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How does MMEY mitigate bioeconomic effects of climate change for mixed fisheries

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Abstract

This paper examines the impact of climate warming on the bio-economic performances of Bay of Biscay mixed fisheries and provides insights into sustainable management strategies for coping with global warming. To achieve this, a dynamic multi-species, multi-class, multi-fleets model is developed and calibrated using biological, economic and environmental data from ICES, European Data Collection Framework and IPCC. Fishing and economic data have been collected within the European Data Collection Framework. The climate represented by the sea surface temperature is assumed to affect species recruitment. Three management strategies are then compared in terms of bio-economic outcomes: Status-Quo (SQ), Multi-species Maximum Sustainable Yield (MMSY) and Multi-species Maximum Economic Yield (MMEY). These strategies are ranked with respect to two constrained RCP climate scenarios. Results exhibit that the SQ strategy is not sustainable and is characterized by a major decline of Sole. By contrast, the MMSY and the MMEY strategies improve the ecological state and economic performance of fisheries. Furthermore, the MMEY strategy yields higher bio-economic performances than MMSY. These bio-economic benefits are however altered by climate change effects. Under the MMEY, fleets with more diversified catch structures perform better facing climate change.

Key words : bio-economics, scenarios, global warming, fisheries, sustainability, Bay of Biscay

1 Introduction

Marine biodiversity and ecosystem are under extreme pressure worldwide because of the intensification of fishing methods and an overall increase of seafood demand. Thus, according to FAO (2014), around 80% of worldwide commercial fish species are over-exploited or fully exploited. Climate change complicates and exacerbates the issues by inducing new, or intensifying existing, risks, uncertainties and vulnerabilities.

In that context, the European Union explicitly accounts for the objectives of mitigating and adapting to the effects of climate change in the area of maritime spatial planning and integrated coastal zone management¹. The Common Fisheries Policy (CFP - Reg. UE 1380/2013 11/12/2013) also reaffirms the obligations associated with the international commitments of a sustainably management of fisheries and to strengthen the existing arrangements. It also puts forward a more regional approach for optimizing the various devices in order to reach, in particular, the maximum sustainable yield by 2020. In the meantime, the Marine Strategy Framework Directive² aims at protecting and conserving the marine biodiversity. Positive economic and social benefits as well as food security are also targeted. In that multi-facet perspective, our paper investigates the ecological and economic performances of the Bay of Biscay mixed fisheries facing climate warming.

In the Bay of Biscay, a warming of $\cong 0.2$ ° C / decade has been observed for the period 1965-2004 between the surface and 200 m depth (Decastro et al., 2009). Such climate changes already impact some fish species. In particular for flat fish species, including Sole, with a wide area within the Bay of Biscay, recent studies have shown spatial correlations between their abundances and the increase in temperature (Hermant et al., 2010). For boreal species, abundance decreases in the Bay while for southern species it increases. Recruitment appears to be the main process affected by climate change (Koutsikopoulos et al., 1998). As the definition of boundaries and access rights is a crucial issue for fisheries management, climate change raises a new challenge to institutions and regulating agencies (Badjeck et al., 2010). Variations in the spatial distribution of species indeed question the update of fishing rights and the geographical redeployment of fleets (Rajudeen, 2013).

As a consequence, designing management tools and public policies that ensure the long-term bioeconomic sustainability of marine fisheries constitutes a major challenge (FAO, 2014). In response, there has been a growing need of integrated assessment tools

¹https://ec.europa.eu/clima/publications_en#Mainstreaming

²Directive 2008/56/EC – EU action in the field of marine environmental policy (Marine Strategy Framework Directive) - <http://eur-lex.europa.eu/legal-content/FR/TXT/?uri=LEGISSUM:l28164>

to support management advices (Thébaud et al., 2014) such as ecosystem-based fishery management (EBFM - Pikitch et al., 2004 ; Link et al., 2017) that aims at integrating the ecological and economic complexities of fisheries, instead of focusing on isolated target species. However, the way to operationalize the EBFM approach remains challenging, especially from the bioeconomic viewpoint (Sanchirico et al., 2008 ; Doyen et al., 2017). New models are needed, notably to integrate the multiple complexities at play (Plaganyi, 2007). In particular, these models are expected to account for the multispecies and multi-fleets nature of fisheries, for the multiple ecosystem services or values they provide as well as for climate impacts. They should also help evaluating the bioeconomic effectiveness and sustainability of current regulatory instruments such as fishing quotas or financial incentives, and designing relevant ecosystem-based management quantitative tools (Patrick and Link, 2015).

Many fish stocks are currently managed to reach their maximum sustainable yield (MSY), through limitations on fishing quotas or efforts (Mace, 2001). At MSY, catches are maximized at levels where the stock can regenerate. This strategy has been set as the main reference point of many world fisheries and is one of the key objective of the new CFP. However the sustainability of this monospecific strategy in multispecies contexts is disputed (Larkin, 1977). In particular, applying MSY policies from single-species assessments in multispecies communities with trophic interactions has been shown to induce biodiversity losses (Walters et al., 2005). Instead of MSY, many resource economists advocate the use of maximum economic yield (MEY) targets, at which profits are maximized (Dichmont et al., 2010). Harvesting at MEY is notably known to favor higher biomasses than harvesting at MSY (Clark, 2010 ; Grafton et al., 2012). In a single-species context, harvesting at MEY is thus a more profitable and viable strategy than maximizing sustainable yield. In that perspective, the MEY management strategy has been chosen as a reference point for Australian fisheries (Dichmont et al., 2010). However, maximizing profits from a single stock can also induce overexploitation and extinction, provided its price is higher than the cost of depleting the stock (Clark, 1973).

To account for the multispecies nature of fisheries, multispecies reference points and targets are now proposed (Moffitt et al., 2015). However, the potential bioeconomic consequences of such multispecies harvesting policies remain largely unknown. There have been attempts at designing multispecies MSY (MMSY) policies, at which total catches are maximized (Mueter and Megrey, 2006). But in mixed fisheries where technical interactions occur, that is when one fishing fleet harvests different species, maximizing total yields has been suggested to endanger some species (Ricker, 1958 ; Legovic and Gecek, 2010 ; Guillen et al., 2013). Potential consequences of multispecies MEY (MMEY), at which total profits are maximized, have also been investigated (Anderson, 1975). As in the single-species case, MMEY is found to be more profitable than MMSY (Guillen et al., 2013), however, MMEY can induce the overexploitation of stocks with low value (Chaudhuri, 1986 ; Guillen et al., 2013 ; Tromeur and Doyen,

forthcoming). In other words, if a multispecies fishery is seen as a portfolio of natural assets, maximizing total profits could neglect the conservation of inferior assets, thus inducing biodiversity losses.

The aim of this paper is to evaluate and compare the bioeconomic merits of MMSY and MMEY policies respectively as well as to question their relevance for operationalizing ecosystem-based management for mixed fisheries facing climate change in the Bay of Biscay. More specifically, this paper examines the impact of climate warming on the bio-economic performances of Bay of Biscay mixed fisheries and gives insights into the sustainable management strategies to cope with global warming. To achieve this, a multi-class, multi-fleets and dynamic model for common sole (*solea solea*) and European hake (*merluccius merluccius*) is developed and calibrated using ICES, European Data Collection Framework and IPCC data.

2 Bay of Biscay Case Study

Our study deals with the mixed fisheries of the Bay of Biscay operating in divisions VIIIa and VIIIb according to the International Council for the Exploration of the Sea (ICES) sections (Figure 1). Regarding fish species, we focus on common sole and hake.

2.1 Sole

Common sole (*solea solea*) is a benthic species whose distribution extends from the West African coasts to the Baltic. In the Bay of Biscay, common sole is in the center of its range area (average latitude 44.5 ° N). So far, the work carried out by Hermant et al. (2010) did not reveal a clear trend in the evolution of its spatial distribution.

The sole appears as a vulnerable stock and is subject since 2002 to a management pattern aiming at restoring the spawning biomass at its level of precaution (Bpa). This goal was reached in 2009 (Figure 2). However, due to surprisingly low recruitment in 2010, the stock is again declining. Consequently, since 2016, a 10% reduction in total allowable catches (TAC) as compared to 2015 and 2014 has been imposed (ICES, 2017) by the European commission inducing a quota of 3420 tons for French fleets (European Union, 2016). Although the spawning biomass of sole recovered for three years, it still remains below the sustainable reference point (Bpa = 13000 tons) since 2013 (ICES, 2017).

2.2 Hake

Distributed in the North-East Atlantic, European hake (*merluccius merluccius*) is present along the coasts from Norway to Mauritania. Temperature is a driver that affects the early stages of hake life (Hermant et al., 2010). Experiments in a controlled environment for the development of hake eggs at different temperatures indeed showed

high mortalities outside the range 10-13° (Guevara-Fletcher et al., 2016). Similarly, studies in the Mediterranean using habitat models show that nurseries require stable background temperatures (11.8-15 ° C), low background velocities (<3.4 cms-1) and productive plankton fronts (Druon et al., 2015). Moreover, as growth or survival of hake juveniles is increased with the availability of adequate feeding, changes in ocean conditions affect prey availability and thus affect migration behavior and hake growth (Benson et al., 2002). Thus, Goikoetxea and Irigoien’s work (2013) in the Northeast Atlantic on hake highlighted the role of the North Atlantic Oscillation (NAO) in the success of recruiting hake for several years (Figure 3). More specific informations about species ecology can be found from the bibliographical synthesis made by Caill-Milly et al. (in press).

