k = 50\%$ for the other fleets. The variable costs include fuel consumption, ice, food and lubricants. Equipment depreciation, maintenance and repairs are incorporated in the fixed costs. Fish selling prices are contingent on marketing channels, the “pirogues” ones are the highest, their catches are directly sold to consumers. The prices, variable costs and fixed costs are those collected for 2008 (table 2) and they are assumed to remain fixed for the duration of the simulation. The total profit $\Pi(t)$ is the sum of profits of all fleets:

$$\Pi(t) = \sum_k \pi_k(t)$$

### *3.5. Fishing scenarios*

From the calibrated model, scenarios are simulated according to different fishing efforts over forty years. We distinguish four scenarios: “closure” (CL), “status quo” (SQ), “economic” (PV) and “co-viability” (CVA). The ecological and economic indicators mentioned previously are evaluated for these four scenarios.

**The “closure” scenario (CL).** This scenario corresponds to the implementation of a no fishing zone on the whole French Guiana coastal area.

- $e_k(t) = 0$, for every fleet $k = 1, 2, 3, 4$ and for every $t = t_1, t_1 + 1, \ldots, t_f$,

where $t_1$ and $t_f$ correspond to January 2010 and December 2050 respectively.

**The “status quo” scenario (SQ).** This scenario simulates a stable fishing effort corresponding to the mean pattern of the efforts between 2006 and 2009:

- $e_k(t) = \bar{e}_k$, for every fleet $k = 1, 2, 3, 4$ and for every $t = t_1, t_1 + 1, \ldots, t_f$,

with $\bar{e}_k$ the mean efforts between 2006-2009 for the fleet $k$, captured in the equation below:

$$\bar{e}_k = \frac{1}{t_1 - 1} \sum_{t=t_0}^{t_1-1} e_k(t)$$

where $t_0$ and $t_1 - 1$ correspond to January 2006 and December 2009 respectively.

**The "economic" scenario (PV).** This scenario maximizes the present value of all the future profits aggregated among the fleets ($\Pi(t)$):

$$\max_{e_k(t)} \sum_{t=t_1}^{t_f} (1+\gamma)^{-t}\Pi(t)$$

where $\gamma$ is the discount factor (we assume that $\gamma = 3\%$).

The efforts $e_k(t)$ represent a control strategy that can be adapted every five years[5]. In other words, eight decisions $(e_k(t_1), e_k(t_2), \cdots, e_k(t_8))$ are available for each fleet $k$ as follows

$$e_k(t) = \begin{cases} e_k(t_1) & \text{for } t = t_1, ..., t_1 + 60 \\ e_k(t_2) & \text{for } t = t_2, ..., t_2 + 60 \\ \vdots & \\ e_k(t_8) & \text{for } t = t_8, ..., t_8 + 60 \end{cases} \tag{3}$$

where $t_1$ and $t_n = t_{n-1} + 60$, for $n = 2$ to 8, are decisive months.

**The "co-viability" scenario (CVA).** It intends to provide a satisfying balance throughout time between profitability of fleets, biodiversity and local food demand. Thus levels of fishing efforts $e_k(t)$ are sought that comply with the bio-economic constraints below:

- A profitability constraint:

$$\pi_k(t) \geq 0, \qquad \forall\ t = t_1, ..., t_f, \quad \forall\ k = 1, \ldots, 4$$

- A species richness constraint:

$$\mathrm{SR}(t) \geq 11, \qquad \forall\ t = t_1, ..., t_f$$

- Food security constraint:

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[5] A refined time decomposition for fishing intensities (for instance a one year time step) would have improved the analysis but requires very demanding computation times. However strategic changes each five years capture some intertemporal flexibility in fishing strategy. We plan to expand the time decision in future models.

$$H(t) \geq H(2009) \cdot (1+d)^t, \qquad \forall\, t = t_1, ..., t_f \ ,$$

where $d$ corresponds to the population growth rate. According to demographic scenario of the doubling of French Guiana population about 2040 (INSEE, 2011), we set $d = 0.03$.

Regarding the latter constraint, the local fish demand is assumed to evolve proportionally to the human population. Moreover, it is assumed that fish species can be substituted in the sense that the consumption of one species can be compensated by a rise in the consumption of other species. Following De Lara and Doyen (2008) and Doyen and De Lara (2010), viable efforts for this scenario are exhibited by the optimizing mechanism:

$$\max_{e_k(t)} \prod_{t=t_1}^{t_f} \mathbf{1}_{\mathbb{R}^+}\Big(\pi_k(t)\Big)\mathbf{1}_{\mathbb{R}^+}\Big(\mathrm{SR}(t) - 11\Big)\mathbf{1}_{\mathbb{R}^+}\Big(H(t) - H(2009)\cdot(1+d)^t\Big)$$

where again efforts $e_k(t)$ are meant to be control strategies that can change each five years as in equation (3) and the $\mathbf{1}_{\mathbb{R}^+}$ represents the characteristic function on positive reals.

## 4. Results

### *4.1. Calibration results*

The best calibration provides a mean relative error between the observed and the simulated catches by species lower than 1%. Figure 2 illustrates the quality of the calibration for the catches of each fleet. The estimated values determined by the calibration are given in tables 3 and 4.

### *4.2. Scenarios effort levels*

Effort multipliers by fleet, based on the mean pattern of efforts between 2006 and 2009 $\bar{e}_k$, of each fishing scenario are displayed in figure 3; the “SQ” effort multiplier equals to one. The “PV” scenario corresponds to the biggest decrease of fishing efforts in the simulation time frame. To maximize the present value of all the future profits, the “PV” scenario implies to stop fishing activity of the “canots créoles” (k=1) and “canots créoles améliorés” (k=2);

"pirogues" (k=3) during the two first decades, and to reduce gradually the "tapouilles" (k=4) fishing effort for the two last decades. The "tapouilles" fishing effort multiplier is 2.4 in the first part of the simulation while the "pirogues" ranges from 2.2 to 7.8 for the second part of the simulation. By contrast, the "CVA" scenario requires all fleets cooperation. Its effort level is on average lower than the "SQ" one except for the "tapouilles" which exhibit an effort multiplier from 0.9 to 6.8. The viable average effort multiplier is 0.7 for the "canots créoles", 0.51 for "canots créoles améliorés", 0.75 for "pirogues" and 3.0 for "tapouilles".

