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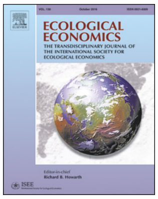

How Does MMEY Mitigate the Bioeconomic Effects of Climate Change for Mixed Fisheries

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ABSTRACT

This paper examines the impact of climate change on the bio-economic performance of Bay of Biscay mixed fisheries and explores the capacity of alternative management strategies to cope with these impacts. A dynamic multi-species, multi-class, multi-fleet model is developed and calibrated using available biological, economic and environmental information for French fleets. Fishing and economic data have been collected within the European Data Collection Framework. Climate represented by the sea surface temperature is assumed to affect species recruitment. Three management strategies are compared in terms of bio-economic outcomes: the Status-Quo (SQ), a Multi-species Maximum Sustainable Yield (MMSY) strategy and a Multi-species Maximum Economic Yield (MMEY) strategy. These strategies are ranked with respect to two contrasted scenarios regarding the Representative Concentration Pathways (RCP) driving climate change. Results show that the SQ strategy is not sustainable and is characterized by a major decline of the key commercial species. By contrast, the MMSY strategy improves the ecological state and economic performance of the fishery. The MMEY strategy yields even greater bio-economic improvements. Bio-economic benefits are however altered by the effects of climate change. Under the MMEY strategy, fleets with more diversified catch structures perform better facing climate change.

1. Introduction

Marine biodiversity and ecosystems are under extreme pressure worldwide with the intensification of fishing driven by an overall increase in seafood demand. According to FAO (2014), around 80% of worldwide commercial fish species are overexploited or fully exploited. Climate change adds to this pressure by inducing new, or intensifying existing, risks and vulnerabilities. In particular, climate change may induce impacts on the productivity and spatial distribution of fish stocks, leading to new challenges for regulating agencies (Badjeck et al., 2010) regarding the definition of stock boundaries and the allocation of fishing rights, as well as to the geographical redeployments of fleets (Rajudeen, 2013).

The European Union explicitly accounts for the objectives of mitigating and adapting to the effects of climate change in marine spatial planning and integrated coastal zone management[1]. The Common Fisheries Policy (CFP - Reg. UE 1380/2013 11/12/2013) also fully incorporates international commitments to manage fisheries for sustainability. It also considers the possibility of developing regional approach to fisheries management, with the aim to achieve maximum sustainable yield by 2020. Adopting a broader perspective, the European Marine Strategy Framework Directive[2] sets objectives with respect to the protection and restoration of marine ecosystems, while also taking into account economic and social benefits, and multiple sources of anthropogenic pressure.

Designing management tools and public policies that ensure the long-term bioeconomic sustainability of marine fisheries constitutes a major challenge (FAO, 2014). The growing requirement for these tools

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[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

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to adopt an ecosystem-based fishery management (EBFM - Pikitch et al., 2004; Link et al., 2017) perspective creates additional complexities (Sanchirico et al., 2008; Doyen et al., 2017). Growing efforts have been devoted to the development of integrated assessment tools to support management advices (Thébaud et al., 2014), taking into account the multiple ecological and economic complexities of fisheries, instead of focusing on isolated target species (Plaganyi, 2007). These approaches are expected to account for the multispecies and multi-fleet nature of fisheries, for the multiple ecosystem services associated with or impacted by them, as well as for the impacts of environmental drivers such as climate change. They are also expected to help evaluate the bioeconomic effectiveness and sustainability of current regulatory instruments such as fishing quotas or financial incentives, and design new tools for ecosystem-based management (Patrick and Link, 2015).

Many fish stocks are currently managed to achieve maximum sustainable yield (MSY), through limitations of catches or fishing efforts (Mace, 2001). At MSY, catches are set such that the stock can produce its greatest regeneration potential. MSY has become 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 debated (Larkin, 1977). In particular, applying MSY policies based on 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 sustainable profits are maximized (Dichmont et al., 2010). In a single-species context, harvesting at MEY is known to favour higher biomasses than harvesting at MSY (Clark, 2010; Grafton et al., 2012). It thus appears a more profitable and viable strategy than maximizing sustainable yield. Indeed, MEY 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, if 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, in which total catches are maximized (Mueter and Megrey, 2006). But in mixed fisheries where technical interactions occur, that is when one fishing fleet jointly harvests different species, maximizing total yields can endanger some species (Ricker, 1958; Legovic and Gecek, 2010; Guillen et al., 2013). The 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.

This article investigates the impacts of climate change on the ecological and economic performance of the Bay of Biscay mixed demersal fishery, and alternative management strategies to cope with these impacts. More specifically, we evaluate and compare the bioeconomic merits of MMSY and MMEY policies respectively, and assess their relevance for operationalizing ecosystem-based management of a mixed fishery facing global warming. The analysis is based on a multi-class, multi-fleet, dynamic model for common Sole (*Solea solea*) and European Hake (*Merluccius merluccius*), calibrated using available biological, economic and environmental information. Section 2 presents the case study, Section 3 describes the bio-economic model as well as the alternative management strategies and climate scenarios tested. Simulation results are presented in Section 4, and Section 5 discusses these results and concludes.

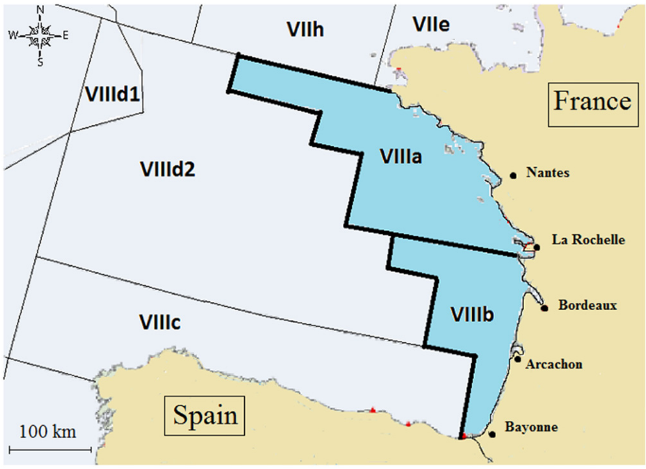

Fig. 1. Map of the Bay of Biscay and ICES divisions. The studying area is in dark grey.

2. Bay of Biscay Case Study

Our study deals with the mixed fisheries of the Bay of Biscay operating in divisions VIIIa and VIIIb of the International Council for the Exploration of the Sea (ICES) (Fig. 1). We focus on two key commercial species caught in the bay: 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 centre of its latitudinal range (average latitude 44.5 ° N). To date, no clear trend in the evolution of its spatial distribution has been identified (Hermant et al., 2010). From 2002, the Bay of Biscay Sole was identified as a vulnerable stock, and subjected to a management strategy aimed at restoring spawning biomass at its level of precaution (Bpa). This goal was reached in 2009 (Fig. 2). However, due to surprisingly low recruitment in 2010, the stock is declining again. 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 then recovered for 3 years, it still remains below the sustainable reference point (Bpa = 13 000 tons) since 2013 (ICES, 2017).

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

In the Bay of Biscay, a warming of ≈ 0.2 °C / decade has been

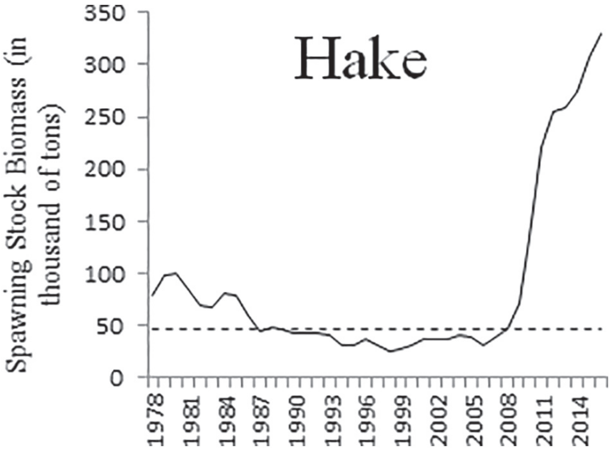

Fig. 3. Historical evolution of the spawning biomass for the European Hake. The dashed line refers to the precautionary threshold (Bpa) estimated at 46 200 tons (ICES, 2016).

observed for the period 1965–2004, between the surface and 200 meter depths (Decastro et al., 2009). This has been shown to impact flat fish species. Recent studies have shown spatial correlation between abundance and the increase in temperature (Hermant et al., 2010): for boreal species, abundance has decreased with warming, while for southern species it has increased. Recruitment is thought to be the main process affected by warming (Koutsikopoulos et al., 1998).

2.2. Hake

Distributed in the North-East Atlantic, European Hake (*Merluccius merluccius*) is present along the coasts from Norway to Mauritania. Although the species suffered from severe overexploitation with a fall in its recruitment in the 1990s (Fig. 3), a recovery of its spawning stock has since been observed (ICES, 2016) following better recruitments and the implementation of a European mono-specific management plan aimed at achieving MSY. 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 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 behaviour and Hake growth (Benson et al., 2002). Thus, Goikoetxea and Irigoien's work (Goikoetxea and Irigoien, 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 (Fig. 3). More specific informations about species ecology can be found from the bibliographical synthesis made by Caill-Milly et al. (in press).

