Groupe de Recherche en
Économie Théorique et Appliquée

How MMEY mitigates bio-economic impacts of climate change on mixed fisheries

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Cahiers du GREThA
n° 2017-22
Décembre

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Comment la stratégie MMEY atténue les effets bio-économiques du changement climatique dans les pêcheries mixtes

Résumé

Cet article étudie l'effet du réchauffement climatique sur les performances bio-économiques des pêcheries mixtes du golfe de Gascogne et fournit un aperçu de la meilleure stratégie de gestion pour faire face au réchauffement climatique. Pour ce faire, un modèle dynamique multi-espèces, multi-classes, multi-flottilles est développé et calibré à l'aide de données biologiques et environnementales du CIEM et du GIEC. Des données économiques et de pêche ont été collectées au sein du DCF européen. Le climat, représenté par la température de la surface de la mer, est supposé affecter le recrutement des espèces. Trois stratégies de gestion sont ensuite comparées en termes de résultats bio-économiques : Statu-Quo (SQ), Multi-species Maximum Sustainable Yield (MMSY), Multi-species Maximum Economic Yield (MMEY), Les stratégies sont classées en fonction de deux scénarios climatiques. Les résultats démontrent que la stratégie SQ n'est pas durable et qu'elle se caractérise par un déclin majeur de la sole. En revanche, les stratégies MMSY et MMEY améliorent l'état écologique et les performances économiques des pêcheries. De plus, la stratégie MMEY produit des performances bio-économiques supérieures à la stratégie MMSY. Ces bénéfices bio-économiques sont cependant altérés par les effets du changement climatique. Dans le cadre du MMEY, les flottilles dotées de captures plus diversifiées sont plus performantes face aux changements climatiques.

Mots-clés: bio-économique ; scénarios ; changement climatique ; pêcheries ; soutenabilité ; golfe de Gascogne

How MMEY mitigates bio-economic impacts of climate change on mixed fisheries

Abstract

This paper examines the effect of climate warming on the bio-economic performance of Bay of Biscay mixed fisheries and provides insights into the best management strategy for coping with global warming. To achieve this, a dynamic multi-species, multi-class, multi-fleets model is developed and calibrated using biological and environmental ICES and IPCC data. Fishing and economic data have been collected within the European DCF. 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), Multispecies Maximum Economic Yield (MMEY). Strategies are ranked with respect to two 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 provides higher bio-economic performances than MMSY. These bio-economic benefits are however altered by climate change effects. Under the MMEY, fleets with more diversified catches perform better facing climate change.

Keywords: bio-economics ; scenarios ; global warming ; fisheries ; sustainability ; Bay of Biscay

JEL: Q22-C53

Reference to this paper: LAGARDE Adrien, AHAD-CISSÉ Abdoul, GOURGUET Sophie, LE PAPE Olivier, THÉBAUD Olivier, CAILL-MILLY Nathalie, MORANDEAU Gilles, MACHER Claire, DOYEN Luc (2017) How MMEY mitigates bio-economic impacts of climate change on mixed fisheries, *Cahiers du GREThA*, n°2017-22.

http://ideas.repec.org/p/grt/wpegrt/2017-22.html.

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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 management[1].

The Common Fisheries Policy (CFP - Reg. UE 1380/2013 11/12/2013) reaffirms the obligations associated with the international commitments of a sustainably management of fisheries and strengthens 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 Startegy Framework Directive[2] (MSFM) aims at protecting and conserving the marine biodiversity. Positive economic and social benefits as well as food security are also targeted.

In the Bay of Biscay, a warming of ≅ 0.2 ° C / decade between the surface and 200 m depth has been observed for the period 1965-2004 (Decastro et al., 2009). Such climate changes already impact some fish species. For flat fish species including Sole with a wide distribution around the Bay of Biscay, recent studies have shown correlations between the abundances of these species 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 impacted process (Koutsikopoulos et al., 1998). As the definition of boundaries and access rights is a particular issue for fisheries resources, climate change poses a new challenge and new conceptions, in particular institutional ones (Badjeck et al., 2010). Variations in the spatial distribution of species indeed question the revision 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 has become a major challenge (FAO, 2014). In response, there has been a growing need of integrated assessment tools to support management advices (Thébaud et al., 2014) such as ecosystem-based fishery management (EBFM), (Pikitch et al., 2004 ; Link et al., 2017 ; Doyen et al.,

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

[2]Directive 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

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 (Sanchirico et al., 2008 ; Doyen et al., 2017), especially from the bioeconomic viewpoint. New models are needed, notably to integrate the multiple complexities at play (Plaganyi, 2007). These models are expected to account for the multispecies and multi-fleets nature of fisheries, for the multiple ecosystem services 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 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 has been introduced in the US' Magnuson-Stevens Act (NOAA, 2007) and consequently 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). 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, although its implementation remains difficult (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). Moreover, in a dynamical context, extinction can follow from maximization of present value, whenever discount rates are sufficiently high (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, it has been suggested that a combined

MEY is susceptible to induce the overexploitation of stocks with low value (Chaudhuri, 1986; Guillen et al., 2013). 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 multispecies MSY and MEY 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 bioeconomic performances of Bay of Biscay mixed fisheries and gives insights into the most sustainable management strategy for coping with global warming. To achieve this, a multi-class, multi-fleets and dynamic model for Sole (*solea solea*) and European hake (*merluccius merluccius*) is developed and calibrated using ICES and IPCC data.

2 Bay of Biscay Case Study

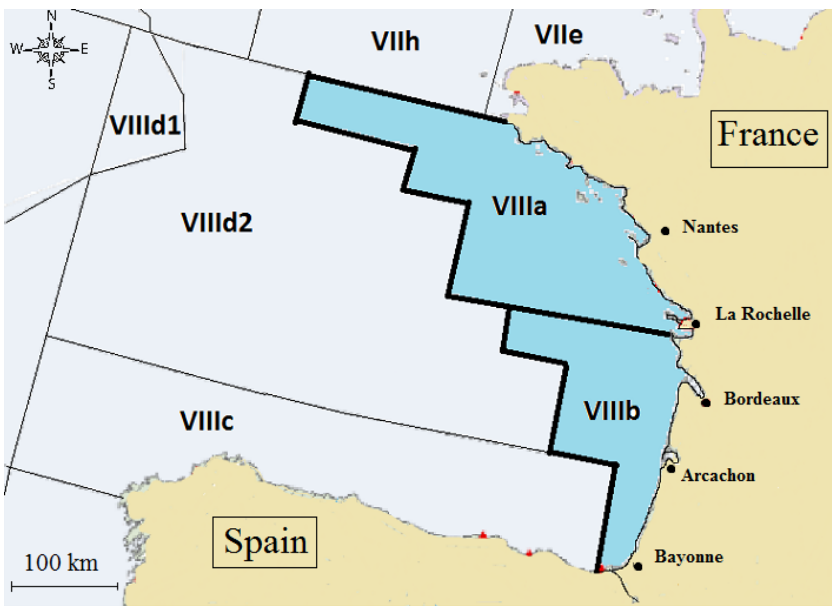

Figure 1: Map of the Bay of Biscay and ICES divisions. The studying area is in blue.