### *4.3. Ecological results*

The evolutions of species richness, marine trophic and Simpson diversity indexes according to the scenarios are plotted in figure 4. First it appears that a loss of species occurs for all scenarios as species richness decreases in every case, except in the closure "CL" scenario as expected. Implementing a no fishing zone keeps the ecosystem species richness at 13. The "SQ" scenario generates the worst result in terms of diversity loss as species richness decreases from 13 to 9. Hence *Crucifix catfish*, *Common snook*, *Silver croaker* and *Bressou catfish* vanish. With the "PV" scenario *Crucifix catfish* and *Bressou catfish* become extinct. The final state of species richness with the "CVA" scenario is qualitatively identical to the "PV" one since 11 species are present at the end while the same species disappear. Two species (*Crucifix catfish* and *Bressou catfish*) become extinct in the "SQ", "CVA" and "PV" scenarios but the extinction periods are not identical: species extinctions are delayed in proportion to decreases in effort level. Extinction periods of these two species correspond respectively to years 2020-2032 for the "SQ" scenario, 2022-2040 for the "CVA" scenario and 2031-2047 for the "PV" scenario.

The changes seen in the other presented diversity indexes are more complex. The species abundances change highly in the simulation time frame. Particularly, a major shock occurs around 2015 for all ecological indicators when some species start to decline. At the start of the simulation the total biomass is not equally distributed between species (SI equals to 0.5), and the marine ecosystem is dominated by species with a low trophic level ( MTI equals to 2.5). At the end of the simulation, for all scenarios, diversity indexes are better than those of the beginning (computed SI ranges from 0.61 to 0.77, the MTI one ranges from 2.79 to 3.08, according to scenarios).

### *4.4. Economic results*

Catches and profits for the "SQ", "PV" and "CVA" scenarios are plotted in figures 5 and 6. Biomass shock in years 2015-2020 is found again in catches and profits. Note that the prices ($p_{i,k}$) are fixed, therefore fish demand is exogenous. The "SQ" scenario seems economically viable, annual profits are positive during the whole period for all fleets except for the "canots créoles" (k=1) in the first year simulation and the "pirogues" (k=3) for 2010-2011 and 2026-2034 periods. Not surprisingly, the "PV" scenario yields the biggest cumulative discounted profit, 1.810 billion euros, versus 159.3 million for "SQ" scenario and 108.5 million for "CVA" scenario. The highest fishing activity occurs in the second part of the simulation for the "pirogues" ($k = 3$). Note that the "pirogues" selling prices are the highest (table 2). The "CVA" scenario provides positive annual profits for each fleet all simulation long despite the fact that the "CVA" fishing effort is lower than the "SQ" one.

By comparing the fish demand curve with the supply curves through the catches by scenario (figure 5), it is apparent that yield levels of the scenarios do not have the same trend as the local fish demand. For a period of several years, the production is lower than the fish demand, except for the "CVA" scenario[6]. The cumulative fish demand over forty years reaches 144,726 tons while the total catches of the "CVA" scenario is one that comes closest with 262,430 tons. The "SQ" scenario yields 284,211 tons whereas the "PV" scenario produces 986,254 tons.

## 5. Discussion

### *5.1. Co-viability as a step towards sustainability*

With regard to sustainability, a total fishery closure is obviously not a satisfactory solution either economically or socially since an entire profession will disappear leading to a loss of

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[6] We assume that prices are fixed and do not clear the market.

income for fishermen and nutritional deficiencies for the local population. It turns out that maintaining constant efforts through the “SQ” scenario is also not a well-suited and sustainable strategy. In fact, in addition to two fleets making no profit (k=1 and k=3) over several years, the “SQ” scenario does not satisfy the constraint of local consumption from years 2028 to 2038 and provides the worst species richness output. Economic data are based on year 2008 which was unusual: fuel prices reached a record, production costs rose a lot,$\cdots$. More generally, the low prices at first sale and the production costs did not allow all vessels to generate profits (Cissé, 2009). This context explain the negative profits of some fleets at the beginning of the simulation. Economically, the largest cumulative discounted profit and the most important total catch is obtained with the “PV” scenario. However the “PV” scenario is not socially sustainable as profits are not evenly distributed between fleets over time. This scenario implies stopping the activities of “canots créoles” (k=1) and “canots créoles améliorés” (k=2), inducing negative profits for these fleets due to fixed costs (figure 6). The “PV” scenario must be understood as a social planner trying to maximize the present value of the global prospective profits and aiming to maintain the potential productive capacity. The existence of some fleets exhibiting negative profits is not problematic under the social planner viewpoint, since overall profits remain positive for each step of the simulation. Moreover the exit of inactive fleets would increase the overall profit even more, since fixed costs are saved. As no unique Pareto optimum emerges, a better bio-economic compromise between biodiversity and socio-economic performances can be reached with the “CVA” scenario. Although two species vanish, this scenario appears as the best compromise : it allows annual positive profits for all fleets and satisfies local consumption during the forty years simulation.

Beyond the analysis on the case study, this work advocates an integrated and multi-criteria approach involving many scientific disciplines, in broad collaborative efforts as suggested by Rice (2010). A wide range of stakeholders are involved in fisheries, including industrial, artisanal, subsistence and recreational fishermen; suppliers and workers in allied industries; managers, environmentalists, biologists, economists; public decision makers and the general public (Hilborn, 2007). Each of these groups has an interest in particular outcomes from fisheries and the outcomes that are considered desirable by one stakeholder may be undesirable to another group (Hilborn, 2008). The consideration of this multi-dimensional nature of marine fisheries management is a way of guaranteeing a reasonable exploitation of aquatic resources, allowing the creation of conditions for sustainability from economic, environmental and social viewpoints. This work is in direct line with these considerations. First of interest is the use of bio-economic models and assessments articulating ecological and socio-economic processes and goals. Moreover by focusing on sustainability and viability, the present model exhibits management strategies and scenarios that account for intergenerational equity and allows a conciliation between the present and the future. As emphasized in Martinet and Doyen (2007) and De Lara and Doyen (2008), viability is closely related to the maximin (Rawlsian) approach with respect to intergenerational equity. In this respect, the CVA strategy turns out to be a promising approach.