2.3. Economic Importance of Hake and Sole Fisheries

Hake and common Sole are among the first four species in terms of the economic value of landings on the French Atlantic coast. On this coast, in 2016, Hake represented 18% of the overall production in value while Sole reaches 6%[3]. Sole is less abundant than Hake which is the dominant species for fisheries in the European Union (EUMOFA, 2015). The price per kilogram of Sole is much higher than that of Hake, due to consumer demand: in 2015, the former was around 12 € per kilogram with a 60 million € market to be compared with a price of 3 € per kilogram, and a 45 million euro market. The high abundance of Hake and the high price of Sole thus explain their major economic value at both French and European levels.

The main French fleets targeting the two species include 400 vessels across the Bay of Biscay and can be divided into three groups of vessels based on their main fishing gears: 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 estimations for the two species can be extracted from population models produced by ICES annually for Sole and quarterly for Hake[4] 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 via the SS3 (Stock Synthesis 3) model based on commercial catches and on abundance data.

Biological parameters are displayed in appendix (Tables 5 and 6) while fishing mortality on Hake and Sole are detailed in Tables 7 and 8. Economic data and transversal data on effort and production by fleet and gear are derived 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 Temperature (SST) data are derived from a project led by the European Union called OpEc[5] 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)[6], many forecasted environmental data. In this paper, we choose to focus on the worst-case and best-case climate scenarios, 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 Fig. 4. These links highlight key interactions. In particular, it is assumed that SST impact recruitment through specific responses of Spawning Stock Biomass (SSB) of the two species. Stock biomass levels along with fishing effort determine catches, profits and biological outcomes. The simulation period is 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:

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[3] http://www.sih.ifremer.fr/content/download/30413/205373/file/Synthese%20de%20la%20Facade%20Atlantique%202016.pdf

[4] In the ICES report, it is hypothesized that no recruits are observed in the fourth quarter, hence the sum of the three first quarters represents the annual spawning stock (ICES).

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

[6] Representative Concentration Pathways.

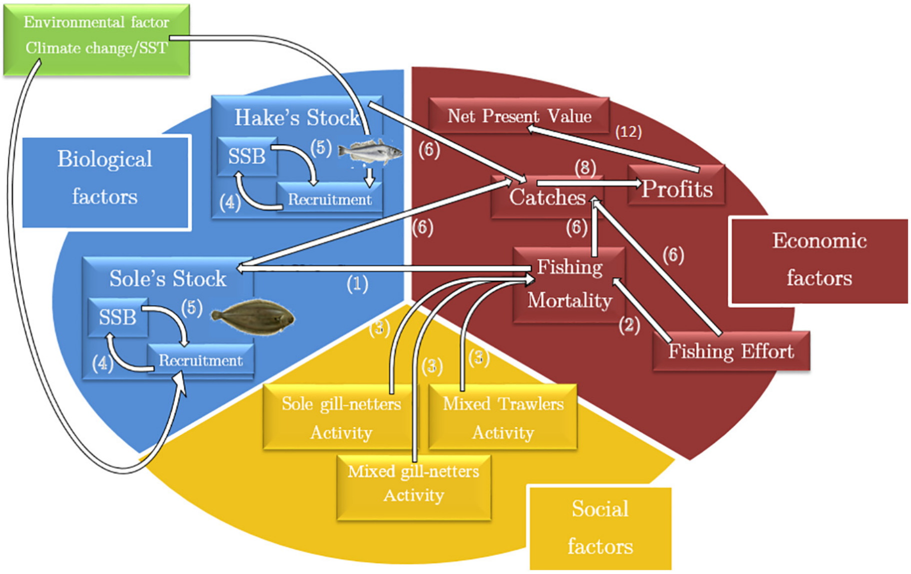

Fig. 4. Relations existing between environmental, biological and economic factors within the bio-economic model. Arrows stand for the interactions between variables while figures between brackets refer to the equations/models that link the various factors within the bio-economic model.

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

where $N_{s,a}(t)$ stands for the abundance of the exploited species, $s = 1,2$ (Sole, Hake respectively) at age $a = 2,\ldots A_s$ at time t. The age class starts at two because the first one stands for recruitment. We assume that there is no biological interaction 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 $m = 13$ sub-fleets f at year $t_0 = 2014$ described by:

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

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:

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

with $e_f(t_0)$ 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, 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 congestion effects (Chu and Kompas, 2014) are very limited. Indeed, the number of vessels which operates in the Sole fishery has decreased by 21% between 2000 and 2011 while French vessels targeting 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:

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

where $\gamma_{s,a}$ stands for the share of fertile 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, $\theta(t)$ 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 2 years for the Sole $\Delta_1 = 1$; about 1 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 behavioural and physiological processes during spawning and larval phase such as metabolic cost of spawners, natural mortality of eggs and larvae, food availability (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[7] of recruits over SSB and SST time series[8] in order to find the recruitment model that best fits the data[9]. We detail and discuss the time lags Δ_s obtained in the results section.

3.3. Economic Scores

Assuming that discards are negligible, landings of the m different sub-fleets equal catches and are defined for each species by the Baranov catch equation:

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[7] Ordinary Least Squared for the log-linearised model for Sole with 22 observations and autoregressive process of order 1 for the log-linearised model for Hake to correct the autocorrelation of its errors with 66 observations.

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

[9] 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.

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

Catches of other species, caught by the m sub-fleets, are described as follows:

$$C_f^{OS}(t) = \beta_f u_f(t)K_f(t_0)e_f(t_0) \tag{7}$$

where β_f stands for the catches per unit of effort of sub-fleet f for other species.

Incomes derived from catches read as follows:

$$Inc_f(t) = \sum_{s}\sum_{a=1}^{A_s} p_{s,a}(t)\upsilon_{s,a}C_{s,a,f}(t) \tag{8}$$

where $\upsilon_{s,a}$, as in Eq. (4), is the mean weight of individuals of species s at age a and $p_{s,a}(t)$ corresponds to the market price (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:

$$\begin{aligned}\pi_f(t) = {} & (Inc_f(t) + \alpha_f u_f(t)K_f(t_0)e_f(t_0))(1 - \tau_f) \\ & - (V_f p(t)e_f(t_0) + c_f^{var} e_f(t_0) + c_f^{fix})u_f(t)K_f(t_0)\end{aligned} \tag{9}$$

α_f corresponds to the income per unit of effort of sub-fleet f from other species. The dynamic of these non-targeted species is explicitly modelled and we assume constant values per unit of effort. For these species, 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 per unit of fishing effort and $c_f^{var}$and c_f^{fix}correspond respectively to the variable[10] and annual[11] (fixed) costs per vessel of sub-fleet f. These parameter values are based on economic data available for 2008 (IFREMER, SIH, DPMA[12], Tables 9 and 10). The price of fuel is considered constant over time, set at 0.5 € per litre.

3.4. Management Strategies

We consider three alternative management strategies: 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 $T = 2088$ such that:

$$u^{SQ}(t) = 1 \qquad \forall\ t = t_0,\ \ldots, T$$

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. Specifically, the objective is to find the constant effort multiplier vector noted $\underset{\cdot}{u}^{MMSY}$ that maximizes the mean total catches over time defined as the average of the total catches over the entire temporal period. To account for the stochasticities affecting both the species prices $p_s(t)$ in Eq. (8) and recruitment dynamics (5) through $\varepsilon_s(t)$, we consider the expected value of the mean catches:

$$C^{MMSY}(\underset{\cdot}{u}) = \mathbb{E}\left[\frac{1}{T}\sum_{t=t_0}^{T}\left(\sum_{f=1}^{m}\left(\sum_{s=1}^{2}\sum_{a=1}^{A_s} C_{s,a,f}(t)\right) + C_f^{OS}(t)\right)\right] \tag{10}$$

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

$$C^{MMSY}(u^{MMSY}) = \underset{u}{max} C^{MMSY}(u) \tag{11}$$

As explained in the introduction, by adopting a multi-species perspective, the MMSY management takes into account the fact that most fleets target multiple species (voluntarily or not). Such a management model thus seems more relevant from an ecosystem-based perspective than single-species management strategies (Voss et al., 2014).

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

$$NPV(\underset{\cdot}{u}) = \mathbb{E}\left[\sum_{t=t_0}^{T}\frac{1}{(1+r)^t}\sum_{f=1}^{m}\pi_f(t)\right] \tag{12}$$

with profits $\pi(t)$ defined in Eq. (9) 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 $\underset{\cdot}{u}^{MMEY}$.

$$NPV(u^{MMEY}) = \underset{u}{max} NPV(u) \tag{13}$$

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

3.5. Climate Scenarios

In our study, we consider two extreme climate scenarios (IPCC, 2013 - RCP 2.6, RCP 8.5) illustrated by Fig. 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 Eq. (5) which affects the species dynamics as a whole and by extension the fisheries.

