

Ecoviability for small-scale fisheries in the context of food security constraints

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Abstract

This paper applies a stochastic viability approach to a tropical small-scale fishery, offering a theoretical and empirical example of ecosystem-based fishery management approach that accounts for food security. The model integrates multi-species, multi-fleet and uncertainty as well as profitability, food production, and demographic growth. It is calibrated over the period 2006-2010 using monthly catch and effort data from the French Guiana's coastal fishery, involving thirteen species and four fleets. Using projections at the horizon 2040, different management strategies and scenarios are compared from a viability viewpoint, thus accounting for biodiversity preservation, fleet profitability and food security. The analysis shows that under certain conditions, viable options can be identified which allow fishing intensity and production to be increased to respond to food security requirements but with minimum impacts on the marine resources.

Keywords: Small-scale fishery, biodiversity, sustainability, profitability, food security, multi-species, multi-fleet, stochasticity, viability, scenario.

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1. Introduction

Reconciling food security with biodiversity protection is among the greatest challenges of the century, especially in the face of demographic transition (Godfray *et al.*, 2010; Rice and Garcia, 2011). The case of fisheries and marine ecosystems is especially challenging in that regard. Marine and coastal ecosystems are experiencing accelerating changes in their populations, species and communities at different biotic scales, with some alarming trends (extinctions, depletion, ...) and largely unknown consequences (Myers and Worm, 2003; Millennium Ecosystem Assessment, 2005; Butchart *et al.*, 2010). Part of the degradation in biodiversity is due to fishing pressure, through processes such as overexploitation and "fishing down the food chain" (Ye *et al.*, 2012). These changes in marine biodiversity in turn impact ecosystem services, including food production capacities and fishing activities -as emphasized by the current stagnation or decline of global catches despite continuous increasing fishing efforts (FAO, 2012). These trends raise key concerns in relation to food security, especially for developing countries with high demographic pressure. In this perspective, the sustainable management of tropical small-scale fisheries is a key issue (Garcia *et al.*, 2008). However the conventional approaches for operationalizing sustainability based on MSY¹, MEY or the ICES² precautionary approach, were globally unable to prevent over-exploitation and fishing overcapacity worldwide (Hall and Mainprize, 2004; Hilborn, 2011). By considering each exploited species separately (Grafton *et al.*, 2007), these approaches often fail to account for the multi-species and multi-fleet interactions which play a important role in fish mortality and fleet profitability. The account for such a bio-economic complexity is especially crucial for small-scale fisheries usually characterized by non-selective fishing vessels.

The need for Ecosystem-Based Fisheries Management (EBFM) advocating an integrated management of marine resources is now widely accepted (Garcia *et al.*, 2003). Such a framework first requires to account for the complexity of ecological mechanisms that encompass community dynamics, trophic webs, geographical processes and environmental uncertainties (habitat, climat). Furthermore, by putting emphasis on sustainability, this approach strives to balance ecological and economic objectives for present and future generations and to handle a large range of goods

¹MSY = Maximum Sustainable Yield; MEY = Maximum Economic Yield

²International Council for the Exploration of the Sea: <http://www.ices.dk>.

and services provided by marine ecosystems (Jennings, 2005), including both monetary and non-monetary values. However, implementing such an approach remains challenging (Sanchirico *et al.*, 2008; Doyen *et al.*, 2013). It requires models, indicators, reference points and adaptive management strategies (King and Mcfarlane, 2006). Plaganyi (2007) provides an overview of the main types of modeling approaches and analyzes their relative merits and limitations 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. The use of ecosystem indicators is analyzed by Rice (2000) and Cury and Christensen (2005).

The present paper proposes to use a bio-economic viability framework as a methodological tool to explore, through modeling and scenarios, the implementation of the EBFM in the case of small-scale fisheries facing food security constraints. Viability modeling is now recognized by a growing number of scholars - e.g. Cury *et al.* (2005); Doyen *et al.* (2007); De Lara *et al.* (2012); Péreau *et al.* (2012); Cissé *et al.* (2013); Thébaud *et al.* (2014)- as a relevant framework for EBFM. Viability theory strives to identify 'viable' paths that ensure the simultaneous fulfillment of several desirable objectives over time (Béné *et al.*, 2001). These objectives, represented through a series of constraints that need to be satisfied throughout time, capture the multi-dimensional nature of sustainability (Doyen and Martinet, 2012). Furthermore, because it takes into account uncertainties, stochastic viability approach appears to be a relevant framework to ensure robust alternative management (Baumgartner and Quaas, 2009; Doyen *et al.*, 2012; Gourguet *et al.*, 2013). Finally Cissé *et al.* (2013) and Hardy *et al.* (2013) recently showed how the viability approach can also provide useful insights in tropical fisheries operating under demographic pressure.

In that context, the coastal fishery in French Guiana provides a very relevant case-study to apply the EBFM together with stochastic viability. This fishery is characterized by various complex features including a high equatorial fish biodiversity impacted by several non-selective fleets and a strong demographic pressure, which eventually is likely to affect the productivity of the fishery and its contribution to local food security.

This work is the first application of stochastic viability approach to a small-scale multi-species and multi-fleet fishery facing demographic pressure and food security constraints in a tropical context.

2. Case study

French Guiana is a French Overseas Territory located in South America between Brazil and Suriname. It has a 350-km coastline and an exclusive economic zone (EEZ) of 130,000 km², which includes 50,000 km² of continental shelf. The small-scale coastal fishery, with landing points spread along the coast, operates up to 16 km offshore at depths of 0-20 m. This multi-species fishery exploits more than 30 species (weakfish, catfish, shark, grouper, etc.) and around 3000 tons are landed annually worth €9 millions. In terms of volume the most important species include the Acoupa weakfish, the Crucifix sea catfish and Green weakfish representing 65% of the annual catches. This fishery is also multi-fleet: the 200 wooden boats include four different types of vessels: *canots créoles* (CC), *canots créoles améliorés* (CCA), *pirogues* (P) and *tapouilles* (T). These four groups of boat differ from each other by the type of engine, type of fishing gear, number of fishers onboard, number of days spent at sea and fishing grounds, thus entailing various catchability and cost parameters. As an EU overseas region, French Guiana coastal fishery is managed under the French and the European legislations through technical measures (maximum net length, minimum mesh size and marine protected area) and access regulation (European and regional licenses). The conditions associated to these management tools do not derived from particular stock assessments, they were essentially set up to preserve the current status quo.

Since 2006, Ifremer³ has been implementing a monitoring system covering all the vessels operating in the fishery. At each landing site, observers from local communities record on a daily basis the catches (by species), the number of crew on board, the fishing area, trip duration, gear used and quantity of fuel and ice consumed by the boats. The socio-economic assessment of the sector informs on production costs, selling prices, fishers living condition and education level.

Currently, the ecological status of the fishery is considered to be healthy, and the biodiversity associated with the resource does not seem to be threatened by fishing activity. No particular negative trend is observed in the catch or in the catch per unit of effort⁴ of the main species and the latest 2010 economic assessment shows that the fishery is profitable even if it is strongly sensitive to the fuel price and the fish selling prices (Cissé *et al.*, 2014). On the demand side, the production

³French Research Institute for Exploitation of the Sea.

⁴This variable is traditionally used in fisheries literature as a proxy for biomass.

is essentially directed to the local consumption. Demographic projections suggest however a 100% increase of the local population over the next 20 years. The question arises therefore on whether the marine ecosystem and the fishing sector will be able to cope with the predicted increase in demand and continue to fulfill their food security function without detrimental effect for the resource.

To examine these issues, this paper proposes to use a bio-economic model which includes multi-species and multi-fleet dynamics based on Lotka-Volterra trophic interactions and that accounts for uncertainty on species growth. The model is calibrated for thirteen species and four fleets using the monthly catch and effort data derived from the Ifremer fishery monitoring system from 2006 to 2010. Scenarios including status quo, maximization of the net present value, and viability strategies are examined and compared. The model aims at improving the knowledge of the French Guiana coastal fishery and at ensuring its future sustainable management relying on an ecosystem based approach.

The paper is structured as follows. Section 3 describes the ecosystem-based model together with the relevant bio-economic indicators and scenarios. Section 4 presents the results of the different fishing scenarios while section 5 discusses those results in relation to sustainability, EBFM and more general fisheries management tools.

3. Methods

3.1. The ecosystem-based model

The stylized bio-economic model, inspired by Cissé *et al.* (2013), rely on a Lotka-Volterra prey-predators dynamic with $n = 14$ species (Table 1) and $m = 4$ fleets exploiting them as displayed by Figure 1. The thirteen selected species contribute around 90% of the annual landings from 2006 to 2010 while a virtual fourteenth species is introduced in the model to capture all the other stocks of the ecosystem. The model is described in discrete time with a monthly step and accounts for uncertainties in species growth. It is assumed that harvesting takes place at the beginning of the period t while regeneration and trophic processes occur at the end. Thus, at each step t , the biomass $B_i(t + 1)$ (kg) of species i at time $t + 1$, after harvesting $H_i(t)$, depends on other stocks $B_j(t)$ and an uncertainty parameter $\epsilon(t)$ through eqs(1)-(3):

$$B_i(t + 1) = g_i(B(t) - H(t), \epsilon_i(t)), \quad (1)$$

with

$$g_i(B_1, \dots, B_n, \epsilon_i) = B_i \cdot \left(1 + r_i - \frac{r_i}{K_i} B_i + \sum_{j \neq i} s_{i,j} B_j + \epsilon_i \right), \quad (2)$$

$$H_i(t) = \sum_{f=1}^m H_{i,f}(t) = \sum_{f=1}^m q_{i,f} e_f(t) B_i(t). \quad (3)$$

In eq(2), r_i and K_i stand respectively for the intrinsic growth rate and the carrying capacity of the species i . $s_{i,j}$ is the trophic effect⁵ of species j on species i . The noise ϵ_i captures the environmental stochasticities affecting the growth of each species i at each step t . It is assumed that the random variables $\epsilon_i(t)$ follow a Gaussian law, independent and identically distributed : $\epsilon \rightsquigarrow \mathcal{N}(0, \sigma^2)$. The parameter $e_f(t)$ in equation (3) represents the fishing effort of fleet f (time spent at sea, in hour) and $q_{i,f}$ measures the catchability of species i by fleet f . The number of the fleet f (from $f = 1$ to $f = 4$) corresponds respectively to CC, CCA, P and T. The catch $H_{i,f}(t)$ of species i by fleet f at time t is estimated using the Schaefer production function as in equation (3).