### *5.2. Co-viability as a step towards EBFM*

Several authors (e.g. Cury et al. (2005)) have proposed the viability approach as a new, innovative and well-suited modeling framework for EBFM. They argue that the viability approach and especially co-viability is relevant in handling EBFM issues because it may account simultaneously for dynamic complexities, bio-economic risks and sustainability objectives balancing ecological, economic and social dimensions for fisheries. In particular, Cury et al. (2005) and Doyen et al. (2007) show how the approach can potentially be useful to integrate ecosystem considerations for fisheries management. Mullon et al. (2004), Doyen et al. (2007), Bene and Doyen (2008) and Chapel et al. (2008) put emphasis on the ability to address complex dynamics in this framework. The computational and mathematical modeling methods proposed in this paper through the CVA strategy are motivated by a similar prospect. One major interest of the co-viability approach is the fact that viability framework is dynamic, thus it allows the capture of the interactions and co-evolution of marine biodiversity and fishing. The dynamics can potentially include complex mechanisms such as trophic interactions, competition, metapopulation dynamics or economic investment process to quote a few. Here the focus is both on trophic and technical interactions through a multi-fleets and multi-species context.

Projections over forty years of different fishing scenarios point out the complexity of mechanisms at play, particularly their non linearity. In regards to this, the trajectories of ecological indicators is representative and should not be interpreted separately. The species richness for the "CL" scenario remains stable to 13 species, meaning that all species are present at the end of the simulation. However, the Simpson and marine trophic indexes reveal that species abundances change through the simulation frame time. Diversity indexes (SI, MTI) values at the end of simulation lead to the following findings : 1) total biomass is better distributed among species and 2) the species with a high trophic level are better represented. Thus, fishing effects on the species can be deduced: fishing leads to the ecosystem specialization and has contrasted effects according to species and fishing efforts. In addition, changes within trophic networks depend on the intensity of the trophic interactions and on the presence of species called "keystones" which are sometimes responsible for major changes within ecosystems (Stevens et al., 2000).

### *5.3. Decision support for the Guiana small-scale fishery*

Small-scale fisheries remain poorly managed because of their heterogeneity, the difficulties in getting consistent and perennial data and the lack of regulation tools. This is more acute in a tropical context where informal activities often dominate and where biodiversity is higher, often with lower stock biomass (this is typically valid for reef ecosystems). In French Guiana, waters are very turbid and productive because of the proximity of the Amazon river. There are no reefs but biodiversity is high, as well as biomass. The bio-economic database monitored from 2005 with observers from local communities who collected time series data, offers the opportunity to go a step further for building management tools. Since the decline of the French Guiana industrial shrimp fishery (Chaboud et al., 2008), the coastal fishery increasingly appears as a sector with a high potential for development. Indeed, the coastal fishery production has increased continuously until it overtook the shrimp and red snapper landings in 2008. However, as previously stated, there is no quota for catches, and no limitation concerning exploited species and their size. Regulation instruments are derived from national and European usual fisheries management. The standards are related to the gear selectivity (mesh size) and the global size of the fleet (total engine power and total vessel capacity)(Cissé, 2009). As the stock status of the main exploited species has not been studied yet, the norm concerning the global size of the fleet was not adapted to the changing level of fish stocks and the management only aimed at displacing the unauthorized boats. The present bio-economic study should contribute to the design of more scientific and relevant assessments and regulations for both the marine ecosystem and this small case fishery.

The fishing scenario outputs show that fishing performances, including food supply and profitability of fleets, can be increased or sustained respectively. In particular, this suggests that the marine ecosystem and the fishing sector could cope with the food demand and contribute to food security. This could have positive consequences for the development of French Guiana, since the coastal fishery plays an important socio-economic role for the small cities along the coastline where more than 90% of the population is located. However, a fish biodiversity loss can occur. This biodiversity erosion could potentially alter some ecosystem services (not taken into account in the current model) and the outcomes of the fishery itself in the long run. Thus some fish stocks should be evaluated more specifically in order to anticipate their depletion (*Crucifix catfish*, *Bressou catfish*). Depending on the endangered stocks, conservative measures on productive and reproductive capacity of these stocks should be taken. This will go through the banning of fishing in nursery areas or the incentive for more selective fishing techniques. Thereby, the co-viability approach can allow a long-term management of the French Guiana coastal fishery, taking into account the multi-specific catches of this case. This approach seems the most appropriate in responding both to the potential food demand, keeping a maximum of species diversity in the ecosystem, and providing profits for fishermen. The CVA scenario suggests that such multi-functional sustainability holds with moderate reinforcement of one fleet ("tapouille") and relative reduction for others ("canots créoles", "canots créoles améliorés" or "pirogues").

## 6. Conclusion

This work aims at contributing to sustainable exploitation systems taking into account interactions between several species and between different fleets exploiting them. The implementation of multi-functionality appears to be a way to warrant an adequate management of aquatic resources allowing the creation of sustainable conditions for economic, environmental and social performances (Lesueur et al., 2006). However sustainability needs to be carefully defined because economic and ecological sustainabilities easily conflict (Pitcher, 2001). It is definitely a question to balance between exploitation (social and economic dimensions) and carrying capacity (environmental dimension). Fisheries are invited to transform their practices progressively, to favor eco-friendly technologies, to reinforce quality and reliability of products and services, and to search for activities generating jobs (Lesueur et al., 2006). Human sciences have to be integrated in the long term to allow management choices to be made according to given public priorities (Blanchard and Maneschy, 2010). A next step would be to integrate social indicators to evaluate also the scenarios regarding social performances such as job satisfaction (Bavinck and Monnereau, 2007).