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 the SQ, MMSY and MMEY strategies.

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. Eqs. (14) and (15) notably highlight the

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[10] The variable costs include oil, supplies, ice, bait, gear, and equipment costs.

[11] The annual cost includes maintenance, repair, management and crew costs, fishing firms, licenses, insurances and producer organisation costs.

[12] 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 stands for Systeme d'Informations Halieutiques, the fisheries information system operated by Ifremer, the French Research Institute for the Exploitation of the Sea (http://wwz.ifremer.fr/institut_eng).

Fig. 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.

importance of lags between recruitment and SSB and SST. The lags are proportional to the time necessary for the species to become an egg, a larvae, a juvenile then a catchable recruit i.e. 2 years for Sole an 1 year for Hake on 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 models 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 confirm that the Ricker model is the best 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

$$N_{1,1}(t+1) = aSSB_1(t-1)e^{bSSB_1(t-1)+c\theta(t-1)^2} + \varepsilon_1(t-1) \tag{14}$$

Hake's SR model

The initial model for Hake is built with quarterly data. As already mentioned, recruits are summed over the first three quarters to obtain annual recruitment.

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

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:

$$N_{2,1}(t+1) = \sum_{i=1}^{3} (aSSB_2(t_i(t))e^{bSSB_2(t_i(t))+c\theta(t_i(t))^2} + \varepsilon_2(t_i(t))) \tag{15}$$

4.2. Status-Quo: Not Ecologically and Economically Viable

Fig. 6 describes the estimated[13] 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. The SSB of Sole and Hake are displayed at the top and profits are displayed at the bottom.

Fig. 6 shows that the SQ strategy is not ecologically or economically viable. The ecological vulnerability relates to Sole biomass which drops below the ICES precautionary limit, even with a favourable climate change scenario, and collapses under the pessimistic climate scenario. The economic vulnerability arises from the worst-case 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 drop in the Sole SSB and could lead to an economic collapse. Management strategies must thus adapt fishing effort in order to moderate the impacts of global warming on bio-economic outcomes.

4.3. MMSY: Not Ecologically Viable but Economically Viable

As illustrated by Fig. 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 best climate scenario, the Sole stock first decreases to stabilize after 15 years at around 8000 tons. The Hake stock displays similar trends as in the SQ strategy, with higher values regardless of climate scenarios.

Interestingly, although the purpose of this strategy is not to maintain the SSB above Bpa, it significantly improves biological outcomes. Indeed, maximizing landings in the future cannot be dissociated from sustaining high levels of stock. Therefore, the MMSY strategy implicitly

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

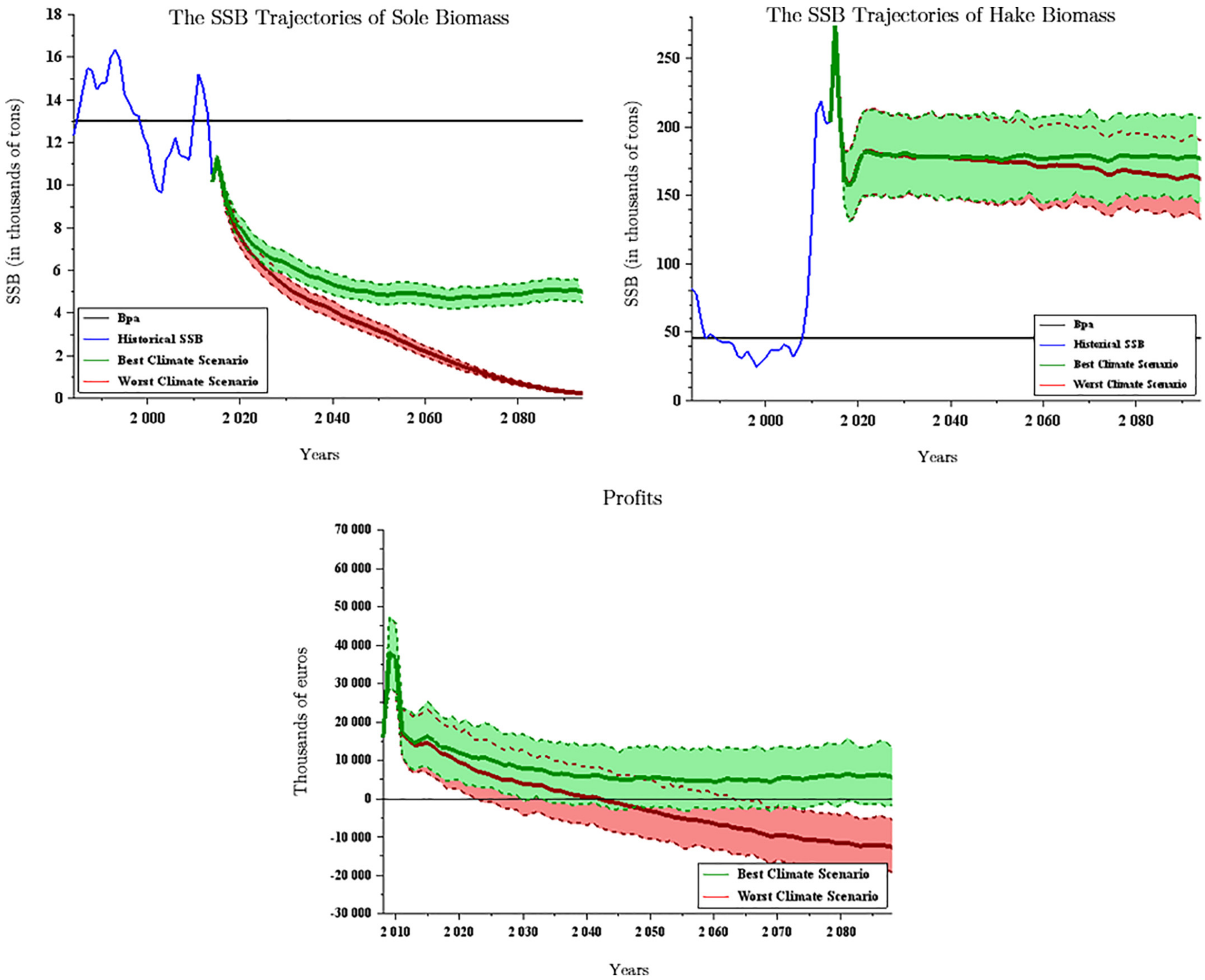

Fig. 6. Strategy Status-Quo - Sole (top left) and Hake (top right) SSB trajectories under the two climate scenarios in thousands of tons. The black solid line represents ICES precautionary threshold (B_{pa}) of the species' stock. The third figure (bottom) represents the total profits over all thirteen sub-fleets. Historical paths are displayed in blue. The 500 simulated trajectories are represented by the coloured 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.

accounts for ecological objectives through the fishing effort mitigation, thus performing better than the SQ strategy. But the strong increase in temperature combined with an excessive fishing effort still entail a decrease in the Sole stock. Indeed, the MMSY strategy tends to focus on the more productive Hake species.

4.4. MMEY: Ecologically Viable and Economically Viable

As illustrated in Fig. 8, the MMEY strategy entails better bio-economic outcomes than the SQ and MMSY strategies.

Regardless of the climate scenario, Hake SSB displays the same trend than in the MMSY strategy (Fig. 8) but at lower levels. Regarding the Sole stock, under the worst climate scenario, the weakness of the underlying MMSY fishing effort multipliers (Table 1) generates an initial recovery of the stock, which however collapses in the long run because of temperature increase. However, the Sole stock remains above its precautionnary threshold under the best climate scenario. Compared to the MMSY strategy, regardless of the climate scenario, profits are higher reaching 60 million euros per year (Fig. 8). This outcome regarding effort is likely to be explained by the weaker price of Hake which leads the MMEY strategy to focus more on Sole profits because it is a more profitable species. On the contrary, the MMSY strategy which aims at maximizing catches focuses on protecting Hake given its high abundance, and on catching other species.

