Optimal bioeconomic management of the Eastern Atlantic Bluefin tuna fishery: where do we stand after the recovery plan?

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Abstract — Highly migratory species, such as tunas and tuna-like species, represent both economically and biologically significant stakes for the world fisheries. The Eastern Atlantic Bluefin tuna (EABFT) is one of the most charismatic tuna species, and faces today a critical phase in its management. After a long period of over-exploitation, the signals from stock assessment are positive and the population seems to have fully recovered. In the present research, we estimate the optimal management strategy, which refers to the dynamic maximum economic yield concept (MEY), for the EABFT based on an age-structured bio-economic model in line with the current assessment of the stock by the International Commission for the Conservation of Atlantic Tunas (ICCAT). Using optimization method and taking total allowable catch (TAC) directly as the state variable, we show that the bio-economic optimal management strategy follows a smooth path converging toward the spawning stock biomass (SSB) steady state which is well above SSB at the maximum sustainable yield (MSY) level whatever the recruitment or global supply scenarios considered. Integrating selectivity as a state variable, the optimal strategy remains close to the current one with a more balanced fishing mortality over all age classes. Finally, applying stochastic dynamic programming, we show that stock measurement errors, which represent a critical issue for highly migratory fish stocks, do not affect the optimal management. The MEY harvest policy estimated is robust to measurement errors. Our results indicate that adopting a new policy based on the dynamic maximum economic yield (MEY) could meet both conservation and economic objectives for the EABFT fishery.

Keywords— *Bioeconomic modeling; Uncertainty; Optimal resource management; Atlantic Bluefin tuna; Fisheries management; International fisheries; Policy making.*

1. Introduction

Highly migratory species, such as tunas and tuna-like species, represent both economically and biologically significant stakes for the world fisheries (Munro et al. 2004, Galland et al. 2016). Tunas are spread and caught over all the oceans (Miyake et al. 2010). They sustain some of the most valuable fisheries and feed international supply chains (Catarci, 2005, Majkowski, 2007). Tunas fisheries are integrated in a global market involving many regional markets (Jeon et al. 2008; Jiménez-Toribio et al. 2010; Guillotreau et al. 2017) under the influence of the worldwide demand for tuna commodities (Catarci, 2005; Mullon et al. 2017). High values on international market make species such as tuna and tuna-like species particularly vulnerable (Colette et al. 2011), and the status of a number of stocks are particularly worrying (Maguire et al. 2006, Juan-Jorda et al. 2011).

The Eastern and Mediterranean stock of the Atlantic Bluefin tuna (EABFT) falls in this group of concerns. The sales value was estimated to more than $700 million in 2014, out of a total end value exceeding $2 billion for the three major BFT species (Galland et al. 2016). The EABFT fishery faces today a critical phase in its management. After a long period of over-exploitation (Fromentin et al. 2014), signs of recovery are evidenced by stock assessment experts (ICCAT 2017). A stock rebuilding plan was launched in 2007 with a 60% likelihood of achieving sustainability by 2022. In 2017, under the majority of recruitment level scenarios[1], the stock had already recovered to the expected level. The new management stakes consist in defining quotas to keep the stock (biomass) above the maximum sustainable yield level (B_{MSY}), despite high pressures from the fishing nations to increase their quotas drastically. The last estimates from the International Commission for the Conservation of Atlantic Tunas (ICCAT) indicate that the stock rebuilding could be achieved by 2022 with probabilities higher than 60% for all recruitment scenarios by setting catch limits up to 30,000 tons (ICCAT, 2017), i.e. more than twice the limits enforced in 2009.

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[1] Three recruitment scenarios are considered in the stock assessment: low, medium and high mean recruitment levels.

In this context of high uncertainties, the new management scheme of ICCAT implies a TAC of up to 32,000 tons by 2020[2]. Is the new management policy based on MSY adapted to the productivity of the EABFT stock, or does it jeopardize the future of the fishery by going back to the crisis situation of the late 2000s?

Shifting objectives from the traditional MSY target to the dynamic maximum economic yield should result in most cases a no-regret situation in which management promotes both larger fish stocks and higher profits ($B_{MEY} > B_{MSY}$[3], Grafton et al. 2007, 2010, Clark, 2010). In a context of international trade, this dual benefit could be strengthened (or mitigated) by the market price response to changes in landings (Sun et al. 2015; Sun et al. 2017; Guillotreau et al. 2017; Tokunaga 2018). Previous bio-economic optimization models analysed optimal harvest in age-structured frameworks compatible with stock assessments procedure. Bertignac et al. (2000) and Kompas et al. (2010) applied stochastic dynamic programming to the Western and Central Pacific tuna fisheries to show that adopting the B_{MEY} target leads to better conservation outcomes with larger fish stocks and higher economic profits than the business-as-usual scenario. Similarly, Kulmala et al. (2008) numerically solve their harvest optimization model for the age-structure population of the Atlantic salmon fishery in the Baltic Sea and demonstrate the economic benefits of the optimal solution without compromising the sustainability of the resource. Finally, Tahvonen et al. (2017) analysed the optimal harvesting strategy of the Baltic cod fishery including gear selectivity as a state variable in a stochastic model. They showed that endogenous selectivity strongly changes the MEY harvest pattern and increase substantially the profit obtained from the fishery. They also highlighted that the stochastic solution can be accurately approximated by the certainty equivalence principle.

The objective of this study is to develop tools for producing economically sound management advice for EABFT. To the best of our knowledge, the only study attempting to estimate economic optimal management of EABFT fishery was Bjorndal & Brasao

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[2] ICCAT Recommendation 17-07 (2017).

[3] This result comes from the literature based on the surplus production model considering reasonable discount rates.

(2006) who based their analysis on an age-structured, multi-gear model which lead to pulse fishing[4] as an optimal solution. In the present research, we propose to update and revisit their estimation by using a discrete age-structured population optimization model for the EABFT in line with the framework used for the stock assessment by ICCAT. This optimization framework based on the general age structured bio-economic model of Tahvonen et al. (2013) uses directly annual harvest, total allowable catch (TAC) as an optimized variable. We extend the model by including non-linear demand function affected by the supply of all Bluefin tuna stock on the global market and stock-dependent harvesting costs. Furthermore, we analyse the effects of considering different recruitment levels according to ICCAT scenarios and different evolution of Bluefin tuna supply levels. Finally, we determine the optimal management when selectivity pattern is integrated as an endogenous variable in addition to the TAC in the model. Our work suggests that adopting the MEY target meets both conservation and economic objectives by keeping the stock to higher level than under the current MSY target and producing higher benefits for the fishery. This result is exacerbated when selectivity is defined endogenously, shifting to a more balanced fishing mortality over all age classes.

Finally, we deal with the specific context of a highly migratory and schooling fishery of high measurement errors[5] on the stock level. Highly migratory species such as the EABFT suffer from a lack of independent observations (i.e. not directly related to catches) to track down changes in stock abundance. The fitting quality of the stock assessment relies on catch per unit of effort (CPUE) indices produced by commercial activities which are, among other factors, affected by recent regulatory measures of the rebuilding plan. The recent development of aerial fishing-independent surveys is a good basis to improve abundance indices (Fromentin et al. 2011). Based on the results from Tahvonen et al., (2017) we did not consider stochastic processes, but we fully acknowledge the presence of measurement errors by extending the previous work of Sethi et al. (2005) to an age-structured framework specifying equilibrium assumptions. Using dynamic stochastic programming, our results indicate that measurement errors

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[4] Periodic fishing.

[5] Equivalent to observation errors.

strongly affect the optimal management of the EABFT fishery, resulting in a lower SSB steady state compared to the full information case.

2. Material and methods

2.1. The Age-Structured model

Following the formulation and notation for an age structured schooling fishery from Tahvonen et al., (2013), we define a discrete age-structured population model for the EABFT. We extend the work of Tahvonen et al. (2013) by integrating a non-linear demand function and a cost function which integrates a stock effect on harvesting cost. We also focus our analysis on measurement errors by extending the previous work of Sethi et al., (2005) using an age structured framework. This section shows the general age structured population model, then the parameterization of the EABFT fishery and finally the numerical analysis of the optimal management.

We define $x_{s,t}$ as the number of fish (in 10^6 individuals) in each age class $s = 1, \dots, n$ and each year $t = 0, 1, \dots, T$. We determine the recruitment function by $\phi(ssb_t)$ and the spawning biomass by ssb_t, considering an equal sex ratio, the first age class of the age-structured population model can be written as:

$$x_{1,t} = \phi(ssb_t) \qquad \text{Eq 1}$$

$$ssb_t = \sum_{s=1}^{n} g_s \,.\, w_s . x_{s,t} \qquad \text{Eq 2}$$

We denote the parameters g_s and w_s the constant age-specific maturities, and weight of fish (kg) respectively.