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.

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

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); the work carried out by Hermant et al. (2010) did not reveal a clear trend in the evolution of its distribution.

The sole stock appears as a fragile 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 finally reached in 2009 (Figure 2). However, due to surprisingly low recruitment in 2010, the stock is again in decline. Consequently, since 2016, a 10% reduction in total allowable catches (TAC) compared to 2015 and 2014 has been imposed (ICES, 2017) by the European commission. Thus, French fleets are forced to harvest a maximum of 3420 tons since this year (European Union, 2016). Although the spawning biomass of sole came back up for three years, it still remains dangerously 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 of Norway to Mauritania. Temperature is a factor that affects the early stages of hake life. Experiments in a controlled environment for the development of hake eggs at different temperatures showed significant mortalities outside the optimal range 10-13° (Guevara-Fletcher et al., 2016). 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). Growth or survival of hake juveniles is increased with the availability

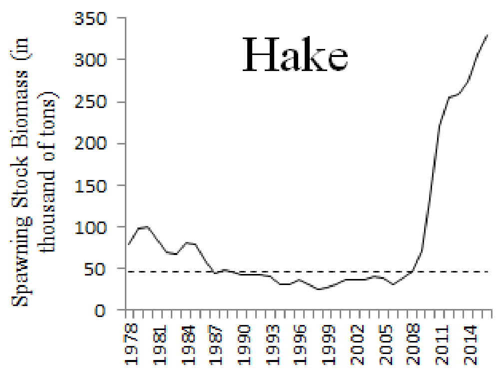

Figure 3: Historical evolution of the spawning biomass for the European hake. The dashed line refers to the precautionary threshold (Bpa) estimated at 46200 tons (ICES, 2016)

of adequate feeding. Changes in ocean conditions may affect prey availability and thus affect migration behavior and hake growth (Benson et al., 2002). 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 An economical interest for 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% for only 2% of the volume (IFREMER, 2017). For the national landings, hake represents 7% of the total value while the sole landings' rise to almost 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), the stock has observed a recovery of its spawning stock (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 almost 12 € per kilo with a 60 million € market against 3€ per kg for hake within a market which represents almost 45 million €. These values can be explained by the marked preference of consumers for sole. Consequently, the high abundance of hake and the high price of sole implies that both species are among the most economically and ecologically interesting.

The main French fleets, presenting here and targeting those two species, may 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 with a population of more than 400 vessels across the Bay of Biscay (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 hake[3] 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 OpEc[4] 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 our two ICES studying areas. For the SST projections over 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 and economic components of the model are described in figure 4. These relations highlight how the different interactions occur: SST impact recruitment through the specific responses of the SSB with respect to the environmental

[3]In 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)

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

[5]Representative Concentration Pathways

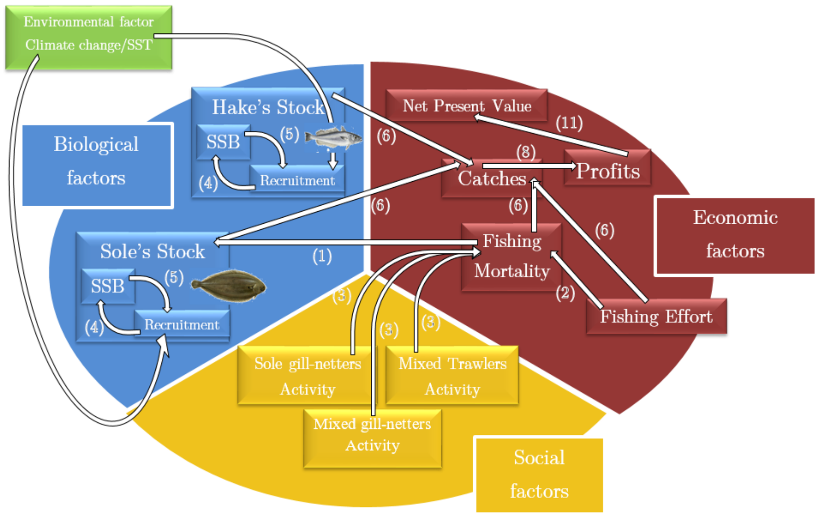

Figure 4: Relations existing between environmental, biological and economic factors within the bio-economic model. Arrows stand for the interactions between variables while figures between brackets refer to the equations/models that link the various factors within the bio-economic model.

context. Then stock levels along with the fishing effort determine the catches, profits and biological outcomes from 2014 until 2088.

3.1 Multi-species age-class dynamic model

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

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

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 first one stands for recruitment. Thus, abundances of species $N_{s,a}(t)$ evolves according to both natural $M_{s,a}$ and total fishing $F_{s,a}(t)$ mortality of the species s at age a. Furthermore, the total fishing mortality $F_{s,a}(t)$ is derived from the sum of the fishing mortality of the 13 fleets f at year $t_0 = 2014$ described such as:

$$F_{s,a} = \sum_{f=1}^{13} u_f(t) F_{s,a,f}(t_0) \tag{2}$$

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

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

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 fleet f on species s at age a.

3.2 Stock-recruitment dynamics

The spawning biomass $SSB_s(t)$ is described by:

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

where $\gamma_{s,a}$ stands for the proportion of mature individuals of species s at age a and $\upsilon_{s,a}$ represents the weights (in tons) of individuals of species s at age a and $a = 1, \ldots, A_s$.

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

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

Here $N_{s,1}(t)$ represents the recruits as explained previously and $\theta(t)$ stands for the sea surface temperature at time t while $\varepsilon_s(t)$ captures the environmental stochasticity affecting the recruitment. In the meantime, 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 $s = 1$ and about one year for hake $s = 2$). This allows us to reach a better representation of the stock recruitment relationship. We will discuss and explain these lags in the results section. The integration of environmental factors in recruitment is in line with recruitment (Cushing, 1982; Glantz, 1992; 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 regressions [6] of recruits over SSB and SST time series[7] in order to find the model that best fits the data.