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

4.5. MMSY, MMEY: A Reduction of Effort Especially for Sole Gill-netters

Table 1 displays the MMSY and MMEY fishing effort multipliers, and the associated mean landings and NPV of returns over the simulation horizon. The MMEY strategy implies an important reduction in the number of boats as almost all the optimal multipliers (u^{MMEY}) are smaller than 1, while the MMSY strategy only mitigates the effort of some fleets. This is in line with the reductions actually observed in the

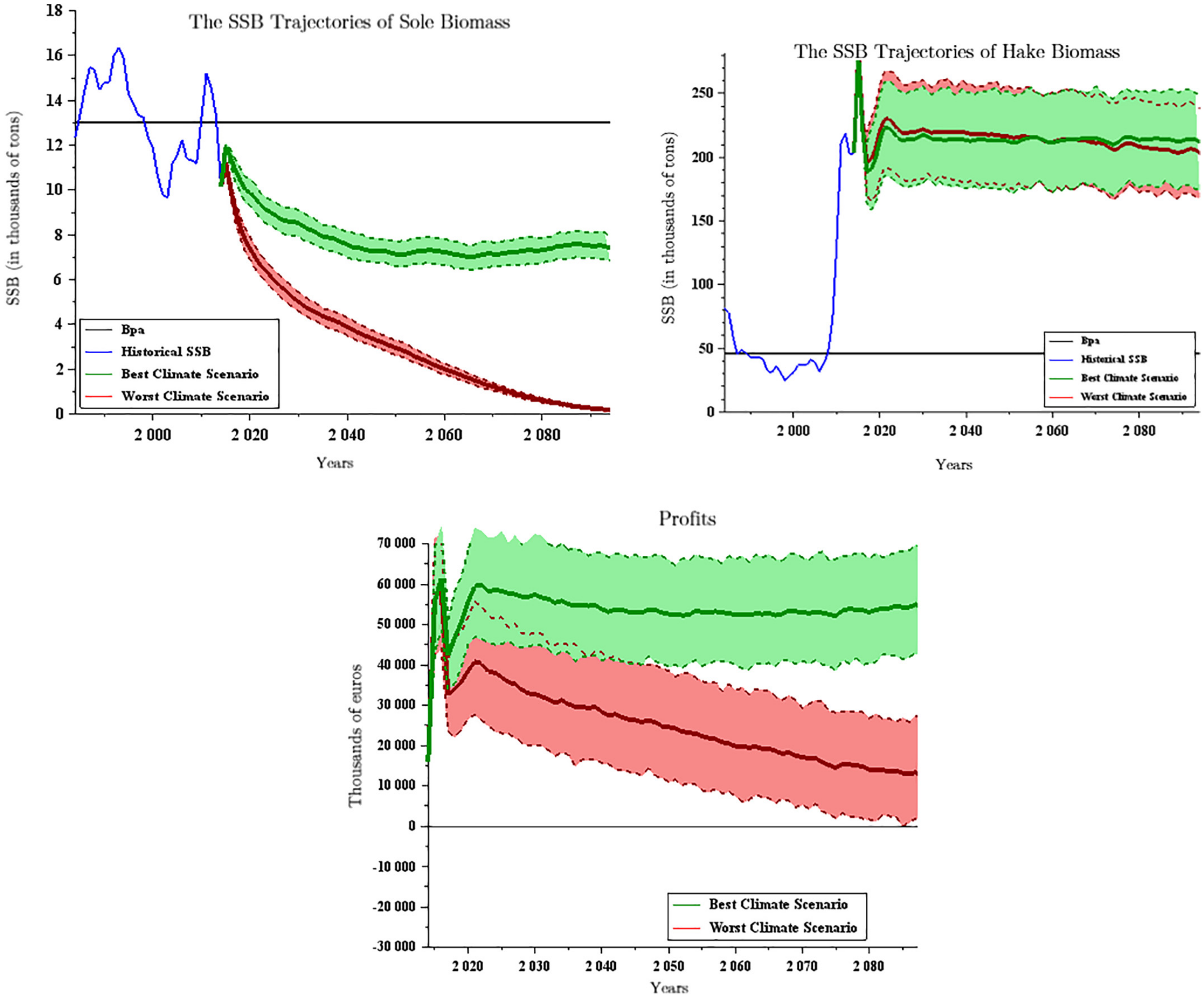

Fig. 7. Strategy MMSY - Sole (top left) and Hake (top right) SSB trajectories under the two climate scenarios in thousands of tons. The black solid line represents ICES precautionary threshold (B_{pa}) of the species' stock. The third figure (bottom) represents the total profits over all thirteen sub-fleets. Historical paths are displayed in blue. The 500 simulated trajectories are represented by the coloured 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.

number of vessels on the Atlantic coast due to the CFP. In particular, for both strategies, a decrease in the effort of Sole gill-netters is observed.

In addition, regardless of the climate scenarios, MMEY multipliers are globally lower than MMSY multipliers for all fleets, but with the same structure. Indeed, fleets with more diversified catches (mixed trawlers and mixed gill-netters) maintain higher effort multipliers according to the strategy and the climate scenario. By contrast, for Sole gill-netters, MMEY and MMSY multipliers are reduced according to the climate scenario and strategy. This stronger mitigation in fishing effort under the MMEY strategy reflects the objective to protect the species with higher economic value. The choice of strategy thus has a major impact on the Sole stock, and fishing effort multipliers for Sole gill-netters play a pivotal role in this strategy.

Results presented in Table 3 show 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: The MMEY as the Best Strategy

Fig. 9 synthesizes the bio-economic scores of the three management strategies by presenting the average NPV of the entire temporal horizon on the Y-axis versus the Simpson's index of diversity[14] on the X-axis. A Simpson's index close to 2 (because we have two species) means a more diversified ecosystem. By contrast, a Simpson's index tending towards one means a lower level of diversity. The figure shows a heterogeneous[15] ecosystem which may be explained by a domination of one species over another (Hake over Sole) or a simple extinction of one

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[14]

$$D = \left[\sum_{s=1}^{2}\left(\frac{\overline{SSB_s}}{\sum_{s=1}^{2}\overline{SSB_s}}\right)^2\right]^{-1}$$

with $\overline{SSB_s} = \frac{1}{T}\sum_{t=1}^{T} SSB_s(t)$

[15] Some species are more abundant than others. In our case, it is Hake.

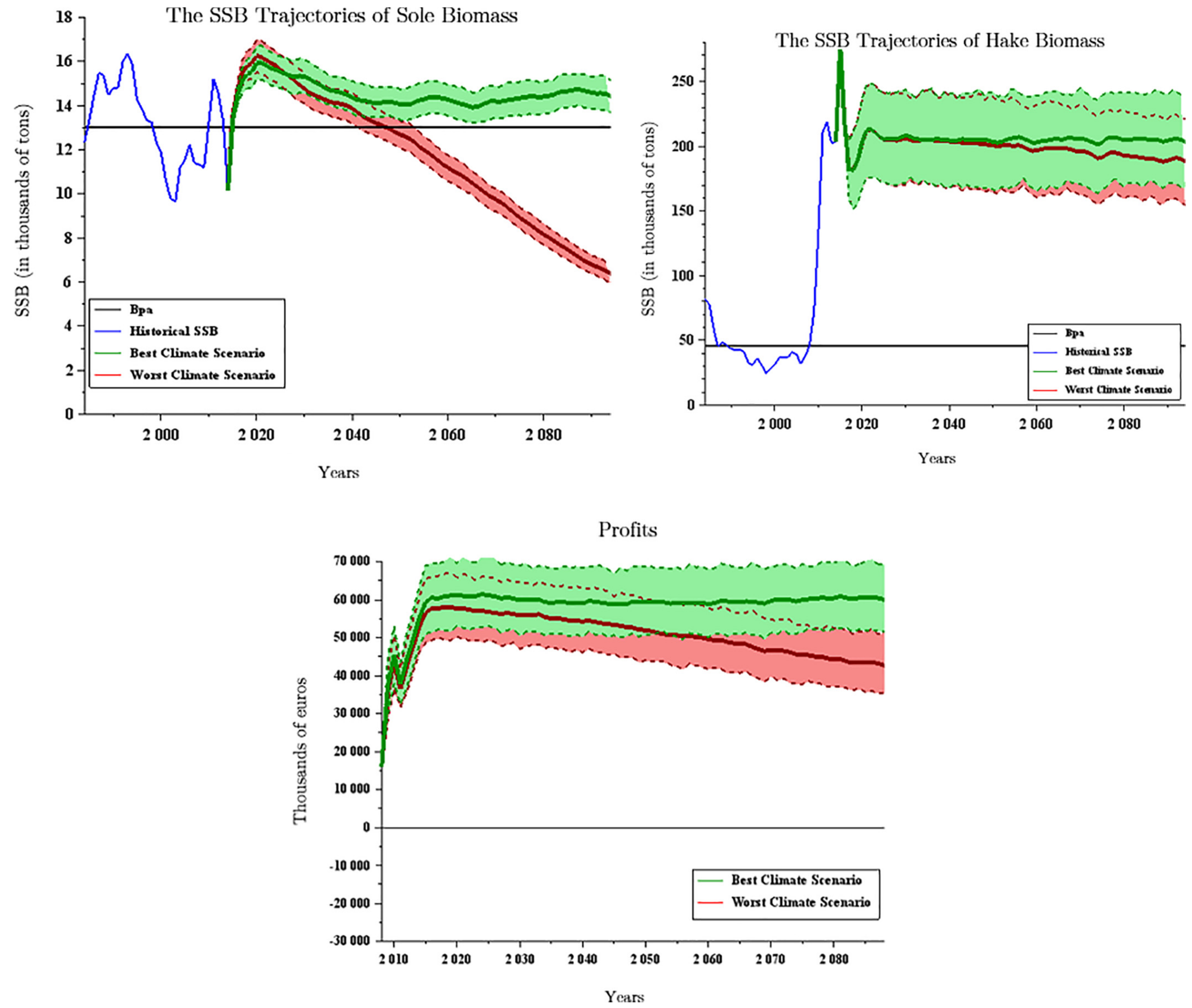

Fig. 8. Strategy MMEY - Sole (top left) and Hake (top right) SSB trajectories under the two climate scenarios in thousands of tons. The black solid line represents ICES precautionary threshold (B_{pa}) of the species' stock. The third figure (bottom) represents the total profits over all thirteen sub-fleets. Historical paths are displayed in blue. The 500 simulated trajectories are represented by the coloured 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.

species (in this case, Sole). Here, the values of the Simpson index are weak < 1.2 indicating that diversity is at stake. This is due to low abundances of Sole, which even collapse under the worst climate scenario for the SQ strategy.