As Tahvonen et al., (2013), we assume that fishing activity takes place every year after recruitment but before natural mortality. We determine total catch (H_t) in biomass (kg) as the decision variable. Denoting $H_t = Fmax_t . B_t^{\chi}$ with $B_t = \sum_{s=1}^{n} sel_s \,.\, w_s . x_{s,t}$ the vulnerable biomass called 'efficient biomass' (Tahvonen et al., 2017), χ the catch-stock elasticity parameter and $Fmax_t$ the fishing mortality at maximum selectivity, we can write the age-structured population model as:

$$x_{s+1,t+1} = \alpha_s . (x_{s,t} - H_t . G_{s,t}), \text{ for } s = 1, \dots, n-2, \qquad \text{Eq 3}$$

$$x_{n,t+1} = \alpha_{n-1}.(x_{n-1,t} - H_t.G_{n-1,t}) + \alpha_n.(x_{n,t} - H_t.G_{n,t}) \qquad Eq\ 4$$

With $G_{s,t} = \frac{sel_s.x_{s,t}}{B_t}$ convert the total catch H_t into the numbers of fish harvested from each age class. We denote the parameters α_s, sel_s the constant age-specific survival rate and fishing selectivity respectively.

We define the utility as the annual profit function, $U(H_t)$, that depends on the total annual catch and the efficient biomass:

$$U(H_t, B_t) = R(H_t) - C(H_t) \qquad Eq\ 5$$

Assuming harvesting costs are proportional to fishing mortality, the cost function is defined as:

$$C(H_t, B_t) = c.H_t.{B_t}^{-\chi} \qquad Eq\ 6$$

With c and χ the cost scale in euros and the schooling parameters respectively.

Revenues depend on the price of Bluefin tuna which is formulated as an overall iso-elastic downward-sloping demand function $P(H_t)$:

$$R(H_t) = P(H_t).H_t \qquad Eq\ 7$$

Finally, the optimization problem is:

$$max_{\{H_t\}} \sum_{t=0}^{T} U(H_t).\delta^t \qquad Eq\ 8$$

With T the finite planning horizon, $\delta = \frac{1}{1+r}$, the discount factor and $r \geq 0$ as the discount rate.

The objective function is subject to equations 1, 2, 3, 4, and the conditions:

$x_{s,0}$ given,

$$x_{s,t} \geq 0\ ,\ for\ s = 1, \ldots, n\ and\ t = 1, \ldots, T;$$

$$H_t \geq 0,\ for\ t = 1, \ldots, T.$$

The biomass and harvest steady state solution of this problem commonly refers to the dynamic maximum economic yield (MEY) concept.

Based on this model, we derive the equilibrium age structured population considering the long term population under a constant fishing mortality F_{max} (Supplementary materials, appendix 1). This leads to the definition of the MSY level which is the management target of EABFT. The MSY level will be the basis for the comparison of the optimal management, but it drastically depends on the recruitment function parameters estimation which is highly variable throughout time. As ICCAT, we consider 3 recruitment levels corresponding to the fitting of the Beverton and Holt relationship for a high recruitment period (1990-2010), a medium recruitment period (1970-2010) which is our reference case and a low recruitment period (1970-1980).

We also compare the outcomes from the recruitment level reference case with scenarios including a non-constant evolution of EABFT's substitutes global supply. We consider two cases: a linear 50% increase or decrease of BFT supply over the next 25 years to estimate the potential impact of exogenous variation of prices on the EABFT management. Finally, we integrate selectivity as an endogenous state variable in the optimization process to evaluate the impact of optimizing selectivity on the dynamic MEY.

2.2. The East Atlantic Bluefin tuna (EABFT) fishery

The Eastern Atlantic Bluefin tuna has been an archetype of the overexploitation and mismanagement of marine resources (Fromentin et al. 2014). Several countries, either coastal or distant water fishing nations, have contributed to a high level of depletion driven by the high market value of the tuna on the Japanese market. The decline in the EABFT has raised considerable concerns about its management in the 2000s (Hurry et al., 2008, ICCAT 2007, ICCAT 2009). Under the governance of ICCAT, a Regional Fishery Management Organization (RFMO), the fishery has suffered, at the same time, from its failure to follow scientific advice and a high level of illegal, unreported and unregulated (IUU) fishing. This situation occurred when the first management regulation based on quotas (TAC) appeared in 1999 and lasted until 2007 with the implementation of a recovery plan for the EABFT fishery. After 2009 and the strict management measures which have been implemented, the stock has showed signs of increase in the last years to peak a potential spawning stock biomass (SSB) value up to 610.10^6 t in 2015 (ICCAT 2017). A combination of a decrease in fishing pressure and potential high recruitment events resulted in a strong increase of the SSB. Presently, the stock is regarded as fulfilling the objective of the recovery plan ($F<F_{0.1}$ and $SSB>SSB_{0.1}$[6]), depending nonetheless on the assessment scenarios and assumptions. The magnitude of the SSB recovery appears to be very sensitive to slight changes in the input data (notably data) and technical assumptions (ICCAT 2017).

Following the standard stock assessment by ICCAT (2014), we consider 10 age classes (n). Age-specific maturities (g_s) and survival rates ($\alpha_s = e^{-m_s}$, with m the natural mortality at age) which are directly taken from the (ICCAT 2017) assessment report. For the age-specific weights (w_s in kg per individual), we use the mean values of the period 2011-2014 (Table 1). Selectivities (sel_s) are estimated by the catch curve analysis method (Kell et al., 2013) for the period 2011-2015 and equal to 1 for the oldest age class by normalization. Recruitment is assumed to follow the Beverton and Holt (1957) recruitment function:

$$x_{1,t} = \phi(ssb_t) = \frac{\phi 1.ssb_t}{\phi 2 + ssb_t} \qquad Eq\ 9$$

We use ICCAT (2017) data on spawning stock biomass and recruitment for the years 1970 to 2010 (corresponding to the medium recruitment scenario of ICCAT), and we estimate the parameters by maximizing the likelihood function assuming a lognormal error structure with the Fisheries library R (‘FLSR’ package in FLCore 3.0, Kell et al. 2007). We constrained the estimation by setting the steepness[7] at 0.99 following ICCAT (2017) parametrisation in order to specify a quasi-constant recruitment level. This yields the estimates of the asymptotic recruitment $\phi 1$ = 2,230,398 recruits (standard

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[6] $F_{0.1}$ and $SSB_{0.1}$ are proxies of F_{MSY} and SSB_{MSY} and are common biological reference points for management (Deriso 1987, Hilborn & Walters 1992).

[7] Steepness represents the fraction of the virgin recruitment expected when SSB has been reduced to 20% of its maximum (Francis, 1992).

deviation 12,672 individuals) and the SSB needed to produce the half of the asymptotic recruitment ϕ2 = 1,155,983 kg (standard deviation 5,403 kg).

Table 1 Biological parameters used in the model.

Age-class [year]	**Survival rate α**	**Maturity g**	**Weight w [kg]**	**Selectivity *sel***	**$X_{s,0}$ [individuals]**
1	0.61	0	4.33	0.002	6,541,127
2	0.79	0	10.66	0.55	5,232,334
3	0.79	0	24.00	0.38	2,185,608
4	0.79	0	35.67	0.67	1,036,139
5	0.79	1	52.33	0.69	595,821
6	0.82	1	72.67	0.34	421,575
7	0.84	1	96.00	0.32	551,023
8	0.86	1	119.33	0.33	824,995
9	0.88	1	144.33	0.35	566,447
10	0.90	1	202.00	1.00	1,417,591

Economic data are limited for this fishery. To estimate the price and the harvesting cost function, we use the data from 2008 to 2015 describing the European purse seine fishery (Supplementary materials, appendix 2), which represents the majority of the TAC (more than 60% since 2008). We estimate the parameters based on the French and Spanish purse seine fleet segment data available from the Scientific, Technical and Economic Committee for Fisheries (STECF 2016) and data on spawning stock biomass from ICCAT (2017).

