A stochastic bio-economic model for the viable management of the Bay of Biscay mixed demersal fisheries

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Abstract

Marine fisheries resources are under extreme pressure worldwide. Marine scientists and stakeholders advocate ecosystem-based fishery management (EBFM) for an effective and sustainable management. However, the way to operationalize such EBFM remains controversial. The stochastic co-viability approach can be a relevant modeling framework for EBFM as it accounts for dynamic complexities, uncertainties, risks and sustainability objectives balancing ecological, economic and social dimensions together with intergenerational equity. The present paper focuses on the case of the mixed demersal fisheries operating in the Bay of Biscay and especially harvesting Nephrops (*Nephrops norvegicus*), Hake (*Merluccius merluccius*) and Sole (*Solea solea*). A bio-economic multi-species and multi-fleets model is developed to examine how to preserve Spawning Stock Biomass (SSB) for every species while preserving the economic profitability for the various fleets at play. First results suggest that the viable strategies require a significant mitigation of the fishing capacities as compared to referenced year 2008 for Nephrops trawlers and gill-netters fleets that are the most contributory fleets to Nephrops and Sole fishing mortality.

Key words: Fisheries, ecosystem-based management, bio-economic model, co-viability, uncertainty, Bay of Biscay

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1 Introduction

Marine biodiversity is under extreme pressure worldwide by increasing loss of populations and species, with highly uncertain consequences. Major threats still remain related to the fishing activities. According to recent estimates (Garcia & Grainger, 2005; FAO, 2009), three quarters of the world's fish stocks are fully exploited or over-exploited and the proportion of those stocks that are too intensively exploited is growing. Consequently, the sustainability of the world fisheries is being seen as a crucial question on the biodiversity agenda for national and international agencies (ICES, 2004; FAO, 1999). However, fisheries managements to date remain generally ineffective. In particular, mono-specific management focusing on the catches of a single targeted species usually ignores both ecosystem complexities and socio-economic dimensions of the problem. Therefore, as attested by FAO (2003); Nomura (2008); Pikitch *et al.* (2004); Kempf (2010), there is nowadays a widespread acceptance that a more integrated perspective is needed at the ecosystem scale which embraces the numerous issues related to marine biodiversity preservation, economic and social objectives of fisheries.

Thus numerous scientists and stakeholders advocate an Ecosystem-Based Fisheries Management (EBFM), as described [1] in FAO (2003). Hence EBFM must manage targeted species in the context of the overall state of the system, habitat, protected species, and non targeted species. Single-species target and limit reference points may still be appropriate, but need to be adapted in the context of these other factors (Pikitch *et al.* , 2004). A more specific goal of EBFM is to reduce excessive levels of bycatch, because juvenile life stages and unmarketable species often play important roles in the ecosystem (Pope *et al.* , 2000; Ballance *et al.* , 1997).

However the way to operationalize such a concept remains controversial as pointed out in Sanchirico *et al.* (2008). There is a growing interest in using bio-economic models as a tool for policy analysis to better understand pathways of development and to assess the impact of alternative policies on the natural resource base and human welfare. Bio-economic models aim to integrate the human dimension into usual ecological models. In the case of fisheries, bio-economic models are used to add the fleet dynamics to the fish population dynamic models. These models can provide a better and more comprehensive indication of the feedback effects between socio-economic activity

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[1] *"An ecosystem approach to fisheries strives to balance diverse societal objectives, by taking account of the knowledge and uncertainties about biotic, abiotic and human components of ecosystems and their interactions and applying an integrated approach to fisheries within ecologically meaningful boundaries."*

and natural resources (Prellezo *et al.* , 2009). In this perspective, viability modeling is presented by several authors (Cury *et al.* , 2005; Doyen *et al.* , 2007) as a relevant potential modeling framework for EBFM. This approach conveys relevant information regarding decision-making for sustainability. In particular, complexities and uncertainties of ecological dynamics and interactions, market dynamics or environmental (habitat, climatic) changes can be taken into account by stochastic viability. It can also integrate risks, precaution and sustainability objectives, thus it does compile ecological, economic and social goals. The co-viability approach (ecological and economic viability) has already been successfully applied to renewable resource management, especially to fisheries in several contexts (Béné & Doyen, 2000; Bene *et al.* , 2001; Doyen & Béné, 2003; Eisenack *et al.* , 2006; Martinet *et al.* , 2007), and also to broader ecosystem or biodiversity dynamics (Chapel *et al.* , 2008; Bene & Doyen, 2008; Doyen *et al.* , 2007; Mullon *et al.* , 2004). This co-viability approach can be useful in this multi-criteria context as this approach could exhibit a domain of possibilities, feasibility and trade-offs between potentially conflicting objectives or constraints to be fulfilled throughout both present and future.

The main objective of this study is to use the viability framework as a methodological support to test and explore through modeling and scenario analysis how the implementation of the Ecosystem Approach can help managing multi species fisheries. More specifically, this article deals with the sustainable management of Bay of Biscay demersal fishery. This multi species and multi fleets fishery provides a challenging example to illustrate the issues of mixed fisheries management. A bio-economic model relying on this case study is built and analyzed. A particular emphasis is put on the joint ecological-economic viability between three exploited fish species (Nephrops, Hake, Sole) and sixteen fleets (trawlers, gill nets, ..) impacting these species.

2 The Bay of Biscay case study

The Bay of Biscay demersal mixed fisheries - catching Hake, Megrim, Sole, Cod, Anglerfish and Nephrops - correspond to the division VIIIa and b of the ICES (Figure 1). Different French, Spanish and Belgium fleets operate in this area. Mean gears used in these fisheries are trawl, gillnet and longline. Bottom trawls, in particular, are known to be poor selective gears. Their use in a multi-species ecosystem induces catches of non-targeted fishes (by-catch) or unwanted length grades of the targeted species. Much of this catch is often discarded with high mortality rates (Alverson *et al.* , 1994). These gears also have strong impacts on habitats due to their exploitation characteristics.

Different surveys, research and data collection programs conducted in the

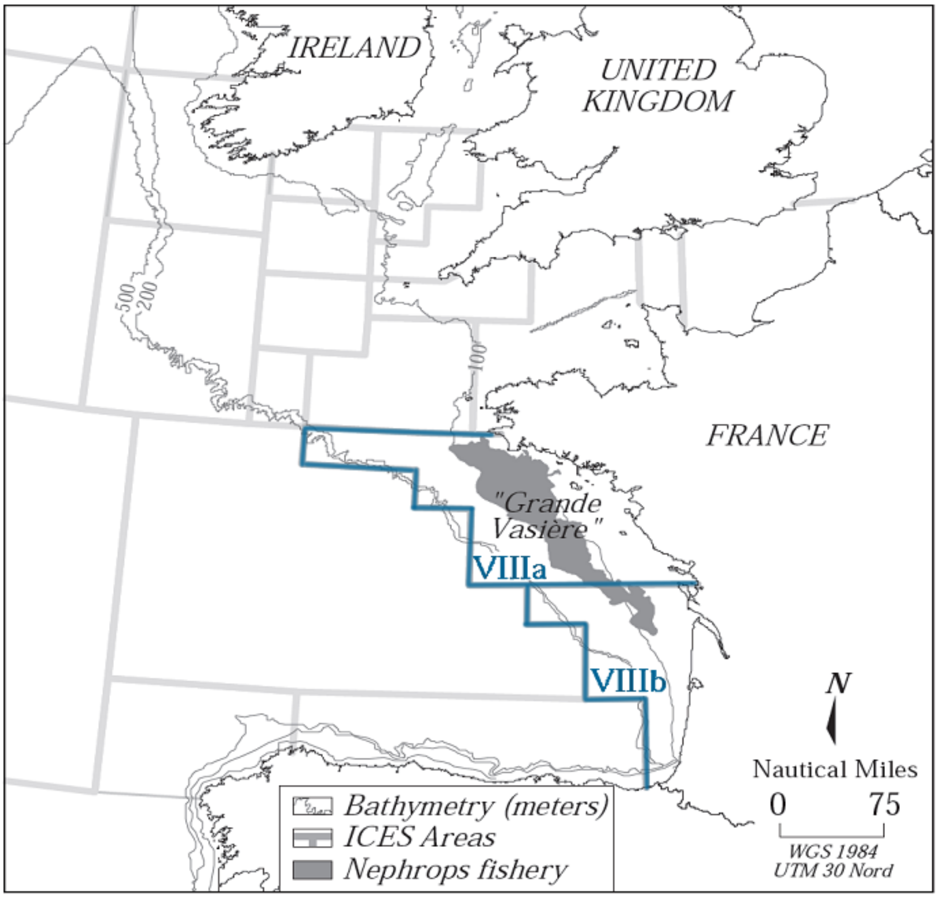

Figure 1. ICES Divisions VIIIa,b Source: Macher *et al.* (2008)

European data collection framework have provided biology and population dynamics data, stock assessment by ICES (International Council for the Exploration of the Sea) and economic data. Among the 200 species caught in the Bay of Biscay, 20 species correspond to 80% in weight of the landings. As displayed by figure 2, the main stocks in percentage of total landings values (around 37% of the French national production value) are Nephrops (Nephrops norvegicus), Hake (Merluccius merluccius), Sole (Solea solea) and Anglerfish (Lophius piscatorius and L. budegassa). In this study, only the dynamics of Hake, Nephrops and Sole are explicitly represented [2]. From fishing strategy analyses, four main fleets have been identified: nephrops trawlers, various fishes trawlers, Sole gill-netters and various fishes gill-netters. These four main fleets involved 577 vessels in 2008 and its turnover amounted to 206 million €. Sixteen sub-fleets are distinguished according to the length class of vessels and to associated cost structure.

[2] In 2007, the ICES working group (WGHMM) rejected the XSA age based assessments of anglerfishes because of data quality (increased discards not incorporated) and ageing problems clearly identified. Therefore there is no age based data used to assess the stocks and useful data are not available until 2012.