3.3 Economic scores

Assuming that discards are neglectable, landings equals catches and are defined by the Baranov catch equation:

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

Incomes derived from catches reads as follows:

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

where $\upsilon_{s,a,f}$ is the mean weight of landed individuals of species s at age a. Price $p_{s,a}(\omega_s(t))$ corresponds to the market value (euros by kg) of species s at age a for year t under the stochastic scenario $\omega_s(t)$.

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

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

α_f corresponds to the income per unit of effort of sub-fleet f of other species caught. The dynamic will not be detailed but we assume to have constant values per unit of effort (VPUE) for other species, thus $Inc_f(t)$ is only a part of the global income. $K_f(t_0)$ represents the number of vessels by sub-fleets f, $e_f(t_0)$ stands for the mean value of fishing effort (i.e. days at sea) by vessels of sub-fleet f, 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 variable[8] and annual[9] (fixed) cost by a vessel of sub-fleet f. These parameters are based on

[6] Ordinary 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

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

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

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

economic data available for 2008 (IFREMER, SIH, DPMA[10], Table 9 and 10). The price of fuel is considered constant over time, set at a price of 0.5 € per liter.

3.4 Fishing strategies

We here consider three fishing 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 fishing strategy entitled Status-Quo (SQ) maintains fishing efforts constant throughout the period of interest such as:

$$u_f^{SQ}(t) = 1 \qquad \forall f = 1, \ldots, 13 \quad \text{and} \quad \forall t = t_0, ..., T \quad \text{with} \quad T = 80$$

Multi-species Maximum Sustainable Yield (MMSY) Strategy: The second strategy aims at reaching a maximum sutainable yield over all species considered, that is to say, to maximize long-term landings of the differents fleets. The objective is to find the best constant effort multiplier vector noted $\underset{\cdot}{u}_f^{MMSY}$ that maximizes total catches. The mean total catches over time is defined as the average of the total catches over the entire temporal horizon and where $\mathbb{E}$ corresponds to the expectations with respect to the parameters such as:

$$C^{MMSY}(\underset{\cdot}{u}_f) = \mathbb{E}\left[\frac{1}{T}\sum_{t=1}^{T}\sum_{s=1}^{2}\sum_{a=1}^{A_s}\sum_{f=1}^{13} C_{s,a,f}(t)\right] \tag{9}$$

with $T = 80$. Once we have the total catches, we are looking for the combination of the best fishing effort multipliers noted $\underset{\cdot}{u}_f^{MMSY}$ that maximize the previous metrics.

$$C^{MMSY}(\underset{\cdot}{u}_f^{MMSY}) = max_{u_f} C^{MMSY}(u_f) \tag{10}$$

As explained in the introduction, by adopting a multi-species point of view, the MMSY management model seems more relevant mainly because most fleets do not target (voluntarily or not) only one species. Thus, this management model could potentially offer a better management from an ecosystem and multi-species perspective than a single-species point of view (Voss et al., 2014).

[10]DPMA 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)

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

$$NPV(\underset{\cdot}{u}_f) = \mathbb{E}\left[\sum_{t=t_0}^{T} \frac{1}{(1+r)^t} \sum_{f=1}^{13} \pi_f(t)\right] \tag{11}$$

with $r = 4\%$ the discount rate. $\mathbb{E}$ corresponds again to the expectations with respect to the stochastic parameter ω and prices p included in the profit formula (equation 8). Maximizing the NPV is equal to reaching the maximum economic yield for both species and so finding the best effort vector noted $\underset{\cdot}{u}_f^{MMEY}$.

$$NPV(\underset{\cdot}{u}_f^{MMEY}) = max_u NPV(\underset{\cdot}{u}_f) \tag{12}$$

To compute the optimal solutions, we used the SCILAB software.

3.5 Climate Scenarios

In our study, we consider two climate scenarios (best scenario: RCP 2.6 and worst scenario : RCP 8.5) illustrated in the figure 5. 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 constat is the result of an increase in warming of 0.06/0.07°C per year over the last 30 years (Le Treut, 2013). We must precise that inter-annual variations induced by atmospheric flux and ocean currents (Michel et al., 2009) are the main causes 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 data are integrated each year in the recruitment formula and impact it which itself affects the SSB, so it is the species stock and by extension the economy that undergoes consequences as a whole. Undoubtedly, the extent of the impact of water temperature differ depending on the climate scenario and species. The conclusions emerging from this difference can then highlight the danger of potential temperature increase. That is what we strive to show in the next section.

4 Results

This section presents the merits of integrating a temperature-dependent stock-recruitment model into our bioeconomic model in order to determine the fishing strategy, that best

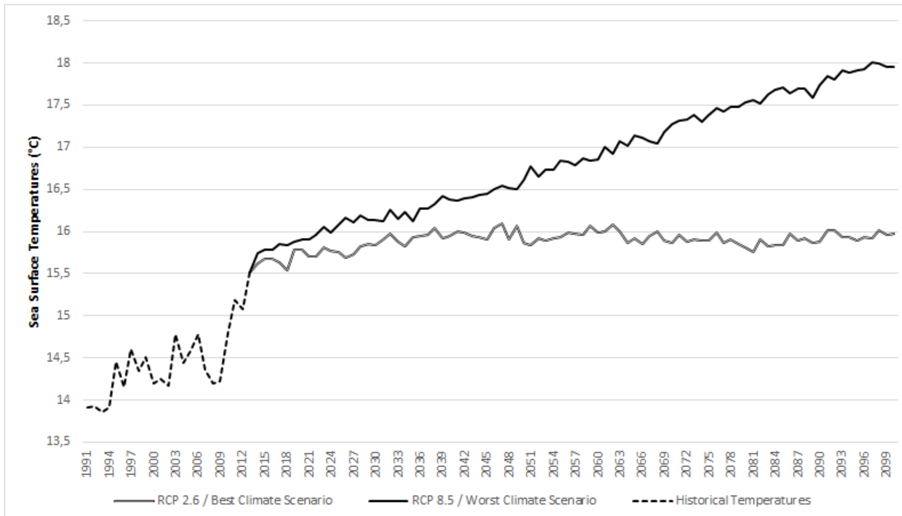

Figure 5: Evolution of historical SST from 1991 to 2013 then SST trajectories according to the two climate scenarios (RCP 2.6 and 8.5) from 2014 to 2100 (IPCC, 2013)

mitigates warming effects among SQ, MMSY, MMEY.