EABFT is a large highly migratory schooling species which is the main target for purse seine commercial fisheries in the Mediterranean Sea. The low TAC level of the early 2010s as well as the good knowledge of seasonal migration and concentration patterns in the Mediterranean (Fromentin & Powers 2005), in combination with technology-based information on the fishing activities and prospecting equipment, result in minor search costs within a short fishing period (usually less than a month, the purse-seiners remaining idle at ports for the rest of the year). We estimate the generalized cost function by mean of non-linear least square method (R package ‘stats’). Using data on catch, efficient biomass and variable costs, we estimate the cost parameter (c) and the catch-stock elasticity parameter (χ) following the relationship:

$$c_t = c.H_t.B_t{}^{-\chi} + \epsilon_t,\ with\ \epsilon_t \sim IIDN(0, \sigma^2)$$

We only include variable costs (c_t) that directly depend on fishing activity including gear and vessel maintenance, fuel and labor (crew wages) costs. Assuming a normal error structure, we obtain the estimate of the cost scale parameter, c = 201.6 € (standard deviation € 2102.5) and the estimate of χ = 0.18 (standard deviation 0.53). This value is consistent with a schooling fishery parameter ($\chi < 1$) and close to previous elasticity used in the literature (χ = 0.2 in Bjorndal & Brasao, 2006).

The EABFT purse fishery is driven by the rising Japanese demand for fatty tuna intended to high-quality sushi/sashimi market. The quasi totality of EABFT caught by purse seiners is sold to fattening farms in the Mediterranean Sea (Mylonas et al., 2010). Since the 1990s selectivity mainly shifts toward large tuna caught in the Western Mediterranean (Fromentin & Bonhommeau., 2011). Tunas are fattened during a 5-7 month period and sold on the Japanese sashimi market when domestic demand is high (usually at the end of the year). Fattened EABFT is mainly sold frozen to the Japanese market, representing more than 80% of the market since 2006 (Mylonas et al., 2010). In the Eastern Mediterranean, a smaller part of EABFT are caught by purse seiners, generally smaller individuals (less than 60 kg), and reared for longer periods (around 2 years) during which initial weight can be doubled (Mylonas et al., 2010).

Despite the relationship between the age, quality and price of tuna (Caroll et al., 2001, Mylonas et al., 2010), we consider a constant price per age. This assumption is adopted because of a lack of price data per age or size, therefore we use the same price for all age groups. We further assume that the overall demand-function is iso-elastically downward-sloping. Thus, the price function $P(H_t)$ is defined as

$$P(H_t) = p.(\,H_t + \,Hbft_t)^{-\varphi} \qquad Eq\ 10$$

With p the theoretical price of the first sold kilos of Bluefin tuna and Hbf_t is defined as the aggregated supply of all other Bluefin tuna species (including Pacific and Southern Bluefin tuna) which are considered as close substitutes on the sashimi-grade tuna market (Sun et al., 2017). Using catch data from the different RFMOs (ICCAT, IATTC, ISC, and CCSBT, Supplementary materials, appendix 3) in charge of the management of Bluefin tuna species and purse seine ex-vessel price from STECF we estimate the price parameter p = 91,983,194 € (standard deviation 8,947,638) using non-linear least square method.

$$p_t = p.(\,H_t + \,Hbft_t)^{-\varphi} + \epsilon_t,\ with\ \epsilon_t \sim IIDN(0,\sigma^2)$$

As Japan is the main market for Bluefin tuna products, we integrate the price scale flexibility parameter φ=0.91 (standard deviation 0.034) estimated by Sun et al., (2017) from an inverse demand analysis of Bluefin tuna auction price. This estimate is based on frozen Bluefin tuna (Pacific and Atlantic) products pricing on the wholesale market (Tsukiji) in Japan. The recent increase of TAC (from 13,500 tons in 2014 to 19,296 tons in 2016, i.e. an increase of 43%) has negatively impacted the global frozen BFT price (11% decrease, Sun et al., 2017) through the auction market in Japan which represents more than 80% of the Bluefin tuna sashimi market in the world (fresh and frozen, Sun et al., 2017). The effect of the EABFT supply on the global sashimi tuna product price is crucial in the analysis of the optimal management. In a near future, only the supply of EABFT is about to vary with an adjustment of the quotas (TAC) after the success of the recovery plan. Thus, we consider in our model a constant supply of BFT (Southern and Pacific Bluefin tuna) substitutes corresponding to the mean harvest from 2008-2015, i.e. 34,636 tons.

2.3. Numerical analysis

We numerically analyse optimal management in a setting of no uncertainty by solving the dynamic optimization model as an open-loop nonlinear programming problem. This is performed using the COBYLA algorithm of the NLopt optimization package (Johnson, 2017) with R (R core team 2017).

We also perform the optimization problem by integrating stock measurement errors. The solution of this problem requires to solve the stochastic program in closed-loop formulation by backward recursion of Bellman's equation. Bellman's (1957) principle of optimality implies that the optimal policy must satisfy the functional equation:

$$V_t(X_t) = max_{0\le H_{t,\dots,T}\le B_{t,\dots,T}}\{\,U(H_t,X_t) + \text{ä}\,.\textstyle\sum_t^T P(X_{t+1}|H_{t+1},X_t).V_{t+1}(X_{t+1})\}\quad Eq\ 11$$

Where X (the number of individuals), represents the state space which determines all states attainable, B the resulting efficient biomass ($B_t = \sum_{s=1}^{n} sel_s\,.w_s.x_{s,t}$), and H (the harvest level in biomass), represents the actions space which determined all possible actions that a theoretical manager could decide. V is the value function, U is the utility function (Equation 5) corresponding to the immediate reward and P represents the transition probability matrix between each state X_t to X_{t+1} given all harvest level H_t. Considering a discount factor ä < 1 , the mapping underlying the Bellman's equation is a strong contraction and thus, by the Contraction Mapping Theorem, possess a unique solution.

For computational effort reasons, we simplify the optimization problem by taking the equilibrium age structure $x_{s,t}$ for each value of the state X_t considering a constant fishing mortality *Fmax* (Supplementary materials, appendix 1 following the specification of Tahvonen et al. 2009).

We include a random variable underpinning the uncertainty in period t, Z_t, which affects stock measurement. This random variable is independent and identically distributed (IID) over years. Integrating a measurement uncertainty implies to define an observation variable of the stock $Xobs_t$, which is defined as follow:

$$Xobs_t = Z_t . X_t \qquad Eq\ 12$$

Where $X_t = \sum_{s=1}^{n} x_{s,t}$. and $Z_t \sim \mathrm{U}(1\text{-}\sigma_m, 1 + \sigma_m)$.

We consider a theoretical manager who only uses the current measurement $Xobs_t$ to form beliefs about the current stock, X_t and select a total allowable catch (TAC) for the fishery based on the current rent $U(H_t)$ from harvesting. Following Sethi et al. (2005), our assumption states that the manager only uses the current assessment when forming expectations. This method specifies the problem as a Markov decision process (MDP) in which the current measurement is the only state variable for the manager's problem. To keep the Markov property, we restrict the problem by defining the probability of a transition from state X_t to X_{t+1} conditionally independent on all past states and actions ($X_{t-1,} X_{t-2}, H_{t-1,} H_{t-2}$ and so on). We assume that the manager ignores past measurements in forming expectations, mainly because of the modeling choice and practical considerations.

We solve this problem on a finite time horizon T = 80 years using value iteration algorithm (following the methodology of Boettiger et al., 2016), but we consider only the 50 first projection years for analysis. We also discretize the state and decision variable space over a regular sequence of a length out of 1000 steps from 0 to 12.10^6 individuals.

The optimal solution of the deterministic closed-loop formulation has to be expressed as a feedback policy, which could refer to a harvest-control rule in fishery management. The feedback policy indicates the optimal harvest quantity H_t as a function of the state of the fishery X_t. As mentioned above, we simplified the optimization problem by assuming an equilibrium age structured population at each discretized state space. Despite this assumption, we control that the solution of the closed-loop formulation is close to the solution of the open-loop formulation. This shows that the approximation to discretize the state space and considering the age structure of the stock at the equilibrium leads to reasonably good results on the aggregated indicators level (Supplementary materials, appendix 4).

3. Results

3.1. Optimal management of Eastern Atlantic Bluefin tuna (EABFT)

In our deterministic model, long term equilibriums are fully determined by the biologic characteristic of the population and the selectivity pattern of the fishery. Harvest at the MSY level for the recruitment reference case reaches a level of 35,800 tons corresponding to a SSB of 197,400 tons (Figure 1). MSY varies between 18,700 tons corresponding to a SSB of 105,000 tons for the low recruitment case and 55,200 tons with a SSB of 302,700 tons for the high recruitment case.