5. Discussion

The above results show benefits to managing the Bay of Biscay mixed fishery with the MMEY strategy. In what follows, we specifically discuss the question of how this strategy mitigates the bioeconomic effects of climate change on such a mixed fishery.

5.1. MMEY as a Win-Win Ecological-Economic Strategy

Fig. 9 shows that the MMSY and the MMEY strategies improve both the ecological state and the 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) holds true for the two climate scenarios and as such is a win-win strategy. This finding is aligned with general results obtained in Grafton et al. (2007) showing that under reasonable assumptions regarding output prices, input 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 the discount rate r exceeds the intrinsic growth rate of the resource, 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 $r = 4$. The MMEY strategy thus generates a positive effect on both fish stocks.

There is of course no guarantee that the profit of each sub-fleet remains positive, given that we maximize the aggregated profits of all sub-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

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).

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)	1.4	0.72	1.99	0.29
Mixed trawlers 12–16 m (45)	1.42	0.84	0.4	1.32
Mixed trawlers 16–20 m (49)	1.2	1.03	1.99	0.53
Mixed trawlers > 20 m (37)	2	0.7	1.95	1.06
Sole gill-netters 0–10 m (28)	0.65	0.51	1.83	0.14
Sole gill-netters 10–12 m (42)	1	0.21	0.86	0.13
Sole gill-netters 12–18 m (40)	0.67	0.23	0.71	0.25
Sole gill-netters 18–24 m (23)	1.33	0.19	0.29	0.53
Mixed gill-netters 0–10 m (32)	1.12	0.74	0.54	0.44
Mixed gill-netters 10–12 m (30)	0.96	1.03	0.69	0.2
Mixed gill-netters 12–18 m (6)	1.77	0.64	2	0.36
Mixed gill-netters 18–24 m (9)	1.33	0.44	0.48	1.12
Mixed gill-netters > 24 m (10)	2	0.96	2	0.83
Mean landings (in thousands of tons)	295	263	303	266
Mean NPV (in millions of euros)	1011	1242	1345	1355

Table 2
Parameters and standard errors of the estimated Ricker model (Eq. (14)) accounting for temperature for Sole. t(17) stands for the Student test with 17 observations.

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 3
Parameters and standard errors of the estimated Ricker model (Eq. (15)) accounting for SST for Hake. t(62) stands for the Student test with 62 observations.

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

SQ depend on climate change intensity. Under the worst-case 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 Fig. 8 (top left).

5.2. Diversification of Fleets Produces Greater Benefits in the Face of Climate Change

MMEY and MMSY efforts draw on a diversification strategy. As said previously, we notice that fishing efforts of the mixed trawlers and mixed gill-netters are higher than those for the Sole gill-netters in these two strategies. Fishing efforts of the Sole gill-netters are on the other hand globally lower for MMEY than for MMSY, which contributes to maintaining a higher SSB of Sole. This stronger reduction of Sole gill-netters effort can be explained by the strong dependency[16] (Figs. 10 and 12) of this fleet on Sole, the pressure on which the MMEY strategy aims to reduce given the vulnerability of Sole to global warming. This also likely contributes to explain why profits are slightly higher under the MMEY strategy as compared to the MMSY strategy, simply because there are more Soles to be caught.

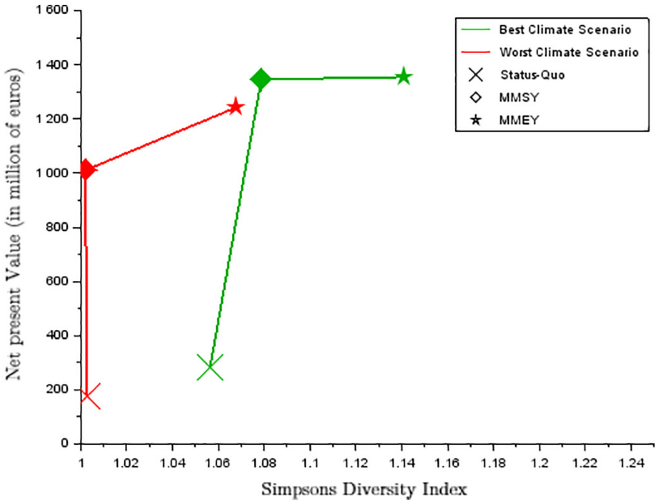

Fig. 9. Simpson's Index of Diversity versus Average Net Present Value.

These results would point to the need for many fleets relying on Sole to diversify their target species, especially if the Sole TAC and therefore landings continue to decrease as they have done for almost 20 years (In appendix: Fig. 11). The price of Sole has risen by 80% between 1994 and 2015 (In appendix: Fig. 13). This explains why sales in value remain high despite their limited share in volume[17] 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 coming years (Lagiere, 2012). This sectoral change may be restricted by a number of factors: on the one hand, the French fleet is aging[18] and the cost of renewing vessels is high[19] for new operators whose number has significantly decreased in the recent years (In appendix: Fig. 14). 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 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 of integrating both the multi-species, multi-fleet nature of fisheries and the effects of temperature and more specifically SST, in recruitment models and in management models of fisheries. This is 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*). In this fishery, the council adopted a control of fishing depending on temperature increase (Hill et al., 2011).

Our results also illustrate the potential of strategies aimed at MMEY to entail greater adaptation capacity in the face of climate change. This

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[16] A high contribution to fishing mortality and a wide share in the overall income of the fleet.

[17] Sales in Volume = landings - unsold.

[18] The average age of French vessels is over 25 years old in 2012. Still in 2012, only 20% of the fleet were under 15 years. By contrast, almost 57% of the ships were older than 25 years of age (Aglia, 2014).

[19] All the more for big vessels.

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, we find that global change impacts should also be taken into account by regulating agencies. This result is line with Chu and Kompas (2014) who claim that reaching the maximum economic yield (when combined with marine protected areas) provides a greater profitability and also ensures a greater conservation benefits for fish stocks.

In the medium to long-term horizon, many fishing fleets may need to adapt to changes induced by global warming. The large levels of investment needed to rejuvenate and adapt the fleets and decreases in quotas for some species will likely create major challenges in the future. In the case of the Bay of Biscay, even if price increases help sustain the profitability of fisheries, national and 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 by refined. In particular, the processes underlying the recruitment dynamics of the species are not fully understood yet, such as processes driving survival success during the juvenile phase (Le Pape and Bonhommeau, 2015).

More globally, from a policy perspective, our results point to the value of adaptive control strategies of marine fisheries, based on the economic, biological and social context, taking into account local and global environmental changes.

Acknowledgements

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Appendix A. Appendix

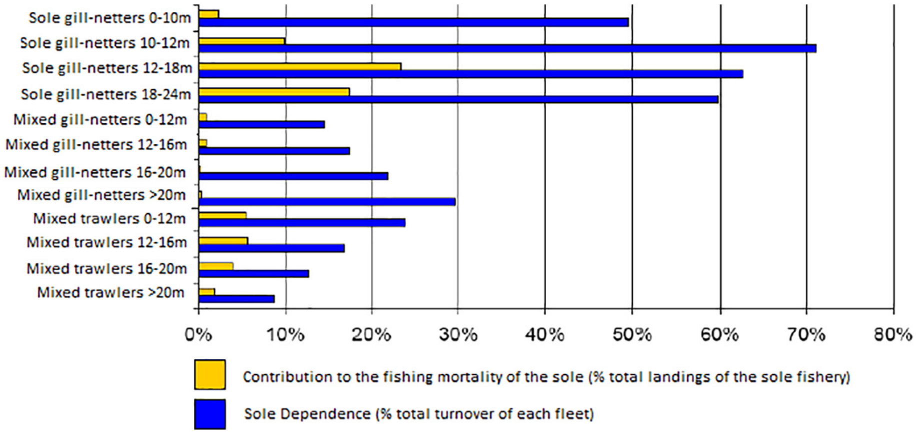

Fig. 10. Contribution to the fishing mortality and dependence on Sole of fleets of Bay of Biscay fishery in 2010 (Aglia, 2014).