2.3 Economical role of Hake and Sole fisheries

Hake and common sole are among the first four species in terms of economic values on the Atlantic coast. In 2015, on the Atlantic coast, Hake represents 20% of the overall production in values while Sole reaches 7% (IFREMER, 2017). For the French landings, hake represents 7% of the total value while the sole rise to 11% (Gourguet et al., 2013). The sole is less abundant than hake which is the dominant species for fisheries in the European Union (EUMOFA, 2015). Indeed, although hake has suffered from severe overexploitation with a fall in its recruitment in the 1990s (Figure 3), a recovery of its spawning stock has been observed (ICES, 2016) in the following years strongly induced by better recruitments and by the European mono-specific management plan set up at that time (MSY). The price per kilo of the sole is much more important than hake. In 2015, it is worth about 12 € per kilo with a 60 million € market to be compared with 3€ per kg for hake within a market which represents 45 million €. These values derive from the marked preference of consumers for sole. Consequently, the high abundance of hake and the high price of sole explains why both species are of major economical interest.

The main French fleets targeting those two species, include 400 vessels across the Bay of Biscay and can be divided into three groups of vessels based on their main gear: various fish trawlers, sole gill-netters and various fish gill-netters. These three fleets can then be separated into 13 sub-fleets ranked by size (Gourguet et al., 2013).

2.4 Data Sources

Recruitment and spawning biomass estimation of the sole and hake have been extracted from population models by the ICES on an annual basis for sole and quarterly for hake³

³In the report made by the ICES, the sea council hypothesizes that no recruits is observed in the fourth quarter, the sum of the three previous quarters represents here the annual and actual spawning stock (ICES)

from 1991 to 2013. Sole data are derived from a population dynamics model named XSA (Extended Survivors Analysis - Shepherd, 1999) while hake data have been estimated through the SS3 (Stock Synthesis 3) model based on commercial catches and on abundance data (ICES). Economic data and transversal data of effort and production by fleet and gear have been collected from the Fisheries Information System of IFREMER and the French Directorate for Fisheries and Aquaculture (DPMA) through the European Data Collection Framework (DCF). Sea Surface Temperatures (SST) arise from a project led by the European Union called OpEc⁴ which aimed at rebuilding the history of all marine ecosystems, biological and historical data such as water temperature, oxygen, salinity. The geographical coordinates used in this study are: latitude (43.75, 47.39) and longitude (-6.90, -2.77). They do not refer to the entire Bay of Biscay but only to ICES divisions VIIIa and VIIIb. For the SST projections until 2100, we rely on the more recent IPCC (Intergovernmental Panel on Climate Change) report which provides, according to four emission scenarios (RCP)⁵, many environmental forecasted data. In this paper, we choose to focus on the worst and best climate scenario, respectively, RCP 8.5 and RCP 2.6.

3 The bio-economic model

We rely on a multi-species, multi-class, multi-fleets and dynamic model in discrete time inspired by Quinn and Deriso (1999), Doyen et al. (2012) and Gourguet et al. (2013). Environmental, biological, economic components and links of the model are described in figure 4. These links highlight how the different interactions occur: SST impact recruitment through the specific responses of the Spawning Stock Biomass (SSB) with respect to the environmental context. Then stock levels along with the fishing effort determine the catches, profits and biological outcomes from 2014 until 2094.

3.1 Multi-species age-class dynamic model

For each species, population dynamics described on a yearly basis by age group is first characterized by natural and fishing mortality mechanisms as follows :

$$\begin{cases} N_{s,a}(t+1) = N_{s,a-1}(t)exp(-M_{s,a-1} - F_{s,a-1}(t)) \\ N_{s,A_s}(t+1) = N_{s,A_s-1}(t)exp(-M_{s,A_s-1} - F_{s,A_s-1}(t)) + N_{s,A_s}(t)exp(-M_{s,A_s} - F_{s,A_s}(t)) \end{cases} \quad (1)$$

where $N_{s,a}(t)$ stands for the abundance of the exploited species, $s = 1, 2$ (sole, hake respectively) at age $a = 2, \dots, A_s$ at time t . The age class starts at two because the

⁴Operational Ecology (End date : 31/12/2014) - <http://marine-opec.eu/>

⁵Representative Concentration Pathways

first one stands for recruitment. We assume that there is not interactions between sole and hake. Thus, abundances of species $N_{s,a}(t)$ evolves according to both natural $M_{s,a}$ and total fishing $F_{s,a}(t)$ mortalities of the species s at age a and time t . Furthermore, the total fishing mortality $F_{s,a}(t)$ is derived from the sum of the fishing mortality of the $m = 13$ fleets f at year $t_0 = 2014$ described by:

$$F_{s,a}(t) = \sum_{f=1}^m u_f(t) F_{s,a,f}(t_0) \quad (2)$$

where $u_f(t)$ stands for the fishing effort multiplier of the sub-fleet f at time t . The initial fishing mortality, $F_{s,a,f}(t_0)$, depends on catchability, effort and number of boats as follows :

$$F_{s,a,f}(t_0) = q_{s,a,f} e_f(t_0) K_f(t_0) \quad (3)$$

with $e_f(t_0)$ is the mean value of fishing effort by vessels of sub-fleet f expressed in number of days at sea, $K_f(t_0)$ is the number of vessels by sub-fleet f , both for the baseline year 2014 and $q_{s,a,f}$ the catchability of the sub-fleet f on species s at age a . Thus, the fishing mortality is assumed to be proportional to effort as in the seminal Graham-Schaefer model. Such an assumption arises from the real situation in the Bay of Biscay where the congestion effects (Chu and Kompas, 2014) are very limited. Indeed, for instance, the number of vessels which operates in the sole fishery has been decreasing of 21% between 2000 and 2011 while French vessels targeting the sole account for about 90% of the total number of boats (Guyader et al., 2017).

3.2 Stock-recruitment dynamics

The spawning biomass $SSB_s(t)$ for the two species is described by:

$$SSB_s(t) = \sum_{a=1}^{A_s} \gamma_{s,a} v_{s,a} N_{s,a}(t) \quad (4)$$

where $\gamma_{s,a}$ stands for the share of fertile individuals of species s at age a and $v_{s,a}$ represents the weights (in tons) of individuals of species s at age a and $a = 1, \dots, A_s$.

We assume that the recruitment dynamics depends on both SSB and sea surface temperature θ in a stochastic way as follows:

$$N_{s,1}(t+1) = f(SSB_s(t - \Delta_s), \theta(t - \Delta_s), \varepsilon_s(t - \Delta_s)) \quad (5)$$

Here $N_{s,1}(t)$ represents the recruits, $\theta(t)$ stands for the sea surface temperature at time t while $\varepsilon_s(t)$ captures the environmental stochasticity affecting the recruitment. Δ_s is a lag with respect to the time necessary for the egg to become a catchable recruit

(about two years for the sole $\Delta_1 = 1$; about one year for hake $\Delta_2 = 0$). The integration of environmental factors in recruitment is in line with Cushing (1982), Glantz (1992) and Laevastu (1993). Recruitment may be affected by sea temperature through many behavioral and physiological processes during spawning and larval phase such as metabolic cost of spawners, natural mortality of eggs and larvae, food availability etc. (Hermant et al., 2010). Different recruitment functions f have been considered here including the Ricker (1958), Beverton-Holt (1957) and Cushing models as displayed in Table 4. Most of these stock-recruitment models are derived from a generalisation of the Ricker and Beverton-Holt model (Hilborn and Walters, 1992). With these different formulations, we performed regressions⁶ of recruits over SSB and SST time series⁷ in order to find the recruitment model that best fits the data. As the biological interactions between temperature and recruitment are complex, another possible approach would have been to use a neural network approach as in Kompas and Chu (2018) which does not require a specific form but is more time-consuming. We detail and discuss the time lags Δ_s obtained in the results section.

3.3 Economic scores

Assuming that discards are neglectable, landings of the m different sub-fleets equals catches and are defined by the Baranov catch equation:

$$C_{s,a,f}(t) = N_{s,a}(t)u_f(t)F_{s,a,f}(t_0) \frac{1 - \exp(-M_{s,a} - \sum_{f=1}^m u_f(t)F_{s,a,f}(t_0))}{M_{s,a} + \sum_{f=1}^m u_f(t)F_{s,a,f}(t_0)} \quad (6)$$

Incomes derived from catches reads as follows:

$$Inc_f(t) = \sum_s \sum_{a=1}^{A_s} p_{s,a}(t)v_{s,a}C_{s,a,f}(t) \quad (7)$$

where $v_{s,a}$, as in equation (4), is the mean weight of individuals of species s at age a and price $p_{s,a}(t)$ corresponds to the market value (euros by kg) of species s at age a for year t assumed to fluctuate randomly according to a Gaussian law.

Profits $\pi(t)$ as the difference between incomes and costs are defined by:

$$\pi_f(t) = (Inc_f(t) + \alpha_f u_f(t)K_f(t_0)e_f(t_0)) (1 - \tau_f) - \left(V_f p(t)e_f(t_0) + c_f^{var} e_f(t_0) + c_f^{fix} \right) u_f(t)K_f(t_0) \quad (8)$$

⁶Ordinary Least Squared for the log-linearised model of the sole with 22 observations and autoregressive process of order 1 for the log-linearised model of the hake to correct the autocorrelation of its errors with 66 observations

⁷By using the Scilab software and one of its econometric modules named GROCER - <http://dubois.ensae.net/grocer.html>

α_f corresponds to the income per unit of effort of sub-fleet f of other species involuntarily caught. The dynamic of these non-targeted species is not detailed but we assume constant values for these species per unit of effort, thus $Inc_f(t)$ is only a part of the global income. τ_f is the landing cost by sub-fleet as a proportion of the gross income, V_f represents the volume of fuel used by fishing effort unit and c_f^{var} and c_f^{fix} corresponds respectively to the variable⁸ and annual⁹ (fixed) costs by a vessel of sub-fleet f . These parameters are based on economic data available for 2008 (IFREMER, SIH, DPMA¹⁰, Table 9 and 10). The price of fuel is considered constant over time, set at a price of 0.5 € per liter.