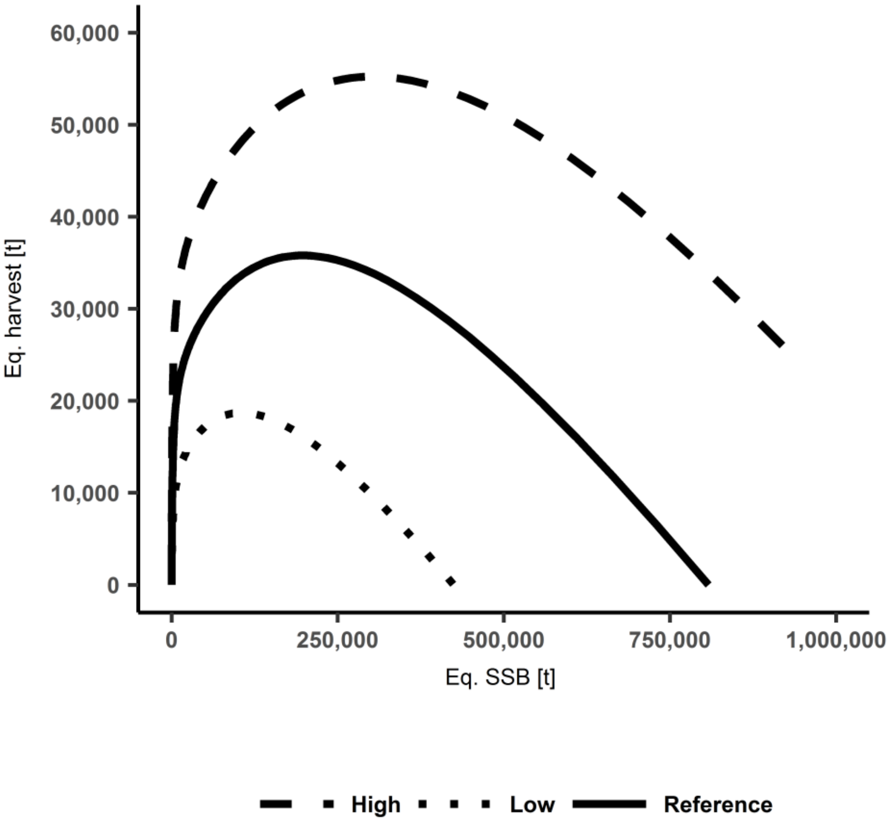

Figure 1 Relationship between the steady state harvest (in tons) and spawning stock biomass (SSB in tons) for the Eastern Atlantic Bluefin tuna (EABFT). The solid line represents the references recruitment case corresponding to the medium recruitment scenario of ICCA which corresponds to data on spawning stock biomass and recruitment for the years 1970 to 2010. The upper dashed line refers to the high recruitment scenario corresponding to the period 1990 to 2010, and the lower dotted line shows the low recruitment scenario corresponding to the period 1970 to 1980.

The optimal management of the EABFT targets the biomass level that maximizes the sum of the discounted (net present) values (NPV) from fishing (Equation 8), this level being called the B_{MEY}. The program is solved in the deterministic open-loop formulation which displays a smooth pathway toward a constant steady state population level (Figure 2). Considering an interest rate of 2%, the optimal steady-state SSB is around

564,600 tons (mean over the period 2055 to 2065), much higher than the SSB at MSY level representing only 35% of the steady state level[8]. Furthermore, this level is higher than the mean SSB level from 1970 to 2009 while the steady state harvest of around 20,100 tons (mean over the period 2055 to 2065) which quite lower than the mean level of the 'over-harvested' period from 1999 to 2009. Moreover, the catch level during this period is likely to be higher than the reported catch because of IUU fishing (ICCAT 2014). Available information on fishing capacity showed that catches of EABFT were seriously under-reported from 1998 to 2007. Under the reference recruitment level, the steady state harvest, representing 56% of the MSY level, is reached after a short period of slightly higher harvest intensity and creates an annual profit of 64 million euros with a high proportion of old age class fish. Along the smooth transition to the steady state, the harvest level gradually decreases while the profit stay quasi-constant, as the market price stays around 8.3 € per kg of fish. However, this result is very sensitive to the cost function parameters. Schooling and cost scale parameters fully determine if the MEY level is determined with a higher SSB and lower catch than MSY or on the contrary if the MEY converge to a level slightly above MSY for the catch and below for the SSB for lower cost and/or lower schooling behavior (χ tends to 1 and/or c tends to 0, see Supplementary materials appendix 5).

The optimal management of the EABFT could be also affected by an exogenous change of global Bluefin tuna supply. A 50% increase of overall Bluefin tuna supply negatively impacts the price from 8.4 to 6.8 € per kg and reduces the profitability of the fishery by 37.4% while a decreasing supply of substitutes increases the price to 11.4 € per kg and raises the profitability by 65.0 % (Figure 2). Furthermore, the recruitment levels affect the productivity of the stock and modify the equilibrium estimation (Figure 1). Assuming a low recruitment level drastically reduces the profit from the fishery with a lower sustainable harvest level of 14,200 tons, increasing the price to 9.26 € per kg. On the contrary, a high recruitment level raises the profit expected from higher harvest level of 24,000 but lowered the price to 7.8 € per kg (Figure 2).

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[8] Refer to the supplementary materials appendix 5 for a sensitivity analysis of the key economic and biological parameters of an optimal policy.

Including selectivity as an endogenous variable in the optimization produces optimal steady states very close to the current selectivity pattern. Considering a perfect and costless selectivity, the steady state harvest level stays around 20,000 tons with a more balanced fishing mortality over all age classes (Figure 3). This result is very sensitive to the estimation of the cost function parameters such as the optimal steady state discussed above (see Supplementary materials, appendix 5). For different combinations of scale cost and schooling parameters, the selectivity pattern switches toward the oldest age class.

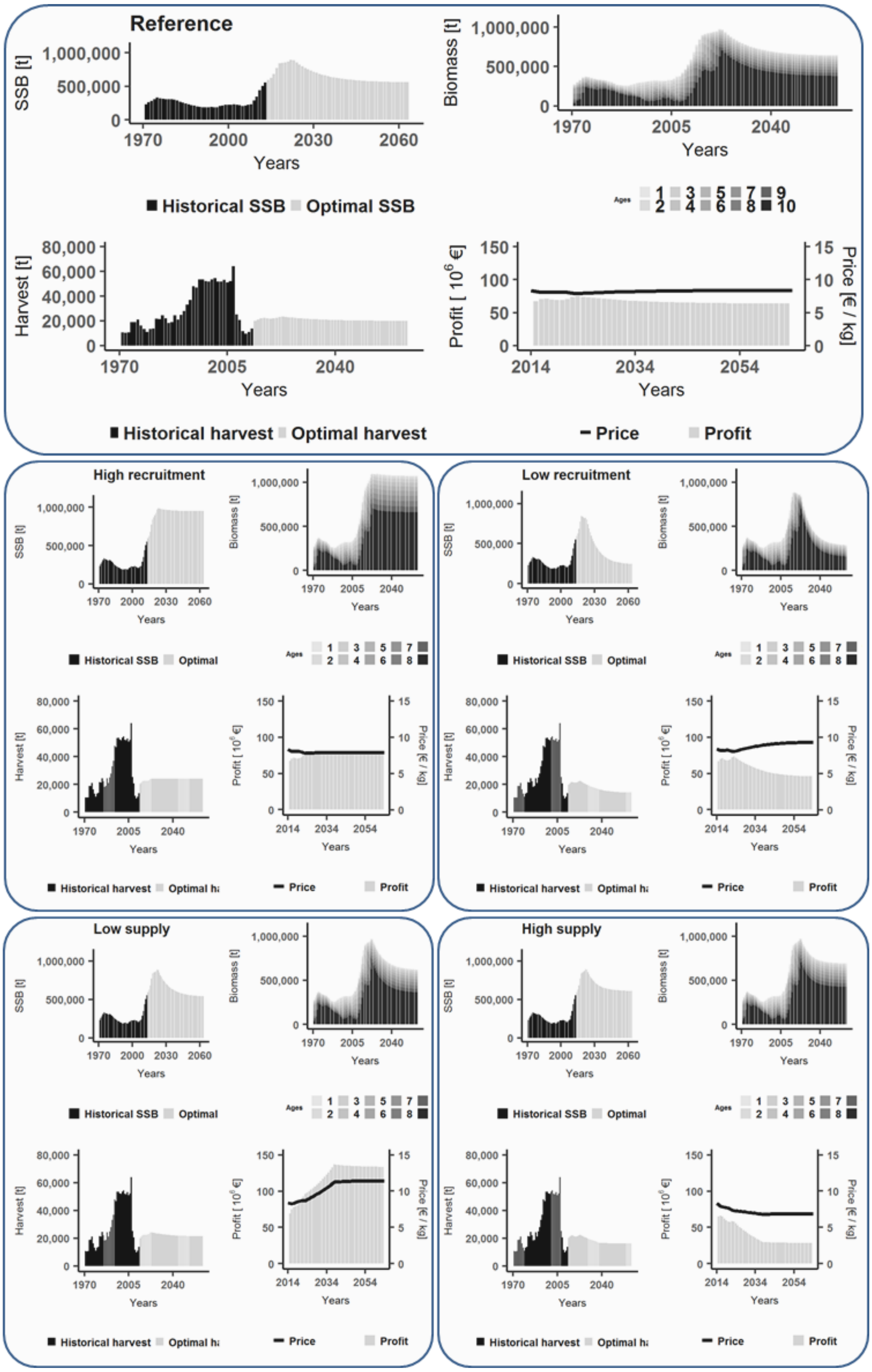

Figure 2 Historical and optimal management of Eastern Atlantic Bluefin tuna (EABFT) with a 2% discount rate for each recruitment level and supply scenarios. Historical data are collected from ICCAT (2017) for the period 1970–2014.