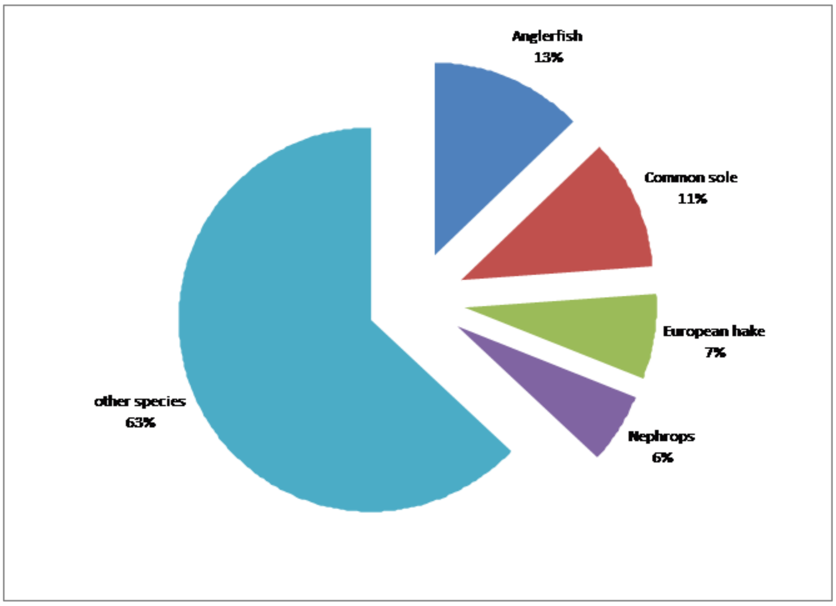

Figure 2. Rate of values of each species in the national French production in 2008. *Data source : Ifremer, SIH, DPMA*

3 The bio-economic model

A model is developed capturing the main biological and economic processes governing these mixed fisheries in order to assess alternative management objectives of these fisheries and to provide sustainable strategies. In particular, the model intends to exhibit fishing scenarios and effort strategies reconciling ecological and economic viability. To achieve this, the bio-economic model relies on the mathematical formalization of controlled dynamic systems (Clark, 1976) and especially discrete time models (De Lara & Doyen, 2008). The evaluation is basically related to a set of ecological and economic constraints capturing the viability of the system. Formulating the constraints in terms of probabilities, the stochastic viability approach (Doyen *et al.* , 2007; Doyen & De Lara, 2010) allows to assess the performances in the uncertain context. This approach expands the PVA (Population Viability Analysis) well-known in biological conservation sciences (Morris & Doak, 2002).

Major ingredients of the bio-economic dynamic model are captured by the conceptual scheme displayed on figures 3 and 4. We here consider the three species, Nephrops, Hake and Sole and the sixteen fleets impacting or exploiting them[3]. The model is an age-structured population one derived from the standard fish stock assessment approach (Quinn & Deriso, 1999). Population dynamics are described on a yearly basis and integrate uncertainties on re-

[3] In fact an other 17th "fleet" takes into account other fishing mortalities (particularly induced from Spanish boats on Hake)

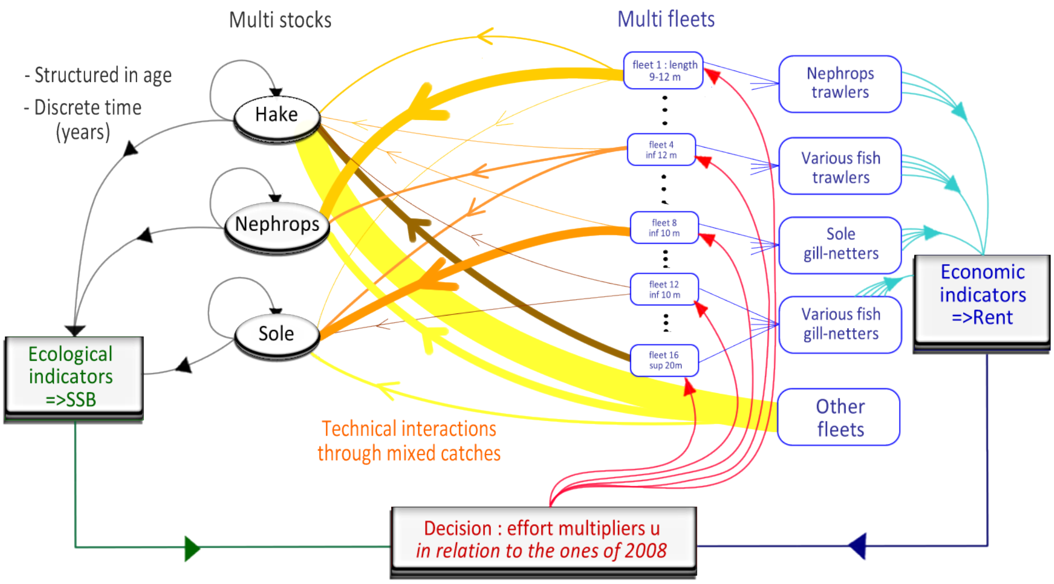

Figure 3. Scheme of the bioeconomic model. The technical interaction arrows are proportionals to the impact of each fleet on the mortality of each species in 2008 (data source: Ifremer, SIH, DPMA).

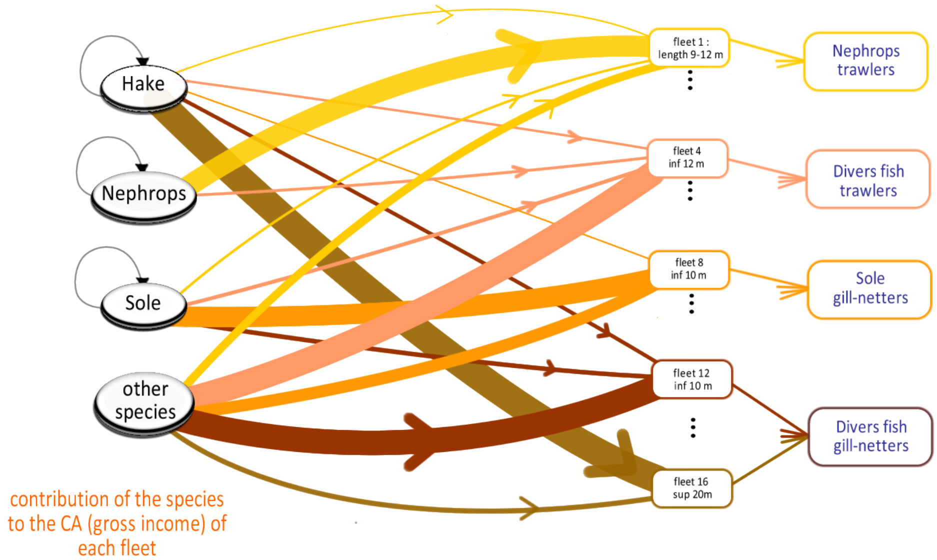

Figure 4. Scheme of the bioeconomic model. The arrows between species and fleets are proportionals to the contribution of each species on the gross income of each fleet in 2008 (data source: Ifremer, SIH, DPMA).

cruitment. Effort multipliers by fleets, compared to 2008, are introduced in the fishing mortalities mechanisms. They play the role of control variables in the management of the system. Technical interactions are taken into consideration through mixed catches due to non selectivity of the fleets. Economic performance indicators are defined in terms of profit by fleet computed from landings, selling prices and cost data. Ecological performance indicators are defined in terms of spawning stock biomass (SSB) of every individual fish stocks. From these ecological and economic indicators, the outcomes of alternative effort strategies can be compared especially in terms of bio-economic co-viability.

3.1 A multi-species, multi-fleets and age-structured dynamics

The age-structured dynamics of the three species are governed by

$$\begin{cases} \mathrm{N}_{s,a}(t+1) = \mathrm{N}_{s,a-1}(t)\exp\left(-M_{s,a-1} - F_{s,a-1}(t)\right), & a = 2,\ldots,A_{s-1} \\ \mathrm{N}_{s,A_s}(t+1) = \quad \mathrm{N}_{s,A_{s-1}}(t)\exp\left(-M_{s,A_{s-1}} - F_{s,A_{s-1}}(t)\right) & \\ \qquad\qquad\qquad +\mathrm{N}_{s,A_s}(t)\exp\left(-M_{s,A_s} - F_{s,A_s}(t)\right) & \end{cases} \tag{1}$$

where $\mathrm{N}_{s,a}(t)$ stands for the abundance of the exploited species $s = 1,2,3$ at age $a = 1,\ldots,A_s$. Thus the state $\mathrm{N}_{s,a}(t+1)$ of the stock at time $t+1$ evolves according both to natural $M_{s,a}$ and fishing $F_{s,a}(t)$ mortality rates of the species s at age a. The fishing mortality $F_{s,a}(t)$ is derived from the fishing mortality of the whole 17 fleets $F_{s,a,f}(t_0)$ at the referenced year t_0 and the effort multipliers u_f by fleet f as in equation (2):

$$F_{s,a}(t) = \sum_{f=1}^{17} F_{s,a,f}(t_0).u_f(t). \tag{2}$$

The year of reference is set at $t_0 = 2008$. We specify later on how fishing mortalities depend both on the fishing efforts (number of day spending at sea) by vessel and the number of vessel by fleet. The biological parameters are described in tables 1, 2 and 3 in appendix respectively for Nephrops, Hake and Sole. The estimated values of fishing mortality $F_{s,a,f}(t_0)$ are detailed in appendix through tables 4, 5 and 6 for Nephrops, Hake and Sole, respectively. The parameter values are derived from ICES databases [4], working group WGHMM (ICES, 2009) and the Ifremer, SIH, DPMA database.