3.4 Management strategies

We here consider three management strategies in order to compare them in terms of bio-economic outcomes: Status-Quo (SQ), Multi-species Maximum Sustainable Yield (MMSY), Multispecies Maximum Economic Yield (MMEY).

Status-Quo Strategy: The first management strategy entitled Status-Quo (SQ) maintains fishing efforts constant throughout the period of interest $t_o = 2014$ to $T = 2094$ such as:

$$u^{SQ}(t) = 1 \quad \forall f = 1, \dots, m \quad \text{and} \quad t = t_0, \dots, T$$

Multi-species Maximum Sustainable Yield (MMSY) Strategy: The second fishing strategy aims at reaching a maximum sustainable yield over all species considered, that is to say, to maximize the aggregated long-term landings of the different fleets. The objective is to find the best constant effort multiplier vector noted u_f^{MMSY} that maximizes total catches. In fact, we maximize the mean total catches over time defined as the average of the total catches over the entire temporal period. Moreover, to account for the stochasticities affecting both the species prices $p_s(t)$ in equation (7) and recruitment dynamics (5) through $\varepsilon_s(t)$, we consider the expected value of the mean catches::

$$C^{MMSY}(u) = \mathbb{E} \left[\frac{1}{T} \sum_{t=t_0}^T \sum_{s=1}^2 \sum_{a=1}^{A_s} \sum_{f=1}^m C_{s,a,f}(t) \right] \quad (9)$$

⁸The variable cost includes oil, supplies, ice, bait, gear, and equipment costs

⁹The annual cost includes maintenance, repair, management and crew costs, fishing firms, licenses, insurances and producer organisation. Those costs date from 2008

¹⁰DPMA stands for Direction des Peches Maritimes et de l'Aquaculture which corresponds to the Directorate for Sea Fisheries and Aquaculture at the French Ministry of Agriculture and Fisheries. SIH means Systeme d'Informations Halieutiques, the fisheries information system monitored by Ifremer, the French Research Institute for the Exploitation of the Sea (http://wwz.ifremer.fr/institut_eng)

Once we have the expected catches, we identify the vector of best fishing effort multipliers denoted by u_f^{MMSY} that maximize the previous metrics:

$$C^{MMSY}(u^{MMSY}) = \max_u C^{MMSY}(u) \quad (10)$$

As explained in the introduction, by adopting a multi-species point of view, the MMSY management takes into account the fact that most fleets do not target (voluntarily or not) only one species. Thus, this management model potentially offers a more relevant management from an ecosystem and multi-species perspective as compared to a single-species point of view (Voss et al., 2014).

Multi-species Maximum Economic Yield Strategy: The third strategy we consider consists in maximizing the Net Present Value (NPV) over the m fleets defined by:

$$NPV(u) = \mathbb{E} \left[\sum_{t=t_0}^T \frac{1}{(1+r)^t} \sum_{f=1}^m \pi_f(t) \right] \quad (11)$$

with profits $\pi(t)$ defined in equation (8) and $r = 4\%$ the discount rate. Again, \mathbb{E} corresponds to the expectations with respect to the stochastic parameter ε_s and prices p_s . Maximizing the NPV relates to the maximum economic yield for both species which explains why we introduce the notation u_f^{MMEY} .

$$NPV(u^{MMEY}) = \max_u NPV(u) \quad (12)$$

To compute numerically the optimal solutions, we have also used the SCILAB software.

3.5 Climate Scenarios

In our study, we consider two extrem climate scenarios (IPCC, 2013 - RCP 2.6, RCP 8.5) illustrated by the figure 5 for the Sea Surface Temperature in the Bay of Biscay. We notice an upward trend for historical temperatures and a recent and sharp increase for the last few years. Indeed, from 2007, after a fall of more than 0.5°C, the Bay of Biscay is getting warmer with a rise of nearly 1.5°C in just 6 years. This outcome is the result of an increase in warming of 0.06/0.07°C per year over the last 30 years (Le Treut, 2013). Inter-annual variations induced by atmospheric flux and ocean currents (Michel et al., 2009) are the main sources of uncertainty and are very difficult to predict even with complex climate models. Yet, the accuracy of climate models is steadily increasing since the 1990s because of the advancement of research, more available data and also due to some major technological discoveries (IPCC, 2013). Therefore, even if these models cannot predict what the temperature will be to the tenth of a degree in 80

years, they are getting closer to reality by relying on verifiable physical principles and on emission scenarios more than likely due to our human activities (IPCC, 2013).

These projected temperature in the Bay of Biscay are integrated each year in the recruitment formula of equation (5) which affects the species dynamics as a whole and by extension the economy.

4 Results

This section presents the merits of integrating a temperature-dependent stock-recruitment model into our bioeconomic model in order to determine the management strategy, that best mitigates warming effects among SQ, MMSY and MMEY.

4.1 Impact of warming on stock-recruitment model

In tables 2 and 3, we present the main results of the statistical analysis of recruitment models. The equations (13) and (14) notably highlight the importance of lags between recruitment and SSB and SST. They are lagged proportionnaly to the time necessary for the species to become an egg, a larvae, a juvenile then a catchable recruit : two years for the sole et one year for hake in average. We know that a recruitment model only driven by SSB is likely to appear less explanatory than a model which includes an environmental factor (Cury et al., 2014). This is highlighted in table 4. Moreover, all estimated coefficients (a, b, c) are statistically significant at the 5% level (Tables 2 and 3). For both species, the Ricker model turns out to be more relevant than the Beverton-Holt, Cushing or Cobb-Douglas model and all coefficients are statistically significant. These conclusions are consistent with the study carried out by Anneville and Cury (1997) which explains that the Ricker model is “the best pattern [...] because it ensures a much stronger regulation”. Beverton and Iles (1998) also confirms that the Ricker model is the best pattern to explain the stock-recruitment relationship especially if the effect of temperature is integrated. The influence of temperature on recruitment, explained by the coefficient c in tables 2 and 3, is negative for both species.

Sole’s SR model

$$N_{1,1}(t+1) = aSSB_1(t-1)e^{-bSSB_1(t-1)-c\theta(t-1)^2} + \varepsilon_1(t-1) \quad (13)$$

Hake’s SR model

Hake’s model is first built with quaterly data. Given that no recruits is observed during the winter quarter so the first three quarters are equals to an entire year. Thus, to harmonize it, we sum the recruits of the three quarters of the previous year in order to transform the quarterly model into a yearly model such as:

$$N_{2,1}(t+1) = n_{2,1}(t_1(t)) + n_{2,1}(t_2(t)) + n_{2,1}(t_3(t))$$

with $n_{2,1}(t_i(t))$ the number of hake recruits of quarter i of year t such as:

$$n_{2,1}(t_i(t+1)) = aSSB_2(t_i(t))e^{-bSSB_2(t_i(t))-c\theta(t_i(t))^2} + \varepsilon_2(t_i(t)) \quad \text{with } i = [1, 2, 3]$$

so the yearly basis model is described as:

$$N_{2,1}(t+1) = \sum_{i=1}^3 (aSSB_2(t_i(t))e^{-bSSB_2(t_i(t))-c\theta(t_i(t))^2} + \varepsilon_2(t_i(t))) \quad (14)$$

4.2 Status-Quo : not ecologically and economically viable

Figure 6 describes the estimated¹¹ bio-economic performances of the SQ strategy under the two climate scenarios : best scenario/RCP 2.6 and worst scenario/RCP 8.5 over the period 2014-2088. On the top, are plotted the SSB of Sole and Hake while profits are displayed on the bottom.

Figure 6 shows that the SQ strategy is not ecologically or economically viable. The ecological vulnerability relates to sole biomass which indeed declines and violates the ICES precautionary limit, even with a favorable climate change scenario, and collapses under the pessimistic climate scenario. The economic vulnerability arises from the worst climate scenario which leads to negative profits in the fishery.

More globally, the SQ strategy highlights the fact that if fishing efforts are not adjusted, global warming will amplify the current fall of the sole SSB and could lead to an economic collapse. Therefore, management strategies are required to adapt fishing effort in order to moderate the impact of global warming on bio-economic outcomes.

4.3 MMSY : not ecologically viable but economically viable

As illustrated by figure 7, the MMSY strategy performs better ecologically and economically than the SQ strategy. As expected, the more extreme the climate scenario, the more negative the impacts.

The decline of sole SSB below its Bpa appears unavoidable but is clearly mitigated by this strategy. Under the worst climate scenario, the weakness of the underlying MMSY fishing effort multipliers (table 1) first generates a recovery of this stock which however collapses in the long run because of the too high rise of temperatures. Under the best climate scenario, the sole stock first decreases to stabilize after 15 years at

¹¹The 500 simulated trajectories are induced by Monte-Carlo replicates of uncertainties. $\varepsilon_s(t)$ assumed to be an i.i.d. centered Gaussian distribution with standard deviations of the species s denoted by σ_s and displayed in tables 2 and 3 i.e $\varepsilon_s(t) \sim N(0, \sigma_s)$.

around 10 000 tons. Hake stock displays similar trends as compared to SQ scenario, with lower values regardless of climate scenarios.