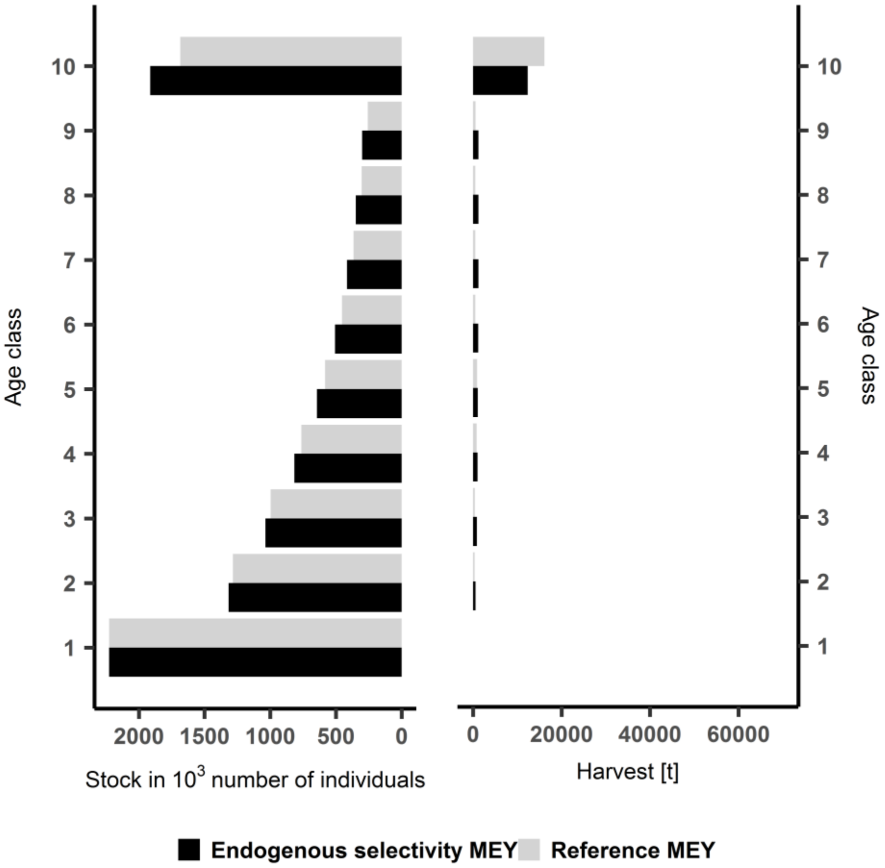

Figure 3 Steady state stock number and harvest per age class for the reference dynamic MEY and dynamic MEY with endogenous selectivity.

The optimal exploitation of fish populations also depends on interest rate levels (Clark 1973). The effect of increasing the discount rate up to 25% does not affect too much the optimal steady state. SSB steady state only decreases by 7% (Figure 4) while the steady state harvest increase of about 18%. Finally, it is worth noticing that the steady state SSB remains higher than MSY level even with high discounting.

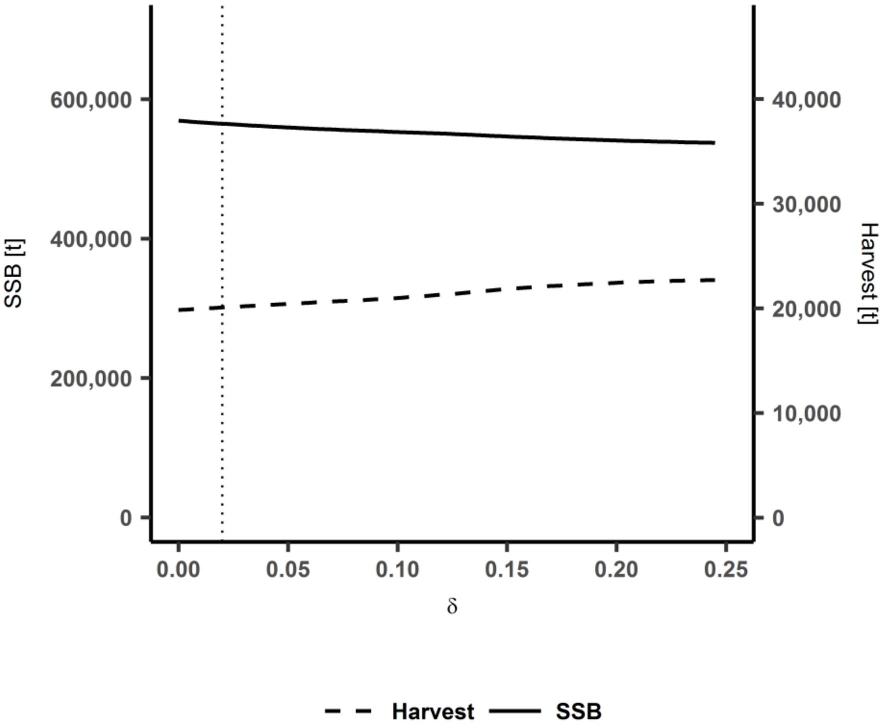

Figure 4 Dependence of the steady state spawning stock biomass (SSB in tons) on the discount rate. The dotted line represents the optimal steady state for the selected model parameters.

3.2. Effect of measurement errors

Measurement errors represent an important feature of the highly migratory species assessment in which the lack of fisheries-independent indices are common. To analyse the effects of measurement uncertainty on management, we consider a stylized representation where a uniformly distributed noise Z_t with different errors level σ_m (0, 0.3, 0.6, 0.9 and 1.2) alters information on stock levels. We simulate 500 times the optimal path (Figure 5) following the optimal policy obtained from the solution to Bellman's equation (Equation 11) under the different uncertainty levels. We observe that measurement uncertainty has an insignificant effect on the optimal harvest path even when the uncertainty level becomes high. The accuracy of information about the resource level does not affect the capacity of a manager to define a TAC-based policy. As described by simulations, measurement uncertainty unambiguously increases the harvest level but reduces the net expected present value (NPV) of the fishery (not shown). The MEY policy defined by a low harvest rate and a high population level is robust to measurement errors. This result is also sensitive to the cost and schooling parameters. As the MEY becomes close to the MSY level, measurement errors increase.