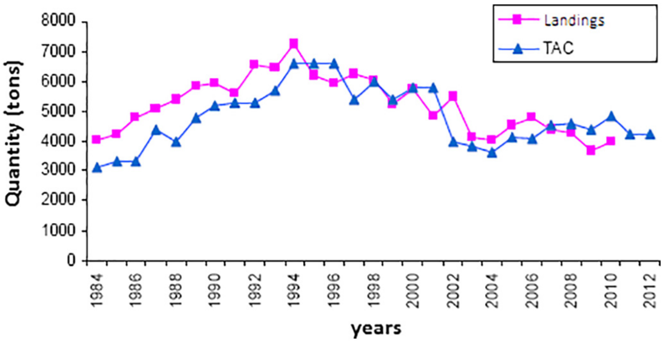

Fig. 11. Comparative evolution of the TAC and landings of the Sole in the Bay of Biscay since 1984 (Lagiere, 2012).

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[20] SceNArios of bioeconomic VIability and REsilience for ecosystem-based fisheries management in Aquitaine

[21] Scenario, fishEry, ecologicAl-economic modelling and VIability nEtWork

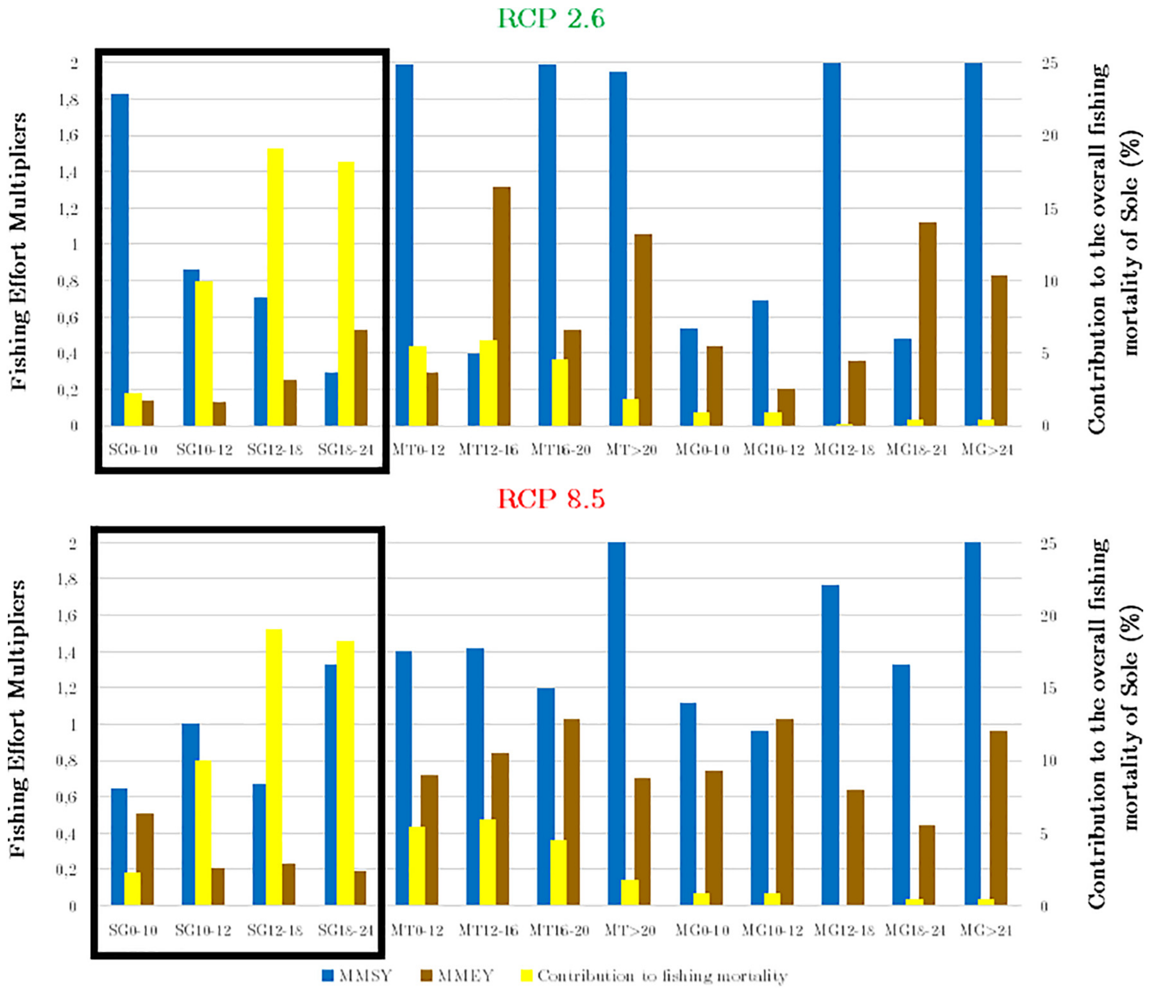

Fig. 12. Fishing effort multipliers (left axis) and contribution to the overall fishing mortality of Sole in percentage (right axis). Sub-fleets (X-axis) are ranked by contribution to Sole mortality with firstly the Sole gill-netters (SG), the Mixed gill-netters (MG) and the Mixed Trawlers (MT). The first figure accounts for the best-case climate scenario (RCP 8.5) and the second (bottom) for the worst climate scenario (RCP 8.5).

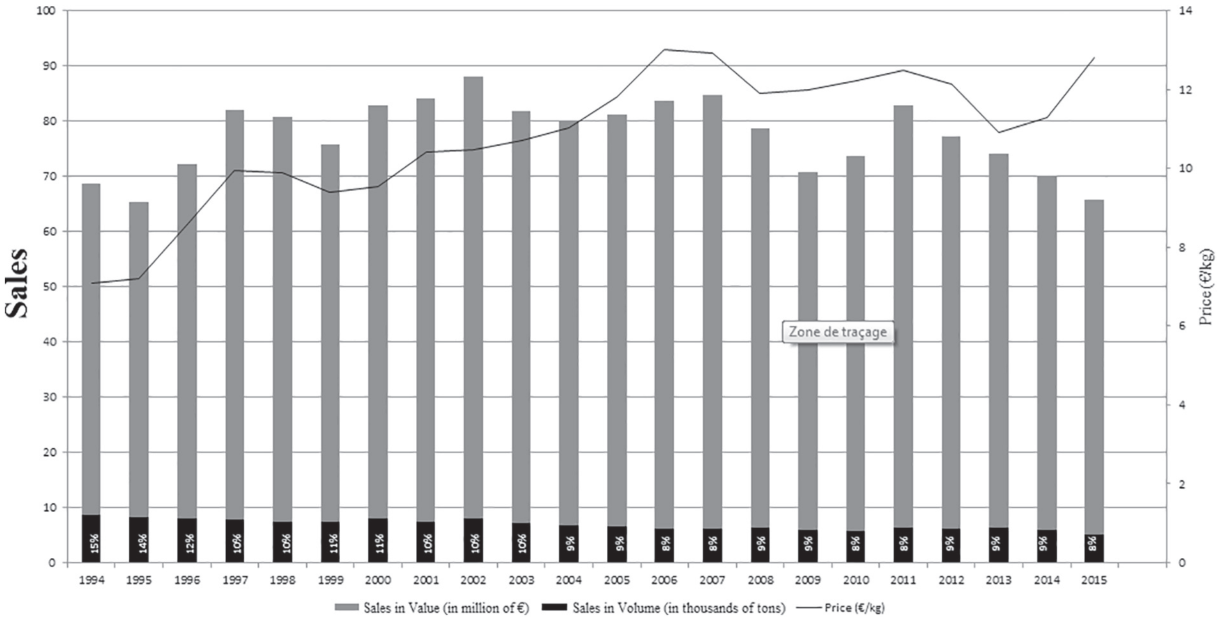

Fig. 13. Sales in volume and in value of the Sole in all auction centres (histogram, left vertical axis) and price curve (right vertical axis). The percentages represent the part of sales in volume compared to sales in value (data source: visionet.franceagrimer.fr).

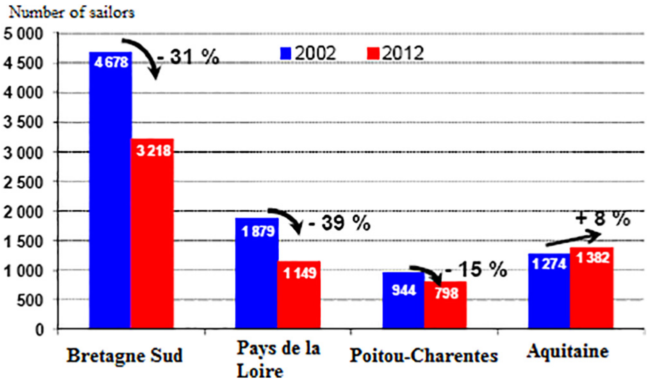

Fig. 14. Numbers of sailors in the Atlantique facade (Aglia, 2014).

Table 4
Type of Stock-Recruitment models with and without environmental factor (θ) affecting recruitment according to the species ($s = 1{,}2$ 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).