Of course, the whole results must be moderated, particularly because of the uncertainties underlying the model and data. In particular, some parameters needs to be reinforced to obtain a more accurate model. Up to now, only shrimps and red snappers fisheries have been widely studied in French Guiana, unlike coastal fishery. Thus, some parameters of the coastal fishery model are estimated from fishbase or from literature. Consequently, it would be fruitful to integrate more values from local field studies dedicated to this ecosystem (for instance, intrinsic growth rates and trophic levels). Stomach content data analysis would especially improve the trophic interactions. Similarly, as landings are computed from catchabilities and initial stocks, it would be important to obtain refined estimation of these parameters. Furthermore, the ecosystem-based model is based on simplified dynamics. Accounting for uncertainties would significantly improve the model and favor a bio-economic risk management and a stochastic analysis (Doyen and De Lara, 2010). It may significantly strengthen the robustness of outcomes and assertions from this dynamic complex model.

Other challenges are numerous, like expanding the number of species to include effects of the fishing activities on the dynamics of other species (as mammals, turtles, birds) and on plankton dynamics. In line with this, comparisons with the Ecopath (EwE) approach can be informative. Another interesting goal is to include the effects of climatic changes, for instance sea surface temperatures (Thebaud and Blanchard, 2011). A spatial expansion of this model can also be considered to integrate for instance the effects of protected surfaces.

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## 8. Appendix

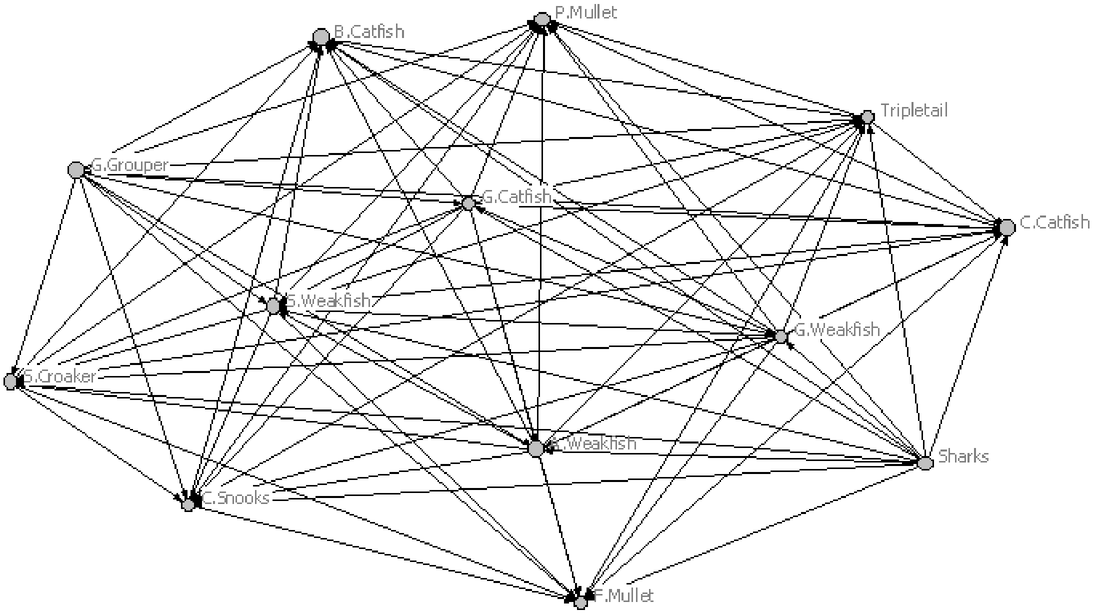

Figure 1: Food web with the thirteen principal exploited species in French Guiana.