Recruitment involves complex biological and environmental processes that vary over time. The recruits $\mathrm{N}_{s,1}(t+1)$ for each species are therefore assumed to be uncertain functions of the spawning stock biomass:

$$\mathrm{N}_{s,1}(t+1) = R_s\Big(\mathrm{SSB}_s(t), \omega_s(t)\Big). \tag{3}$$

[4] `http://www.ices.dk/datacentre/StdGraphDB.asp`

The spawning stock biomass $\mathrm{SSB}_s(t)$ of the species s is given by:

$$\mathrm{SSB}_s(t) = \sum_{a=1}^{A_s} \gamma_{s,a} \upsilon_{s,a} \mathrm{N}_{s,a}(t) \tag{4}$$

with $(\gamma_{s,a})_{a=1,\dots,A_s}$ the proportions of mature individuals at age a and $(\upsilon_{s,a})_{a=1,\dots,A_s}$ the weights of individuals at age a. The function R_s represents the specific stock-recruitment relationship of each species s while $\omega_s(t)$ stands for uncertainties (environmental or demographic) affecting the stock recruitment relationships through different possible scenarios Ω. In the present case-study, following STECF (2008) and the method of the working group WGHMM, the recruitment relationship of the species is set through an Ockham-Razor function as in O'Brien *et al.* (2002):

$$R_s(\mathrm{SSB}_s, \omega_s) = \begin{cases} \omega \rightsquigarrow \mathcal{U}_s & \text{if } \mathrm{SSB}_s \geq B_s^{\mathsf{lim}} \\ \mathrm{SSB}_s . \dfrac{\overline{R}_s}{B_s^{\mathsf{lim}}} & \text{if } \mathrm{SSB}_s \leq B_s^{\mathsf{lim}} \end{cases} \tag{5}$$

Here $\mathcal{U}_f$ stands for the uniform distribution relying on the historical time serie R_s^t of recruitment [5] (ICES, 2009). ICES limit biomass B_s^{lim} and the mean historical recruitment $\overline{R}_s$ values are specified in table 7 of appendix.

3.2 Catches and gross incomes

For each period t, the exploitation of the three species is described by the catches $C_{s,a,f}(t)$. These catches depend on initial fishing mortalities $F_{s,a,f}(t_0)$, fishing multipliers $u_f(t)$ that correspond in this study to number of vessels multipliers and abundances $\mathrm{N}_{s,a}(t)$ through the Baranov catch equations:

$$C_{s,a,f}(t) = \mathrm{N}_{s,a}(t) u_f(t) F_{s,a,f}(t_0) \frac{1 - \exp\left(-M_{s,a} - \displaystyle\sum_{f=1}^{N_f} u_f(t) F_{s,a,f}(t_0)\right)}{M_{s,a} + \displaystyle\sum_{f=1}^{N_f} u_f(t) F_{s,a,f}(t_0)}. \tag{6}$$

The initial fishing mortality $F_{s,a,f}(t_0)$ can be expressed as in equation (7) :

$$F_{s,a,f}(t_0) = q_{s,a,f} . e_f(t_0) . \mathrm{K}_f(t_0), \tag{7}$$

[5] R_s^i is the sample i for the species s and $\mathbb{P}(R_s = R_s^i) = \frac{1}{I}$ with I the number of possible values. Gaussian and continuous uniform distribution were also tested but did not significantly modify the results. Furthermore this "historical data series" method is used by the scientists of the working group WGHMM of the ICES.

with $e_f(t_0)$ the mean value of fishing efforts (number of day at sea) by vessel of sub-fleet f and $\mathrm{K}_f(t_0)$ the number of vessel by sub fleet f both for the baseline year 2008. Their values are given in the table 11. $q_{s,a,f}$ is the fishing mortality of species s at age a by unit of fishing effort and by vessel of fleet f. The catchabilities are supposed constant over the simulation period.

The gross income of each fleet's catch $\mathrm{CA}_f(t)$ is then estimated by introducing the market price of the species, recorded for different commercial categories (corresponding to different age groups), along with the estimates of discard rates, so that:

$$\mathrm{CA}_f(t) = \sum_s P_{s,a} \sum_{a=1}^{A_s} \upsilon_{s,a,f} C_{s,a,f}(t)(1 - d_{s,a,f}) \tag{8}$$

where $P_{s,a}$ is the market price (by kg) of species s at age a, $\upsilon_{s,a}$ is the mean weight of species s at age a of landings and $d_{s,a,f}$ represent the discard rate of individuals of age a by fleet f. Fish price data $P_{s,a}$ are displayed in appendix for each species in tables 1, 2 and 3. They are based on ex-vessel prices for the three species and for different market categories (defined in terms of the size.age of fish) recorded in French harbors, and obtained from the fisheries information system monitored by Ifremer (`www.ifremer.fr.anglais/`). Discards ratio were calibrated on the data available in the ICES working group WGHMM. [6]

3.3 Profits

It is assumed that the economic value of each fleet relies on its economic profitability accounting for both gross income and costs per unit of effort (Macher *et al.* , 2008). The profit of the fleet f, π_f is estimated as follows:

$$\pi_f(t) = \mathrm{CA}_f(t)(1 + \alpha_f)(1 - \tau_f) - (c_f^{var}.e_f(t_0) + c_f^{fix})\mathrm{K}_f(t_0).u_f(t). \tag{9}$$

where

- τ_f is the landing tax by sub-fleet,

[6] A difference in discards between the Nephrops trawlers and the other fish trawlers is made. The Nephrops trawlers have a stronger impact on the first age class of Hake than the other trawlers. As discarding rate for Hake and Sole is not known per sub-fleet, we assume that the discarding rate is the same for each sub-fleet, equal to the discarding rate of the whole fleet and assumed to be constant over the simulation period. For the same reason, fishing mortality is allocated between the sub-fleets according to their contribution to total landings instead of catches (see in appendix : tables 4, 5 and 6 for the values of fishing mortalities by sub-fleet on Nephrops, Hake and Sole and the tables 8, 9 and 10 for the estimated discards).

- α_f corresponds to the rate of income of the sub-fleet f derived from the catches of other species not taken into account in the current model. The values are based on the data of gross incomes 2008 (Ifremer, SIH, DPMA) and assumed to be constant over the simulation period.
- c_f^{var} is the total variable cost by fishing effort unit (day at sea) and by vessel of sub-fleet f including fuel cost, oil, supplies, ice, bait and device cost,
- c_f^{fix} correspond to the fixed costs by vessel of the sub-fleet f including licenses, maintenance and repair costs, insurance premium etc.... Their values are set through the reference year 2008.

The whole set of previous parameters needed for estimating the profits is displayed in the tables 11 and 12 in appendix.

3.4 The co-viability diagnostic

The co-viability of the system is examined by simultaneously assessing biological and economic risks as in Béné & Doyen (2000); Bene *et al.* (2001); Doyen & Béné (2003); Eisenack *et al.* (2006); Martinet *et al.* (2007); Bene & Doyen (2008); Doyen *et al.* (2007). First, an ecological objective, inspired by the ICES precautionary approach and related to population viability analysis (PVA), consists in ensuring the conservation of the fish species through constraints on their Spawning Stock Biomass :

$$\mathrm{SSB}_s(t) \geq B_s^{\mathsf{pa}}, \qquad s = 1, 2, 3. \tag{10}$$

Second, the economic viability analysis (EVA) aims at maintaining positive profits of each sub-fleet throughout time:

$$\pi_f(t) > 0, \qquad f = 1, \ldots, 16. \tag{11}$$

The co-viability approach (CVA) requires that both the PVA and the EVA apply to jointly warrant the conservation of species and the profitability of the fishing fleets. Thus, in a stochastic context, given a scenario of effort multiplier by fleet u, the bio-economic performance and risk is evaluated by the probability of coviability defined by:

$$\mathbb{P}_{\mathrm{CVA}}(u) = \mathbb{P}\Bigg(\text{ constraints (10) and (11) are satisfied for } t = t_0, \ldots, T \Bigg).$$

Of interest are vectors of effort multiplier by fleet u such that the probability of coviability $\mathbb{P}_{\mathrm{CVA}}$ is high enough :

$$\mathbb{P}_{\mathrm{CVA}}(u) \geq \beta.$$

where β stands for some confident rate (typically 90%, 99% or 100%).

From the bio-economic dynamic model and the previous co-viability analysis, different fishing strategies relying on multipliers u_f are compared. Strategies considered include "Status Quo" (SQ), "Net Present Value" (NPV), "Co-viability" (CVA), "Mono-specific management on Sole" (SOL) and "Mono-specific management on Nephrops" (NEP) strategies. The associated effort multipliers (u^{SQ}, u^{NPV}, u^{CVA}, u^{SOL} and u^{NEP} respectively) can differ between sub-fleets but it is assumed for sake of simplicity that they remain constant in time. Projections and viability are computed over twenty years ($T = 20$) starting from the initial stock abundances $\mathrm{N}(t_0)$ at year $t_0 = 2008$. The values of initial states are given by tables 2, 1 and 3 in appendix. For each fishing strategy u, the viability probabilities are approximated by the percentage of viable trajectories among 1000 simulated trajectories. Each trajectory corresponds to different recruitment levels $\omega(.) = (\omega_1(.), \omega_2(.), \omega_3(.))$ for the three species randomly selected each year according to equation (5). These ω_i are assumed to be independent and identically distributed.

The status quo (SQ) strategy. This strategy simulates a steady fishing mortality which is associated with the 2008 baseline year fishing effort:

$$u_f^{\mathrm{SQ}}(t) = 1, \qquad \forall\ t = 2009, \dots, 2030, \ \ \forall\ f = 1, \dots, 16.$$

The Net Present Value (NPV) strategy is a conventional economic strategy relying on the maximization of the expected sum of discounted profits. The net present value is here calculated as the aggregated value among the fleets

$$\mathrm{NPV}(u) = \mathbb{E}_\omega \left[\sum_{t_0}^{T} \frac{1}{(1+\varrho)^t} \sum_{f=1}^{16} \pi_f(t) \right] \tag{12}$$

where the discount rate is set to $\varrho = 4\%$. The associated effort multipliers u^{NPV} are the one that maximizes the NPV as follows:

$$\mathrm{NPV}(u^{\mathrm{NPV}}) = \max_u \mathrm{NPV}(u). \tag{13}$$

The co-viability (CVA) strategy intends to conjointly guarantee stocks conservation and economic viability of the fishing fleets. This requires that ecological and economic constraints defined in (10) and (11) are satisfied. The associated optimal effort multipliers u^{CVA} are obtained by maximization of the viability probability $\mathbb{P}_{\mathrm{CVA}}(u)$:

$$\mathbb{P}_{\mathrm{CVA}}(u^{\mathrm{CVA}}) = \max_u \mathbb{P}_{\mathrm{CVA}}(u).$$