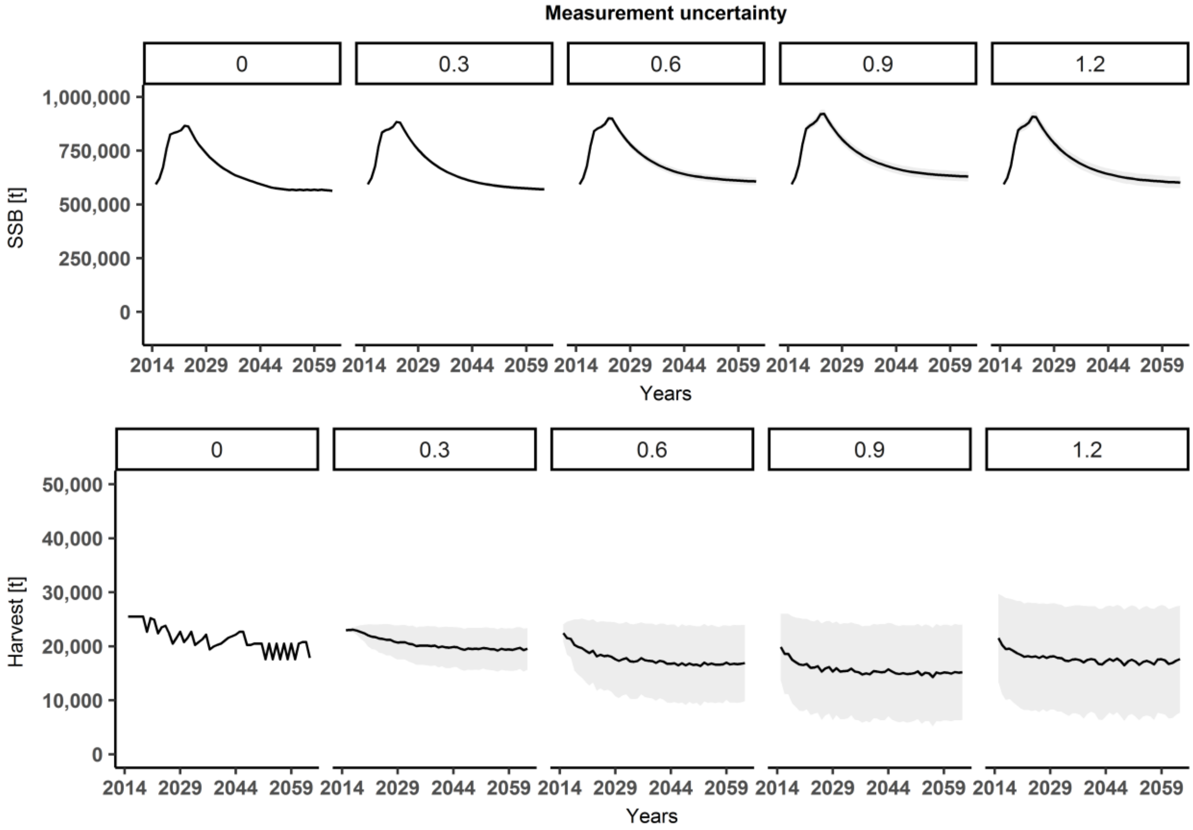

Figure 5 Results of 500 independent simulations of the closed-loop optimization model with different level of uniformly distributed measurement uncertainties ($\acute{o}_m =$ 0; 0.3; 0.6; 0.9 *and* 1.2*). On the top charts, the optimal path of spawning stock biomass (SSB in tons) from 2014 to 2064. On the bottom charts, the optimal path of harvest (in tons) from 2014 to 2064. The grey shaded region represents the standard deviations.*

4. Discussion

This study provides a bioeconomic model of the EABFT fishery in line with the ICCAT stock assessment procedure. This work updates previous analysis of Bjorndal & Brasao (2006) which found out pulse fishing as optimal management. We outline the optimal dynamic exploitation of the EABFT fishery by setting directly the harvest level as a fishing quota (TAC) and considering an age structured model which explicitly takes into account the schooling behavior of Bluefin tuna. Our model integrates the effect of the global supply of EABFT close substitutes on the price, analyses the effects of different recruitment levels and selectivity as an optimized variable. Using actual economic data of the European purse seine fishery, the model has been applied to determine the optimal economic policy for EABFT fishery.

4.1. Toward a new management target

After the success of the stock recovery plan launched in 2009, the definition of the pathway toward the optimal management target is crucial for the management of the EABFT fishery. The bio-economic optimal management strategy defines a pathway converging toward the steady state starting with high harvest rate to reach a SSB steady state slightly inferior to the SSB at the MSY level (even with zero discounting). This result contradicts what has been observed in Tahvonen et al. (2017), and supports the message from previous economic studies showing that the MEY management policy leads to a 'no regret' situation, increasing both the stock size and economic profits (Grafton et al., 2010). Moreover, the sharp decrease of the SSB steady state compared to the steady state harvest with an increasing discount rate widens the gap between the MEY and MSY outcomes. In face of a highly uncertain future, the EABFT fishing industry has strong incentives to harvest more and overexploit the stock beyond the MSY level.

A key issue in the assessment of the EABFT fishery is the confidence that scientists put in the magnitude of the recent SSB recovery, which mainly relies on a high estimate of recruitment levels from 2004 to 2007 (ICCAT, 2017). We integrate to our model the 3 recruitment scenarios used in the projection scenarios by ICCAT to explore the effect of a potential discrepancy in the recruitment level. Considering a constant selectivity pattern, the different levels of recruitment does not qualitatively affect the results, the SSB steady state remains higher than the SSB at the MSY level. However, quantitative results change substantially, considering a low recruitment instead of a high recruitment level modifies the steady state harvest level from around 24,000 to 14,000 tons. The precautionary approach (De Bruyn et al., 2013) would suggest to deal with different scenarios and to implement a smooth pathway toward the target SSB which ensures to reach the MSY by 2022 for EABFT fishery (ICCAT, 2017). For each recruitment level, reaching MSY in the short run (by 2022) fulfill this condition. However, in the long run the uncertainty in the estimated productivity could jeopardize the conservation effort made during the stock rebuilding phase. Adopting a more cautious target, such as MEY, should smooth potential errors in the measurement and the productivity of the EABFT.

4.2. Fishing selectivity

When harvesting selectivity is costless and perfectly adjusted, the optimal path keeps the same qualitative property but harvest is balanced over all age classes. Under the assumption of a constant price per age class, this new selectivity pattern results in a slightly higher harvest in term of biomass and consequently a higher profit. Selective gear such as purse seine could potentially detect and select quite uniform schools of tuna which are often organized according to their size (Newlands et al., 2006; Ottolenghi, 2008; Bauer et al., 2015). However, at low fishing mortality a balanced harvesting selectivity is economically promoted, and serves both conservation and economic performance of the fishery, ensuring in the long run higher profits than the current selectivity pattern and conservation objective by maintaining stock levels above the MSY limit even if productivity is uncertain. The demographic structure of stocks is an important factor affecting the resilience of a population facing environmental variability (Perry et al. 2010). Maintaining a high proportion of old individuals which contribute the most to reproduction is also an important factor to decrease fluctuations in population abundance (Anderson et al., 2008). In addition, fishing alters life-history traits with an evolutionary side effect, affecting maturity, growth and leads to a loss of genetic diversity and sub-populations (Planque et al. 2010, Garcia et al., 2012). In an ecosystem context, under the synergic effect of fishing activity and climate change, community structure can shift toward new states with lowest productivity rates. Some Mediterranean fish stocks, hakes and small pelagic fishes, have already undergone such shifts (Hidalgo et al., 2011; Saraux et al., 2017). Our results support the new paradigm of balanced harvesting instead of the current increased selectivity objective. At the ecosystem level, balanced harvesting have been shown to produce better conservation result regarding both exploited and unexploited species which structured the ecosystem. Removing parts of the ecosystem can lead to unintended consequences even for exploited species managed under the MSY policy.

4.3. Global supply and international market

The supply on the global Bluefin tuna market also plays a critical influence on the price and the profit of the EABFT fishery. The 50-year horizon net present value is increased by 20% when the supply of EABFT substitutes is reduced by 50% over the period. Even if the price flexibility does not qualitatively affect the optimal management, the price responsiveness substantially affects the profitability of the fishery. The scale flexibility smaller than unity evaluated by Sun et al., (2017) creates an incentive from the EABFT fishery to maintain high catch level. The potential increase of the EABFT TAC under the optimal management path will negatively affect other BFT fisheries and justify coordination and a consistent management across RFMOs (Allen et al., 2010; Sun et al., 2017). In our modeling framework, we exclude investment, technical change and overcapacity management issues which are nevertheless important in a fishery which has undergone an over 50% reduction of its activity within a couple of years. Selecting a smooth pathway strategy toward the MEY or MSY objective is a preferable option for managers to ensure a safe investment context, keeping the supply chain unchanged, avoiding overcapacity, maintaining confidence in the future and holding low discount rate values to avoid a detrimental ''race to fish'' (Armsworth & Roughgarden 2003; Patterson et al., 2007; Boettiger et al., 2016).

4.4. Measurement errors

When considering only the current measurement information, results from Sethi et al., (2005) does not hold in the age-structured context when the dynamic MEY is defined for low harvest rate and high population level. High measurement uncertainty -which is the norm rather than the exception- only affects the optimal policy by reducing the SSB steady state, and increasing the harvest while decreasing the profitability. We have based our model on specific assumptions reducing the information to the existing knowledge of the system. These assumptions lead to a counter intuitive policy which is less cautious than under a complete information setting. Conversely, the precautionary principle fosters more cautious harvest levels to ensure the conservation of the resource in the face of ambiguity (De Bruyn et al., 2013). This result exacerbates the need for a cautious target, such as MEY, in face of potential high measurement errors affecting the EABFT.

5. Conclusion

As pointed out in this study, conservation and economic objectives are still aligned if we consider age structured models, especially when the considered species is a long-lived species. MEY as a new management reference point has the advantage to be robust to high measurement uncertainty and foster balanced harvesting. These characteristics are crucial if we consider the management of the EABTF at the scale of its ecosystem. Keeping low catch rate has both the advantage to maintain ecosystem resilience, and smoothing stock variation over time. MEY policy has the potential to create confidence in the future of fishery and promote consistency between RFMOs to maintain a high price on the global market.