3.2. Model and calibration inputs

Values used to estimate the model parameters arise from different sources. Daily observations (catches and fishing efforts) from the landing points all along the coast are available from January 2006 to December 2010. Every month during this 60-month period, for each of the four fleets, fishing effort and catches were identified for the thirteen species, representing a total of 3360 observations. Moreover, we use Leopold (2004) and Fishbase⁶ to characterise the trophic interactions between species, including the sign of the relationship and the intrinsic growth rates. Initial stocks, catchabilities, trophic intensities values of the ecosystem as well as the standard deviation of growth were estimated through a least square method. This method consisted in minimizing the mean square error between the monthly observed catches $H_{i,f}^{\text{data}}$ and the catches $H_{i,f}$ simulated by the model as defined by eq(3):

$$\min_{B_0, s, q, \sigma} \mathbb{E}_\epsilon \left[\sum_{t=\text{January } 2006}^{\text{December } 2010} \sum_{i=1}^{13} \sum_f^4 \left(H_{i,f}^{\text{data}}(t) - H_{i,f}(t) \right)^2 \right]. \quad (4)$$

Here (B_0, s, q, σ) is the set of parameters to be identified. B_0 is the vector (14×1) of initial stock abundance (corresponding to december 2005 situation), s is the matrix (14×14) of

⁵positive if j is a prey of i and negative if j is a predator of i .

⁶<http://www.fishbase.org>

interactions between species including trophic intensities, q is the matrix (14×4) of catchabilities and σ is the standard deviation of random distribution ϵ . Results of the calibration process are displayed in Table A.3 and Table A.4. For species that are not caught by a given fleet, catchability parameters $q_{i,f}$ were set at zero, as shown in Table A.3 (typically fleet 4).

The numerical implementations of the model are carried out with the scientific software SCILAB 5.3.3 ⁷. The nonlinear optimization problem (Equation 4) was solved numerically using the Scilab routine ‘optim_ga’ which relies on an evolutionary (or genetic) algorithm⁸ as in [Gourguet et al. \(2013\)](#); [Cissé et al. \(2013\)](#); [Hardy et al. \(2013\)](#).

3.3. Model outputs: ecological scores and risks

The model is used to build and compare different fishing scenarios from $t_1 = 2011$ to the time horizon $T = 2040$. In order to analyze and investigate sustainable futures for this fishery, we aim at evaluating the effort scenarios $e(t)$ in both ecological and economic terms. Thus indicators are computed to assess the performances and risks for both the ecosystem and the fishery. We first focus on biodiversity metrics. Although choice of biodiversity indicators remains debated -see e.g. [Magurran \(2007\)](#)- and every of them has limitations, we selected the species richness and marine trophic indicators.

Species richness. Species richness $SR(t)$ indicates the estimated number of species represented in the ecosystem. In our model, it is assumed that a species disappears whenever its biomass falls under a predetermined viability limit B_{lim} . This threshold B_{lim} which corresponds to a proxy of the ICES precautionary reference points is here set to 1‰ of the initial biomass B_0 . The indicator SR is computed as follows:

$$SR(t) = \sum_i \mathbf{1}_i(B_i(t)), \quad (5)$$

⁷SCILAB (<http://www.scilab.org>) is an open-source software dedicated to scientific calculus and well suited to the simulation of dynamic systems.

⁸See http://help.scilab.org/docs/5.3.3/en_US/optim_ga.html for details on ‘optim_ga’. A genetic algorithm is a search heuristic that mimics the process of natural evolution. This heuristic is routinely used to generate solutions to nonlinear optimization.

with the indicator (boolean) function

$$\mathbf{1}_i(B) = \begin{cases} 1 & \text{if } B \geq B_{\text{lim},i} \\ 0 & \text{otherwise.} \end{cases}$$

Rare species have a relatively huge impact on this index.

Marine trophic index. The trophic level indicates the location of a species in a food web, starting with producers (*e.g.*, phytoplankton, plants) at level 0, and moving towards primary consumers that eat primary producers (level 1) and secondary consumers that eat primary consumers (level 2), and so on. In marine ecosystems, the trophic levels vary from zero to five (top predators). The marine trophic index $\text{MTI}(t)$ of an ecosystem is the sum of the trophic levels of the species present in this ecosystem, weighted by their relative abundances (Pauly and Watson, 2005). In our case the marine trophic index $\text{MTI}(t)$ is therefore the weighted sum of the trophic levels of the thirteen species T_i presented in Table 1, as follows:

$$\text{MTI}(t) = \frac{1}{N(t)} \sum_{i=1}^{13} T_i N_i(t). \quad (6)$$

Biodiversity risks. As mentioned in the introduction, the paper applies a stochastic viability approach consisting in the identification of control options that allow the dynamic system to remain in probability within a viable space defined by a combination of bio-economic constraints. The first biodiversity constraint is made up by the biodiversity indexes defined earlier, as no reference points exists for the studied species. This constraint is about maintaining both the SR index and the MTI above the minimum observed for the status quo scenario (defined in section 3.5 and denoted by SQS):

$$\text{SR}(t) \geq \min_{t=t_1, \dots, T} \text{SR}^{\text{SQS}}(t), \quad \text{MTI}(t) \geq \min_{t=t_1, \dots, T} \text{MTI}^{\text{SQS}}(t). \quad (7)$$

This constraint guarantees biodiversity sustainability and stands for a precautionary approach. Given a sequence of efforts $e(t)$, we denote by $\text{PVP}(e)$ (Population Viability Probability) the probability that the biodiversity constraints are satisfied throughout time:

$$\text{PVP}(e) = \mathbb{P}\left(\text{Constraints (7) are satisfied.}\right), \quad (8)$$

3.4. Model outputs: economic scores and risks

We now turn to the assessment of the fishing sector through the estimation of the production and profitability values and the bio-economic risks of the fishery. These are provided by eqs (9) and (12).

Food supply and food security. The total catches $H(t)$ within the fishery plays the role of food supply:

$$H(t) = \sum_f \sum_i H_{i,f}(t). \quad (9)$$

The food security constraint is linked to the ability of the fishery to satisfy the local food consumption. This constraint is demanding because it reflects an increase in the local fish consumption at an annual rate of $d = 3\%$, following the demographic projection which predicts a doubling of the French Guiana's population by 2030 (INSEE, 2011). It is assumed however that fish species can be substituted, in the sense that a drop in the supply of one species can be compensated for, by a rise in the consumption of other species. Consequently the food security reads

$$H(t) \geq H(2010) \cdot (1 + d)^t, \quad \text{for } t = t_1, \dots, T, \quad (10)$$

where d stands for the growth rate of the population and 2010 catches stand for the baseline. Given a sequence of efforts $e(t)$, we denote by FVP(e) (Food Viability probability) the probability to comply with the food security constraint:

$$\text{FVP}(e) = \mathbb{P}\left(\text{Constraint (10) is satisfied.}\right), \quad (11)$$

Profits and profit viability. The profit $\pi_f(t)$ of each fleet f is derived from the landings of each species $H_{i,f}$, the landing prices $p_{i,f}$, fixed costs c_f^f , variable costs c_f^v and the crew share earnings β_f as follows:

$$\pi_f(t) = (1 - \beta_f) \left(\sum_i p_{i,f} H_{i,f}(t) - c_f^v e_f(t) \right) - c_f^f. \quad (12)$$

Table A.5 in Appendix (Appendix A.2) provides the estimated values of the parameters involved. Prices, variable costs and fixed costs are those collected for year 2010. They are assumed to remain unchanged throughout the simulations. Share contract β is the salary system commonly used in this fishery for fleets 2 and 4. Crews are remunerated with a share of the landing value minus the variable costs. This share is usually 50%. For fleets crews 1 and 3 are mostly made up of boat

owners, occasionally assisted by a family member. If there is a pay system for these fleets, it differs from one owner to another. Hence, to simplify, we set $\beta_f = 0$ for fleets 1 and 3 and $\beta_f = 0.5$ for fleets 2 and 4. Variable costs c_f^v include fuel consumption, ice, food and lubricants. Equipment depreciation, maintenance and repairs are incorporated in the fixed costs c_f^f .