4.1 Impact of warming on stock-recruitment model

In the tables 1 and 2, we present the main results of the regressions. The equations 13 and 14 notably highlight the importance of lags between recruitment and SSB and SST in this paper. 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 ; table 4). This is highlighted in table 4. Moreover, all estimated coefficients (a, b, c) are statistically significant at the 5% level (Table 1 and 2). 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. We see the influence of temperature on recruitment in Table 1 and 2. Explained by the coefficient c, the impact is negative for both species. However, some species are much more impacted by warming than these ones (Hermant et al., 2010).

Sole's SR model

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

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

Table 1: Parameters and standard errors of the estimated Ricker model (equation 13) accounting for environmental factor for sole.

Hake's SR model

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

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

with $t = t_1 + t_2 + t_3$ and

$$N_{2,1}(t_i+1) = aSSB_2(t_i-2)e^{-bSSB_2(t_i-2)-c\theta(t_i-2)^2} + \varepsilon_2(t_i-2) \qquad \forall i = [1,2,3]$$

so the yearly basis model is described as:

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

Hake	Standard Error (σ)		0,633434	
	Sum of squared residuals		25,278034	
	$R^2 = 0{,}27$	a	b	c
	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 2: Parameters and standard errors of the estimated Ricker model (equation 14) accounting for environmental factor for hake.

4.2 Status-Quo : not ecologically and economically viable

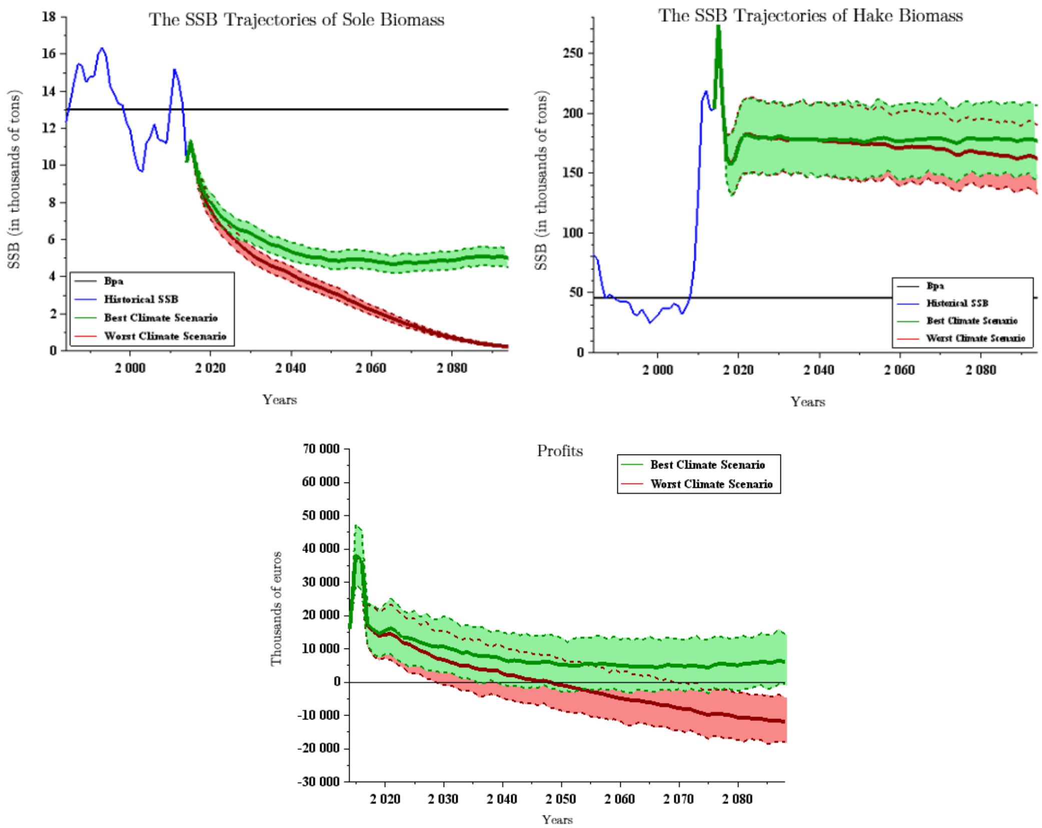

Figure 6: Strategy Status-Quo - Sole (top left) and Hake (top right) SSB trajectories under the three climate scenarios in thousands of tons. The black solid line represents the precautionnary threshold of the species' stock (Bpa). The third figure (bottom) represents the total profits over all thirteen fleets. The field of the 500 simulated trajectories under the best climate scenario is in green and in red under the worst. The solid lines within colored fields display the average of these 500 trajectories with respect to the climate scenario.

Figure 6 describes the estimated[11] 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

[11] 500 trajectories are represented via an uncertainty factor in the recruitment formula such as : $N_{s,1}(t) = N_{s,1}(t) + \varepsilon_s(t)$ with $\varepsilon_s \in [-\sigma_s, \sigma_s]$ where σ_s represents the standard error of the regression of the species s

displayed on the bottom.

The SQ strategy is not ecologically or economically viable. Sole biomass trends negatively, even with a favorable climate change scenario, and collapses under the pessimistic climate scenario. Hake biomass remains above its Bpa under both scenarios, given the high initial levels of abundance observed in the fishery. While the best climate scenario allows the fishery to remain viable, the worst scenario leads to negative profits in the fishery.

More globally, the SQ strategy highlights the fact that if fishing effort is not adjusted, global warming will amplify the current fall of the sole SSB and will lead to an economic collapse also to an collapse of Sole (under the worst climate scenario). Therefore, management strategies are required that adjust fishing effort in order to moderate the impact of global warming on bio-economic outcomes.