Interestingly, although the purpose of this strategy is not to maintain the SSB above Bpa's, it significantly improves biological outcomes. Indeed, maximizing landings in the future can not be dissociated from sustaining high level of stock. Therefore, the MMSY strategy implicitly accounts for ecological objectives through the fishing effort mitigation, thus performing better than the SQ strategy.

4.4 MMEY : ecologically viable and economically viable

As displayed by figure 8, the MMEY strategy displays better bio-economic performances than the SQ and MMSY strategy.

Regardless of the climate scenario, the sole and hake SSB display the same trend than in the MMSY strategy (figure 8) but at higher levels for Sole. Nevertheless, for hake, the SSB remains at lower values whatever the climate scenario. Compared to the MMSY strategy, under the best climate scenario, profits are multiplied by more than two, reaching 60 million of euros per year. However, under the worst climate scenario, profits are lower (Figure 8). This could be explained by the weak price of hake which leads the MMEY strategy to focus much more on Sole's profits and conservation. On the contrary, the MMSY strategy which aims at maximizing catches has a wider interest to protect hake, taking advantage of its high abundance.

The MMEY strategy emerges as the best way to mitigate climate change effects. In the next section, we elaborate on the explanation for such outcomes in terms of fishing efforts.

4.5 MMSY, MMEY : reduction of efforts especially for sole gill-netters

Table 1 displays the different MMSY and MMEY fishing effort multipliers, mean landings and the NPV over the entire temporal horizon. Firstly, the MMSY and MMEY strategies imply an important mitigation of the number of boats as almost all the optimal multipliers (u_f^{MMSY} , u_f^{MMEY}) are smaller than 1. This is in line with the actual mitigation of the number of vessels on the Atlantic coast due to the CFP.

We also notice that, regardless of the climate scenarios, MMEY multipliers are globally higher than MMSY multipliers for mixed trawlers and mixed gill-netters. By contrast, MMEY multipliers for sole gill-netters are lower than MMSY multipliers for all climate scenarios¹². The choice of strategy has thus a major impact on the sole

¹²Except for the two smallest sub-fleets of the sole-gill netters fleet under the worst climate scenario. That is explained by their weaker contribution of the sole mortality (figure 10) than the two biggest sub-fleets

stock. In particular, the fishing effort multipliers of sole gill-netters plays a pivotal role for the sole stock.

Moreover, table 3 indicates that climate change significantly affects the performances of these strategies as well as the computation of optimal management. In particular, in table 1, we ascertain that NPV and landings are lower under the worst climate scenario/RCP 8.5 with respect to each strategy.

4.6 Bioeconomic synthesis displays the MMEY as the best strategy

Figure 9 synthesizes the bio-economic scores of the three management strategies through the average NPV of the entire temporal horizon on the Y-axis versus the Simpson's index of diversity¹³ on the X-axis. A Simpson's index close to 2 (because we have two species) means a more diversified ecosystem. By contrast, if the Simpson's index tends to one it means we have a lower level of diversity. The figure shows an heterogeneous¹⁴ ecosystem which may be explained by a domination of one species on another (hake on sole) or a simple extinction of one species (in this case, Sole). Here, the values of Simpson index are weak <1.2 indicating that diversity is at stake. This is due to low abundances of sole, which even collapses under the worst climate scenario for the SQ strategy.

5 Discussion

In this last section, we discuss the benefits of managing a mixed fishery with the MMEY strategy and address the first question raised by the title of the paper.

5.1 MMEY as an ecological and economic win-win strategy

Figure 9 shows that the MMSY and the MMEY strategies improve both the ecological state and economic performance of the fishery as compared to the SQ strategy. Furthermore, the MMEY strategy yields bio-economic gains as compared to MMSY. This ranking $SQ < MMSY < MMEY$ (in the pareto sense) hold true for the two climate and as such is a win-win strategy. Such finding is aligned with general results obtained in Grafton et al. (2007) showing that under reasonable prices, costs, and discount rates, fishing at (dynamic) MEY promotes larger fish stocks and higher profits than fishing at MSY. Although Clark (1973) explains that maximizing NPV can lead to extinction if

¹³

$$D = \left[\sum_{s=1}^2 \left(\frac{S\bar{S}B_s}{\sum_{s=1}^2 S\bar{S}B_s} \right)^2 \right]^{-1}$$

with $S\bar{S}B_s = \frac{1}{T} \sum_{t=1}^T SSB_s(t)$

¹⁴Some species are more abundant than others. In our case, it is Hake.

the discount rate r exceeds the intrinsic growth rate of the fishery, more recent studies (Grafton et al., 2010, 2012) have shown that bio-economic gains can occur for dynamic MEY even when the discount rate exceeds the intrinsic growth rate. This result applies in our case for several reasons including the recovery of hake in the past few years and the low discount rate used $r = 4$. Therefore, our economic strategy MMEY generates a positive effect on both fish stocks.

Nevertheless, there is no guarantee that the profit of each sub-fleet remains positive because we maximize the aggregated profits of all fleets. Indeed fishing effort multipliers will be higher for the more profitable sub-fleets while less profitable sub-fleets will see their effort reduced in the MMEY strategy.

Moreover, the ecological gains of MMEY as compared to MMSY and SQ depending on climate change intensity. Under the highest climate change scenario, the simpson index gain is indeed very limited. This is due to the fact that the sole stock is strongly altered under this scenario as illustrated by figure 8 (top left).

5.2 Diversification of fleets produces greater benefits in the face of climate change

MMEY efforts draws on a strategy of diversification. First, we notice that fishing effort of the mixed trawlers and mixed gill-netters for the MMEY strategy are globally higher than those in MMSY strategy. That could explain why profits are higher for this latter strategy as compared to the MMSY strategy. On the contrary, fishing efforts of the sole gill-netters are globally lower for MMEY than for MMSY. This can be explained by the strong dependency¹⁵ (figure 10, 12) of the sole gill-netters on the sole which MMEY efforts aims at avoiding because of the vulnerability of the sole due to global warming.

Therefore, many fleets relying on the sole may have to diversify their activities and change their targets especially if sole TAC and therefore landings continue to decrease as for almost 20 years (Figure 11). The price of sole has risen by 80% between 1994 and 2015 (Figure 13). This explains why sales in value remain high despite their limited share in volume¹⁶ which is steadily decreasing (Aglia, 2014). Moreover, because of negative warming effects on targeted species, new commercial strategies and a reorganisation of the sector might be observed in the next years (Lagiere, 2012). This sectoral change may be restricted by a number of factors : on the one hand, the French fleet is aging¹⁷ and the cost of renewing is high¹⁸ for new operators whose number has significantly decreased in the last years (Figure 14). On the other hand it is much more

¹⁵A high contribution to fishing mortality and a wide share in the overall income of the fleet

¹⁶Sales in Volume = landings - unsold

¹⁷The average age of French vessels is over 25 years old in 2012. Still in 2012, only 20% of the fleet was under 15 years. In contrast, almost 57% of the ships had more than 25 years (Aglia, 2014)

¹⁸Furthermore for big vessels

difficult for large vessels operators especially for sole gill-netters to adapt their fishing gears (Lagiere, 2012). Conversely, small vessels are already using 2 to 3 different gears per year. With the introduction of European regulations on discards, using case-by-case solutions for fleets to deal with discarding and gearing patterns appears to be one key of success (Morandeau et al., 2014).

5.3 Perspectives

With this study, we underline the importance to integrate both multi-species, multi-fleet nature of fisheries as well as upstream temperature and more specifically SST in recruitment models and in management models of fisheries. This in line with Hughes et al. (2005) who claim : “restoring marine [...] ecosystems after they have degraded is much more difficult than maintaining them in good condition”. Such an ecosystem policy has already been tested by the Pacific Fishery management Council in 1998 in the management of sardine stocks (*Sardinops Sagax*). The council adopted a control of fishing depending on temperature increase (Hill et al., 2011).

More specifically, our results illustrate the potential of strategies aimed at MMEY to entail greater adaptation capacity in the face of climate change. This result is to place in the context of policy objectives which at the moment largely focus on mono-MSY or MMSY. So as to avoid harmful effects, global changes impacts have to be taken into account by regulating agencies which could be more efficient as almost half of mondial stocks are currently managed with the MSY method and as we have proved with the MMEY approach. This is in line with Chu and Kompas (2014) who claim that reaching the maximum economic yield, when combined with marines protected areas provides a better profitability and also ensures a higher conservation level regarding fish stocks.

In the medium to long-term horizon, it may be a large part of fleets which should adapt to changes induced by global warming. The large level of investment needed to rejuvenate the fleet and the decrease of quotas for some species will likely create major challenges in the future. Even if the increase in prices sustains profits, for the Bay of Biscay, governments or European institutions will have a crucial role to play.

The relevance of the adaptive, ecosystem and ecological-economic strategy advocated in our study should also draw on better knowledge on environmental changes. In that regard, the findings of Poloczanska et al. (2016) already observing a movement of marine species sensitive to warming towards the poles should be refined. In particular, the processes underlying the recruitment dynamics of the species are not fully understood yet such as the processes in survival success during the juvenile phase (Le Pape and Bonhommeau, 2015).

More globally, from a policy perspective, our results suggest to have an adaptive control of the fishery based on the economic, biological and social context and especially on the local and global environmental changes.