The Sole (SOL) strategy investigates a monospecific management focusing on Sole. The effort multiplier u^{SOL} only accounts for constraints on the Sole combining stock viability through $\mathrm{SSB}_3(t)$ requirements with profitability goals through positive profits $\pi_f(t)$ for Sole gill-netter fleets ($f = 8, \ldots, 11$):

$$\begin{cases} \mathrm{SSB}_3(t) \geq B_3^{\mathsf{pa}} \\ \pi_f(t) > 0 \text{ for } f = 8, \ldots, 11 \\ u_f(t) = 1 \text{ for } f \neq 8, \ldots, 11 \end{cases} \tag{14}$$

The associated effort multiplier u^{SOL} is obtained by maximization of Sole viability objectives as follows:

$$u^{\mathrm{SOL}} \in \operatorname*{Argmax}_u \mathbb{P}\Big(\text{constraints (14) are satisfied for } t = t_0, \ldots, T \Big)$$

The Nephrops (NEP) strategy investigates a monospecific management focusing on Nephrops. Similarly to the SOL strategy, the effort multiplier u^{NEP} copes only with constraints related to Nephrops through SSB_1 and the profits $\pi_f(t)$ of Nephrops trawlers ($f = 1, 2, 3$):

$$\begin{cases} \mathrm{SSB}_1(t) \geq B_s^{\mathsf{pa}} \\ \pi_f(t) > 0 \text{ for } f = 1, 2, 3 \\ u_f(t) = 1 \text{ for } f \neq 1, 2, 3 \end{cases} \tag{15}$$

Similarly, the associated effort multiplier u^{NEP} is induced by maximization of Nephrops viability objectives as follows:

$$u^{\mathrm{NEP}} \in \operatorname*{Argmax}_u \mathbb{P}\Big(\text{constraints (15) are satisfied for } t = t_0, \ldots, T \Big)$$

4 Results

The numerical implementations and computations of the model have been carried out with the scientific software SCILAB[7] 5.2.2. Outcomes of the five

[7] SCILAB is a freeware dedicated to engineering and scientific calculus. It is especially well-suited to deal with dynamic systems and control theory.

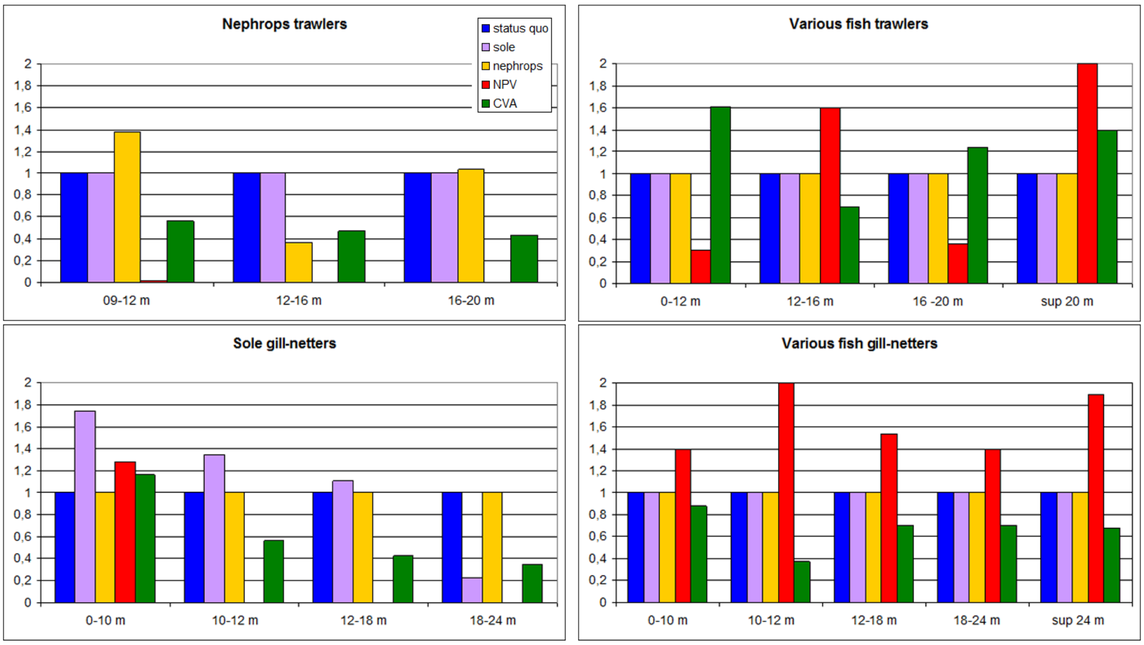

Figure 5. Effort multipliers u_f pending the different sub-fleets f and the four strategies SQ(in blue), NPV(in red), CVA(in green), SOL(in purple), NEP(in yellow)

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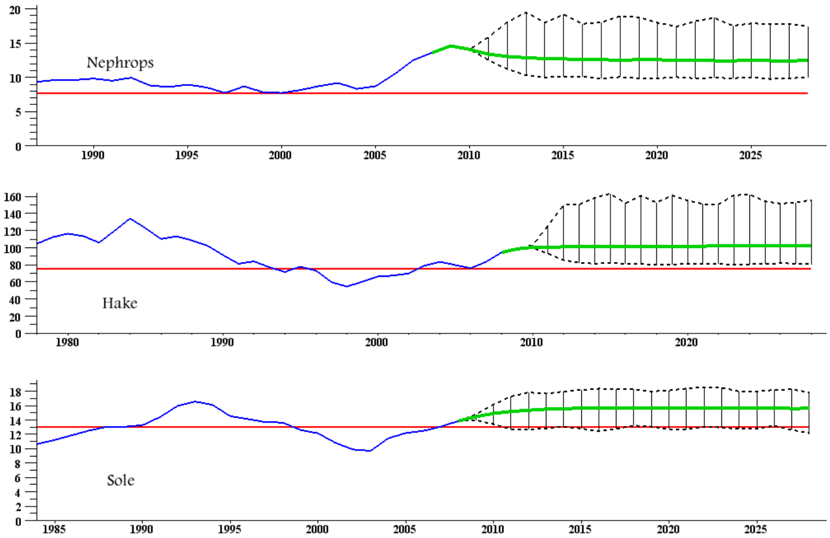
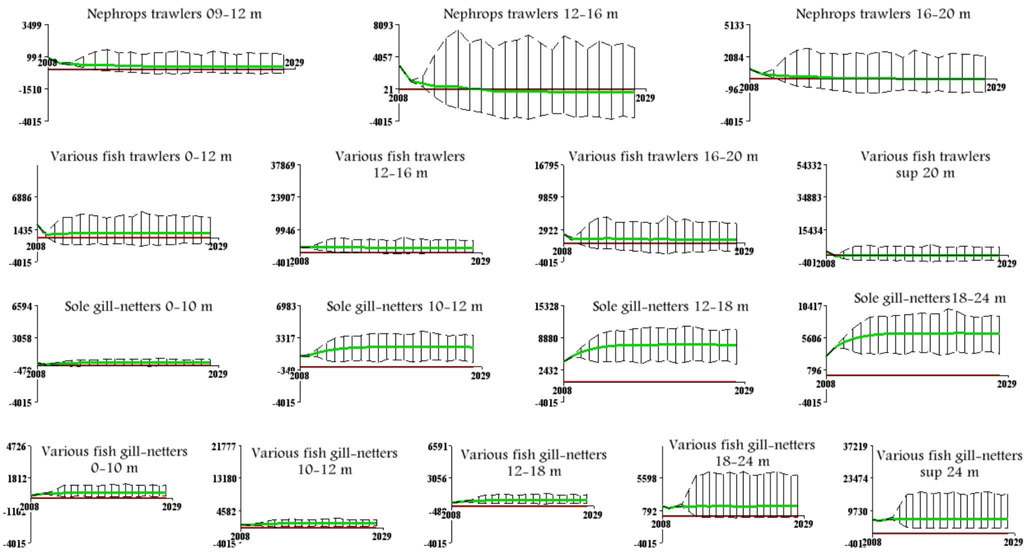
strategies are compared according both to their effort multiplier values in figure 5 and their co-viability performances in figures 6, 7, 8, 9 and 10.

4.1 Status quo strategy : not economically viable

Figure 6 shows the projections at the 2030 horizon under the status quo strategy of the SSB(t) of each species and the profits $\pi_f(t)$ of each fleet. Figure 6(a) first illustrates that this strategy is ecologically viable since the population viability probability is close to one with PVA$(u^{\text{SQ}}) = 0.985$. Only some trajectories for sole violate the precautionary threshold B_3^{pa}. The other species fluctuate in safety zones despite the uncertainties affecting their recruitment. In other words, the ecological risk is low. By contrast, the economic viability is at stake as displayed by figure 6(b) and the fact that EVA$(u^{\text{SQ}}) = 0$. This value means that for each of the 1000 trajectories, there are at least one time where one (or more) profit is inferior or equal to zero. In particular, the trawlers and particularly the Nephrops trawlers $f = 1, 2, 3$ may encounter severe difficulties.

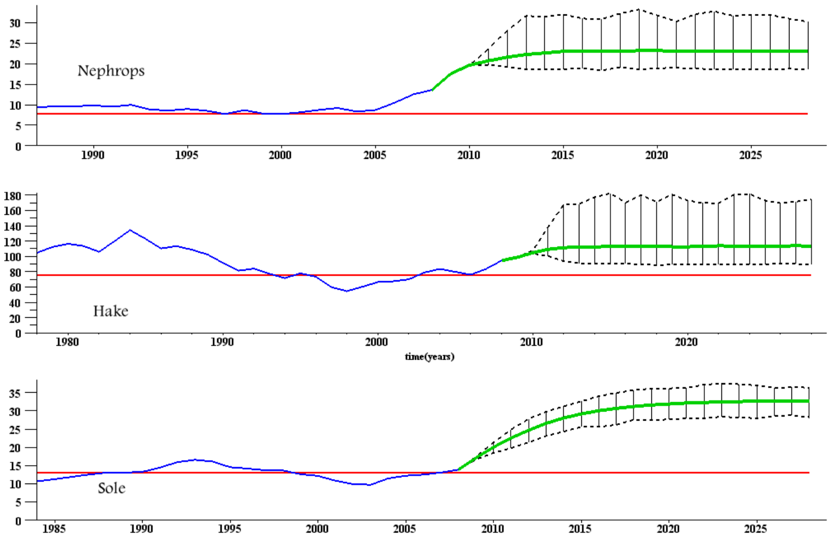


(a) Spawning stock biomass $\mathrm{SSB}_s(t)$ in tons$*10^3$ of each species s.