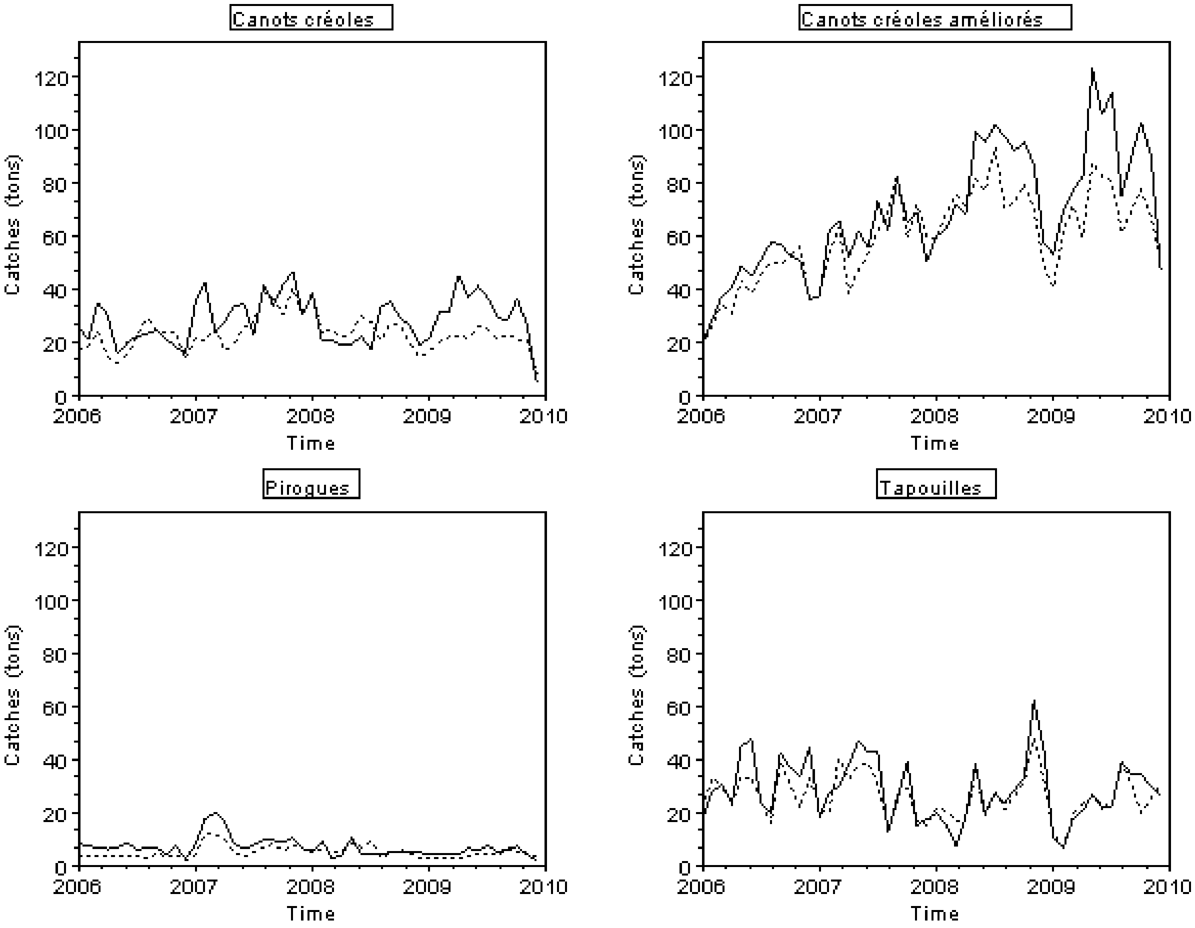

Figure 2: Monthly simulated catches $\sum_i h_{i,k}(t)$ (dotted line) and observed catches $\sum_i h_{i,k}^{\text{data}}(t)$ (solid fine) by fleets of the 13 selected species from years 2006 to 2009.

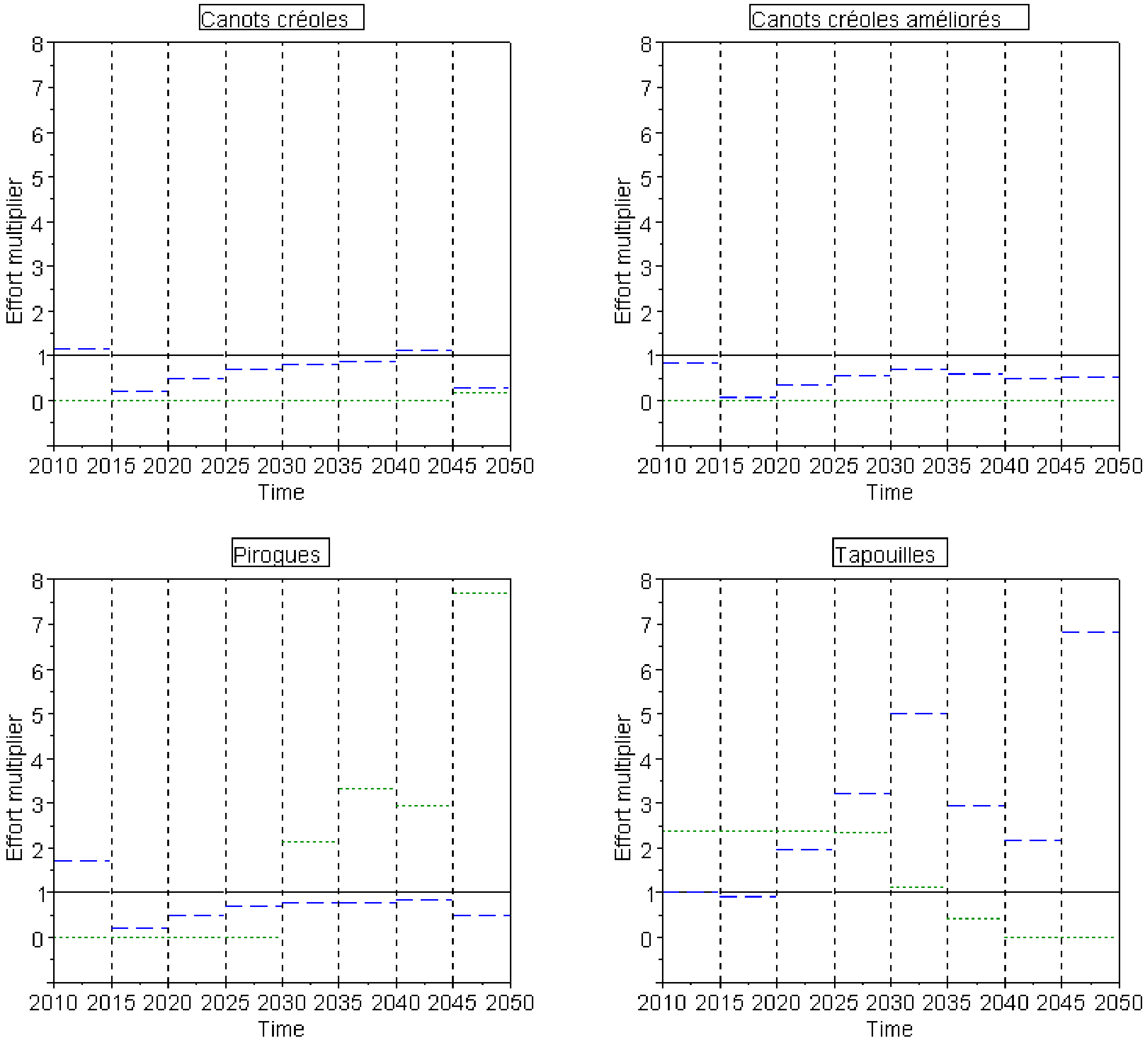

Figure 3: Fishing effort multiplier by fleet and scenario, “Status quo” (black solid line), “Economic” (green dotted line), “Co-viability” (blue dashed line).