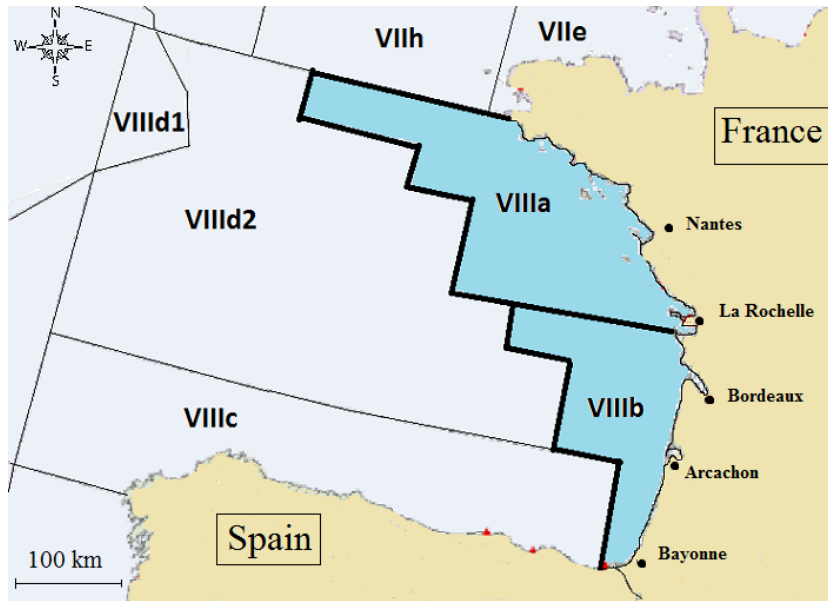


Figure 1: Map of the Bay of Biscay and ICES divisions. The studying area is in blue.



Figure 2: Historical evolution of the spawning biomass for the common sole. The dashed line refers to the precautionary threshold B_{pa} . (ICES, 2017)

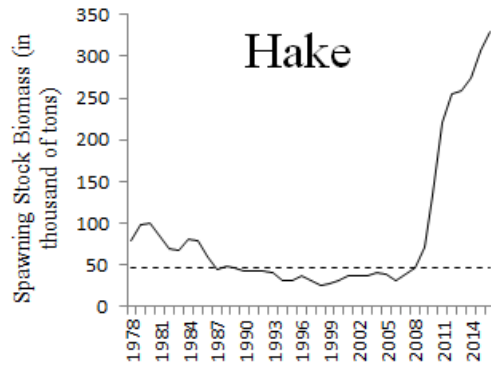


Figure 3: Historical evolution of the spawning biomass for the European hake. The dashed line refers to the precautionary threshold (Bpa) estimated at 46200 tons (ICES, 2016)

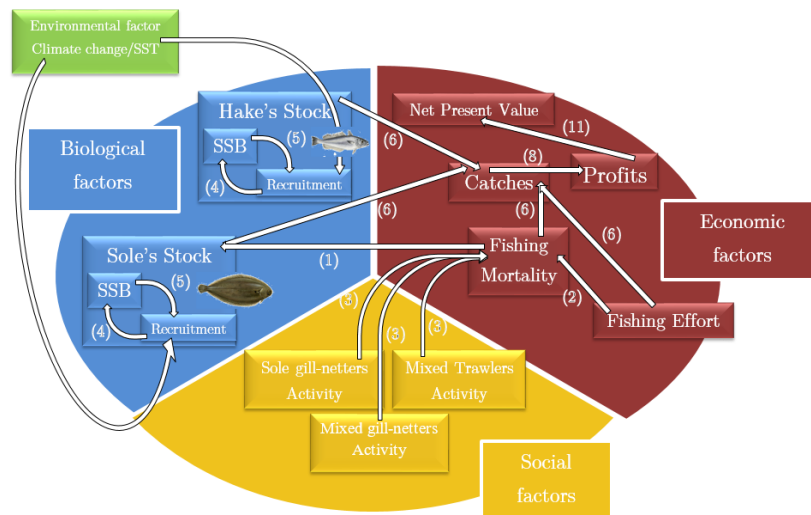


Figure 4: Relations existing between environmental, biological and economic factors within the bio-economic model. Arrows stand for the interactions between variables while figures between brackets refer to the equations/models that link the various factors within the bio-economic model.

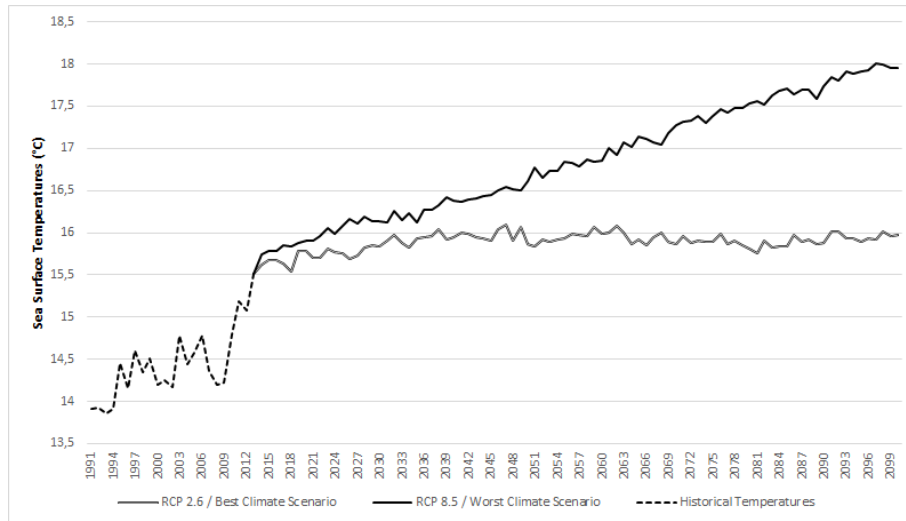


Figure 5: Historical trajectories of SST in the Bay of Biscay from 1991 to 2013 and projections of SST trajectories according to the two climate scenarios (RCP 2.6 and 8.5) from 2014 to 2100

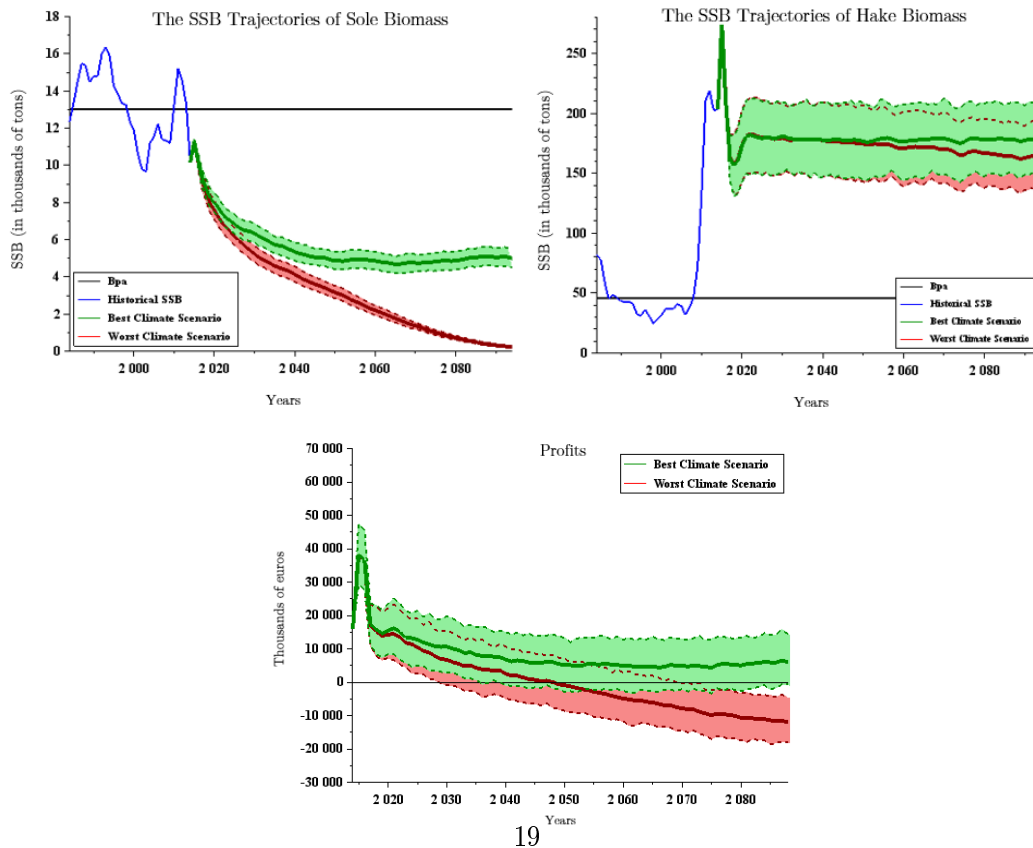


Figure 6: Strategy Status-Quo - Sole (top left) and Hake (top right) SSB trajectories under the two climate scenarios in thousands of tons. The black solid line represents ICES precautionary threshold (B_{pa}) of the species' stock. The third figure (bottom) represents the total profits over all thirteen sub-fleets. Historical paths are displayed in blue. The 500 simulated trajectories are represented by the colored areas depending on the climate scenario (green : best/RCP 2.6 and red : worst/RCP 8.5). The solid lines within green and red areas display the average of these 500 trajectories.