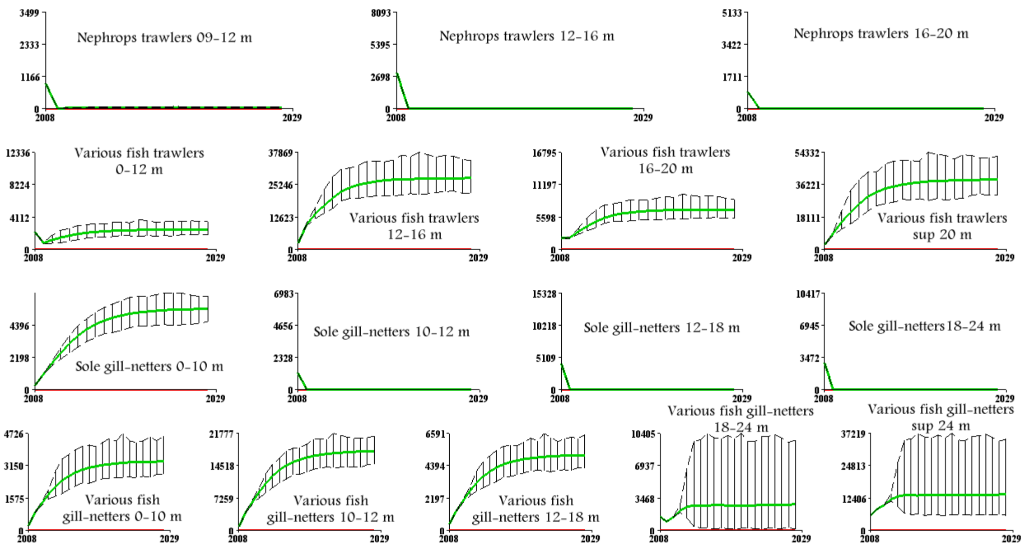


(b) Profits $\pi_f(t)$ in €$*10^3$ of each sub-fleet f.

Figure 6. Status quo scenario $u^{\mathrm{SQ}}(t) = 1$: Evolution (mean and dispersion) of the $\mathrm{SSB}_s(t)$ of each species and profits $\pi_f(t)$ of each sub-fleet according to time t. In each sub-figure, the viability thresholds are in red (Bpa reference points for the sub-figure in (a) and 0 (strictly positive profits required) for those in (b)). The set of possibilities that includes all of the 1000 simulated trajectories is represented in dark with the limits in dotted line and the vertical bar represented the confidence interval at 100%. The green line is the median value of the 1000 trajectories at each time of the projection. The lines in blue in (a) are the historical SSB (before 2008) for each species: Nephrops ($s = 1$), Hake ($s = 2$) and Sole ($s = 3$).



(a) Spawning stock biomass $\mathrm{SSB}_s(t)$ in tons$*10^3$ of each species s.



(b) Profits $\pi_f(t)$ in €$*10^3$ of each sub-fleet f.

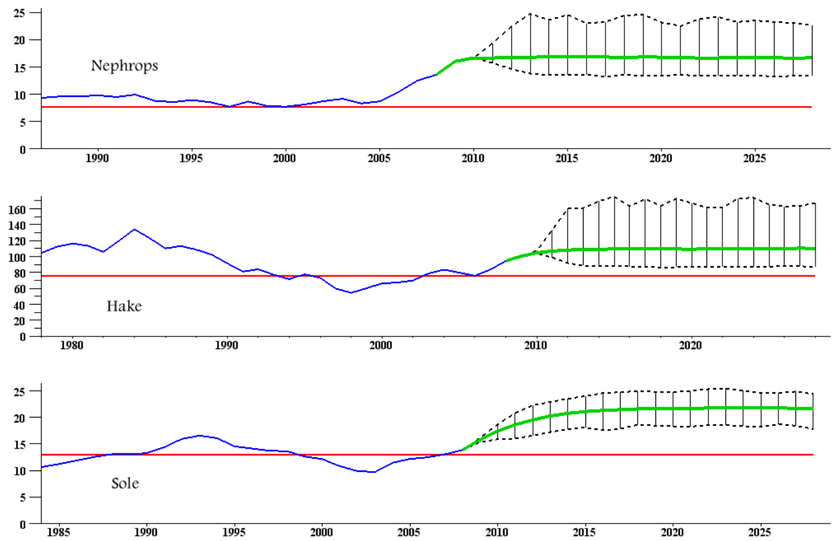
Figure 7. Net present value scenario u^{NPV}: Evolution (mean and dispersion) of the $\mathrm{SSB}_s(t)$ of each species and profits $\pi_f(t)$ of each sub-fleet according to time t. In each sub-figure, the viability thresholds are in red (Bpa reference points for the sub-figure in (a) and 0 (strictly positive profits required) for those in (b)). The set of possibilities that includes all of the 1000 simulated trajectories is represented in dark with the limits in dotted line and the vertical bar represented the confidence interval at 100%. The green line is the median value of the 1000 trajectories at each time of the projection. The lines in blue in (a) are the historical SSB (before 2008) for each species: Nephrops ($s = 1$), Hake ($s = 2$) and Sole ($s = 3$).

4.2 NPV *strategy: not economically viable*

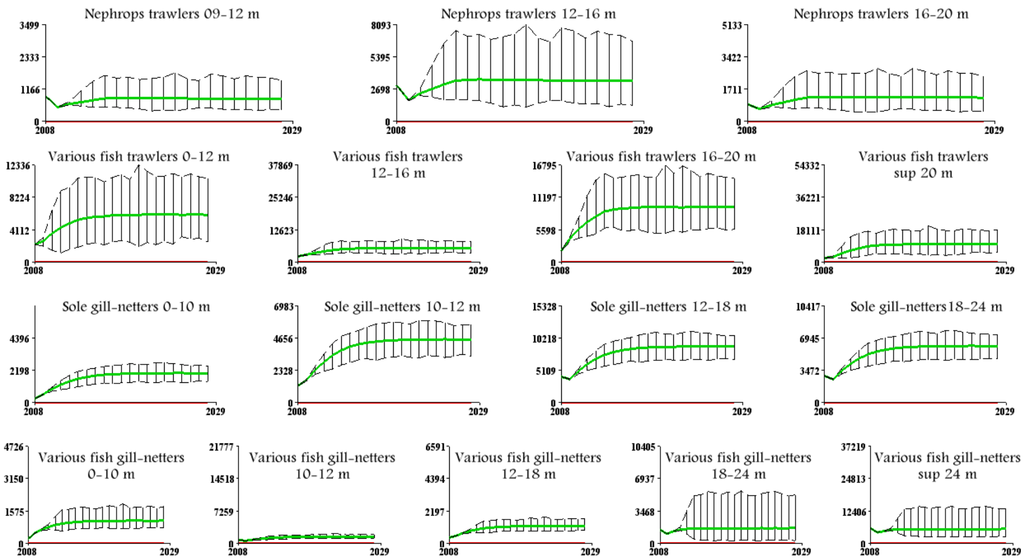
Figure 7 displays the evolution of the SSB and the profits with the fishing multiplier u^{NPV} that maximizes the net present value as defined in (13). This strategy turns out to be ecologically viable with a strong population viability $\text{PVA}(u^{\text{NPV}}) = 1$. Thus significant improvements in the status of stocks occur in the long run especially for Nephrops and Sole species as shown in figure 7(a). However this strategy is not economically viable for some sub-fleets and consequently the whole economic viability probability collapses $\text{EVA}(u^{\text{NPV}}) = 0$ because the profitability of these fleets vanishes as depicted by figure 7(b). Such non economic viability stems from the no-take $u_f = 0$ of specific fleets as the Nephrops trawlers $f = 1, 2, 3$ or larger Sole gill-netters $f = 9, 10, 11$ as captured by figure 5. Based on the economic and production data used in this application, these latter fleets appear to be relatively less efficient than the others in the model, hence their contribution to catches and landings under a NPV strategy would be reduced to zero. In other words, the lack of co-viable outcomes raised by such NPV strategy is due to some intra-fleet economic heterogeneity.

4.3 CVA *strategy: ecologically and economically viable*

Figures 8 illustrates this co-viability strategy which aims at optimizing the co-viability probability mixing ecological and economic constraints as defined in (10) and (11). As expected, this strategy is ecologically viable with some guaranteed population viability $\text{PVA}(u^{\text{CVA}}) = 1$ and biomass trajectories lying above the precautionary thresholds B_s^{pa} for every species as displayed by 8(a). Moreover the economic performance of this strategy is also satisfying in terms of economic viability with a profitability probability $\text{EVA}(u^{\text{CVA}}) = 1$. As illustrated in 8(b), every fleet exhibits strictly positive profits throughout time. As shown by figure 5, such relevant bio-economic outcomes are obtained by a specific redistribution of fishing intensity u_f among the fleets with no exclusion of fleets. Nevertheless, the strategy suggests that fleets capacity would be significantly reduced for fleets contributing to an important part of the fishing mortality for Nephrops and Sole (corresponding to nephrops trawlers $f = 1, 2, 3$ and large sole gill netters $f = 9, 10, 11$) while low impacting fleets (as the various fish trawlers $f = 4, 6, 7$) could increase their effort according to the assumption of the model.

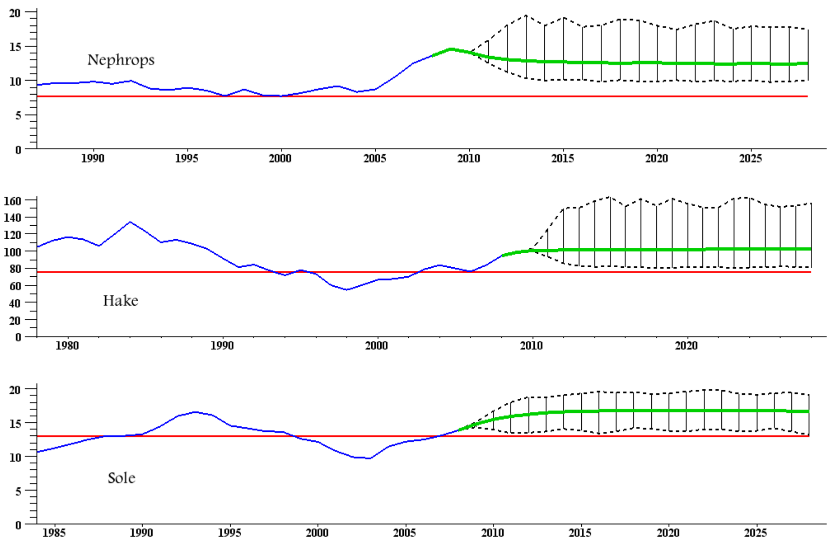


(a) Spawning stock biomass $\mathrm{SSB}_s(t)$ in tons$*10^3$ of each species s.