To analyze the economic risks, we adopt a viability viewpoint and define the profit viability as the prevention of negative profits for every fleet at any time:

$$\pi_f(t) \geq 0, \quad \text{for } t = t_1, \dots, T, \quad \text{for every } f = 1, \dots, 4. \quad (13)$$

This constraint holds for each fleet separately and not for the aggregated profit. Accounting for the uncertainties affecting the system dynamics, we define the ‘Income Viability Probability’ $\text{IVP}(e)$ of a given effort pattern $e(t)$ as the probability to comply with this profitability constraint:

$$\text{IVP}(e) = \mathbb{P}\left(\text{Constraint (13) is satisfied.}\right). \quad (14)$$

3.5. Fishing scenarios

To evaluate the viability of the French Guiana coastal fishery, we compare three different fishing scenarios at the time horizon $T = 2040$. The *status quo* scenario (SQS) is exploratory without normative goals. Fishing efforts $e(t)$ are imposed throughout time and the ecosystem evolves accordingly. The two other scenarios, entitled *economic scenario* (ECOS) and *eco-viability scenario* (EVS) are ‘normative’ as they are forward-looking scenarios: one or several objectives are set at the beginning and the fishing effort strategies that allow to achieve the objectives is computed accordingly. From the calibrated model, the three scenarios were evaluated over thirty years and 100 replicates simulating the random variables and capturing the stochasticity $\epsilon(\cdot) = (\epsilon_1(\cdot), \epsilon_2(\cdot), \dots, \epsilon_T(\cdot))$.

The status quo scenario (SQS). This scenario simulates a steady fishing effort based on the mean pattern of the observed efforts between 2006 and 2010:

$$e_f(t) = \bar{e}_f, \quad \text{for } f = 1, \dots, 4 \quad \text{for } t = t_1, \dots, T$$

with \bar{e}_f representing the mean effort monthly observed between 2006-2010 for the fleet f .

In the two normative scenarios, it is assumed that the fishing efforts rely on a feedback control strategy $e_f(t, B)$ that can be adapted every 15 years in such a way that fishing effort choices are

made at the start of the two simulation periods⁹. These scenarios rely on a ‘non-anticipative’ stochastic control approach (Shapiro *et al.*, 2009). At the first period t_1 of the decision process, the fishing effort is assumed to depend only on the information on the initial state $B(t_1)$ available throughout the period. Thereby at the start of the second period t_2 , we have a number of possible states of the biomass induced by the different replicates of ϵ drawn randomly. For each of these possible state $B(t_2)$, a new decision about fishing effort is taken $e(t_2, B(t_2))$ again in the form of a feedback control depending on the state of the eco-system at time t_2 :

$$e_f(t) = \begin{cases} e_f(t_1, B(t_1)) & \text{for } t = t_1, \dots, t_1 + 179 \\ e_f(t_2, B(t_2)) & \text{for } t = t_2, \dots, T \end{cases}$$

where $t_1 = 1$ and $t_2 = 180$ are decisive months.

The economic scenario (ECOS). This scenario maximizes the net present value of all the future profits aggregated among all fleets $\pi(t)$:

$$\pi(t) = \sum_f \pi_f(t). \quad (15)$$

The net present value depends on fishing effort patterns as follows:

$$\text{NPV} = \mathbb{E}_\epsilon \left[\left(\sum_{t=1}^{T-1} (1 + \gamma)^{1-t} \pi(t) \right) + \gamma^{-1} \cdot (1 + \gamma)^{1-T} \pi(T) \right],$$

where γ is the discount rate set at $\gamma = 3\%$. We assume that profits continue indefinitely at the level corresponding to the one during the terminal year, $\pi(T)$. The optimal program underlying the ECO scenario is defined by:

$$\max_{e(t_1), e(t_2)} \text{NPV}(e). \quad (16)$$

Note that this optimal strategy does not guarantee individual profitability among all fleets but represents the viewpoint of a central planner maximizing the expected sum of discounted profits at the aggregated scale.

⁹A refined time decomposition for fishing intensities (for instance, a five-year time step) would have improved the analysis by capturing a broader intertemporal flexibility in fishing strategy. However, it would have required very demanding computation times given the dimensions of the system considered.

The Eco-viability scenario (EVS). The purpose of this scenario is to provide a satisfactory balance over time between fleet profitability, biodiversity viability and food security. This strategy is assessed in terms of probability for these three objectives to be met over time. Thus the eco-viability probability can be written as:

$$\text{EVP}(e) = \mathbb{P}\left(\text{Constraints, (7), (10) and (13) are satisfied.}\right). \quad (17)$$

The viable efforts for EVS are obtained by maximizing the eco-viability probability:

$$\max_{e(t_1), e(t_2)} \text{EVP}(e). \quad (18)$$

4. Results

Appendix ([Appendix A.1](#)) provides details on the quality of the calibration and appendix ([Appendix A.2](#)) reports the estimated parameters. Figure 2 displays the set of optimal effort $e_f(t, B)$ solutions of the intertemporal programs corresponding to each normative scenario (u^{EVS} and u^{ECOS}) for the two parts of the simulation. The box plots shown in the second part exhibit the range of effort multipliers achieving the scenarios depending to uncertainties on growth and stochasticity. These effort multipliers are computed from the fishing levels¹⁰ normalized by the status quo level. Table (2) presents the economic and ecological viabilities probabilities and the net present values for each scenario.

4.1. Status quo scenario: Weak economically and unviable for food security

This scenario corresponds to a case where fishing efforts are maintained constant during the 30 years of the simulation at levels equivalent to those observed between 2006 and 2010. The corresponding effort multipliers are therefore equal to 1.

The numerical simulations of figure 3 -c first show that from 2030, the maximum total catches pass below the food security threshold. Thus SQS fails to satisfy the food security requirement for all simulations ($\text{FVP}(u^{\text{SQS}}) = 0$). Economically as well, SQS does not do great: 40 out of the 100 simulations lead to conditions where the profitability constraints are satisfied ($\text{IVP}(u^{\text{SQS}}) = 0.4$).

¹⁰We assume that the number of vessels remain the same during the simulation time (65 for $f = 1$, 60 for $f = 2$, 46 for $f = 3$ and 9 for $f = 4$) and the maximum feasible efforts per month is 500 hours per vessel.

This scenario yields a net present value equals to 42.8 millions of euros cumulated over the 30 years (Table 2).

Figures 3 -a and b show that the species richness fall to the 10 viability threshold, and few species (*sharks*, *Gillbacker catfish* and *Goliath Grouper*) disappear. The marine trophic index MTI shows a very slow decline but remains above the viability threshold¹¹

4.2. Economic scenario (ECOS): Ecologically, economically and food security unviable

The economic scenario seeks to ensure the maximization of the present (discounted) total profit at the aggregated fleet level. It is characterised by the highest effort multiplier, particularly for fleets 1 and 3 (Figure 2-b) for which the specific multipliers reach their maximum values, while the activity of the two others fleets (2 and 4) are significantly reduced especially during the first period. As a consequence, the profitability constraint is not satisfied for these last two fleets -as shown in Figures 5-e and g. Through ECOS, the fishery yields the highest net present value, around 196.2 millions of euros. However this positive economic outcome is achieved at the detriment of the ecological viability of the system ($PVP(u^{ECOS}) = 0$). In particular the species richness falls to 8 (cf. Figure 5-a). In addition to the 4 species that were already getting extinct under SQS, two additional species are projected to disappear under ECOS: *fat snook* and *bressou catfish*. Finally the high harvesting levels induced by this scenario allow to satisfy the food security constraints in 48 out of 100 runs ($FVP(u^{ECOS}) = 0.48$).

4.3. Eco-viability scenario: a viable strategy from economic, ecological and food security viewpoints

The eco-viability scenario aims at satisfying simultaneously IVP, PVP and FVP constraints. The numerical simulations show that the effort multipliers associated to the ‘eco-viable’ trajectories are higher than the SQS baseline (Figure 2-a). These effort multipliers are consistent as the corresponding fleets are typically small-scale with relatively low fishing efforts (less than 15 hours per week). From an ecological perspective, the simulations indicate that the PVP objective is satisfied 100% of the time ($PVP(u^{EVS}) = 1$) although -as it was the case for the SQ scenario- the SR index falls to the biodiversity threshold around the year 2025 (Figures 4-a and b). The

¹¹ As most of the species accounting for the modeled ecosystem have high trophic level, the MTI index is not sensitive to changes in the species abundances.

profitability constraints are respected for all trajectories ($IVP(u^{EVS}) = 1$) and the food security condition is satisfied for 90% of the trajectories tested: only 10 of these do not satisfy the food security constraint ($FVP(u^{EVS}) = 0.9$). This happens essentially during the last years of the simulations ((Figure 4-c) when the population has doubled and the demand for food is higher than ever. This scenario yields a net present value ranging between 109.4 and 110.9 millions according to the set of possible fishing efforts.

5. Discussion

5.1. Eco-viability as a way to integrate ecological, economics but also social considerations

As expected, the economic scenario (ECOS) yields the greatest net present value over the simulation period (Figure 7) but it is a no-win strategy because ecologically and economically risky (Figure 6). As in Cissé *et al.* (2013) and Doyen *et al.* (2012), this scenario put emphasis on the most efficient fleets in economic terms. Here the fleets 1 and 3 exhibit the best economic performances even if their catches are lower in terms of volumes. In fact these vessels have the lowest fixed costs due to the scanty equipment involved and benefit from the high selling prices since their products are directly sold to the consumers (i.e. no middlemen).

The eco-viability scenario (EVS) appears as the most conservative management strategy and the stochastic approach guarantees its sustainability in an uncertain context. This scenario exhibits a high probability to achieve the economic, ecological and food security constraints together. Moreover this scenario reveals an increase of the net present value between 66.1 – 68.1 M€ compared to baseline SQS. Contrasted with ECOS, the economic cost of sustainability can be evaluated by the difference of cumulative profits between these two scenarios (EVS and ECOS). This cost -between 85.3 and 86.8 M€ (196.2 minus 109.4-110.9) has to be balanced with the benefit of a high probability to ensure a viable management of the fishery (Figure 7). The ecological sustainability gained through the EVS has to be compared with the unsustainability of ECOS both in terms of species richness and in probability of remaining above the thresholds, and in terms of probability with the SQ scenario (Figure 8). Finally the benefits of EVS also go beyond the satisfaction of the food security constraints (at least until 2035) as it helps maintaining positive profits for all the fleets in the fishery.