4.3 MMSY : not ecologically viable but economically viable

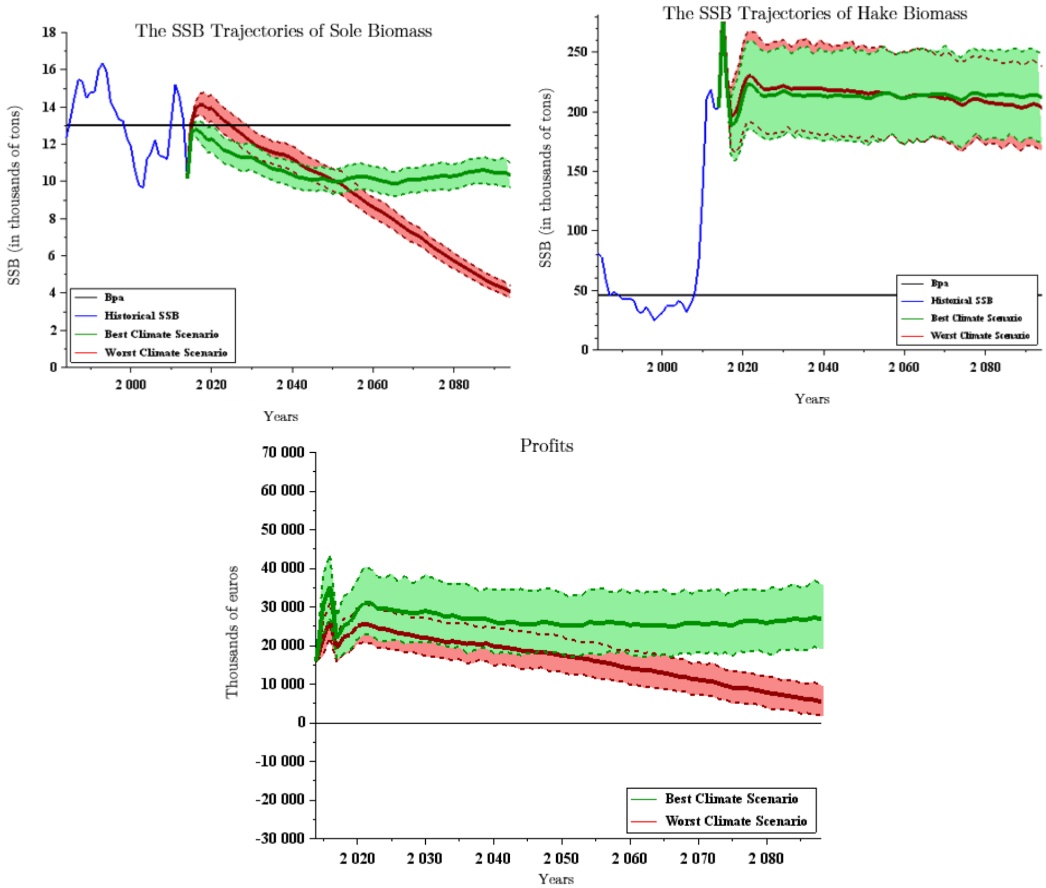

Figure 7: Strategy MMSY - Sole (top left) and Hake (top right) SSB trajectories under the two climate scenarios. The black solid line represents the precautionnary threshold of the species' stock (Bpa). The third figure (bottom) represents the total profits of all thirteen fleets. The field of the 500 simulated trajectories under the best climate scenario is in green and in red under the worst. The solid lines within colored fields display the average of these 500 trajectories with respect to the climate scenario.

The MMSY strategy performs better ecologically and economically than the SQ strategy. As expected, the more extreme the climate scenario is, the more negative the impact is.

The decline of sole SSB below its Bpa appears still inevitable but is clearly mitigated by this strategy. Under the worst climate scenario, the weakness of the fishing effort multipliers first generates a recovery of this stock which collapses however on the long run because of the too high rise of temperatures. Under the best climate scenario, the sole stock decreases initially but then stabilizes after 15 years at around 10 000 tons. The Hake stock displays similar trends as in the SQ scenario, with lighter values regardless of climate scenarios.

Interestingly, although the purpose of this strategy is not to maintain the SSB above Bpas, it significantly improves biological outcomes. Indeed, maximizing landings can not be dissociated from sustainably high level of stock. Therefore, the MMSY strategy, which requires explicit landing goals, implicitely accounts for ecological objectives through the fishing effort structure, thus performing better than the SQ strategy.

4.4 MMEY : ecologically viable and economically viable

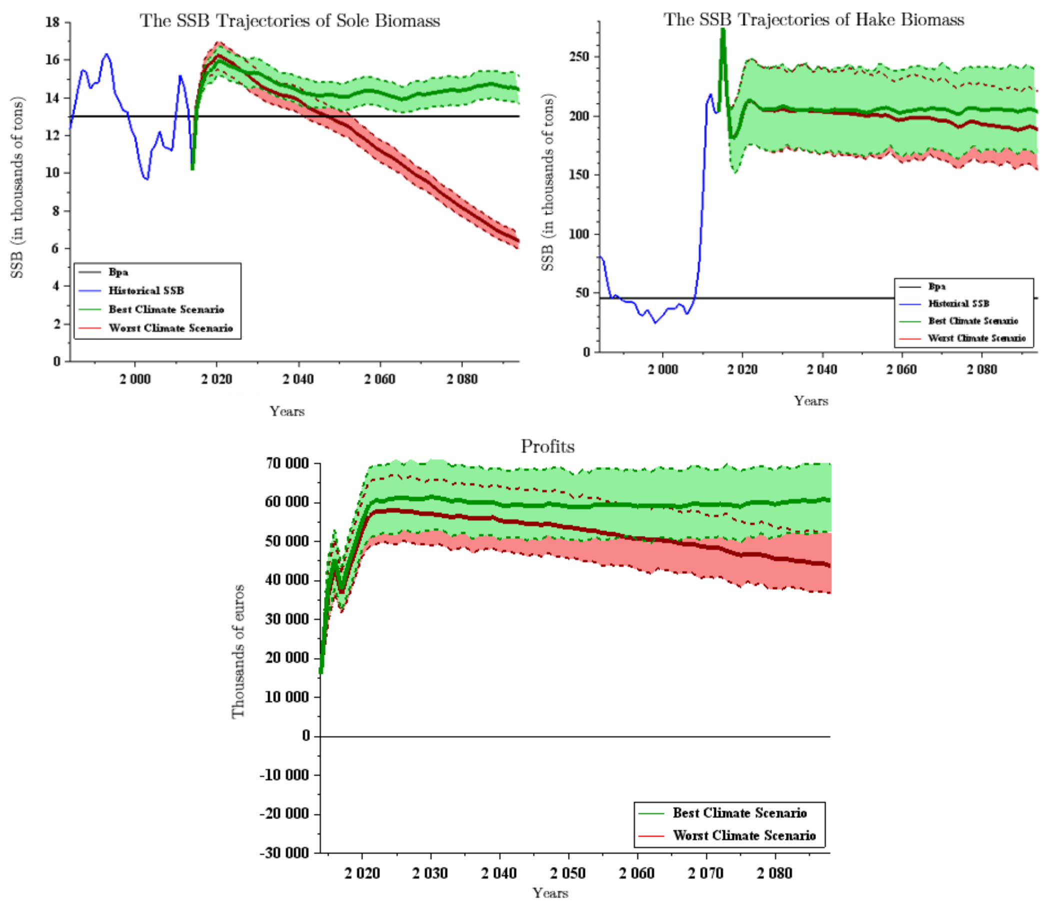

Figure 8: Strategy MMEY - Sole (top left) and Hake (top right) SSB trajectories under the two climate scenarios. The black solid line represents the precautionnary threshold of the species' stock (Bpa). The third figure (bottom) represents the total profits of all thirteen fleets. The field of the 500 simulated trajectories under the best climate scenario is in green and in red under the worst. The solid lines within colored fields display the average of these 500 trajectories with respect to the climate scenario.