Table 1: the thirteen selected species representing about 90% of the catches of the fishery.

| Common name | Scientific name | Trophic level (Fishbase) |
|---|---|---|
| Acoupa weakfish | *Cynoscion acoupa* | 4.05 |
| Crucifix sea catfish | *Hexanematichtys proops* | 4.35 |
| Green weakfish | *Cynoscion virescens* | 4.03 |
| Common snooks | *Centropomus parallelus, Centropomus undecimalus* | 4.2 |
| Sharks | *Sphyrna lewini, Carcharhinus limbatus, Mustelus higmani* | 4.5 |
| Smalltooth weakfish | *Cynoscion steindachneri* | 3.25 |
| South american silver croaker | *Plagioscion squamosissimus* | 4.35 |
| Tripletail | *Lobotes surinamensis* | 4.04 |
| Gillbacker sea catfish | *Arius parkeri* | 4.11 |
| Bressou sea catfish | *Aspistor quadriscutis* | 3.5 |
| Goliath grouper | *Epinephelus itajara* | 4.09 |
| Flathead grey mullet | *Mugil cephalus* | 2.13 |
| Parassi mullet | *Mugil incilis* | 2.01 |

Table 2: 2008 economic data (variable costs, fixed costs and selling prices).

| | Fleets | | | |
|---|---|---|---|---|
| | "canots créoles "<br>(fleet $k = 1$) | "canots créoles améliorés"<br>(fleet $k = 2$) | "pirogues"<br>(fleet $k = 3$) | "tapouilles"<br>(fleet $k = 4$) |
| 2006-2009 average boats number | 71 | 60 | 45 | 10 |
| Variable costs per fishing hour( €) | 5.83 | 5.40 | 8.52 | 8.22 |
| Annual fixed costs per boat( €) | 8610 | 8958 | 3770 | 29833 |
| Selling prices ( €) | | | | |
| A.weakfish | 3.08 | 2.31 | 4.00 | 2.23 |
| C.catfish | 1.85 | 1.49 | 3.00 | 1.25 |
| G. weakfish | 1.45 | 1.42 | 2.50 | 1.56 |
| C. snooks | 2.83 | 2.09 | 4.00 | 2.23 |
| Sharks | 1.78 | 1.07 | 3.00 | 0.94 |
| S.weakfish | 2.40 | 1.98 | 3.28 | 2.23 |
| S. croaker | 1.68 | 1.89 | 3.71 | 1.50 |
| Tripletail | 1.97 | 1.29 | 1.65 | 1.97 |
| G. catfish | 5.68 | 4.23 | 6.00 | 4.00 |
| B. catfish | 1.74 | 1.73 | 3.00 | 1.73 |
| G.grouper | 3.73 | 3.98 | 4.00 | 2.43 |
| F. mullet | 3.96 | 2.48 | 4.20 | 2.50 |
| P. mullet | 3.81 | 2.00 | 5.00 | 2.00 |

Table 3: Initial stocks and intrinsic growth rate of selected species from calibration.

| Species($i$) | Initial stocks (December 2005) $B_i(0)$ unit tons | Intrinsic growth rate $r_i$ $*10^{-2}$(Fisbase) | Intrinsic growth rate $*10^{-2}$(Calibration) | Catchability fleet $k = 1$ ($q_{i,1}$) $*10^{-7}$ | Catchability fleet $k = 2$ ($q_{i,2}$) $*10^{-7}$ | Catchability fleet $k = 3$ ($q_{i,3}$ ) $*10^{-7}$ | Catchability fleet $k = 4$ ($q_{i,4}$ ) $*10^{-7}$ |
|---|---|---|---|---|---|---|---|
| A. weakfish | 7,152 | 2.08 | 1.97 | 2 | 4 | 0.95 | 10 |
| C. catfish | 301 | 5.95 | 5.95 | 68 | 31 | 33 | 24 |
| G. weakfish | 26,816 | 0.16 | 0.15 | 0.41 | 0.39 | 0.2 | 0.88 |
| C. snooks | 144 | 4.21 | 4.08 | 41 | 26 | 47 | 4 |
| Sharks | 10,370 | - 4.72 | - 3.67 | 0.38 | 0.46 | 0.25 | 2 |
| S. weakfish | 25,825 | 0.64 | 0.69 | 0.06 | 0.09 | 0.1 | 0. |
| S.croaker | 129 | 3.44 | 3.08 | 13 | 16 | 54 | 0. |
| Tripletail | 1,307 | 9.34 | 8.87 | 0.14 | 0.08 | 0.02 | 0.02 |
| G. catfish | 67 | 2.59 | 2.70 | 28 | 37 | 68 | 0.31 |
| B. catfish | 36 | 4.21 | 4.66 | 48 | 18 | 143 | 0. |
| G. grouper | 2,040 | - 2.26 | - 1.92 | 4 | 0.49 | 0.3 | 0.12 |
| F. mullet | 28,902 | 5.31 | 3.33 | 0.005 | 0.003 | 0.004 | 0. |
| P. mullet | 38,718 | 7.03 | 5.62 | 0.002 | 0.0001 | 0.004 | 0. |

Table 4: Trophic relations matrix, $S_{i,j}$ ($*10^{-12}$) from calibration.

| Species | A.weak. | C.cat. | G. weak. | C. snoo. | Sharks | S.weak. | S. croa. | Triple. | G. cat. | B. cat. | G.grou. | F. mul. | P. mul. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A.weak. | - 24.41 | 25.59 | - 216.8 | 3.02 | - 39.81 | 1.81 | 0.70 | 0.64 | - 23.06 | 1.72 | - 202.6 | 28.57 | 36.22 |
| C.cat. | - 204.8 | - 104.9 | - 14.41 | - 46.93 | - 4.41 | - 36.96 | 5779 | - 267.9 | - 45.73 | 2228 | - 18.62 | 7.27 | 17.28 |
| G. weak. | 22.30 | 1.80 | - 3.98 | 2.14 | - 44.67 | 2.21 | 6.41 | 1.48 | - 54.18 | 10.40 | - 28.08 | 1.22 | 14.43 |
| C. snoo. | - 24.18 | - 17.25 | - 17.10 | - 16.34 | - 85.37 | - 1.57 | - 133.2 | - 71.13 | - 121.5 | 0.43 | - 26.01 | 1.76 | 2.90 |
| Sharks | 4.98 | 0.551 | 5.58 | 10.67 | - 4.86 | 0.40 | 23.51 | 5.45 | 35.10 | 1.30 | - 147.7 | 29.35 | 25.10 |
| S.weak. | - 59.91 | 4.62 | - 23.82 | 0.19 | - 3.22 | - 0.17 | 22.16 | 5.67 | - 7.16 | 3.87 | - 9.92 | 6.27 | 9.47 |
| S. croa. | - 5.64 | -46338 | - 51.29 | 16.65 | - 188.1 | - 177.2 | - 26.26 | - 2.07 | - 10.47 | 6.98 | - 21.08 | 5.30 | 20.94 |
| Triple. | - 5.1 | 28.05 | - 11.86 | 8.53 | - 43.61 | - 45.36 | - 8.12 | - 256.2 | - 134.7 | 8.96 | - 26.35 | 4.39 | 0.78 |
| G. cat. | 2.88 | 5.72 | 6.77 | 15.19 | - 280.8 | 0.89 | 1.31 | 16.84 | - 114.53 | 4.76 | - 9.48 | 4.93 | 8.10 |
| B. cat. | - 13.77 | -17831 | - 83.25 | - 3.43 | - 10.43 | -30.93 | - 55.84 | - 71.71 | - 38.12 | 0. | - 206.5 | 0. | 0. |
| G.grou. | 25.33 | 2.33 | 3.51 | 3.25 | - 30.49 | 1.24 | 2.63 | 3.29 | 1.18 | 25.82 | - 10.74 | 22.79 | 3.86 |
| F. mul. | - 228.5 | - 58.2 | - 9.79 | - 14.05 | - 234.8 | - 50.19 | - 42.4 | - 35.12 | - 39.44 | 0. | - 182.3 | 0. | 0. |
| P. mul. | - 289.8 | - 138.3 | - 115.5 | - 23.2 | - 200.8 | - 75.72 | - 167.5 | - 6.22 | - 64.79 | 0. | - 30.88 | 0. | 0. |