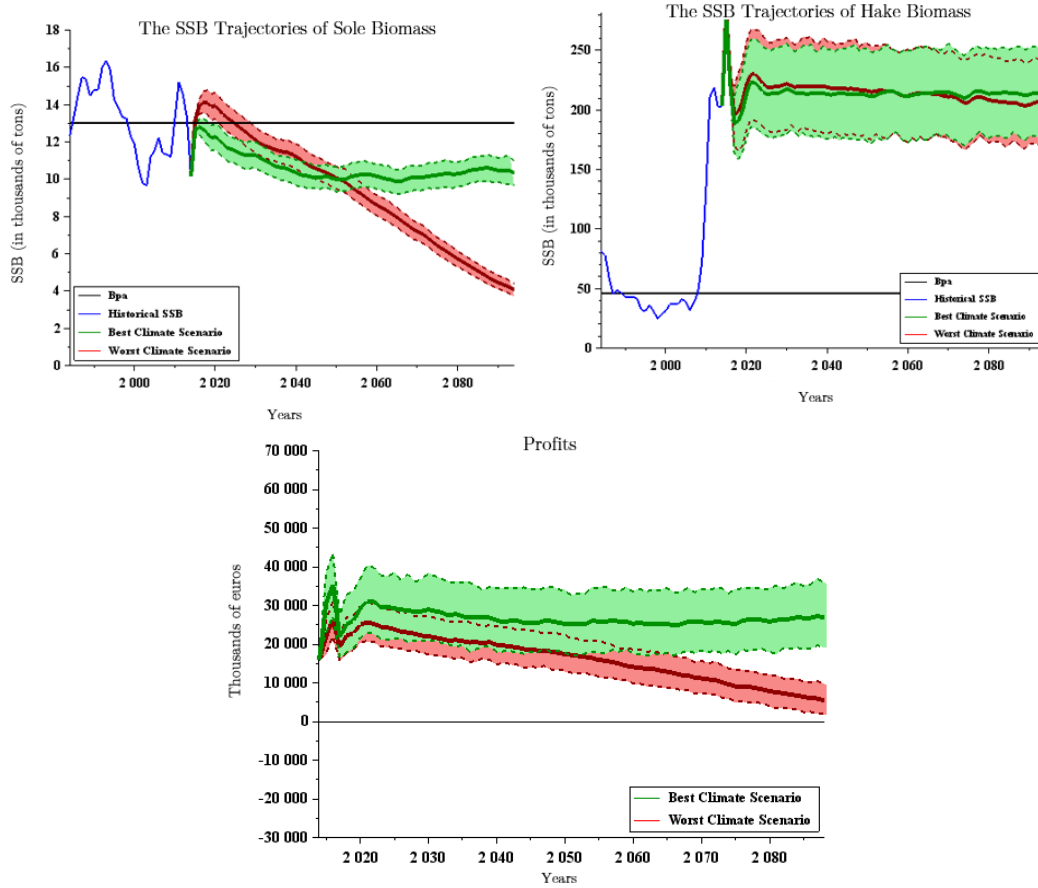


Figure 7: Strategy MMSY - Sole (top left) and Hake (top right) SSB trajectories under the two climate scenarios in thousands of tons. The black solid line represents ICES precautionary threshold (B_{pa}) of the species' stock. The third figure (bottom) represents the total profits over all thirteen sub-fleets. Historical paths are displayed in blue. The 500 simulated trajectories are represented by the colored areas depending on the climate scenario (green : best/RCP 2.6 and red : worst/RCP 8.5). The solid lines within green and red areas display the average of these 500 trajectories.

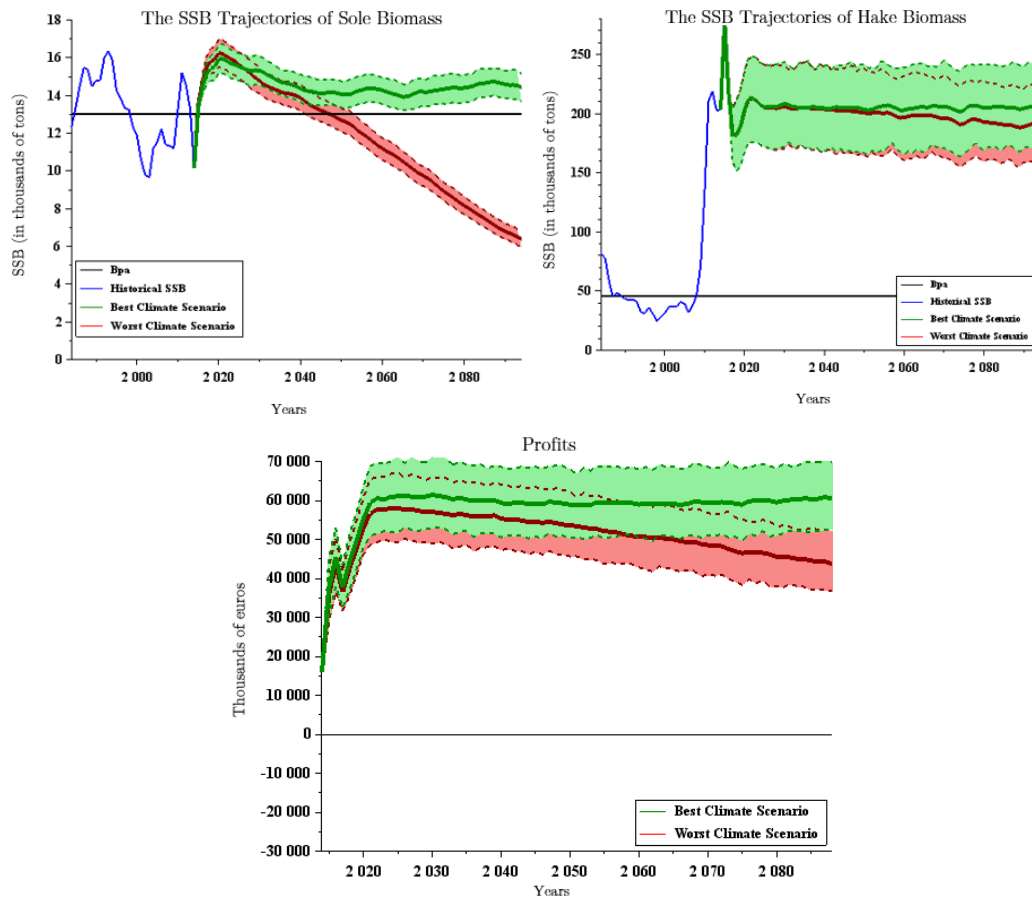


Figure 8: Strategy MMEY - Sole (top left) and Hake (top right) SSB trajectories under the two climate scenarios in thousands of tons. The black solid line represents ICES precautionary threshold (B_{pa}) of the species' stock. The third figure (bottom) represents the total profits over all thirteen sub-fleets. Historical paths are displayed in blue. The 500 simulated trajectories are represented by the colored areas depending on the climate scenario (green : best/RCP 2.6 and red : worst/RCP 8.5). The solid lines within green and red areas display the average of these 500 trajectories.

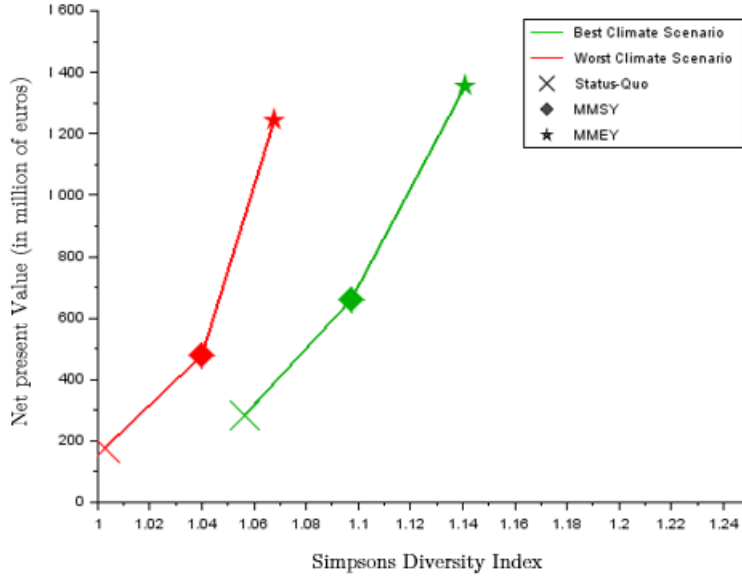


Figure 9: Simpson’s Index of Diversity versus Average Net Present Value.

Type of fleet (number of vessels - $K_f(2008)$)	RCP 8.5		RCP 2.6	
	u_f^{MMSY}	u_f^{MMEY}	u_f^{MMSY}	u_f^{MMEY}
Mixed trawlers 0-12 m (110)	0	0.72	0.44	0.29
Mixed trawlers 12-16 m (45)	0.08	0.84	0	1.32
Mixed trawlers 16-20 m (49)	0.02	1.03	0.21	0.53
Mixed trawlers >20 m (37)	0.02	0.7	0.04	1.06
Sole gill-netters 0-10 m (28)	0.07	0.51	0.36	0.14
Sole gill-netters 10-12 m (42)	0.01	0.21	0.72	0.13
Sole gill-netters 12-18 m (40)	0.85	0.23	0.79	0.25
Sole gill-netters 18-24 m (23)	0.71	0.19	0.78	0.53
Mixed gill-netters 0-10 m (32)	0.22	0.74	0.66	0.44
Mixed gill-netters 10-12 m (30)	0.23	1.03	0.81	0.2
Mixed gill-netters 12-18 m (6)	0.74	0.64	0.66	0.36
Mixed gill-netters 18-24 m (9)	0.34	0.44	0.45	1.12
Mixed gill-netters >24 m (10)	0.49	0.96	1.12	0.83
Mean Landings (in thousands of tons)	142	137	148	144
Mean NPV (in millions of euros)	478	1242	658	1355

Table 1: Fishing effort multipliers for MMEY and MMSY strategies with respect to the two climate scenarios. Numbers between brackets refer to the number of vessels in 2008 (Gourguet et al., 2013).