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 regardless of the climate scenario. Under the best climate scenario, profits are multiplied by more than two, reaching 60 million of euros per year. 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. Thus, the MMEY strategy emerges as the best way to mitigate climate change effects. We elaborate on the reasons for such outcomes related to the structure of fishing effort multipliers in the next section.

4.5 MMSY, MMEY efforts : an activity reduced for sole gill-netters

Table 3 displays the different MMSY and MMEY fishing effort multipliers as well as the economic outcomes i.e mean landings and the NPV of the entire temporal horizon. We first observe that, globally, the MMSY and MMEY strategies imply a important mitigation of the number of boats as almost all the optimal multipliers ($\underset{\cdot}{u}_f^{MMSY}$, $\underset{\cdot}{u}_f^{MMEY}$) 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. (SOURCCCCCCE)

Such an outcome indicates that climate change significantly affects the performances of these strategies as well as the computation of optimal management. Indeed, in figure 3, we ascertain that NPV and landings are lower under the worst climate scenario/RCP 8.5 with respect to each strategy. Furthermore, the MMEY strategy displays a better NPV while the MMSY strategy observes higher landings. This is consistent with the purpose of each strategy.

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 3: Optimal 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).

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 scenarios[12]. The choice of strategy has thus a major impact on the sole stock. In particular, the MMSY fishing effort multipliers of sole gill-netters plays a pivotal role for the sole stock.

4.6 Bioeconomic synthesis displays the MMEY as the best strategy

Figure 9 synthesizes the bio-economic outcomes of the three management strategies through the average NPV of the entire temporal horizon on the Y-axis versus the Simpson's index of diversity[13] on the X-axis. A Simpson's index close to 2 (because we

[12]Except 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

[13]

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

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

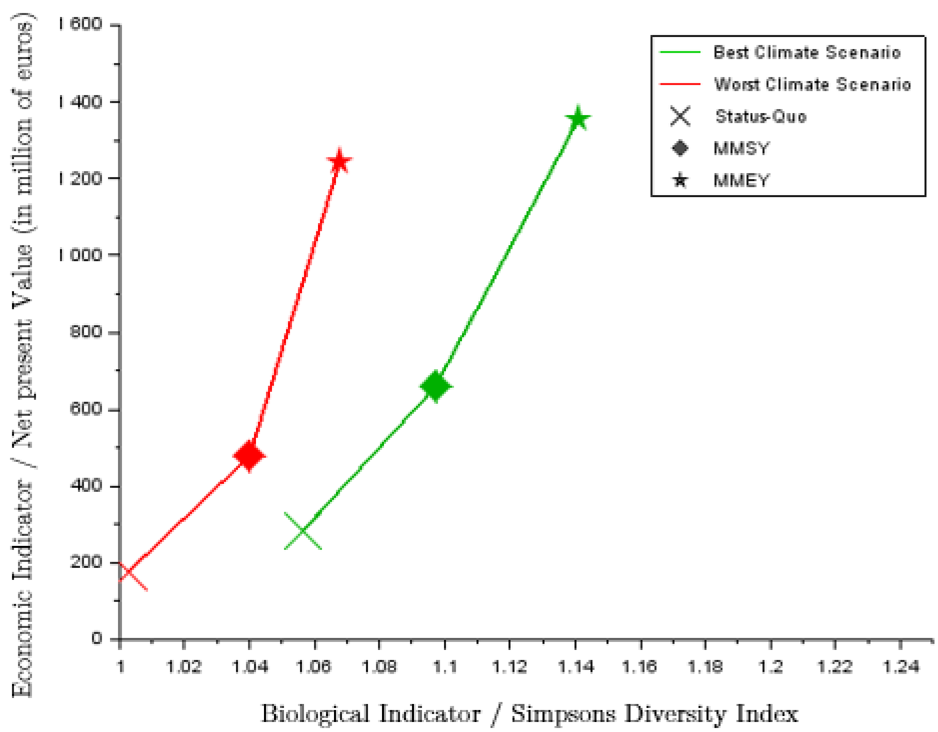

Figure 9: Simpson's Index of Diversity versus Average Net Present Value.

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 a wide heterogeneity of the 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 ever 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 adress the first question asked in the title by the figure 9.

5.1 MMEY as an ecological and economic win-win strategy

Figure 9 shows that the MMSY and the MMEY strategies improve 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 scenarios: is in this case a win-win strategy.

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 fleets will see their effort reduced in the MMEY strategy.

Clark (1973) explains that maximizing NPV with no biological or social constraint may deplete the stock. Indeed, if the discount rate (r) exceed the intrinsic growth rate of the fishery, it is possible to have an 'optimal' extinction. Fortunately, this result does not apply in our case, mainly because of the recovery of hake in the past few years. Therefore, our economic strategy generates a positive effect on the two fish stocks.

However, the ecological gains of MMEY are strongly altered by high climate change effects. Under the highest climate change scenario, the simpson index gain is very limited . This is due to the fact that the sole stock is strongly alterered under this scenario as illustrated by figure 8 (top left).

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

Comparing the multipliers of the MMSY and MMEY strategy, we observe that both strategies imply low fishing effort multipliers for sole gill-netters compared to other fleets, regardless of the climate scenario. This entails a reduction of fishing effort for the fleets which have a greater contribution to the overall fishing mortality of Sole

(Figure 10). This observation can be explained in two ways: fishing effort multipliers major in hake[14] or they diversify their targets. We can not really elicit any responses regarding this assumption mainly because we are only focusing on two species. Figure 12 seems showing that fleets are not majoring in one species but on the contrary, they diversify their targets so as to avoid the plummet of the sole's stock and to still be able to make profit with this benthic species.

Furthermore, we notice that fishing effort multipliers of the mixed trawlers and mixed gill-netters for the MMSY strategy are as a whole lower than those in MMEY strategy. That could explain why profits are higher for this strategy compared to the MMSY strategy. On the contrary, fishing effort multipliers of the sole gill-netters are globally lower for MMEY than for MMSY, which explains why the sole SSB is higher under this strategy for both climate scenarios.