Identifying the conditions that ensure the economic and environmental sustainability and food security is an important advantage of EVS. Moreover, as demonstrated in ?, viability is closely related to the maximin (Rawlsian) approach with respect to intergenerational equity. It thus contributes to sustain ecosystem and services over the long run. As recognized by [Baumgartner and Quaas \(2009\)](#), viability approach appears as a condition for strong sustainability purposes since several criteria are taking into account and reached separately.

While [Péreau *et al.* \(2012\)](#) consider the maintain of the fleets within the fishery as a social constraint, this paper includes for the first time in a bio-economic model food security issues as a new social constraint. This issue is important especially for small-scale fisheries [Hardy *et al.* \(2013\)](#). As pointed out by [Béné \(2006\)](#); [Béné *et al.* \(2010\)](#), it is also important to include population growth in the management plans of small-scale fisheries because, in many developing countries, fishes are the main protein provider.

5.2. Eco-viability and EBFM

The viability approach appears as a well-suited modeling framework for EBFM to deal with complexity, uncertainties and precautionary approaches. Indeed, the viability approach, simultaneously accounts for dynamic complexities, risks and uncertainty, sustainability objectives for fisheries. In particular, [Cury *et al.* \(2005\)](#) and [Doyen *et al.* \(2007\)](#) show how the method can potentially be useful for integrating ecosystem considerations for fisheries management. [Mullon *et al.* \(2004\)](#) and [Chapel *et al.* \(2008\)](#) emphasize the ability to address complex dynamics in this framework. The computational and mathematical modeling methods proposed in this paper through EVS are motivated by a similar prospect.

One major advantage of the eco-viability approach is the fact that the viability framework is dynamic and thus makes it possible to capture 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 processes. Here the focus is both on trophic and technical interactions through a multi-fleet and multi-species context. This paper contributes to the guidance on how to operationalize EBFM especially in tropical small-scale fishery, where data and reference points are often missing. In addition, taking into account the food security objective to deal with the potential rise of fish demand through local population

growth is a step forward for an ecosystem approach (Hilborn, 2011).

The need of robust and precautionary approach is relevant to tackle EBFM particularly when knowledge is insufficient (Pikitch *et al.*, 2004). The stochastic viability approach used in this work appears as a well suited way to operationalize sustainable small-scale fishery in an uncertain context.

As in Doyen *et al.* (2012) and Gourguet *et al.* (2013), stochastic scenarios presented here allow to account for the complexities and uncertainties of mechanisms at play, particularly their nonlinearity. Ecological dynamics and technical interactions but also trophic webs, or environmental (habitat, climatic) uncertainties are addressed. In this paper inasmuch no reference points are available for species studied, we adopt a precautionary approach considering both two ecological indexes with reasonable chosen thresholds. The computed set of fishing efforts of normative scenarios by the non-anticipativity stochastic method, give high improvements compared to Cissé *et al.* (2013) because they rely on feedback controls and consequently more adaptive accounting for uncertainties affecting the exploited ecosystem. The EVS scenario exhibits a sustainable match with economic and ecological issues together with food security constraint with a high probability.

5.3. Decision support for the French Guiana small-scale fishery

The first assessment of the French Guiana small-scale coastal fishery has been carried out by Cissé *et al.* (2014) stressing the socio-economic importance of this fishery. In fact due to its status of European overseas territory, regulations tools are derived from commonly used national and European fisheries management systems. The technical management measures consist of maximum net length (2500 m), minimum mesh size (40 mm), marine protected area (8 km²) and trawl ban under 30 m deep. The access to the fishery is regulated by European and regional licenses. There is no quota for catches and no limitations concerning exploited species and their size. The only aim of the current management strategy is to prevent fishing activity by unauthorized boats. Actually, up to now, as many tropical multi-species fisheries, there are no studies on the stock status for the main exploited species. The data monitoring system, implemented since 2006, does not present time series data enough longer to tackle such goals. Nevertheless the available data are satisfactory to bioeconomic modeling purpose as in Cissé *et al.* (2013).

The present study provides new insights in complement to Cissé *et al.* (2013), improving our understanding of the case study. First, fishing scenario outputs show that fishing performance,

including food supply and fleets profitability, can be increased or sustained with lesser impact to marine ecosystem. Particularly EVS aims to reconcile economic and ecological sustainability with the growing food demand contributing hence to food security, with a high probability. Secondly, it appears that the loss of species cannot be avoided. This loss of biodiversity could potentially alter some ecosystem services (not taken into account in this model) and the outcomes of the fishery itself in the long run. Depending on the endangered stocks, conservation measures for the productive and reproductive capacities of these stocks should be taken. Banning fishing in nursery zones or promoting more selective fishing techniques could be an alternative. Lastly, EVS does not entail a severe reduction of harvesting, the fishing effort remains relatively high compared to SQS.

Contrasted with SQS, EVS gives insights on the status of the French Guiana coastal fishery. The fishery is not currently fully exploited and may support higher fishing level without jeopardizing ecological and economic sustainability. This fishery does not suffer from overcapacity. Therefore the uncertainties underlying the model and the assumptions should lead to consider more precautionary approaches and alternative options to face the future local fish demand, as aquaculture. In the way to improve our knowledge of the complex ecosystem and thus the management plans, the methodological interest of sustaining the Fishery Information System of the French Guiana coastal fishery appears obvious.

5.4. Perspectives

The present paper is a step forward in the understanding, the assessment and the management of the French Guiana coastal fishery inasmuch a robust approach based on stochastic viability methods is used. Therefore many improvements are noted. First of all, the uncertainty underlying the model has been estimated within the calibration process of the unknown biological parameters of the model, by least square method. A more accurate option is to calibrate the noise parameter ex post with for instance a Kalman filter for nonlinear process (see [Kwasniok \(2012\)](#)). Moreover, the assumption of keeping fixed some economic parameters during the period simulation has to be relaxed. Taking into account stochasticity on costs as fuel price is necessary to improve the predictions of the model. Another step will consist on considering the illegal fishing activity of foreign fleets (from Guiana, Suriname and Brazil), which are not yet taking into account in the study. Furthermore, it will be fruitful to compare the present results with other simplified dynamic

model, as Gompertz model for instance (see [Mutshinda *et al.* \(2009\)](#)). In fact there is no proof that the Lotka-Volterra dynamics used in this work is the more accurate for the French Guyana coastal ecosystem. Lastly, it would be interesting to extend the number of species in order to include the effects of fishing activities on the dynamics of other species (such as mammals, turtles or birds) and on plankton dynamics as suggested by [Pikitch *et al.* \(2004\)](#). Another interesting goal would be to include the effects of climatic changes, for instance sea surface temperatures ([Keyl and Wolff, 2008](#); [Thébaud and Blanchard, 2011](#)).

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

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

Table 2: The viability probabilities and net present values of the different fishing scenarios

Scenarios \ Probabilities	PVP	FVP	IVP	EVP	NPV(M euros)
Status quo	1	0	0.4	0	42.8
Economic	0	0.48	0	0	196.2
Eco-viability	1	0.9	1	0.9	109.4 - 110.9

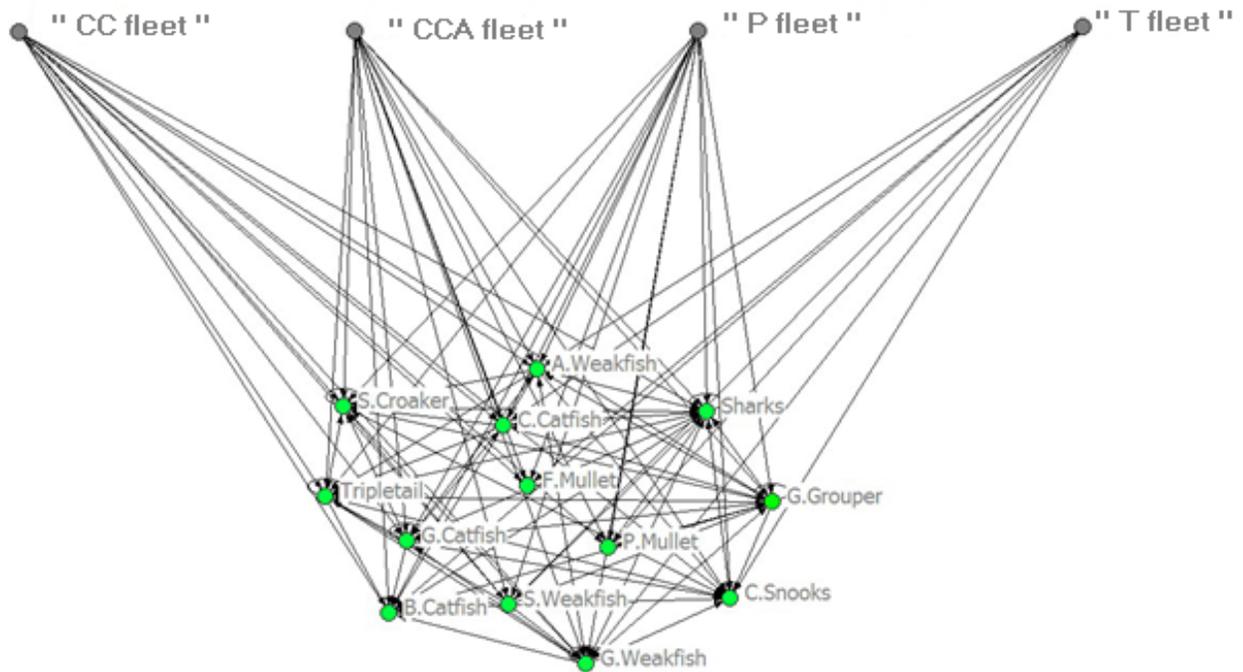


Figure 1: Food web of the thirteen main species and the four fleets exploiting them in the French Guiana coastal fishery.