However, in face of strong individual incentives to increase TAC, ICCAT agreed on an increase of TAC up to 36,000 tons by 2020. A new approach should be considered to create new economic incentives, even when full property rights are defined, to allow the sustainability of fishery resources. Society benefits should be considered by including ecosystem services values to compensate losses from direct use of the resource (TACs).

6. Acknowledgments

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8. Supplementary materials

Appendix 1 Equilibrium age structured relationship.

Following Tahvonen et al. (2009), the age structure equilibrium is defined as:

$$x_{s+1,\infty} = x_{s,\infty}.\text{ì}_s \qquad \textit{Eq A1}$$

With $\text{ì}_s = \text{á}_s.(1 - sel_s.Fmax)$, for s = 1, ..., n-2 and $\text{ì}_{n-1} = \frac{\text{á}_{n-1}.(1-sel_{n-1}.Fmax)}{1-\text{á}_n+\text{á}_n.sel_n.Fmax}$

Considering $h_s = x_s.sel_s.Fmax$, the equilibrium age structure for s=2,…,n can be written as:

$$x_{s,\infty} = \text{ö}_s.x_{1,\infty} \qquad \textit{Eq A2}$$

$$\text{ö}_s =.\prod_{i=1}^{s-1}\text{ì}_i \quad , s{=}2,\ldots,n \qquad \textit{Eq A3}$$

Given the Beverton and Holt (1957) recruitment function, we could write:

$$x_{1,\infty} = \frac{\phi_1.D.x_{1,\infty}}{\phi_2+D.x_{1,\infty}} \qquad \textit{Eq A4}$$

$$x_{1,\infty} = \phi_1 - \frac{\phi_2}{D} \qquad \textit{Eq A5}$$

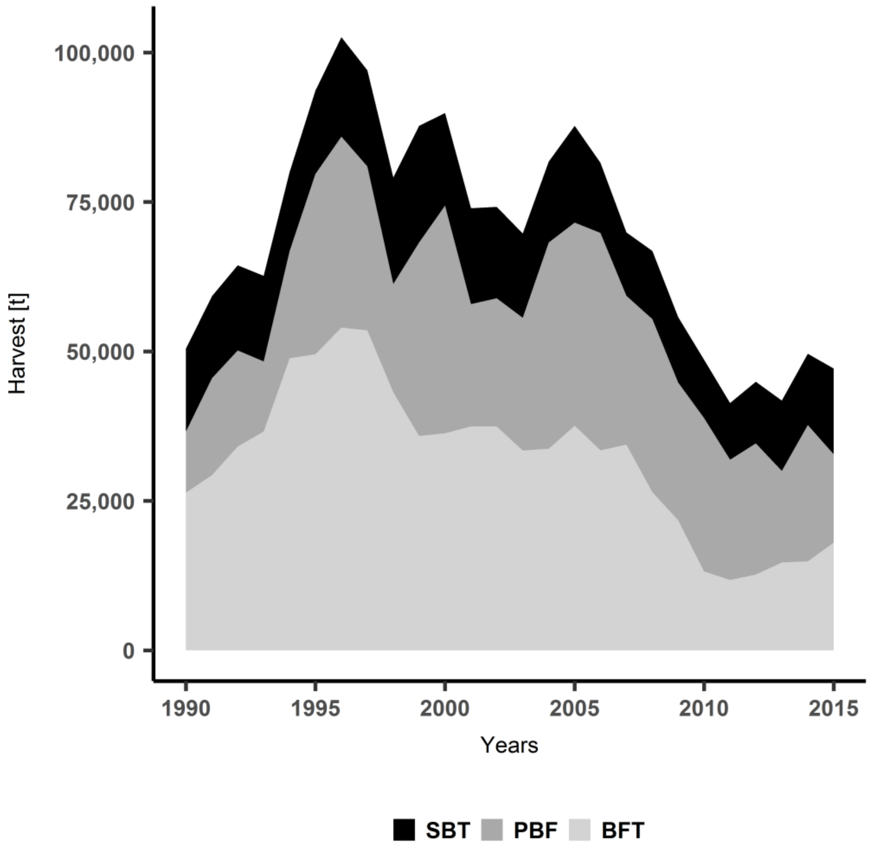
With ϕ_1, $\phi_2$the Beverton & Holt stock recruitment parameters and $D = \sum_{s=1}^{n} w_s.g_s.\text{ö}_s$, the equilibrium spawning stock biomass becomes:

$$ssb_\infty = x_{1,\infty}.\sum_{s=1}^{n} w_s.g_s.\text{ö}_s \qquad \textit{Eq A6}$$

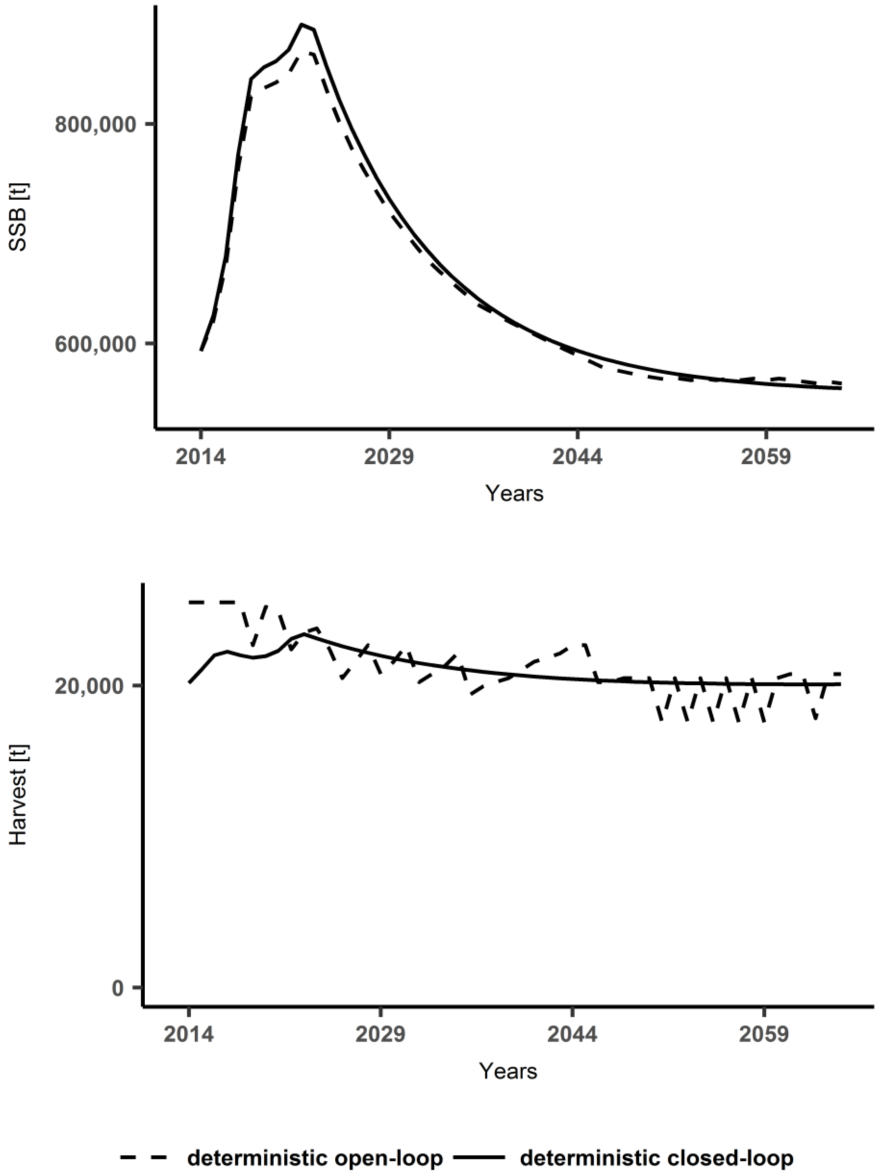
Appendix 2 Data on East Atlantic Bluefin tuna (EABFT) French and Italian purse seine fishery from statistics of the Scientific, Technical and Economic Committee for Fisheries (STECF, 2016).

Year	**EABFT purse seine sample catch [tons]**	**EABFT biomass [tons]**	**EABFT purse seine ex-vessel price [€/kg]**	**EABFT purse seine sample variable costs [€]**
2008	1,232.5	381,594.1	6.9	13,653,086
2009	1,936.2	416,981.8	3.3	8,838,653
2010	1,714.1	466,756.9	9.6	8,324,184
2011	2,525.6	511,832.2	8.1	5,936,655
2012	1,886.1	579,709.6	12.9	13,433,724
2013	3,089.4	678,571.3	11.1	27,883,858
2014	1,319.1	772,906.6	11.5	17,605,153
2015	4,419.3	849,264.2	10.8	15,769,493

Appendix 3 Cumulative annual supply of the global Bluefin tuna by species. In dark the historic of Southern Bluefin tuna (SBT, data from the CCSBT catch data base), in dark grey the catch of Pacific Bluefin tuna (PBF, data from the IATTC and ISC catch data base) and in light grey the catch of Atlantic Bluefin tuna (BFT, data from the ICCAT catch data base).