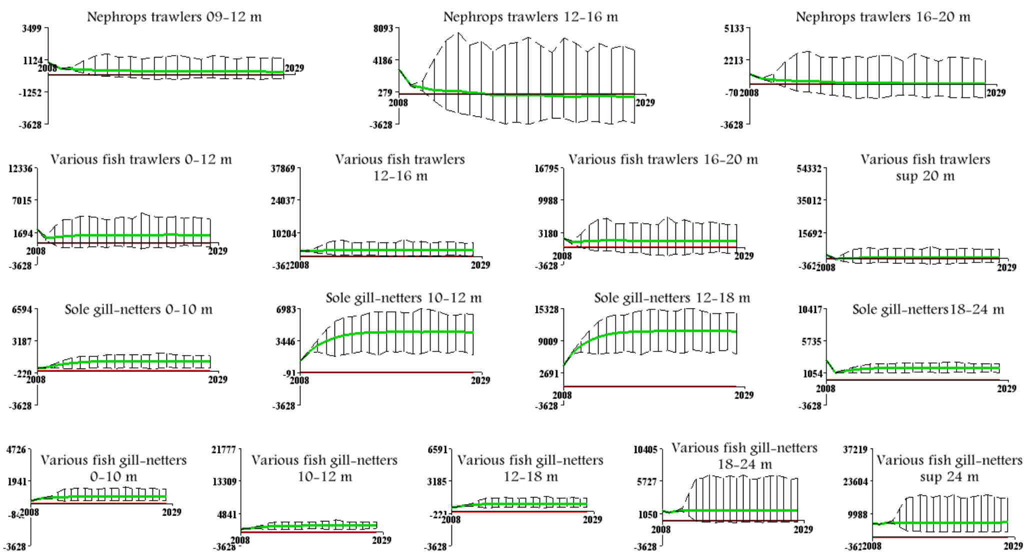


(b) Profits $\pi_f(t)$ in €$*10^3$ of each sub-fleet f.

Figure 8. Co-viability scenario u^{CVA}: Evolution (mean and dispersion) of the $\mathrm{SSB}_s(t)$ of each species and profits $\pi_f(t)$ of each sub-fleet according to time t. In each sub–figure, the viability thresholds are in red (Bpa reference points for the sub-figure in (a) and 0 (strictly positive profits required) for those in (b)). The set of possibilities that includes all of the 1000 simulated trajectories is represented in dark with the limits in dotted line and the vertical bar represented the confidence interval at 100%. The green line is the median value of the 1000 trajectories at each time of the projection. The lines in blue in (a) are the historical SSB (before 2008) for each species: Nephrops ($s = 1$), Hake ($s = 2$) and Sole ($s = 3$).



(a) Spawning stock biomass $\mathrm{SSB}_s(t)$ in tons$*10^3$ of each species s.



(b) Profits $\pi_f(t)$ in €$*10^3$ of each sub-fleet f.

Figure 9. Mono-specific scenario for Sole u^{SOL}: Evolution (mean and dispersion) of the $\mathrm{SSB}_s(t)$ of each species and profits $\pi_f(t)$ of each sub-fleet according to time t. In each sub-figure, the viability thresholds are in red (Bpa reference points for the sub-figure in (a) and 0 (strictly positive profits required) for those in (b)). The set of possibilities that includes all of the 1000 simulated trajectories is represented in dark with the limits in dotted line and the vertical bar represented the confidence interval at 100%. The green line is the median value of the 1000 trajectories at each time of the projection. The lines in blue in (a) are the historical SSB (before 2008) for each species: Nephrops ($s = 1$), Hake ($s = 2$) and Sole ($s = 3$).

4.4 *Sole strategy: not economically viable*

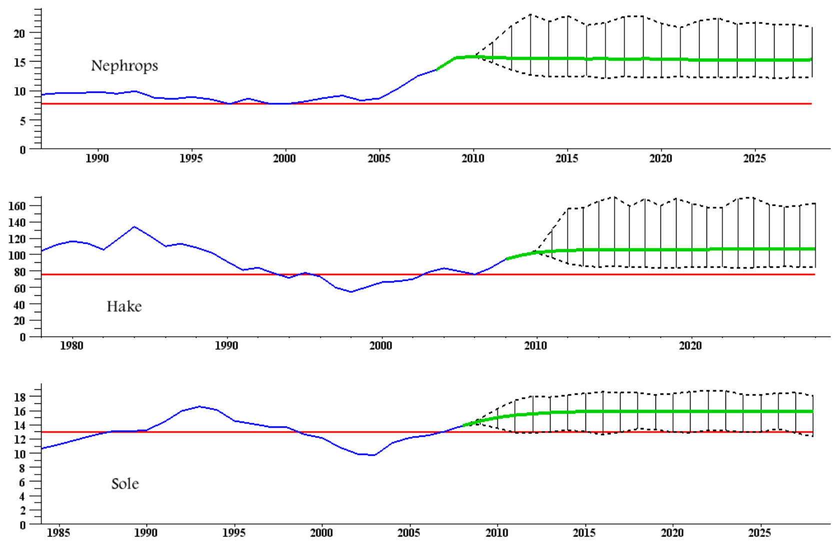
The SOL strategy relies on a mono-specific management targeting Sole as defined by (14). Hence only efforts u_f related to Sole netters $f = 8, 9, 10, 11$ are affected by such a strategy as detailed by figure 5. This suggests that the smallest (in size) Sole gill netters $f = 8, 9, 10$ should be favored with such a strategy. As shown by 9(a), this strategy is ecologically viable as $\mathrm{PVA}(u^{\mathrm{SOL}}) = 1$. Similarly the economic viability in particular for the smallest Sole gill-netter fleets is improved as illustrated by 9(b). However the strategy as a whole is not economically sustainable because the first fleets $f = 1, \ldots, 7$ including Nephrops trawlers and various fish gill-netters do not adapt their fishing effort and thus do not improve their profitability. They may face severe profit depletions in the future as in the baseline SQ.

4.5 *Nephrops strategy: not economically viable*

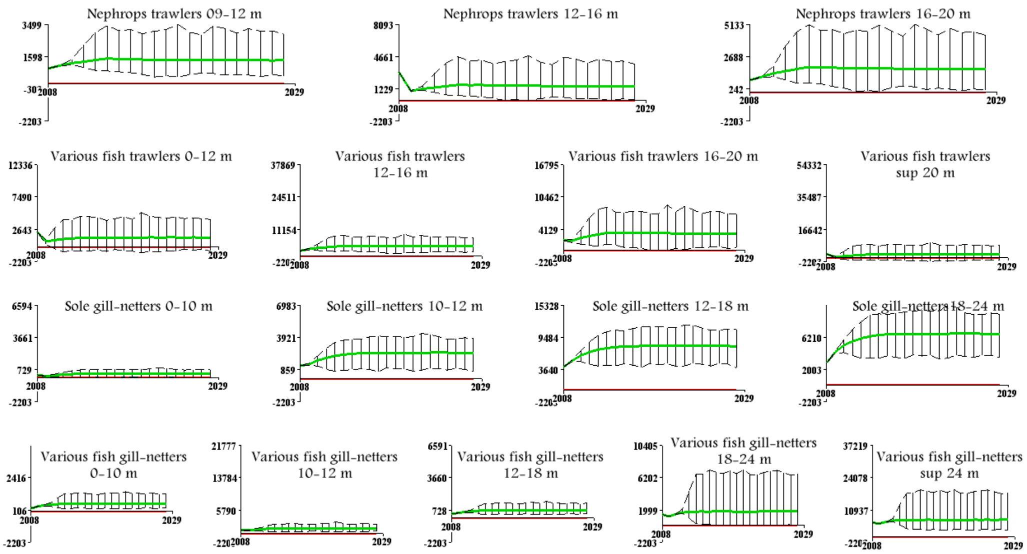
The NEP strategy relies on a mono-specific management targeting Nephrops as defined by (15). Hence only efforts u_f of Nephrops trawlers $f = 1, 2, 3$ are impacted by such strategy as detailed by figure 5. This suggests that the smallest (in size) $f = 1$ should be favored ($u_1 \approx 140\%$) while by contrast moderate size trawlers ($u_2 \approx 40\%$) should lessen the effort with such a strategy. As shown by 10(a), this strategy is ecologically acceptable since population viability probability is high $\mathrm{PVA}(u^{\mathrm{NEP}}) = 0.994$, although some risk persists for Sole as in the baseline SQ. Not surprisingly, the Nephrops stock is especially improved. Similarly the economic viability for the nephrops trawlers fleets is restored as illustrated by 10(b). However such a mono specific strategy is not co-viable in the sense defined here, because the Sole gill-netters do not modify their fishing effort and thus do not prevent risk on their profitability as in status quo SQ. Note however that NEP strategy displays a better economic performance than the mono-specific management SOL focusing on Sole in the viability sense since $\mathrm{EVA}(u^{\mathrm{NEP}}) = 0.58$ and $\mathrm{EVA}(u^{\mathrm{SOL}}) = 0.004$.

5 Discussion

This work first contributes to the design of sustainable exploitation systems taking into account the multi-functionality of fisheries. It postulates that regulations of fisheries should rely on a conciliation of biodiversity conservation and socio-economic objectives. The modeling and the results provide quantitative and qualitative insights on the the Bay of Biscay demersal fisheries system. It especially points out the economic vulnerabilities especially for some sub-fleets



(a) Spawning stock biomass $\mathrm{SSB}_s(t)$ in tons$*10^3$ of each species s.