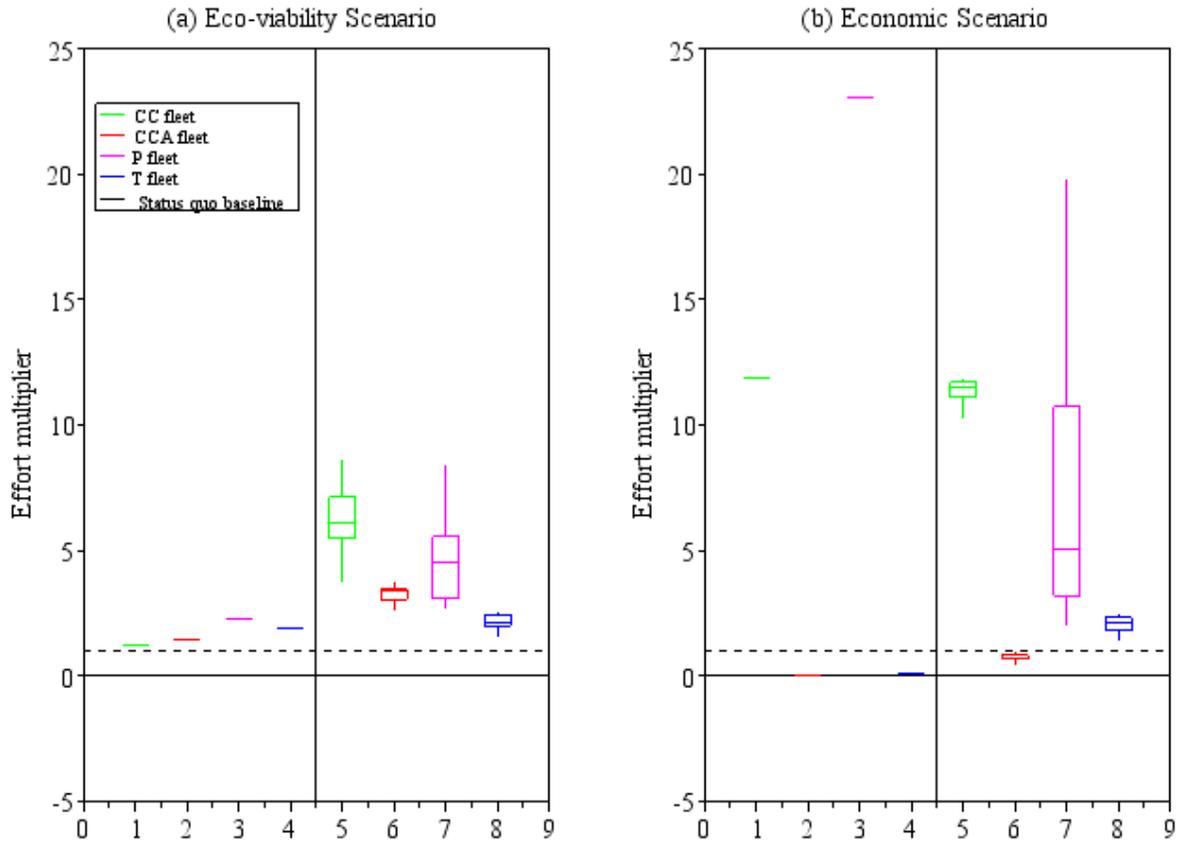


Figure 2: **Fishing effort multipliers**, by scenario and fleet (from 1 to 4), based on the comparison between effort $e_f(t)$ and the mean pattern of efforts \bar{e}_f between 2006 and 2010: $u_f(t) = \frac{e_f(t)}{\bar{e}_f}$. The box plots in the second simulation period show the different prospective fishing efforts according to uncertainties.

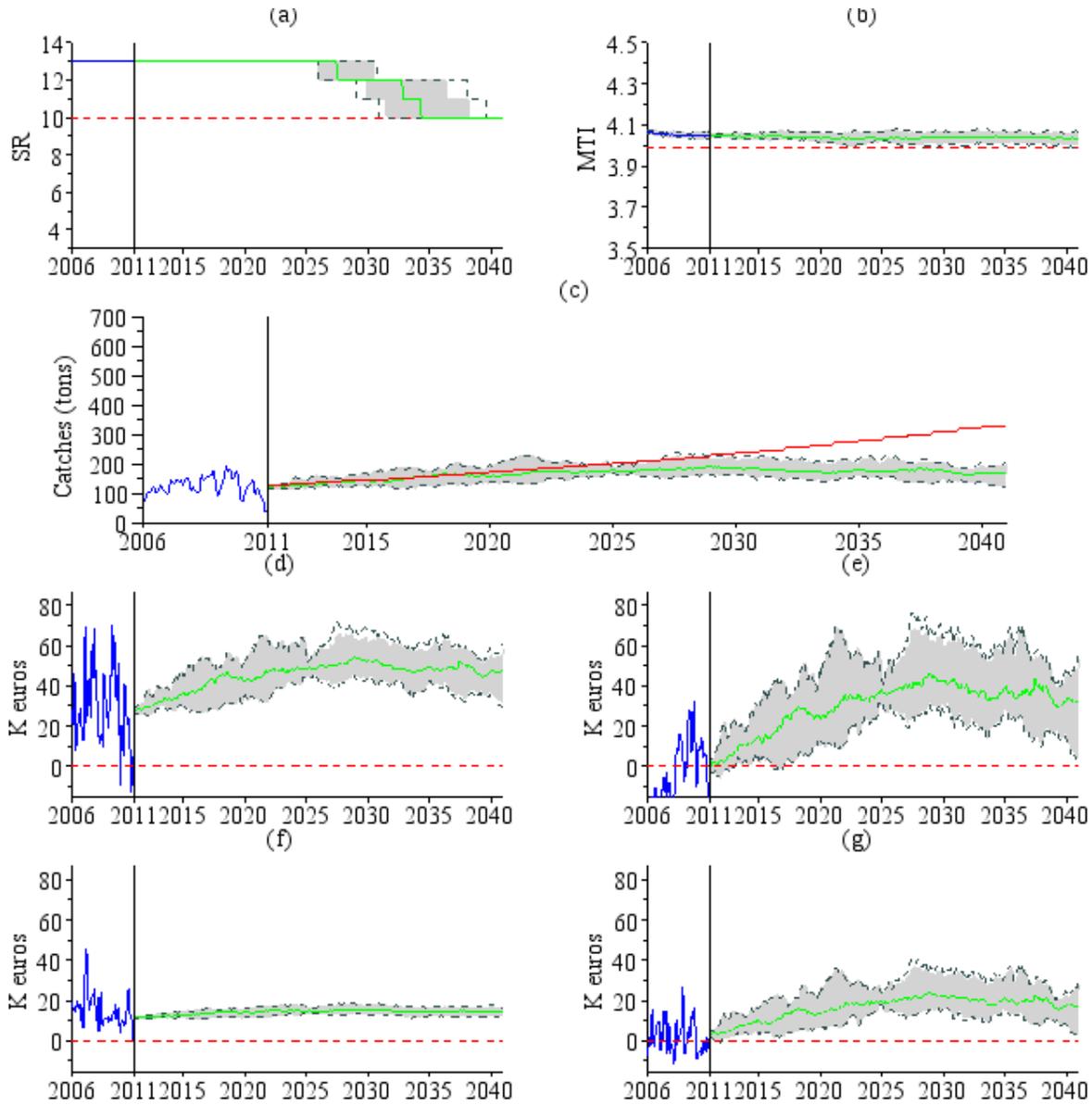


Figure 3: **Main outputs for the status quo scenario (SQS)** with $u_f^{SQS}(t) = 1$: Evolution of the species richness (a), marine trophic index (b), total catches (c) and profits by fleet (d. fleet 1; e. fleet 2; f. fleet 3; g. fleet 4). The dark dotted lines stand for the set of possibilities including the 100 simulated trajectories and the gray fields include 95% of the latter. The green lines represent the median values of the 100 trajectories. The red dashed lines stand for the viability thresholds. The blue lines correspond to the historical paths between 2006 and 2011.