From the economic viewpoint, given that increased SST effect on SSB is more accentuated on sole, we can hypothesize that fleets which have a strong dependency on this species in their turnover would be the most sensitive to an increase of this negative climate impact. As we are almost sure that global warming should persist in the next years (IPCC, 2013) regardless of the climate scenario, fishing effort should orientate towards fleets whose contribution to the fishing mortality will be less important. In fact, as shown by Macher and Boncoeur (2010), the optimal selectivity of a fleet depends negatively on the level of effort. Thus, lower fishing effort such as sole gill-netters fishing efforts favour a diversification of species caught by these fleets regardless of the climate scenario.

Therefore, many fleets relying on the sole will have to diversify their activities and change their targets especially if TAC of sole and therefore landings continue to decrease as they have been for almost 20 years (Figure 11). The price of sole has rised by 80% between 1994 and 2015 (Figure 13). This explains why sales in value remain high despite their limited share in volume[15] 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 aging[16] and the cost of renewing is high[17] for new operators whose number has significantly decreased in the last years (Figure 14) and on the other hand it is much more 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

[14]The fleets targeting strongly the sole decrease their effort in order to increase the effort of fleets which mainly targets hake

[15]Sales in Volume = landings - unsold

[16]The 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 constrast, almost 57% of the ships had more than 25 years (Aglia, 2014)

[17]Furthermore for big vessels

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

In the medium to long-term vision, it will probably be a large part of the French fleet which will have to adapt to biological changes induced by global warming. The large level of investment needed to rejuvenate the fleet and the decrease of quotas for some species is creating and is likely to create major problems in the future. Even if the increase in prices sustains profits and if the external or internal demand follows, governments or European institutions will have a crucial role to play.

Poloczanska et al. (2016) are already observing a movement of marine species sensitive to warming towards the poles. Fortunately, in our two ICES studying divisions, the sole stock is not supposed to be affected by this effect mainly because it is a subtropical species with its centre of distribution in the Bay of Biscay (Desaunay et al., 2006). However, the processes implicitly determining in recruitment assessment are not fully understood yet such as the processes in survival success during the juvenile phase (Le Pape and Bonhommeau, 2015).

Nevertheless, we can now assume that global warming alters sustainable gains that could be earned by management strategies in an ecosystem approach. The results for our case study 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 have to be mitigated by management structures which are already set up but which could be more efficient (almost half of mondial stocks are managed with the MSY method) as we have proved it in our study with the MMEY method.

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 variable and fluctuating depending on temperature increase, however the temperature index used in this model (SPSST[18]) was not truly reflecting the temperature in the studying area, namely the area of the greatest spawning activity (Hill et al., 2011).

From a policy perspective, such results would lead to suggest the need for management strategies to periodically adapt fishing effort regulations based on the economic,

[18]Scripps Pier Sea Surface Temperature

social context and especially on the local and global environnemental changes.

Acknowledgment

This work has been carried out with the financial support of COTE LabEx, through the NAVIRE project (SceNArios of bioeconomic VIability and REsilience for ecosystem-based fisheries management in Aquitaine) in association with GRETHA (CNRS-Univ. of Bordeaux), IRSTEA, IFREMER and Campus DoMar (Spain). This study also relates to the network SEAVIEW (Scenario, fishEry, ecologicAl-economic modelling and VIability nEtWork).

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Appendix

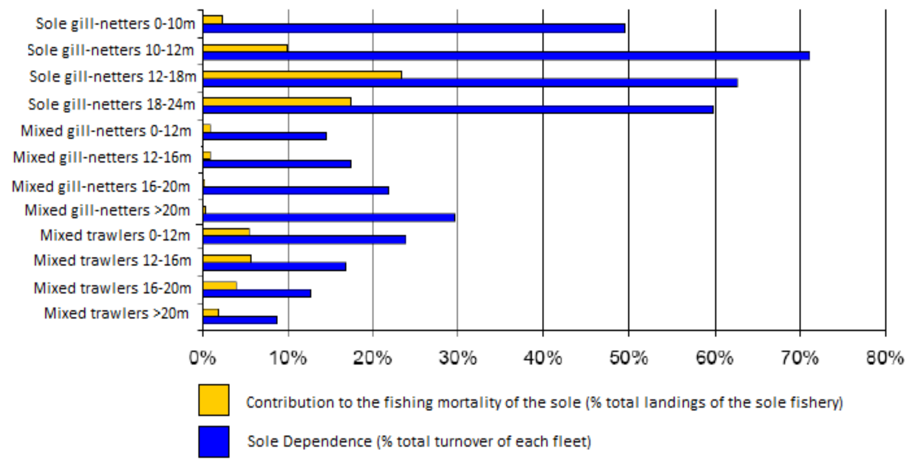

Figure 10: Contribution to the fishing mortality and dependence on sole of fleets of Bay of Biscay fishery in 2010 (Aglia, 2014)

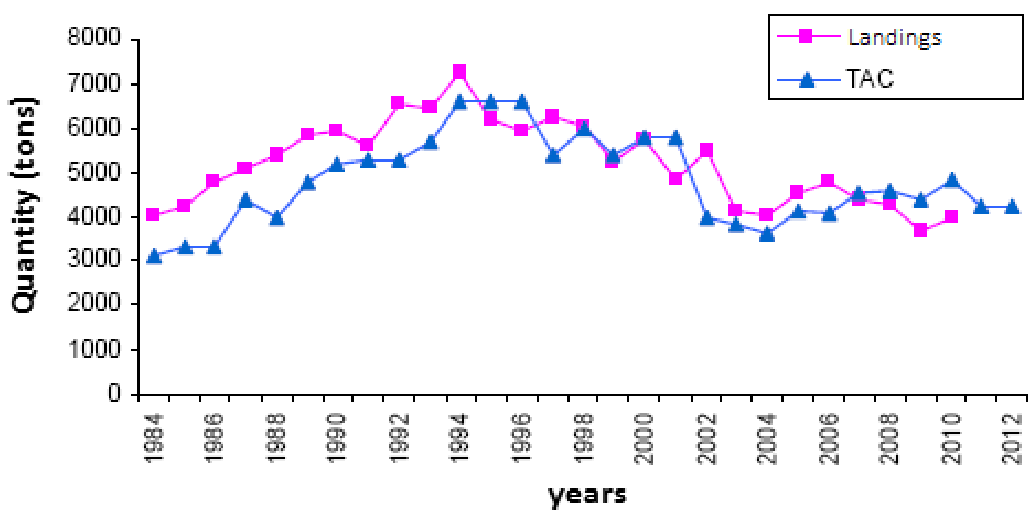

Figure 11: Comparative evolution of the TAC and landings of the sole in the Bay of Biscay since 1984 (Lagiere, 2012)