(b) Profits $\pi_f(t)$ in €$*10^3$ of each sub-fleet f.

Figure 10. Mono-specific scenario for Nephrops u^{NEP}: Evolution (mean and dispersion) of the $\mathrm{SSB}_s(t)$ of each species and profits $\pi_f(t)$ of each sub-fleet. In each sub-figure, the viability thresholds are in red (Bpa reference points for the sub–figure in (a) and 0 (strictly positive profits required) for those in (b)). The set of possibilities that includes all of the 1000 simulated trajectories is represented in dark with the limits in dotted line and the vertical bar represented the confidence interval at 100%. The green line is the median value of the 1000 trajectories at each time of the projection. The lines in blue in (a) are the historical SSB (before 2008) for each species: Nephrops ($s = 1$), Hake ($s = 2$) and Sole ($s = 3$).

as Nephrops trawlers combined with slight ecological risks especially for Sole. Based on the reference data used to calibrate the model, simulations stress that the status quo strategy, consisting of maintaining fishing efforts at the level of the 2008 baseline is not economically sustainable and viable, as the profitability constraints can be violated with a high level of confidence. This suggests that regulations and public policies targeting fishing intensity would be relevant. However, the net present value strategy, focusing on economic performances by providing the greatest expected cumulative discounted profit is not viable in economic terms as defined in this analysis. It imposes to displace some sub-fleets in particular Nephrops trawlers and bigger length sub-fleets of Sole gill-netters. The mono-specific management on Sole has a satisfying ecological viability and even if this strategy is viable for the Sole gill-netters, it is not the case for some other sub-fleets. In contrast, the mono-specific management on Nephrops has a better economic performance than the previous strategy. However this strategy is not viable for all the sub-fleets although the risk to violate the ecological precautionary threshold remains moderate. Finally the coviability strategy allows compliance with all the constraints in such a complex and uncertain context since it is both ecologically and economically viable for all species and sub-fleets. The CVA strategy suggests a reduction in the number vessels of Nephrops trawlers, 12-16 m various fish trawlers, Sole gill-netters over 10 m, and various gill-netters, but an increase in the number of vessels of the various fish trawlers under 12 m and over 16 m, and of the Sole gill-netters under 10 m. These results are strongly linked to the fact that the Nephrops trawlers and Sole gill-netters are the ones that contribute the most to the fishing mortality, especially for the Nephrops and the Sole. They are also very dependent on these species (i.e. the figure 4). Results underline the overcapacities existing in this fishery.

Beyond the previous methodological analysis on the case study, this work advocates for 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, scientists, environmentalists, economists, public decision maker or the general public (Hilborn, 2007b). 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 appears as a way to guarantee a reasonable exploitation of aquatic resources allowing to create conditions of sustainability from economic, environmental and social viewpoints (Lesueur *et al.* , 2007). The present work is in direct line with these considerations. First of interest is the use of bio-economic models and assessments articulating ecological and economic processes and goals. Moreover by focusing on sustainability and viability, the present model exhibits management strategies and scenarios that allows a conciliation between present and future and account for intergenerational equity. As emphasized in De Lara & Doyen (2008) or Martinet & Doyen (2007), 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. Here the co-viability strategy appears as the most appropriate both to preserve the spawning stock biomass of every species as in the ICES precautionary approach and to warrant economic profits for each sub-fleet throughout time. Considering a multi-criteria performance that includes concerns for the maintenance of active and profitable fishing fleets, along with the preservation of all fish stocks they depend upon, CVA performs better than other strategies. In particular, among the considered strategies, it is the only strategy that prevents economic risk for every fleet. Typically, the NPV strategy by focusing on economic issues favors the most efficient fleets and tends to exclude other fleets. From the ecological viewpoint, the CVA strategy reduces the ecological risk related to Sole. More generally, CVA can be a fruitful framework for sustainability because it can deal with a large range of goods and services provided by marine ecosystems along time. Hence the co-viability approach can be useful in this multi-criteria context as this approach could exhibit a domain of possibilities, feasibility and trade-offs between potentially conflicting objectives or constraints to be fulfilled throughout both present and future. The approach can contribute to a better governance and social acceptance of fisheries as a responsible use of marine ecosystems and biodiversity. It can facilitate the reduction of conflicts among competing users or stakeholders. Such approach has already been applied to renewable resource management, especially to fisheries in several contexts (Béné & Doyen, 2000; Bene *et al.* , 2001; Doyen & Béné, 2003; Eisenack *et al.* , 2006; Martinet *et al.* , 2007). In this perspective, steady states and sustainable yield indicators (Maximum Sustainable Yield, Maximum Economic Yield) have been shown to be particular cases of viability. In this sense, the viability approach expands the equilibrium approach (Bene *et al.* , 2001; De Lara & Doyen, 2008). Tichit *et al.* (2007); De Lara & Doyen (2008) also shows how the so-called Population Viability Analysis (PVA) focusing on conservation biology is a particular case of viability modeling and viable control approach. In the same vein, De Lara *et al.* (2007) examine the relationships between sustainable management objectives and reference points in the ICES precautionary approach to fish stock management. The present work reinforces the relevance of the approach in a complex and applied context though a multi-species and multi-fleets management.

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 to handle 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); Doyen *et al.* (2007) show how the approach can potentially be useful to integrate ecosystem considerations for fisheries management. Chapel *et al.* (2008); Bene & Doyen (2008); Doyen *et al.* (2007); Mullon *et al.* (2004) put emphasis on the ability to address complex dynamics in this framework. The computational and mathematical modeling methods proposed in the present paper through the CVA strategy are motivated by a similar prospect. One major interest of co-viability approach, strategies and management is the fact that viability framework is dynamic, thus allowing to capture the interactions and co-evolution of marine biodiversity and fishing. The dynamics can potentially include complex mechanisms such as trophic interactions, competition, metapopulations dynamics or economic investment process to quote a few. Here the focus is on technical interactions through a multi-fleets and multi-species context. Typically, the model pays attention to the bycatch mechanisms of trawlers on hakes. For the specific case-study, the comparison of mono-specific approaches for Sole or Nephrops with the more integrated perspective of CVA stresses the fact that complex and dynamic mechanisms should be accounted to handle in a relevant way the whole management of these fisheries and biodiversity through an ecosystem approach. Another major interest of co-viability approach with respect to EBFM is the account of uncertainties. Stochastic or robust viability (Doyen & De Lara, 2010) allows to coping with risks and precaution which is a major ingredient of EBFM (Sanchirico *et al.* , 2008). Stochastic viability allows in particular to account for the uncertainties of ecological dynamics and interactions that encompass community evolutions, market dynamics or environmental (habitat, climatic) changes. Such a modeling framework is thus relevant for the study of vulnerability of fish-fishery systems and the mitigation of bio-economic risks. Here the focus is on recruitment stochasticities. Typically, while SQ strategy does not seem dangerous on average, it is a risky scenario because some recruitment patterns may yield detrimental trajectories in economic and/or ecological terms. By contrast, CVA management guarantees safety evolutions whatever the uncertainties affecting the species dynamics.

Several expansions of this ecosystem-based model can be considered, as the account of more demersal commercial species (for example Anglerfish which is another key species landed by some fleets). The future integration of more fleets in the model - in particular the Spanish and Belgium fishing pressure - should reinforce the relevance of the approach. Moreover, many studies relating mainly to trawling and dredging showed a depletion of the habitat, a handing-over in suspension of the sediments of surface and damages on the structure of the benthic communities (Collie *et al.* , 2000) that entail variations of the production processes (Jennings *et al.* , 2001). It is also necessary to integrate trophic interactions. The use of refined time (for instance in month) and spatial scales to capture migration, reproduction period and pattern of exploitation constitutes major issues. As regard human processes and pressures, the development of socio-economic and behavioral dimensions are main goals.

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6 Appendix

Age a	1	2	3	4	5	6	7	8	9
Initial abund. $N_{1,a}(t_0)$ ($*10^3$ indv)	642616	650008	328988	180528	65279	23173	8304	4257	4679
Maturity $\gamma_{1,a}$	0	0	0,75	1	1	1	1	1	1
Mean weight(kg\ indv) $\upsilon_{1,a}$	0,004	0,009	0,016	0,027	0,037	0,046	0,058	0,068	0,091
Natural mortality $M_{1,a}$	0,3	0,3	0,25	0,25	0,25	0,25	0,25	0,25	0,25
Mean price(€\ kg) $p_{1,a}$	10,1	10,1	9,1	9,1	9,1	9,1	14,6	14,6	17,6

Table 1
Nephrops parameters $s = 1$, $t_0 = 2008$ *source : ICES; Ifremer, SIH* .

Age a	0	1	2	3	4	5	6	7	8+
Initial abund. $N_{2,a}(t_0)$ ($*10^3$ indv)	236062	132608	61571	25195	5219	1606	497	162	45
Maturity $\gamma_{2,a}$	0	0,11	0,73	0,93	0,99	1	1	1	1
Mean weight(kg\ indv) $\upsilon_{2,a}$	0,029	0,25	0,716	1,572	2,503	3,452	4,393	5,773	6,747
Natural mortality $M_{2,a}$	0,4	0,4	0,4	0,4	0,4	0,4	0,4	0,4	0,4
Mean price(€\ kg) $p_{2,a}$	2	2	2,9	4,1	5,5	6,9	6,9	6,9	6,9

Table 2
Hake parameters $s = 2$, $t_0 = 2008$ *source : ICES; Ifremer, SIH.* The current assessment of the Hake stock in Bay of Biscay was based on hypothesis of a low growth, nonetheless new surveys give a new age-length key and consequently denigrated this hypothesis, and validated hypothesis of fast growth. Hence new assessment is needed and it changes all parameters. This new evaluation will be include in the next ICES report(and the values used in this study are the new one) but not in the current.