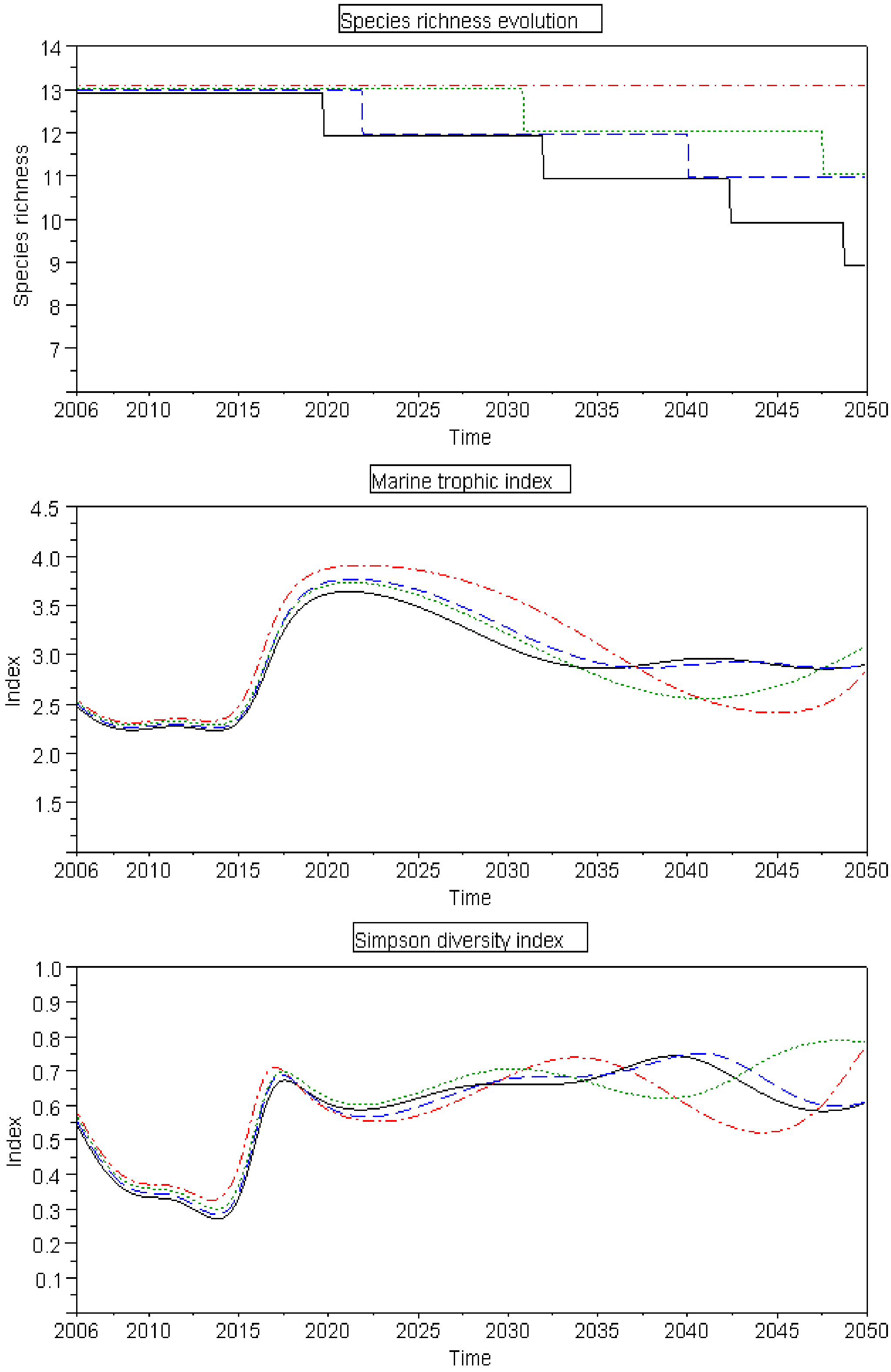

Figure 4: Species richness, Marine trophic and Simpson indexes according to scenarios : “Protected area” (red dash-dotted line), “Status quo” ( black solid line), “Economic” (green dotted line), “Co-viability” (blue dashed line).