Sole	Standard Error (σ)		0,2037519	
	Sum of squared residuals		0,8302967	
	R ² = 0,51		a	b
	Estimation	58,106969	-0,0000743	-0,012258
	t(17)	5,0245006	-3,3391635	-3,6149265
	p-value	0,000065	0,0032687	0,0017274

Table 2: Parameters and standard errors of the estimated Ricker model (equation 13) accounting for temperature for sole. t(17) stands for the Student test with 17 observations.

Hake	Standard Error (σ)		0,633434	
	Sum of squared residuals		25,278034	
	R ² = 0,27		a	b
	Estimation	4,4805325	-0,0000067	-0,0020034
	t(62)	6,5098007	-4,2417837	-2,163427
	p-value	1,418E-08	0,000074	0,034309

Table 3: Parameters and standard errors of the estimated Ricker model (equation 14) accounting for SST for hake. t(62) stands for the Student test with 62 observations.

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¹⁹SceNARios of bioeconomic VIability and REsilience for ecosystem-based fisheries management in Aquitaine

²⁰Scenario, fishEry, ecologicAl-economic modelling and VIability nEtWork

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Appendix

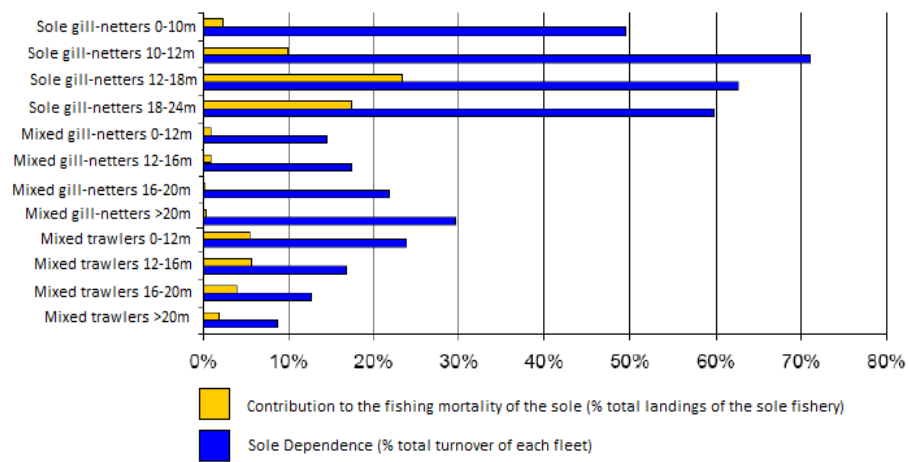


Figure 10: Contribution to the fishing mortality and dependence on sole of fleets of Bay of Biscay fishery in 2010 (Aglia, 2014)

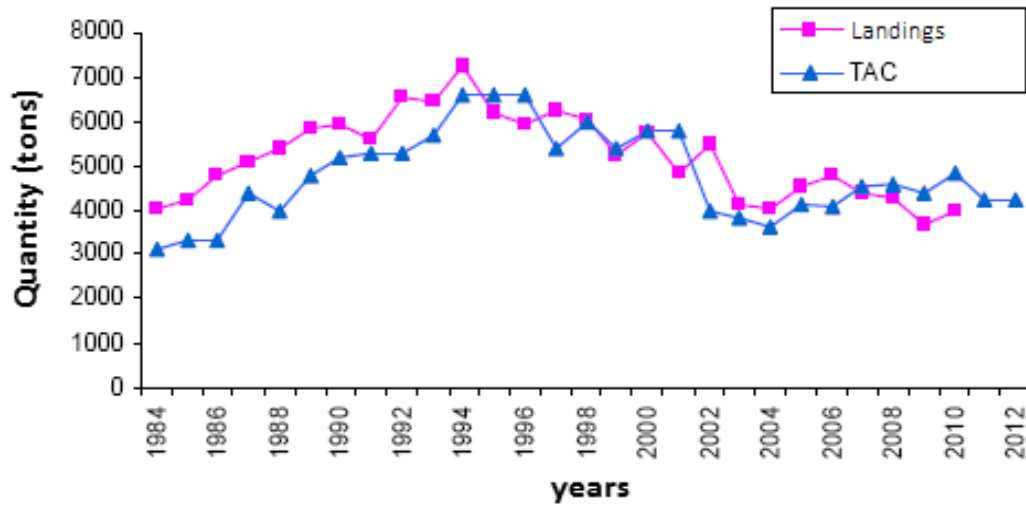


Figure 11: Comparative evolution of the TAC and landings of the sole in the Bay of Biscay since 1984 (Lagiere, 2012)

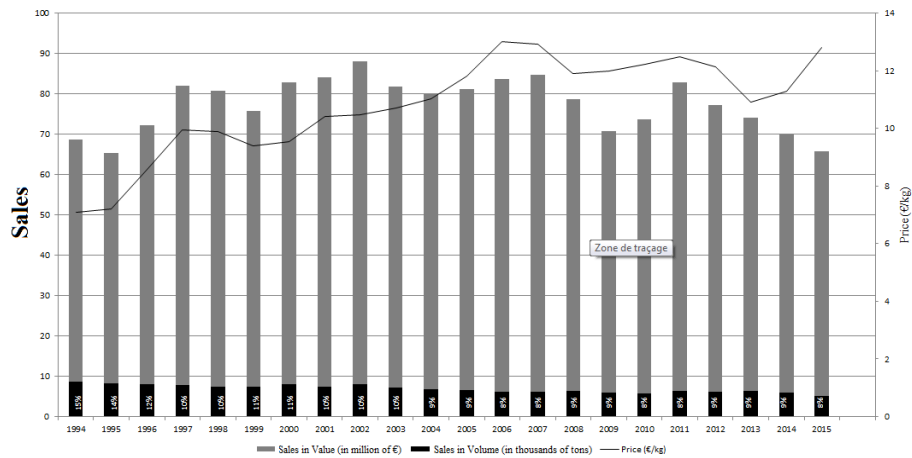


Figure 13: Sales in volume and in value of the sole in all auction centres (histogram, left vertical axis) and price curve (right vertical axis). The percentages represent the part of sales in volume compared to sales in value. (data source : visionet.franceagrimer.fr)

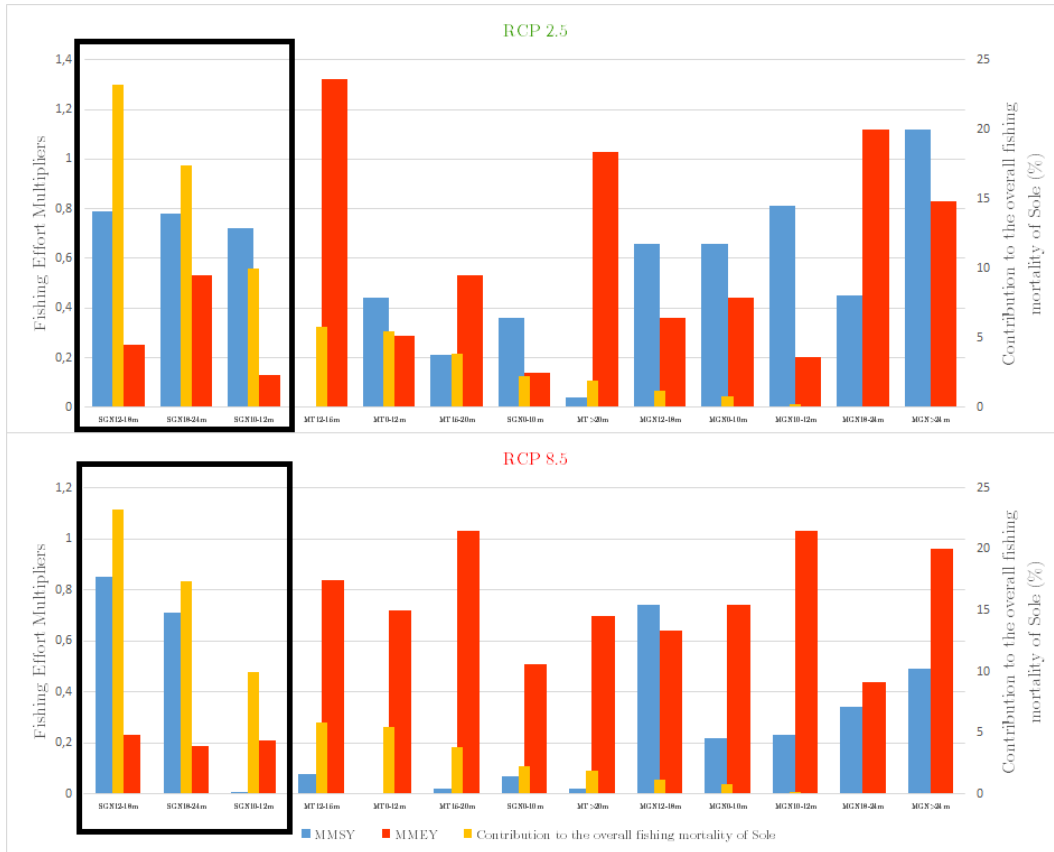


Figure 12: Fishing effort multipliers (left axis) and contribution to the overall fishing mortality of Sole in percentage (right axis). Fleets (X-axis) are ranked by contribution to sole mortality with SGN=Sole gill-netters, MGN=Mixed gill-netters and MT=Mixed Trawlers. The first figure accounts for the best climate scenario (RCP 2.6) and the second (bottom) for the worst climate scenario.