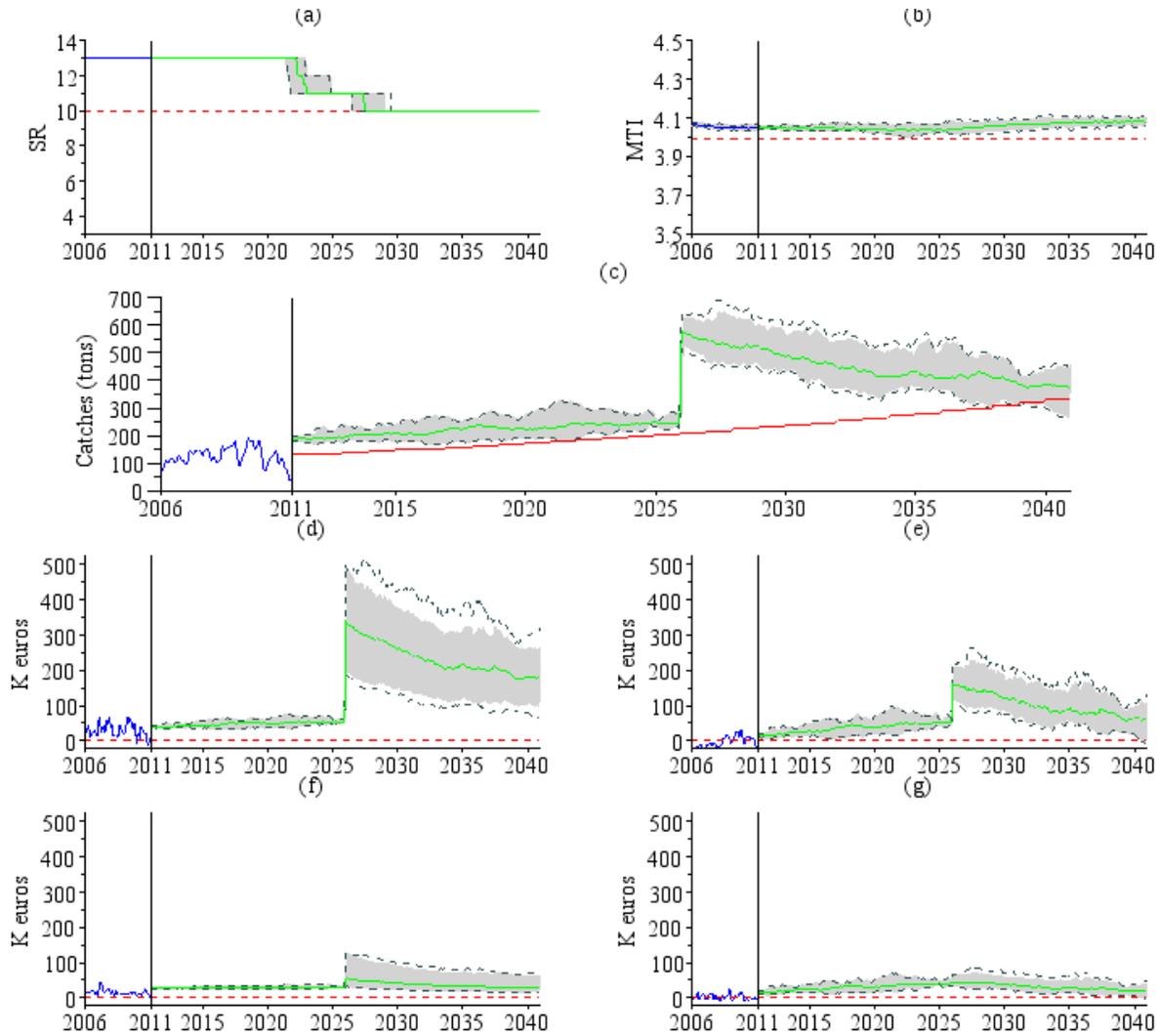


Figure 4: **Eco-viability scenario (EVS)** main outputs with $u_f^{EVS}(t)$: Evolution of the species richness (a), marine trophic index (b), total catches (c) and profits by fleet (d. fleet 1; e. fleet 2; f. fleet 3; g. fleet 4). The dark dotted lines stand for the set of possibilities including the 100 simulated trajectories and the gray fields include 95% of the latter. The green lines represent the median values of the 100 trajectories. The red dashed lines stand for the viability thresholds. The blue lines correspond to the historical paths between 2006 and 2011.

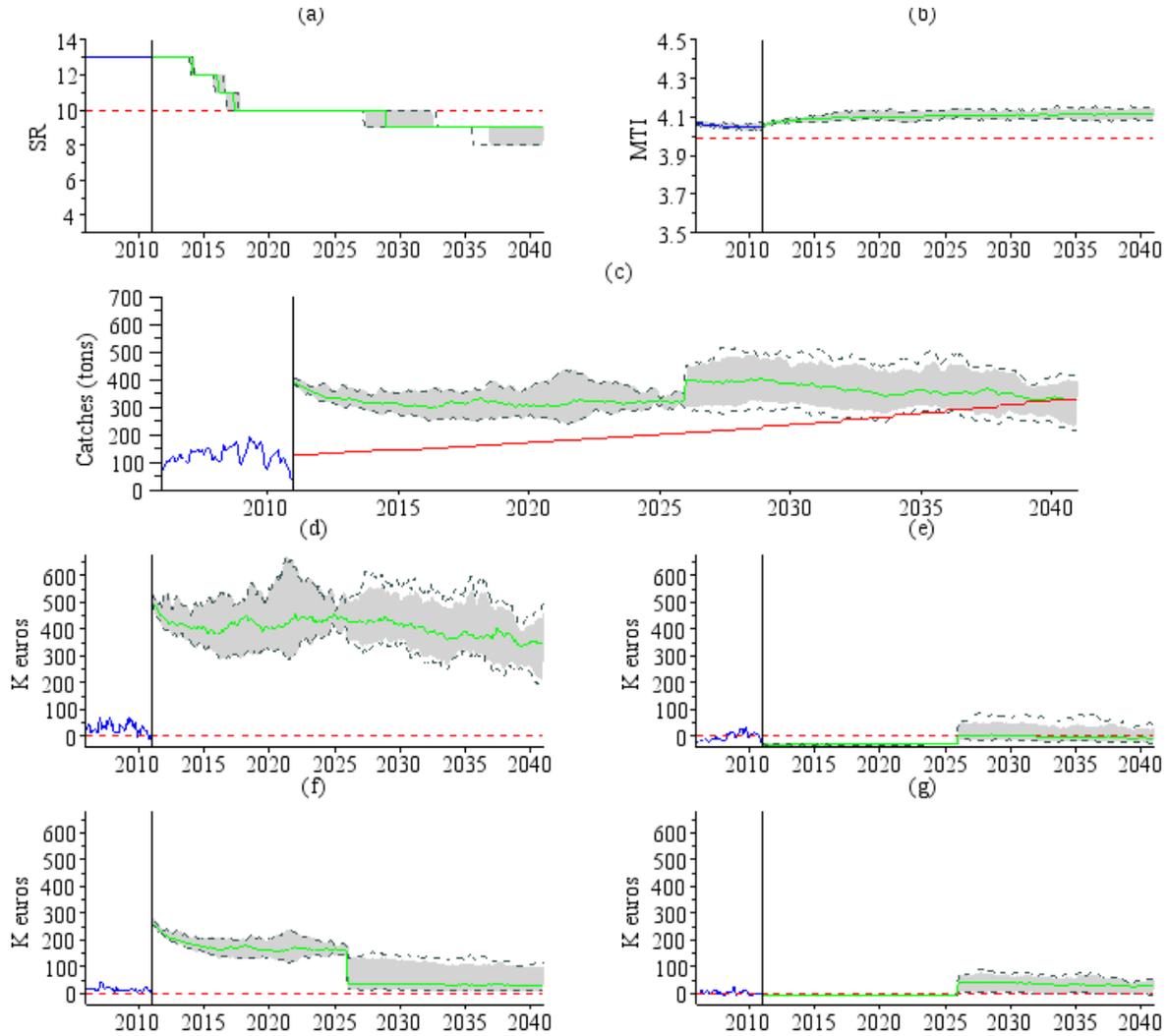


Figure 5: **Economic scenario (ECOS)** main outputs with $u_f^{ECOS}(t)$: Evolution of the species richness (a), marine trophic index (b), total catches (c) and profits by fleet (d. fleet 1; e. fleet 2; f. fleet 3; g. fleet 4). The dark dotted lines stand for the set of possibilities including the 100 simulated trajectories and the gray fields include 95% of the latter. The green lines represent the median values of the 100 trajectories. The red dashed lines stand for the viability thresholds. The blue lines correspond to the historical paths between 2006 and 2011.