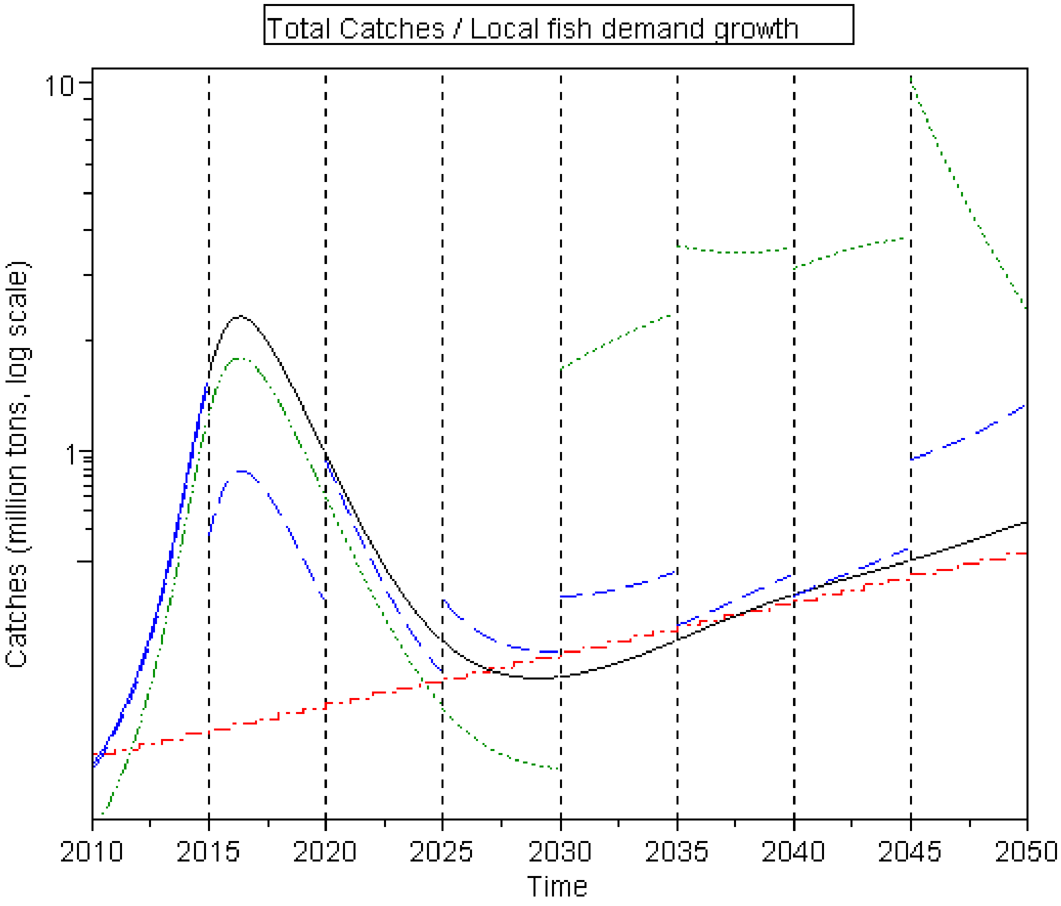

Figure 5: Total catches by scenario, "Status quo" (black solid line), "Economic" (green dotted line), "Co-viability" (blue dashed line); Local fish demand growth (red dash-dotted line).

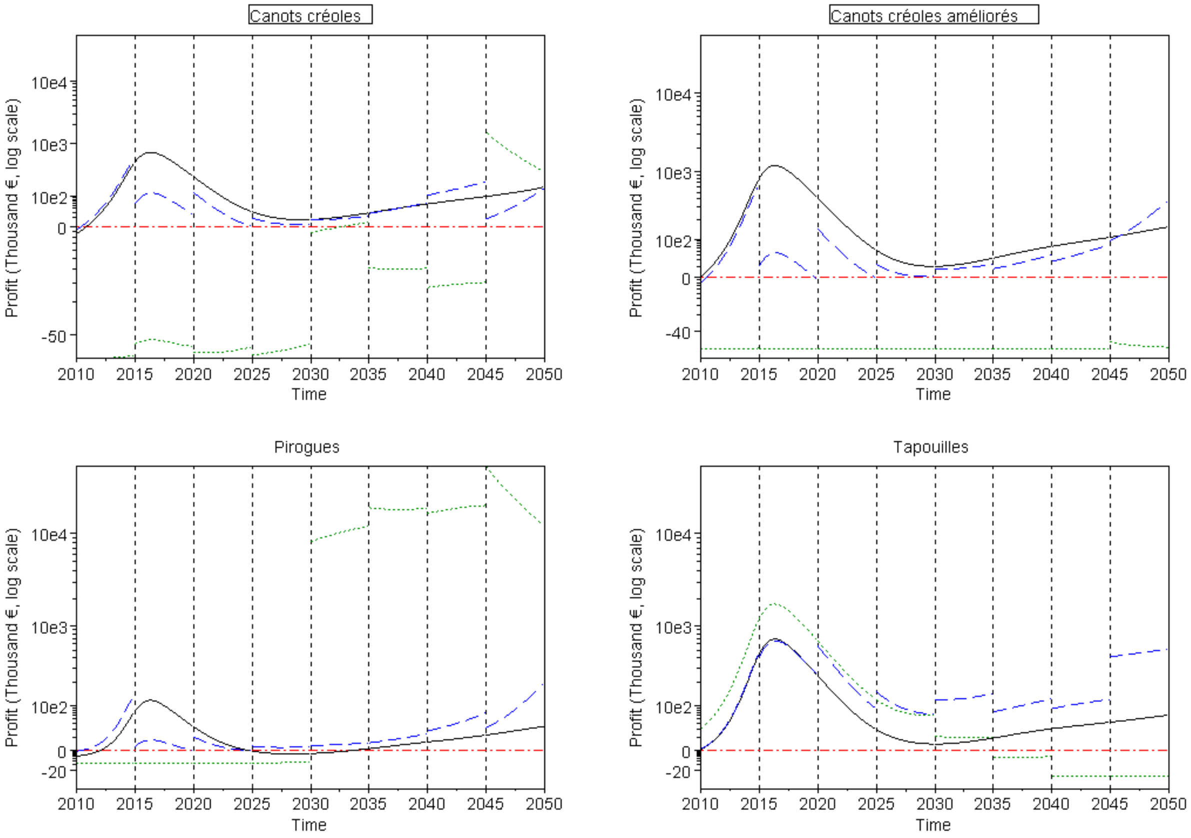

Figure 6: Profits by fleet and scenario, “Status quo” (black solid line), “Economic” (green dotted line), “Co-viability” (blue dashed line), Profitability threshold (red dash-dotted line).

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