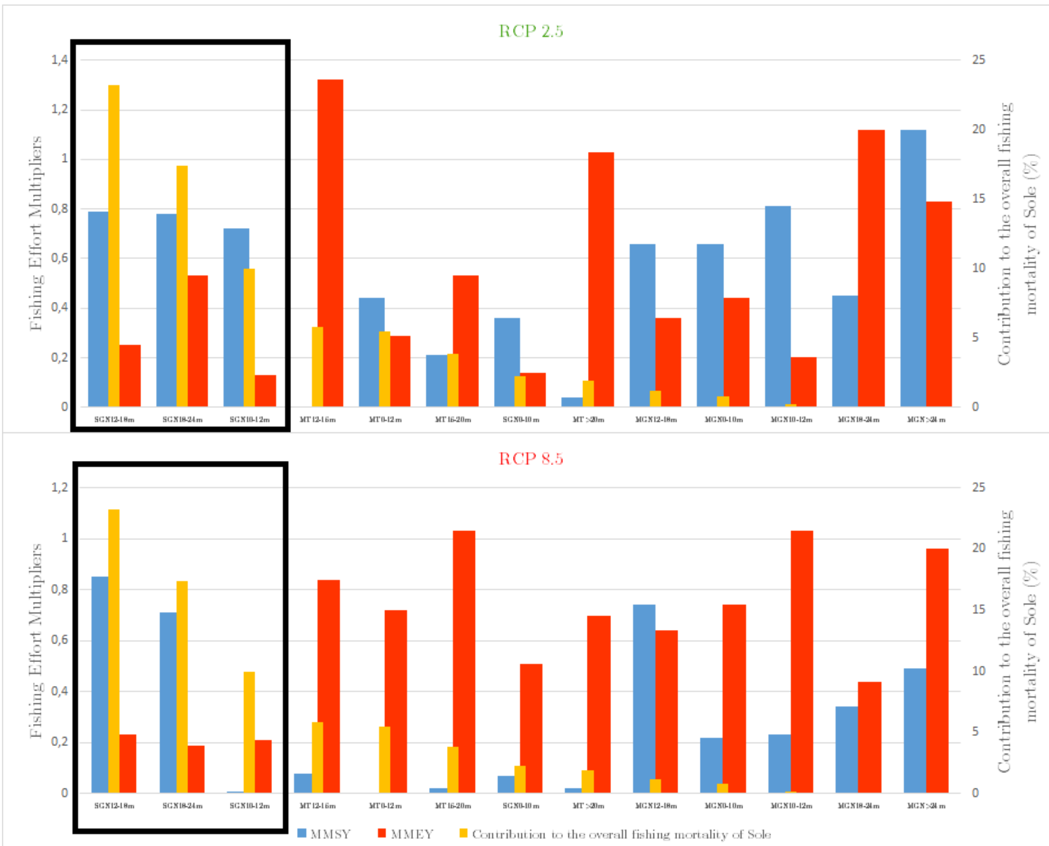

Figure 12: Fishing effort multipliers (left axis) and contribution to the overall fishing mortality of Sole in percentage (right axis). Fleets (X-axis) are ranked by contribution to sole mortality with SGN=Sole gill-netters, MGN=Mixed gill-netters and MT=Mixed Trawlers. The first figure accounts for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

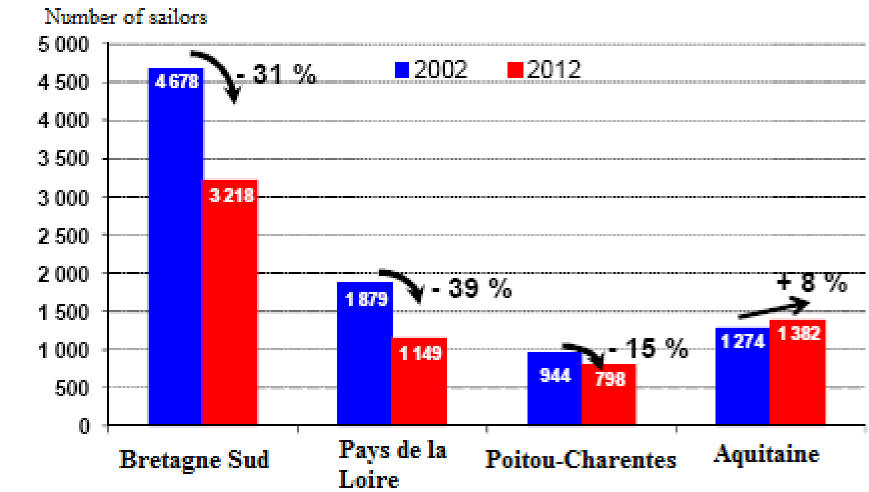

Figure 14: Numbers of sailors in the Atlantique facade (Aglia, 2014)

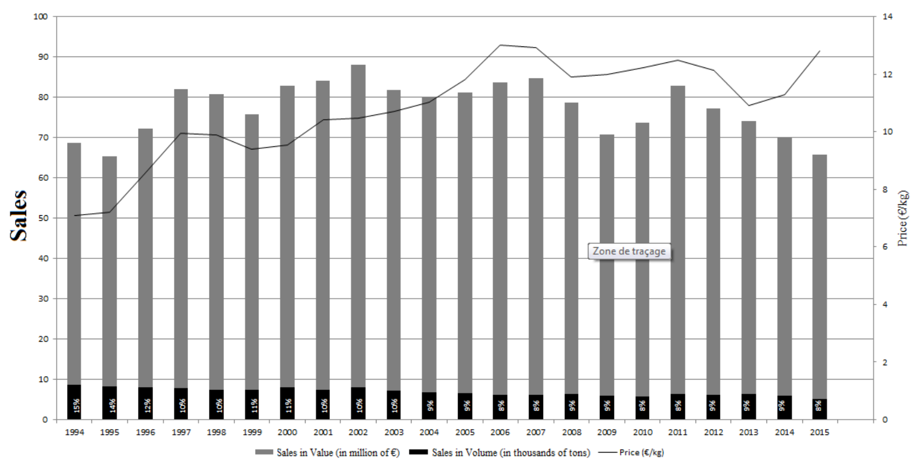

Figure 13: Sales in volume and in value of the sole in all auction centres (histogram, left vertical axis) and price curve (right vertical axis). The percentages represent the part of sales in volume compared to sales in value. (data source : visionet.franceagrimer.fr)

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

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 pass one or several associated statistical tests (test de White, Chow, Jarque and Bera and Durbin and Watson).

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) $\upsilon_{1,a}$	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) $\upsilon_{2,a}$	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

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

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