Type of SR model	Equation
Cushing (− 3.31|0.56)	$N_{s,1}(t+1) = aSSB_s(t-\Delta_s)^b\theta(t-\Delta_s)^c + \varepsilon_s(t)$
Ricker (− 2.5|0.25)	$N_{s,1}(t+1) = aSSB_s(t-\Delta_s)e^{+bSSB_s(t-\Delta_s)} + \varepsilon_s(t)$
Ricker2 (− 3.37|0.66)	$N_{s,1}(t+1) = aSSB_1(t-\Delta_s)e^{-bSSB_1(t-\Delta_s)-c\theta(t-\Delta_s)^2} + \varepsilon_1(t-\Delta_s)$
B-H (− 3.08|0.10)	$N_{s,1}(t+1) = \frac{SSB_s(t-\Delta_s)}{b + aSSB_s(t-\Delta_s)} + \varepsilon_s(t)$
B-H 2 (− 3.79|0.57)	$N_{s,1}(t+1) = \frac{SSB_s(t-\Delta_s)}{b + aSSB_s(t-\Delta_s) + c\theta(t-\Delta_s) + d\theta(t)^2} + \varepsilon_s(t)$

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

Age a	2	3	4	5	6	7	8+
Initial abund. $N_{1,a}(t_0)$ (*10^3 indv)	23 191	17 416	10 707	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 6
Hake parameters,($s = 2$),$t_0 = 2008$. 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)	236 062	132 608	61 571	25 195	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 7
Values of fishing mortality on Sole ($s = 1$): $F_{1,a,f}(t_0)$. Source: ICES; Ifremer, SIH, 2008.

Sub-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

(*continued on next page*)

Table 7 (*continued*)

Sub-fleets	2	3	4	5	6	7	8+
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 8
Values of fishing mortality on Hake ($s = 2$): $F_{2,a,f}(t_0)$. Source: ICES; Ifremer, SIH, 2008.

Sub-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 9
Initial number of vessels $K_f(t_0)$, effort by vessel $e_f(t_0)$, rate of extra fishing income α_f and rate of extra fishing catches β_f of the thirteen sub-fleets. Source: Ifremer, SIH, DPMA, 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	Catches from other species (in kg/effort unit) β_f
Mixed trawlers 0–12 m ($f = 1$)	110	157.7	622	201
Mixed trawlers 12–16 m ($f = 2$)	45	192.7	1375	429
Mixed trawlers 16–20 m ($f = 3$)	49	180.3	1751	490
Mixed trawlers > 20 m ($f = 4$)	37	197.1	3597	1003
Sole gill-netters 0–10 m ($f = 5$)	28	139	311	71
Sole gill-netters 10–12 m ($f = 6$)	42	145.5	503	115
Sole gill-netters 12–18 m ($f = 7$)	40	202.9	765	162
Sole gill-netters 18–24 m ($f = 8$)	23	201.7	1150	251
Mixed gill-netters 0–10 m ($f = 9$)	32	153.8	303	59
Mixed gill-netters 10–12 m ($f = 10$)	30	178.8	847	173
Mixed gill-netters 12–18 m ($f = 11$)	6	145	1466	339
Mixed gill-netters 18–24 m ($f = 12$)	9	210.3	1500	348
Mixed gill-netters > 24 m ($f = 13$)	10	260.6	1141	346

Table 10
Mean reference costs 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	77 779
Mixed trawlers 12–16 m ($f = 2$)	0.05	863	108	218 506
Mixed trawlers 16–20 m ($f = 3$)	0.07	1076	188	245 285
Mixed trawlers > 20 m ($f = 4$)	0.07	1999	308	388 951
Sole gill-netters 0–10 m ($f = 5$)	0.06	78	70	56 601
Sole gill-netters 10–12 m ($f = 6$)	0.05	290	140	132 326
Sole gill-netters 12–18 m ($f = 7$)	0.08	348	213	256 373
Sole gill-netters 18–24 m ($f = 8$)	0.07	622	453	378 872
Mixed gill-netters 0–10 m ($f = 9$)	0.05	59	28	42 874
Mixed gill-netters 10–12 m ($f = 10$)	0.05	248	69	111 911
Mixed gill-netters 12–18 m ($f = 11$)	0.06	396	230	223 622
Mixed gill-netters 18–24 m ($f = 12$)	0.07	811	595	513 353
Mixed gill-netters > 24 m ($f = 13$)	0.03	1099	556	913 096

References

Aglia, 2014. Suivi des résultats économiques et analyse financière des entreprises de pêche dans les régions de aglia (1987-2012). In: Technical report, Laurent Baranger, Jean-François Bigot, Arnaud Souffez, Yves Perraudeau.

Anderson, L.G., 1975. Analysis of open-access commercial exploitation and maximum economic yield in biologically and technologically interdependent fisheries. J. Fish. Board Can. 32 (10), 1825–1842.

Anneville, Cury, 1997. Stock-recrutement et espace. approche par la modélisation individus centrée. In: DEA de Biomathématiques.

Badjeck, M.-C., Allison, E.H., Halls, A.S., Dulvy, N.K., 2010. Impacts of climate variability and change on fishery-based livelihoods. Mar. Policy 34 (3), 375–383.

Benson, A.J., McFarlane, G.A., Allen, S.E., Dower, J.F., 2002. Changes in Pacific Hake (*Merluccius productus*) migration patterns and juvenile growth related to the 1989 regime shift. Can. J. Fish. Aquat. Sci. 59 (12), 1969–1979.

Beverton, R.J.H., Holt, S.J., 1957. On the dynamics of exploited fish populations, fishery investigations series II Volume XIX, Ministry of Agriculture. Fish. Food.

Beverton, R.J.H., Iles, T.C., 1998. Stock, recruitment and moderating processes in flatfish. J. Sea Res. 39, 41–55.

Caill-Milly, N., Morandeau, G., Castège, I., Sanchez, F., Lissardy, M., Chust, G., Borja, A., Auby, I., Lapègue, S., Prou, J., Oger-Jeanneret, H., Lassalle, G., Prévost, E., Buoro, M., Lobry, J., De Pontual, H., De Casamajor, M., Biais, G., d'Elbée, J., 2018. Les ressources exploitées par la pêche et la conchyliculture. In: AcclimaTerra, Le Treut, H. (Eds.), Anticiper les changements climatiques en Nouvelle-Aquitaine. Pour agir dans les territoires. Éditions Région Nouvelle-Aquitaine. 978-2-9564516-0-0, pp. 200–223 Chap.8 (Editions Région Nouvelle-Aquitaine).

Chaudhuri, K., 1986. A bioeconomic model of harvesting a multispecies fishery. Ecol. Model. 32 (4), 267–279.

Chu, L., Kompas, T., 2014. Targets and fisheries management in the Asia and Pacific region. Asia Pac. Policy Stud. 1 (3), 615–622.

Clark, C.W., 1973. The economics of overexploitation. Science 181 (4100), 630–634.

Clark, C.W., 2010. Mathematical Bioeconomics: The Mathematics of Conservation. vol. 91 John Wiley & Sons.

Council, P.F.M., 1998. Amendment 8 of the Coastal Pelagic Species Fishery Management Plan, Appendix D. Description and Identification of Essential Fish Habitat for the Coastal Pelagic Species Fishery Management Plan.

Cury, P.M., Fromentin, J.-M., Bonhommeau, S., 2014. Resolving Hjort's dilemma: how is recruitment related to spawning stock biomass in marine fish? Oceanography 27 December.

Cushing, D.H., 1982. Climate and Fisheries. Academic Press.

Decastro, M., Gomez-Gesteira, M., Alvarez, I., Gesteira, J., et al., 2009. Present warming within the context of cooling-warming cycles observed since 1854 in the Bay of Biscay. Cont. Shelf Res. 29 (8), 1053–1059.

Dichmont, C., Pascoe, S., Kompas, T., Punt, A.E., Deng, R., 2010. On implementing maximum economic yield in commercial fisheries. Proc. Natl. Acad. Sci. 107 (1), 16–21.

Doyen, L., Béné, C., Bertignac, M., Blanchard, F., Cissé, A.A., Dichmont, C., Gourguet, S., Guyader, O., Hardy, P.-Y., Jennings, S., et al., 2017. Ecoviability for ecosystem-based fisheries management. Fish Fish.

Doyen, L., Thebaud, O., Béné, C., Martinet, V., Gourguet, S., Bertignac, M., Fifas, S., Blanchard, F., 2012. A stochastic viability approach to ecosystem-based fisheries management. Ecol. Econ. 75, 32–42.

Druon, J.-N., Fiorentino, F., Murenu, M., Knittweis, L., Colloca, F., Osio, C., Mérigot, B., Garofalo, G., Mannini, A., Jadaud, A., et al., 2015. Modelling of European Hake nurseries in the Mediterranean Sea: an ecological niche approach. Prog. Oceanogr. 130, 188–204.

EUMOFA, 2015. Etude de cas : La transmission des prix dans la fili'/ere du merlu frais en espagne. In: Technical report. European Market Observatory for fisheries and aquaculture products.