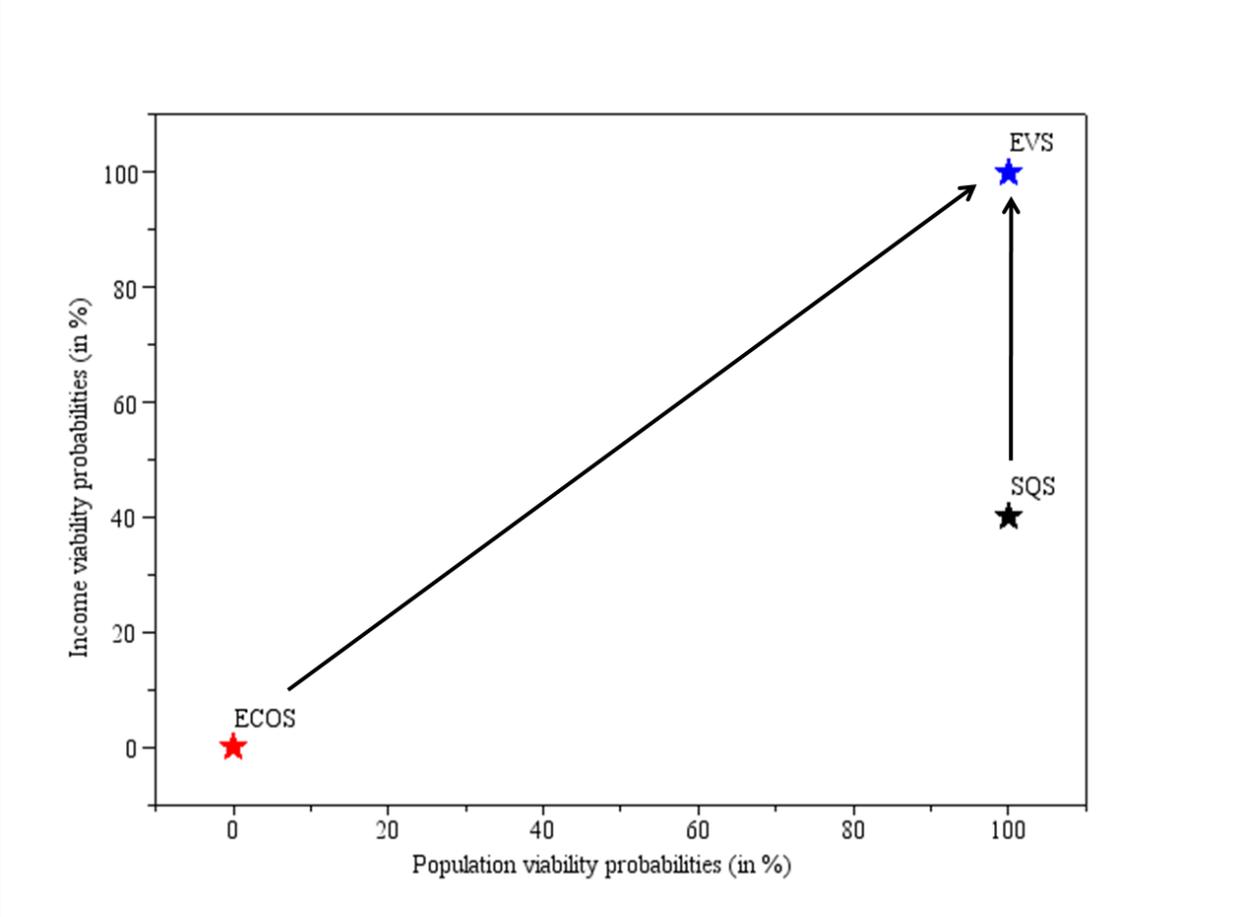


Figure 6: Income viability probabilities (IVP) versus ecological viability probabilities (PVP) for the scenarios SQS, ECOS and EVS.

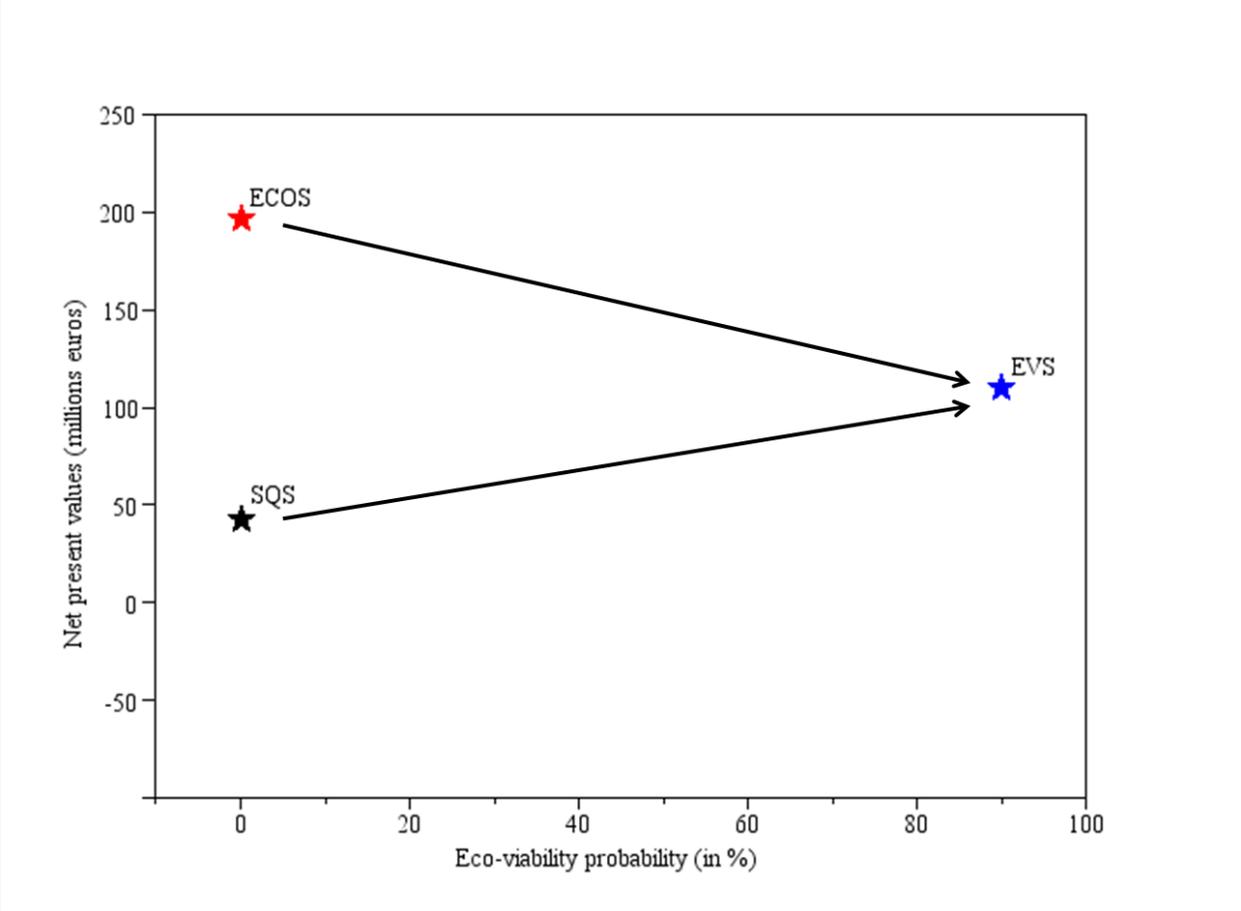


Figure 7: Net present values (NPV) versus eco-viability probabilities (EVP) for the scenarios SQS, ECOS and EVS.

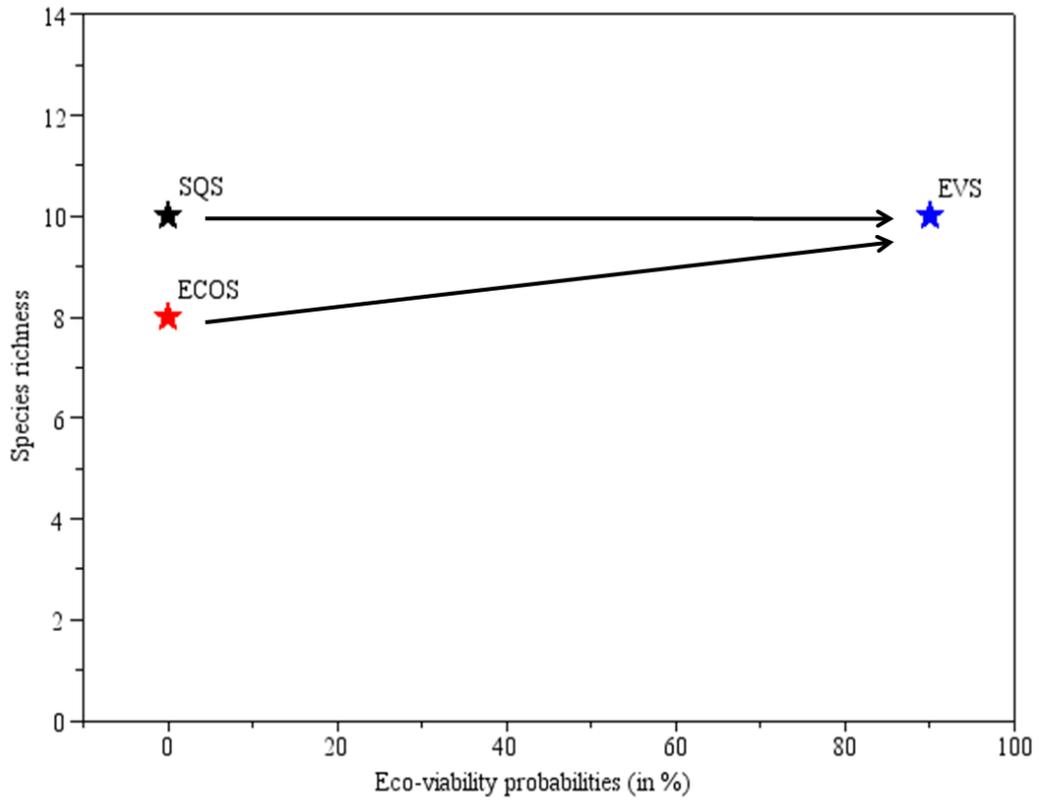


Figure 8: Species richness versus Eco-viability probabilities (EVP) for each scenario.

Appendix A. Appendix

Appendix A.1. Calibration results

Figure (A.9) presents the historical and simulated catches by fleet. For each fleet f were computed the mean relative errors Δ_f , in Euclidean or quadratic norm, between observed and simulated catches from January 2006 to December 2010,

$$\Delta_f^* = \sqrt{\frac{1}{60} \sum_{t=t_0}^{t_1-1} \left(\frac{(H_f^{data}(t) - H_f(t))}{H_f(t)} \right)^2}$$

where $H_f(t) = \sum_i H_{i,f}(t)$ stands for catches by fleet f at time t over the whole 13 species i . The mean relative errors equal $\Delta_1^* = 0.33$ for fleet 1, $\Delta_2^* = 0.17$ for fleet 2, $\Delta_3^* = 0.40$ for fleet 3 and $\Delta_4^* = 0.32$ for fleet 4.