Appendix 4 Comparison of the deterministic numerical closed and open-loop formulations from 2015 to 2065 for harvest (in tons) and spawning stock biomass (SSB in tons) path.



Appendix 5 Sensitivity analysis.

We assess the effect of key parameters uncertainties on the steady state optimal levels based on the open-loop formulation of the model. For each parameter set, we generate 1000 observations assuming normal distributions with means given by their estimates and standard deviation derived from the estimation. We carry out the sensitivity analysis using the latin hypercube sampling (LHS) method from the 'pse' package in R (Chalom et al., 2017).

An important drawback of age structured population model is the necessity to specify a stock-recruitment relationship. Stock recruitment models are low explanatory because of the low availability of recruitment data and the variability of the recruitment process independently of the spawning biomass (Hilborn & Walters, 1982). EABFT is not an exception, and the existence of a density dependence mechanism has not been observed because of the lack of contrast in the available recruitment data (time series begin well after the stock has been reduced by exploitation, ICCAT 2017). The choice of the Beverton and Holt function is controversial and leads to the estimation of highly uncertain parameters (mean recruitment levels over different periods are used for projections in the EABFT stock assessment procedure, ICCAT 2017). We also analyse the effect of the variations of the catch-stock elasticity parameter ($\div$) which influences the hyperstabiliy of the harvest productivity through the cost function. Moreover, we jointly evaluate those 2 parameters, and the effects of economic parameters which are related to the performance of the fishery. We analyse the effects of changes in the cost function parameter (c) which is subjects to large uncertainty. We only have 8 observations of variable costs and aggregate landings from the STECF data, and consequently few degrees of freedom. We also consider the price function parameter (p), the price scale flexibility parameter (φ) and the estimation of EABFT substitutes' supply ($Hbft$).

The optimal SSB steady state is very sensitive to economic parameters variations and shows a skewed right distribution with a peak centered on 190,000 tons slight below the SSB at MSY level (Figure A4.1). We observe the inverse pattern for the optimal harvest steady state which shows a long tail to the left of a mode centered on the steady state of 40,000 tons slightly above the MSY level. However, the optimal steady state profit shows large variations on the right of its optimal steady state. The partial rank correlation coefficients (PRCCs, Figure A4.2) measure how strong the linear associations between the optimal steady state SSB and the cost, price and recruitment function parameters are, after removing the linear effect of the other parameters. PRCCs show strong negative effects of the stock elasticity parameter (÷) and the price flexibility parameter (φ) on the optimal SSB steady state. We also notice a strong positive relationship between the cost scale parameter (c) on the SSB steady state. The dynamic MEY is fully determined and very sensitive to economic parameters.

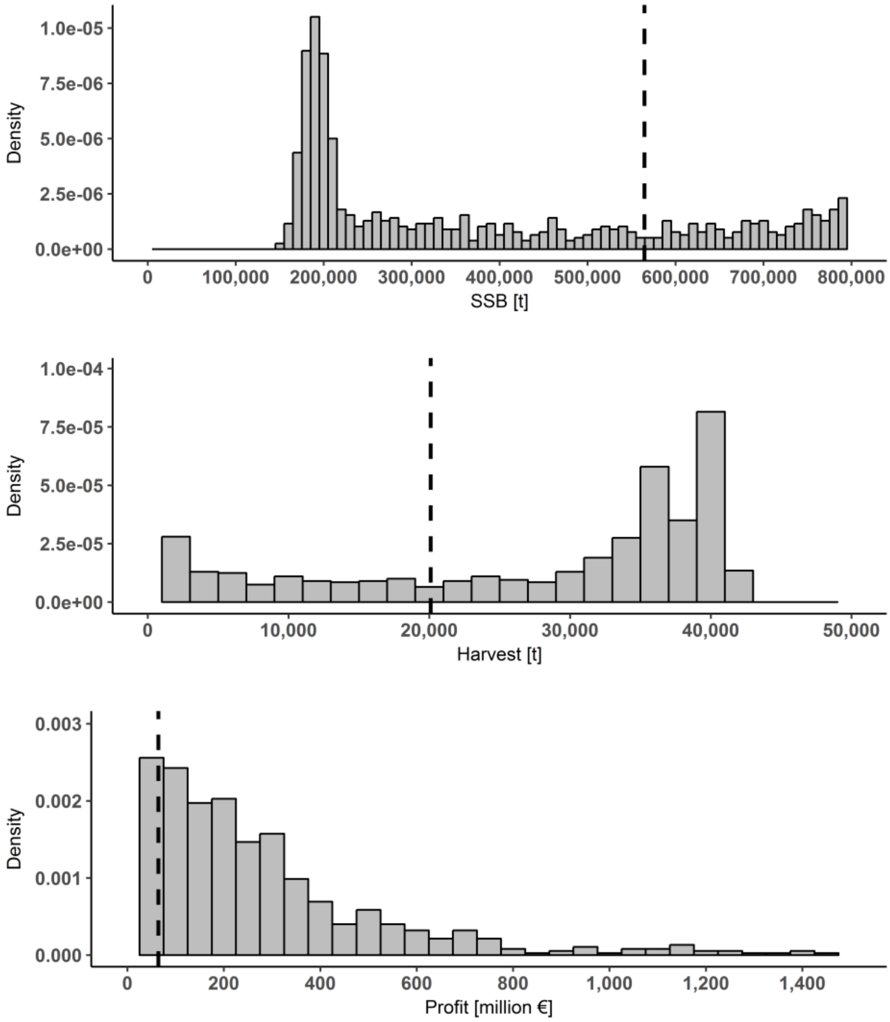
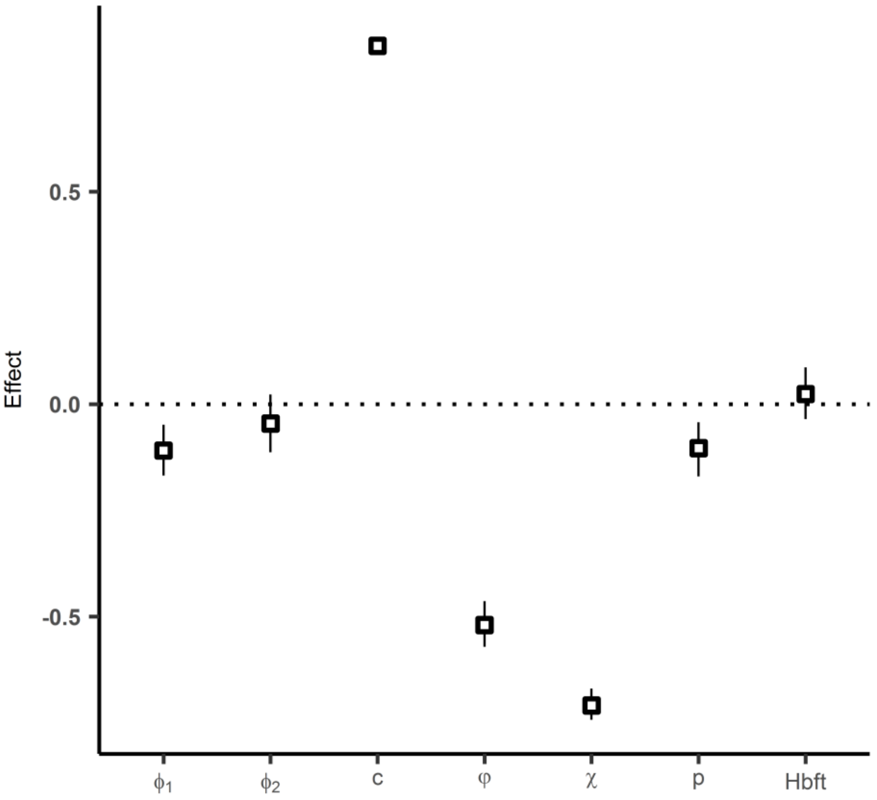


Figure A4.1 Histogram of the effects of stock recruitment and cost function on optimal steady-state spawning stock biomass (SSB in tons), harvest (tons) and profit (10^6 €) for 1000 randomly drawn parameter sets. The dotted line represents the optimal steady state for the selected model parameters.



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815 *Figure A4.2 Partial rank correlation of key functions parameters on the SSB optimal steady*
816 *state level.*

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