FAO, 2014. The state of world fisheries and aquaculture. In: Technical report. Food and Agriculture Organization of the United Nations.

Glantz, M., 1992. Climate Variability, Climate Change, and Fisheries. Cambridge University Press.

Goikoetxea, N., Irigoien, X., 2013. Links between the recruitment success of Northern European Hake (*Merluccius merluccius* L.) and a regime shift on the N-E atlantic continental shelf. Fish. Oceanogr. 22 (6), 459–476.

Gourguet, S., Macher, C., Doyen, L., Thebaud, O., Bertignac, M., Guyader, O., 2013. Managing mixed fisheries for bio-economic viability. Fish. Res. 140, 46–62.

Grafton, Q.R., Kompas, T., Che, T.N., Chu, L., Hilborn, R., 2012. BMEY as a fisheries management target. Fish Fish. 13 (3), 303–312.

Grafton, R.Q., Kompas, T., Chu, L., Che, N., 2010. Maximum economic yield. Aust. J. Agric. Resour. Econ. 54 (3), 273–280.

Grafton, R.Q., Kompas, T., Hilborn, R.W., 2007. Economics of overexploitation revisited. Science 318 (5856) 1601–1601.

Guevara-Fletcher, C., Alvarez, P., Sanchez, J., Iglesias, J., 2016. Effect of temperature on the development and mortality of European Hake (*Merluccius merluccius* L.) eggs from southern stock under laboratory conditions. J. Exp. Mar. Biol. Ecol. 476, 50–57.

Guillen, J., Macher, C., Merzereaud, M., Bertignac, M., Fifas, S., Guyader, O., 2013. Estimating MSY and MEY in multi-species and multi-fleet fisheries, consequences and limits: an application to the Bay of Biscay mixed fishery. Mar. Policy 40, 64–74.

Guyader, O., Levieil, D., Macher, C., Péreau, J.-C., Thébaud, O., Ulrich, C., 2017. Modelling Institutional Arrangements and Bio-economic Impacts of Catch Share Management Systems: Application to the Bay of Biscay Sole Fishery. Ph.D. thesis. Economies and Finances. Université de Bretagne occidentale, Brest.

Hermant, M., Lobry, J., Bonhommeau, S., Poulard, J.-C., Le Pape, O., 2010. Impact of warming on abundance and occurrence of flatfish populations in the Bay of Biscay (France). J. Sea Res. 64 (1), 45–53.

Hilborn, R., Walters, C.J., 1992. Quantitative fisheries stock assessment: choice, dynamics and uncertainty. Rev. Fish Biol. Fish. 2 (2), 177–178.

Hill, K.T., Crone, P.R., Lo, N.C., Macewicz, B.J., Dorval, E., McDaniel, J.D., Gu, Y., 2011. Assessment of the Pacific sardine resource in 2011 for US management in 2012. In: NOAA Technical Memorandum NMFS-SWFSC. 487.

Hughes, T.P., Bellwood, D.R., Folke, C., Steneck, R.S., Wilson, J., 2005. New paradigms for supporting the resilience of marine ecosystems. Trends Ecol. Evol. 20 (7), 380–386.

ICES, 2016. Hake in division IIIa, subaeras IV, VI & VII, ans divisions VIIIa,b,d (Northern Stock), ICES Advice 2016. In: Technical report. ICES.

ICES, 2017. Bay of Biscay and Atlantic Iberian waters stock sole in divisions VIIIa, b; ICES advice 2017. In: Technical report. ICES.

IPCC, 2013. IPCC Fifth Assessment Report (WGI AR5) chap. 9. In: Technical report. Intergovernmental Panel on Climate Change.

Kompas, T., Chu, L., 2018. MEY for a short-lived species: a neural network approach. Fish. Res. 201, 138–146.

Koutsikopoulos, C., Beillois, P., Leroy, C., Taillefer, F., 1998. Temporal trends and spatial structures of the sea surface temperature in the Bay of Biscay. Oceanol. Acta 21 (2), 335–344.

Laevastu, T., 1993. Marine Climate, Weather and Fisheries. Fishing News Books.

Lagiere, R., 2012. Evolution du systeme de gestion de la pecherie de sole du golfe de Gascogne et analyse preliminaire de la dynamique des flottilles. Memoire fin d'etudes. Agrocampus Ouest.

Larkin, P.A., 1977. An epitaph for the concept of maximum sustained yield. Trans. Am.

Fish. Soc. 106 (1), 1–11.

Le Pape, O., Bonhommeau, S., 2015. The food limitation hypothesis for juvenile marine fish. Fish Fish. 16 (3), 373–398.

Le Treut, H., 2013. Les impacts du changement climatique en Aquitaine: un état des lieux scientifique. Presses universitaires de Bordeaux.

Legovic, T., Gecek, S., 2010. Impact of maximum sustainable yield on independent populations. Ecol. Model. 221 (17), 2108–2111.

Link, J.S., Thébaud, O., Smith, D.C., Smith, A.D., Schmidt, J., Rice, J., Poos, J.J., Pita, C., Lipton, D., Kraan, M., et al., 2017. Keeping humans in the ecosystem. ICES J. Mar. Sci.

Mace, P.M., 2001. A new role for MSY in single-species and ecosystem approaches to fisheries stock assessment and management. Fish Fish. 2 (1), 2–32.

Michel, S., Vandermeirsch, F., Lorance, P., 2009. Evolution of upper layer temperature in the Bay of Biscay during the last 40 years. Aquat. Living Resour. 22 (4), 447–461.

Moffitt, E.A., Punt, A.E., Holsman, K., Aydin, K.Y., Ianelli, J.N., Ortiz, I., 2015. Moving towards ecosystem-based fisheries management: options for parameterizing multi-species biological reference points. Deep-Sea Res. II Top. Stud. Oceanogr.

Morandeau, G., Macher, C., Sanchez, F., Bru, N., Fauconnet, L., Caill-Milly, N., 2014. Why do fishermen discard? Distribution and quantification of the causes of discards in the southern Bay of Biscay passive gear fisheries. Mar. Policy 48, 30–38.

Mueter, F.J., Megrey, B.A., 2006. Using multi-species surplus production models to estimate ecosystem-level maximum sustainable yields. Fish. Res. 81 (2), 189–201.

Patrick, W.S., Link, J.S., 2015. Myths that continue to impede progress in ecosystem-based fisheries management. Fisheries 40 (4), 155–160.

Pikitch, E., Santora, C., Babcock, E., Bakun, A., Bonfil, R., Conover, D., Dayton, P., Doukakis, P., Fluharty, D., Heneman, B., et al., 2004. Ecosystem-based fishery management. Science 305 (5682), 346–347.

Plaganyi, E., 2007. Models for an Ecosystem Approach to Fisheries. Food & Agriculture Org. Number 477.

Poloczanska, E.S., Burrows, M.T., Brown, C.J., Garcia Molinos, J., Halpern, B.S., Hoegh-Guldberg, O., Kappel, C.V., Moore, P.J., Richardson, A.J., Schoeman, D.S., et al., 2016. Responses of marine organisms to climate change across oceans. Front. Mar. Sci. 3, 62.

Quinn, T.J., Deriso, R.B., 1999. Quantitative Fish Dynamics. Oxford University Press.

Rajudeen, R., 2013. Expansion of *Lophius piscatorius* distribution in iceland: exploring the ecological and economic viability for establishing sustainable monkfish fisheries in northwestern Iceland.

Ricker, W., 1958. Maximum sustained yields from fluctuating environments and mixed stocks. J. Fish. Board Can. 15 (5), 991–1006.

Sanchirico, J.N., Smith, M.D., Lipton, D.W., 2008. An empirical approach to ecosystem-based fishery management. Ecol. Econ. 64 (3), 586–596.

Shepherd, J., 1999. Extended survivors analysis: an improved method for the analysis of catch-at-age data and abundance indices. ICES J. Mar. Sci. J. Conseil. 56 (5), 584–591.

Thébaud, O., Doyen, L., Innes, J., Lample, M., Macher, C., Mahevas, S., Mullon, C., Planque, B., Quaas, M., Smith, T., et al., 2014. Building ecological-economic models and scenarios of marine resource systems: Workshop report. Mar. Policy 43, 382–386.

Tromeur, E., Doyen, L., 2018. Optimal harvesting policies threaten biodiversity in mixed fisheries. Environ. Model. Assess.

Union, E., 2016. Council regulation (EU) 2016/72 of 22th January 2016. In: Technical Report. European Union Council.

Voss, R., Quaas, M.F., Schmidt, J.O., Hoffmann, J., 2014. Regional trade-offs from multi-species maximum sustainable yield (MMSY) management options. Mar. Ecol. Prog. Ser. 498, 1–12.

Walters, C.J., Christensen, V., Martell, S.J., Kitchell, J.F., 2005. Possible ecosystem impacts of applying MSY policies from single-species assessment. ICES J. Mar. Sci. J. Conseil. 62 (3), 558–568.