Age a	2	3	4	5	6	7	8+
Initial abund. $N_{3,a}(t_0)$ ($*10^3$ indv)	23191	17416	10707	4864	3425	2627	2590
Maturity $\gamma_{3,a}$	0,32	0,83	0,97	1	1	1	1
Mean weight(kg\ indv) $\upsilon_{3,a}$	0,189	0,241	0,297	0,352	0,423	0,449	0,599
Natural mortality $M_{3,a}$	0,1	0,1	0,1	0,1	0,1	0,1	0,1
Mean price(€\ kg) $p_{3,a}$	8,6	10,2	12,3	14,2	14,2	14,2	13,9

Table 3
Sole parameters $s = 3$, $t_0 = 2008$ *source : ICES; Ifremer, SIH.*

Fleets \ Age a	1	2	3	4	5	6	7	8	9
Nephrops trawlers	0.099	1.595	2.307	2.293	2.022	2.04	2.045	2.067	2.067
	0.59	9.486	13.719	13.632	12.02	12.13	12.156	12.287	12.287
	0.21	3.374	4.88	4.849	4.275	4.314	4.324	4.37	4.37
Various fish trawlers	0.011	0.181	0.262	0.26	0.229	0.231	0.232	0.234	0.234
	0.11	1.77	2.56	2.543	2.243	2.263	2.268	2.292	2.292
	0.129	2.07	2.994	2.975	2.623	2.647	2.653	2.681	2.681
	0.028	0.453	0.655	0.651	0.574	0.579	0.58	0.587	0.587
Sole gill-netters	0.	0.	0.	0.	0.	0.	0.	0.	0.
	0.	0.	0.	0.	0.	0.	0.	0.	0.
	0.	0.	0.	0.	0.	0.	0.	0.	0.
	0.	0.	0.	0.	0.	0.	0.	0.	0.
Various fish gill-netters	0.	0.	0.	0.	0.	0.	0.	0.	0.
	0.	0.	0.	0.	0.	0.	0.	0.	0.
	0.	0.	0.	0.	0.	0.	0.	0.	0.
	0.	0.	0.	0.	0.	0.	0.	0.	0.
	0.	0.	0.	0.	0.	0.	0.	0.	0.
Other fleet	0.919	14.758	21.344	21.208	18.701	18.872	18.913	19.116	19.116

Table 4
The values of fishing mortality on Nephrops $s = 1 : F_{1,a,f}(t_0)$ (/100). *source : ICES; Ifremer, SIH, 2008.*

Fleets \ Age a	0	1	2	3	4	5	6	7	8+
Nephrops trawlers	0.891	0.449	0.096	0.012	0.021	0.016	0.014	0.018	0.027
	5.115	2.576	0.551	0.067	0.119	0.09	0.083	0.104	0.153
	3.258	1.64	0.351	0.042	0.076	0.058	0.053	0.066	0.097
Various fish trawlers	1.628	1.293	0.638	0.168	0.225	0.074	0.03	0.015	0.007
	1.826	1.451	0.716	0.189	0.252	0.083	0.034	0.017	0.008
	1.639	1.302	0.643	0.17	0.226	0.075	0.03	0.015	0.007
	1.093	0.868	0.429	0.113	0.151	0.05	0.02	0.01	0.005
Sole gill-netters	0.	0.001	0.008	0.04	0.071	0.037	0.013	0.005	0.003
	0.	0.002	0.021	0.105	0.187	0.096	0.034	0.013	0.008
	0.	0.004	0.04	0.202	0.359	0.186	0.065	0.026	0.016
	0.	0.009	0.091	0.458	0.814	0.42	0.148	0.059	0.037
Various fish gill-netters	0.	0.003	0.026	0.131	0.233	0.12	0.042	0.017	0.01
	0.	0.002	0.021	0.105	0.186	0.096	0.034	0.013	0.008
	0.	0.004	0.039	0.199	0.353	0.182	0.064	0.025	0.016
	0.	0.05	0.492	2.476	4.396	2.269	0.8	0.317	0.198
	0.	0.135	1.336	6.721	11.933	6.158	2.173	0.861	0.536
Other fleet	2.219	25.281	44.426	73.419	76.369	84.334	72.808	87.524	87.97

Table 5
The values of fishing mortality on Hake $s = 2 : F_{2,a,f}(t_0)$ (/100). *source : ICES; Ifremer, SIH, 2008.*

Fleets \ Age a	2	3	4	5	6	7	8+
Nephrops trawlers	0.155	0.197	0.143	0.118	0.076	0.083	0.083
	0.909	1.145	0.877	0.778	0.837	0.823	0.823
	0.472	0.594	0.455	0.404	0.434	0.427	0.427
Various fish trawlers	1.357	1.728	1.255	1.033	0.669	0.732	0.728
	1.433	1.805	1.382	1.227	1.319	1.297	1.298
	1.655	2.085	1.597	1.417	1.524	1.499	1.499
	0.71	0.895	0.685	0.608	0.654	0.643	0.643
Sole gill-netters	0.198	0.51	0.765	0.825	0.971	0.946	1.074
	1.081	2.78	4.174	4.5	5.297	5.164	5.859
	1.806	6.451	8.651	9.353	14.752	14.541	13.821
	1.501	5.361	7.189	7.772	12.259	12.083	11.485
Various fish gill-netters	0.046	0.118	0.177	0.191	0.224	0.219	0.248
	0.128	0.33	0.495	0.534	0.628	0.613	0.695
	0.08	0.284	0.381	0.412	0.65	0.64	0.609
	0.	0.	0.	0.001	0.001	0.001	0.001
	0.	0.	0.	0.	0.	0.	0.
Other fleet	6.154	11.331	7.159	7.215	8.978	7.903	8.322

Table 6
The values of fishing mortality on Sole $s = 3$: $F_{3,a,f}(t_0)$ (/100) *source : ICES; Ifremer, SIH, 2008.*

	Nephrops	Hake	Sole
B_s^{lim} (tons)	7733	54521	9706
B_s^{pa} (tons)	7733	75784	13000
$\overline{R}_s$ (10^3 individuals)	699387	241776	23414

Table 7
Biological reference points B_s^{lim}, B_s^{pa} and mean recruitment $\overline{R}_s$ for every species. This last one is computed over 1987-2006 for the Nephrops, 1992-2006 for the Hake and 1993-2006 for the Sole. *source : ICES; Ifremer, SIH.*

Main fleets \ Age a	1	2	3	4	5	6	7	8	9
Nephrops trawlers	0.999	0.972	0.344	0.063	0.023	0.013	0.014	0.017	0.01
Various fish trawlers	0.999	0.972	0.344	0.063	0.023	0.013	0.014	0.017	0.01
Sole gill-netters	0.999	0.972	0.344	0.063	0.023	0.013	0.014	0.017	0.01
Various fish gill-netters	0.999	0.972	0.344	0.063	0.023	0.013	0.014	0.017	0.01

Table 8
Estimated discard in percentage for Nephrops $s = 1 : d_{1,a,f}$. *source : ICES; Ifremer, SIH, 2008.*

Main fleets \ Age a	0	1	2	3	4	5	6	7	8+
Nephrops trawlers	0.999	0.374	0.	0.	0.	0.	0.	0.	0.
Various fish trawlers	0.998	0.237	0.	0.	0.	0.	0.	0.	0.
Sole gill-netters	0.	0.	0.	0.	0.	0.	0.	0.	0.
Various fish gill-netters	0.	0.	0.	0.	0.	0.	0.	0.	0.

Table 9
Estimated discard in percentage for Hake $s = 2 : d_{2,a,f}$. *source : ICES; Ifremer, SIH, 2008.*

Main fleets \ Age a	2	3	4	5	6	7	8+
Nephrops trawlers	0.15	0.01	0.	0.	0.	0.	0.
Various fish trawlers	0.15	0.01	0.	0.	0.	0.	0.
Sole gill-netters	0.15	0.01	0.	0.	0.	0.	0.
Various fish gill-netters	0.15	0.01	0.	0.	0.	0.	0.

Table 10
Estimated discard in percentage for Sole $s = 3 : d_{3,a,f}$. *source : ICES; Ifremer, SIH, 2008.*

Fleets	length(m)	nb vessel : $\mathrm{K}_f(t_0)$	fishing effort/vessel (nb day at sea): $e_f(t_0)$	rate of income from other species : α_f
Nephrops trawlers $f = 1, 2, 3$	09-12 m	19	170.3	0.327
	12-16 m	75	183.4	0.332
	16 -20 m	22	177.	0.414
Various fish trawlers $f = 4, 5, 6, 7$	0-12 m	110	157.7	2.738
	12-16 m	45	192.7	1.886
	16-20 m	49	180.3	2.128
	sup 20 m	37	197.1	8.779
Sole gill-netters $f = 8, 9, 10, 11$	0-10 m	28	139.	0.97
	10-12 m	42	145.5	0.508
	12-18 m	40	202.9.	0.473
	18-24 m	23	201.7	0.474
Various fish gill-netters $f = 12, 13, 14, 15, 16$	0-10 m	32	153.8	2.91
	10-12 m	30	178.8	4.782
	12-18 m	6	145.	1.248
	18-24 m	9	210.3	0.477
	sup 24 m	10	260.6	0.189

Table 11
Initial number of vessels $\mathrm{K}_f(t_0)$, effort by vessel $e_f(t_0)$ and rate of extra fishing income α_f of the sixteen fleets. *source : Ifremer, SIH, DPMA, 2008*

Fleets	length(m)	landing tax : τ_f	total variable cost by fishing effort unit by vessel (in €): c_f^{var}	fixed costs by vessel (in €): c_f^{fix}
Nephrops trawlers $f = 1, 2, 3$	09-12 m	0.04	282	101837
	12-16 m	0.05	413	174104
	16-20m	0.07	631	234836
Various fish trawlers $f = 4, 5, 6, 7$	0-12 m	0.05	171	77779
	12-16 m	0.05	543	218506
	16-20 m	0.07	729	245285
	sup 20 m	0.07	1305	388951
Sole gill-netters $f = 8, 9, 10, 11$	0-10 m	0.06	110	56601
	10-12 m	0.05	285	132326
	12-18 m	0.08	391	256373
	18-24 m	0.07	774	378872
Various fish gill-netters $f = 12, 13, 14, 15, 16$	0-10 m	0.05	58	42874
	10-12 m	0.05	192	111911
	12-18 m	0.06	434	223622
	18-24 m	0.07	1018	513353
	sup 24 m	0.03	1114	913096

Table 12
Mean reference costs of the sixteen fleets. *source : Ifremer, SIH, DPMA, 2008*