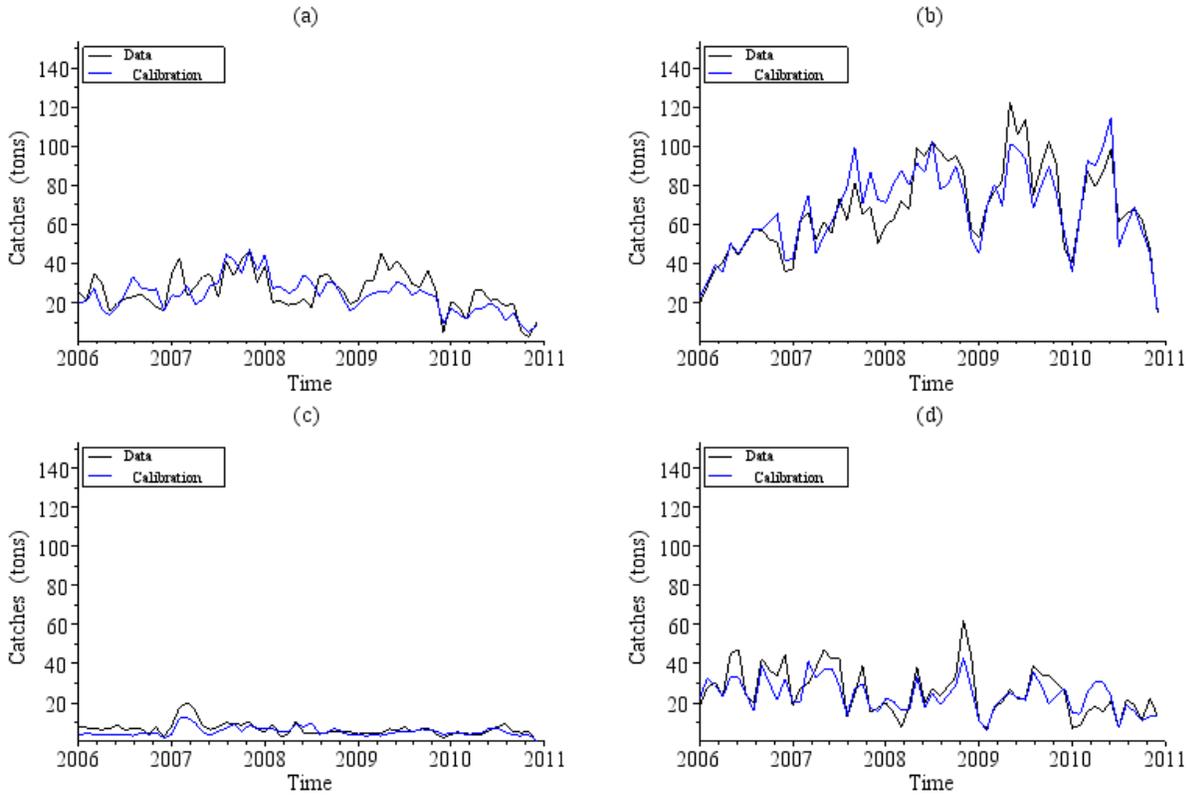


Figure A.9: Comparison by fleet (a. fleet 1; b. fleet 2; c. fleet 3; d. fleet 4) f between historical catches $\sum_i H_{i,f}^{data}(t)$ and simulated catches $\sum_i H_{i,f}(t)$.

Appendix A.2. Details on estimated biological parameters

Table A.3: Initial stocks, intrinsic growth rates, catchabilities of selected species and uncertainty parameter from calibration.

Species(i)	Initial stocks (December 2005) $B_i(0)$ (tons)	Intrinsic growth rate (r_i) (Fisbase) $*10^{-2}$ (/month)	Catchability fleet $f = 1$ $(q_{i,1})$ $*10^{-7}$ (/hour)	Catchability fleet $f = 2$ $(q_{i,2})$ $*10^{-7}$ (/hour)	Catchability fleet $f = 3$ $(q_{i,3})$ $*10^{-7}$ (/hour)	Catchability fleet $f = 4$ $(q_{i,4})$ $*10^{-7}$ (/hour)	Uncertainty parameter σ^2 (%)
A. weakfish	17,358	2.08	1.04	1.76	0.33	3.85	3.01
C. catfish	15,448	5.95	1.36	0.67	0.67	0.44	3.01
G. weakfish	7,111	0.16	1.61	1.50	0.93	3.56	3.01
C. snooks	390	4.21	14.35	8.09	10.98	1.64	3.01
Sharks	274	- 4.72	11.67	12.17	16.19	43.47	3.01
S. weakfish	2,301	0.64	1.50	1.43	1.56	0.	3.01
S.croaker	252	3.44	6.36	4.32	7.48	0.	3.01
Tripletail	476	9.34	9.72	9.29	5.28	3.01	3.01
G. catfish	93	2.59	29.89	35.19	33.80	17.22	3.01
B. catfish	214	4.21	7.92	2.65	23.39	0.	3.01
G. grouper	268	- 2.26	17.88	4.18	11.00	7.05	3.01
F. mullet	260	5.31	6.11	2.53	6.27	0.	3.01
P. mullet	187	7.03	9.61	1.41	15.63	0.	3.01

Table A.4: Trophic relations matrix, $s_{i,j}$ ($*10^{-12}$ /kg) from calibration. Values given are the trophic effect of species (i) on species (j): positive if j is a prey of i and negative if j is a predator of i . The intra-specific interactions $s_{i,i}$ refer to: $s_{i,i} = -r_i/K_i$

	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.	- 330.20	1.0D-09	- 9.2D-04	1.1D-04	- 8.2D-09	- 8.5D-10	2.1D-04	2.4D-04	- 4.2D-09	1.8D-04	- 4.2D-09	1.1D-09	1.0D-09
C. cat.	- 8.1D-09	- 4066.7	- 8.3D-04	- 6.3D-09	- 4.7D-09	- 1.0D-03	- 8.1D-09	- 1.1D-03	- 5.2D-09	8.7D-10	- 5.3D-04	1.8D-04	2.6D-04
G. weak.	1.1D-04	1.0D-04	- 56.8	1.5D-09	- 5.0D-09	- 2.3D-09	1.7D-09	1.0D-09	- 8.7D-04	1.2D-09	- 6.0D-09	1.2D-04	1.0D-09
C. snoo.	- 9.40-04	- 1.0D-08	- 1.2D-08	- 14602.2	- 7.7D-04	- 4.4D-09	- 1.1D-03	- 5.3D-09	- 9.3D-04	1.1D-04	- 5.3D-04	5.6D-05	4.7D-05
Sharks	1.0D-09	5.8D-10	6.2D-10	9.6D-05	- 12439.5	8.7D-05	3.1D-04	2.1D-04	9.5D-10	9.4D-10	- 4.4D-04	1.3D-04	1.2D-09
S. weak.	- 1.5D-08	1.2D-04	- 5.6D-09	5.5D-10	- 6.9D-04	- 690.4	1.3D-09	1.5D-04	- 9.9D-04	1.0D-09	- 7.7D-09	2.0D-04	4.1D-10
S. croa.	- 1.7D-03	- 3.3D-09	- 1.4D-08	1.3D-04	- 2.5D-03	- 1.1D-08	- 41463.6	- 3.0D-09	- 4.8D-09	1.3D-09	- 2.6D-04	1.0D-09	2.9D-04
Triple.	- 1.9D-03	- 1.1D-03	- 8.0D-09	- 3.3D-09	- 1.7D-03	- 1.2D-03	- 6.7D-09	- 183356.2	- 5.4D-09	6.8D-05	- 3.3D-09	5.7D-10	7.3D-05
G. cat.	5.3D-10	6.6D-10	1.0D-04	1.1D-04	- 7.6D-09	1.2D-04	6.0D-10	6.8D-10	- 57697.8	5.3D-05	- 4.8D-09	1.5D-04	8.4D-10
B. cat.	- 1.4D-03	- 7.0D-09	- 1.0D-08	- 9.4D-04	- 7.5D-09	- 8.2D-09	- 1.0D-08	- 5.5D-04	- 4.2D-04	- 180203.8	- 4.9D-09	0.	0.
G. grou.	5.2D-10	6.7D-05	7.5D-10	6.7D-05	- 1.5D-03	9.6D-10	3.2D-05	4.1D-10	6.0D-10	6.1D-10	- 16485.4	5.8D-10	1.2D-09
F. mul.	- 8.8D-09	- 1.5D-03	- 1.0D-03	- 4.4D-04	- 1.0D-03	- 1.6D-03	- 8.0D-09	- 4.6D-09	- 1.2D-03	0.	- 4.7D-09	- 169046.3	0.
P. mul.	- 8.4D-09	- 2.0D-03	- 8.2D-09	- 3.7D-04	- 1.0D-08	- 3.2D-09	- 2.3D-03	- 5.8D-04	- 6.7D-09	0.	- 9.9D-09	0.	- 310836.5

Appendix A.3. Economic data

Table A.5: 2010 economic data (variable costs, fixed costs and selling prices).

	Fleets			
	'canots créoles ' (fleet $f = 1$)	'canots créoles améliorés' (fleet $f = 2$)	'pirogues' (fleet $f = 3$)	'tapouilles' (fleet $f = 4$)
2006-2010 average boats number	64.6	59.4	45.6	8.8
Variable costs c_f^v (EURO/fishing hour)	3.19	8.19	1.61	14.85
fixed costs per boat c_f^f (EURO/annum)	3398	6530	195	13880
Selling prices $p_{i,f}$ (EURO/kg)				
A. weakfish	2.73	2.17	3.41	2.30
C. catfish	1.12	0.89	1.40	0.98
G. weakfish	2.01	1.34	3.45	1.38
C. snooks	3.18	2.22	2.72	2.29
Sharks	1.05	0.74	1.28	0.65
S. weakfish	3.16	2.21	3.43	2.21
S. croaker	3.86	1.87	1.85	1.85
Tripletail	1.46	1.34	2.72	1.38
G. catfish	1.93	2.02	3.53	1.93
B. catfish	1.58	1.09	1.91	1.09
G. grouper	3.11	2.41	1.6	1.6
F. mullet	2.79	2.38	4.58	2.38
P. mullet	2.55	2.01	3.40	2.01