Type of SR model	Equation
<u>Cushing</u> (-3.31 0.56)	$N_{s,1}(t+1) = aSSB_s(t-\Delta_s)^b\theta(t-\Delta_s)^c + \varepsilon_s(t)$ (15)
<u>Ricker</u> (-2.5 0.25)	$N_{s,1}(t+1) = aSSB_s(t-\Delta_s)e^{+bSSB_s(t-\Delta_s)} + \varepsilon_s(t)$ (16)
Ricker 2 (-3.37 0.66)	$N_{s,1}(t+1) = aSSB_1(t-\Delta_s)e^{-bSSB_1(t-\Delta_s)-c\theta(t-\Delta_s)^2} + \varepsilon_1(t-\Delta_s)$ (17)
<u>B-H</u> (-3.08 0.10)	$N_{s,1}(t+1) = \frac{SSB_s(t-\Delta_s)}{b + aSSB_s(t-\Delta_s)} + \varepsilon_s(t)$ (18)
<u>B-H 2</u> (-3.79 0.57)	$N_{s,1}(t+1) = \frac{SSB_s(t-\Delta_s)}{b + aSSB_s(t-\Delta_s) + c\theta(t-\Delta_s) + d\theta(t)^2} + \varepsilon_s(t)$ (19)

Table 4: Type of Stock-Recruitment models with and without environmental factor (θ) affecting recruitment according to the specie ($s = 1, 2$ respectively Sole, Hake). Numbers between brackets correspond respectively to the AIC criterion and R^2 associated to the model. The underlined models do not satisfy one or several associated statistical tests (test de White, Chow, Jarque and Bera and Durbin and Watson).

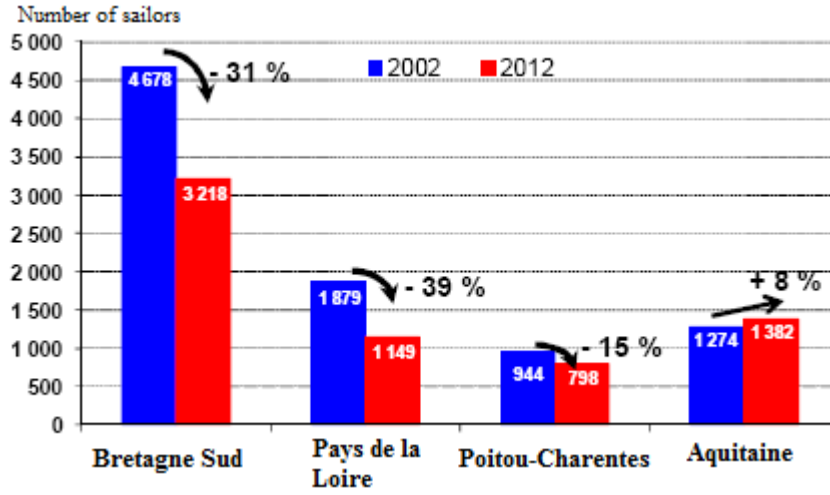


Figure 14: Numbers of sailors in the Atlantic facade (Aglia, 2014)

Age a	2	3	4	5	6	7	8+
Initial abund. $N_{1,a}(t_0)$ ($*10^3$ indv)	23191	17416	10707	4864	3425	2627	2590
Maturity $\gamma_{1,a}$	0.32	0.83	0.97	1	1	1	1
Mean weight (kg/indv) $v_{1,a}$	0.189	0.241	0.297	0.352	0.423	0.449	0.599
Natural mortality $M_{1,a}$	0.1	0.1	0.1	0.1	0.1	0.1	0.1

Table 5: Sole parameters, ($s = 1$), $t_0 = 2008$. Source: ICES; Ifremer, SIH, DPMA.

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) $v_{2,a}$	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

Table 6: Hake parameters, ($s = 2$), $t_0 = 2008$. Source: ICES; Ifremer, SIH, DPMA.

Fleets	2	3	4	5	6	7	8+
Mixed trawlers 0-12 m	0.014	0.017	0.013	0.01	0.007	0.007	0.007
Mixed trawlers 12-16 m	0.014	0.018	0.014	0.012	0.013	0.013	0.013
Mixed trawlers 16-20 m	0.017	0.021	0.016	0.014	0.015	0.015	0.015
Mixed trawlers >20 m	0.007	0.009	0.007	0.006	0.007	0.006	0.006
Sole gill-netters 0-10 m	0.002	0.005	0.008	0.008	0.01	0.009	0.011
Sole gill-netters 10-12 m	0.011	0.028	0.042	0.045	0.053	0.052	0.059
Sole gill-netters 12-18 m	0.018	0.065	0.087	0.094	0.148	0.145	0.138
Sole gill-netters 18-24 m	0.015	0.054	0.072	0.078	0.123	0.121	0.115
Mixed gill-netters 0-10 m	0	0.001	0.002	0.002	0.002	0.002	0.002
Mixed gill-netters 10-12 m	0.001	0.003	0.005	0.005	0.006	0.006	0.007
Mixed gill-netters 12-18 m	0.001	0.003	0.004	0.004	0.006	0.006	0.006
Mixed gill-netters 18-24 m	0	0	0	0	0	0	0
Mixed gill-netters >24 m	0	0	0	0	0	0	0
Other Fleets	0.062	0.113	0.072	0.072	0.09	0.079	0.083

Table 7: The values of fishing mortality on Sole ($s = 1$): $F_{1,a,f}(t_0)$. Source: ICES; Ifremer, SIH, 2008.

Fleets	0	1	2	3	4	5	6	7	8+
Mixed trawlers 0-12 m	0.016	0.013	0.006	0.002	0.002	0.001	0	0	0
Mixed trawlers 12-16 m	0.018	0.015	0.007	0.002	0.003	0.001	0	0	0
Mixed trawlers 16-20 m	0.016	0.013	0.006	0.002	0.002	0.001	0	0	0
Mixed trawlers >20 m	0.011	0.009	0.004	0.001	0.002	0	0	0	0
Sole gill-netters 0-10 m	0	0	0	0	0.001	0	0	0	0
Sole gill-netters 10-12 m	0	0	0	0.001	0.002	0.001	0	0	0
Sole gill-netters 12-18 m	0	0	0	0.002	0.004	0.002	0.001	0	0
Sole gill-netters 18-24 m	0	0	0.001	0.005	0.008	0.004	0.001	0.001	0
Mixed gill-netters 0-10 m	0	0	0	0.001	0.002	0.001	0	0	0
Mixed gill-netters 10-12 m	0	0	0	0.001	0.002	0.001	0	0	0
Mixed gill-netters 12-18 m	0	0	0	0.002	0.004	0.002	0.001	0	0
Mixed gill-netters 18-24 m	0	0	0.005	0.025	0.044	0.023	0.008	0.003	0.002
Mixed gill-netters >24 m	0	0.001	0.013	0.067	0.119	0.062	0.022	0.009	0.005
Other Fleets	0.022	0.253	0.444	0.734	0.764	0.843	0.728	0.875	0.88

Table 8: The values of fishing mortality on Hake ($s = 2$): $F_{2,a,f}(t_0)$. Source: ICES; Ifremer, SIH, 2008.

Fleets	Nb vessel $K_f(t_0)$	Fishing effort/vessel (nb day at sea) $e_f(t_0)$	Income from other species (in €/effort unit) α_f
Mixed trawlers 0-12 m ($f = 1$)	110	157.7	622
Mixed trawlers 12-16 m ($f = 2$)	45	192.7	1375
Mixed trawlers 16-20 m ($f = 3$)	49	180.3	1751
Mixed trawlers >20 m ($f = 4$)	37	197.1	3597
Sole gill-netters 0-10 m ($f = 5$)	28	139	311
Sole gill-netters 10-12 m ($f = 6$)	42	145.5	503
Sole gill-netters 12-18 m ($f = 7$)	40	202.9	765
Sole gill-netters 18-24 m ($f = 8$)	23	201.7	1150
Mixed gill-netters 0-10 m ($f = 9$)	32	153.8	303
Mixed gill-netters 10-12 m ($f = 10$)	30	178.8	847
Mixed gill-netters 12-18 m ($f = 11$)	6	145	1466
Mixed gill-netters 18-24 m ($f = 12$)	9	210.3	1500
Mixed gill-netters >24 m ($f = 13$)	10	260.6	1141

Table 9: Initial number of vessels $K_f(t_0)$, effort by vessel $e_f(t_0)$ and rate of extra fishing income α_f of the thirteen sub-fleets. Source: Ifremer, SIH, DPMA, 2008

Fleets	Landing cost τ_f	Volume of fuel (in L/effort unit) V_f^{fuel}	Variable cost by vessel (in €/effort unit) c_f^{var}	Annual cost by vessel (in €) c_f^{fix}
Mixed trawlers 0-12 m ($f = 1$)	0.05	257	44	77779
Mixed trawlers 12-16 m ($f = 2$)	0.05	863	108	218506
Mixed trawlers 16-20 m ($f = 3$)	0.07	1076	188	245285
Mixed trawlers >20 m ($f = 4$)	0.07	1999	308	388951
Sole gill-netters 0-10 m ($f = 5$)	0.06	78	70	56601
Sole gill-netters 10-12 m ($f = 6$)	0.05	290	140	132326
Sole gill-netters 12-18 m ($f = 7$)	0.08	348	213	256373
Sole gill-netters 18-24 m ($f = 8$)	0.07	622	453	378872
Mixed gill-netters 0-10 m ($f = 9$)	0.05	59	28	42874
Mixed gill-netters 10-12 m ($f = 10$)	0.05	248	69	111911
Mixed gill-netters 12-18 m ($f = 11$)	0.06	396	230	223622
Mixed gill-netters 18-24 m ($f = 12$)	0.07	811	595	513353
Mixed gill-netters >24 m ($f = 13$)	0.03	1099	556	913096

Table 10: Mean reference costs of the thirteen sub-fleets. Source: Ifremer, SIH, DPMA, 2008