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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 estimation uncertainties, which represent a critical issue for EABFT, do not affect the optimal management. The MEY harvest policy estimated is robust to stock estimation uncertainties. 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.*

34 **1. Introduction**

35 Highly migratory species, such as tunas and tuna-like species, represent both
36 economically and biologically significant stakes for the world fisheries (Munro et al.
37 2004, Galland et al. 2016). Tunas are spread and caught over all the oceans (Miyake et al.
38 2010). They sustain some of the most valuable fisheries and feed international supply
39 chains (Catarci, 2005, Majkowski, 2007). Tunas fisheries are integrated in a global
40 market involving many regional markets (Jeon et al. 2008; Jiménez-Toribio et al. 2010;
41 Guillotreau et al. 2017) under the influence of the worldwide demand for tuna
42 commodities (Catarci, 2005; Mullon et al. 2017). High values on international market
43 make species such as tuna and tuna-like species particularly vulnerable (Colette et al.
44 2011), and the status of a number of stocks are particularly worrying (Maguire et al.
45 2006, Juan-Jorda et al. 2011).

46 The Eastern and Mediterranean stock of the Atlantic Bluefin tuna (EABFT) falls in this
47 group of concerns. The end value was estimated to more than \$700 million in 2014, out
48 of a total end value exceeding \$2 billion for the three major BFT species (Galland et al.
49 2016). The EABFT fishery faces today a critical phase in its management. After a long
50 period of over-exploitation (Fromentin et al. 2014), signs of recovery are evidenced by
51 stock assessment experts (ICCAT 2017). A stock rebuilding plan was launched in 2007
52 with a 60% likelihood of achieving sustainability by 2022. In 2017, under the majority of
53 recruitment level scenarios¹, the stock had already recovered to the expected level. The
54 new management stakes consist in defining quotas to keep the stock (biomass) above
55 the maximum sustainable yield level (B_{MSY}), despite high pressures from the fishing
56 nations to increase their quotas drastically. The last estimates from the International
57 Commission for the Conservation of Atlantic Tunas (ICCAT) indicate that the stock
58 rebuilding could be achieved by 2022 with probabilities higher than 60% for all
59 recruitment scenarios by setting catch limits up to 30,000 tons (ICCAT, 2017), i.e. more
60 than twice the limits enforced in 2009.

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

61 In this context of high uncertainties, the new management scheme of ICCAT implies a
62 TAC of up to 32,000 tons by 2020². Is the new management policy based on MSY
63 adapted to the productivity of the EABFT stock, or does it jeopardize the future of the
64 fishery by going back to the crisis situation of the late 2000s?

65 Shifting objectives from the traditional MSY target to the dynamic maximum economic
66 yield should result in most cases a no-regret situation in which management promotes
67 both larger fish stocks and higher profits ($B_{MEY} > B_{MSY}$ ³, Grafton et al. 2007, 2010, Clark,
68 2010). In a context of international trade, this dual benefit could be strengthened (or
69 mitigated) by the market price response to changes in landings (Sun et al. 2015; Sun et
70 al. 2017; Guillotreau et al. 2017; Tokunaga 2018). Previous bio-economic optimization
71 models analyzed optimal harvest in age-structured frameworks compatible with stock
72 assessments procedure. Bertignac et al. (2000) and Kompas et al. (2010) applied
73 stochastic dynamic programming to the Western and Central Pacific tuna fisheries to
74 show that adopting the B_{MEY} target leads to better conservation outcomes with larger
75 fish stocks and higher economic profits than the business-as-usual scenario. Similarly,
76 Kulmala et al. (2008) numerically solve their harvest optimization model for the age-
77 structure population of the Atlantic salmon (*Salmo salar*) fishery in the Baltic Sea and
78 demonstrate the economic benefits of the optimal solution without compromising the
79 sustainability of the resource. Finally, Tahvonen et al. (2017) analyzed the optimal
80 harvesting strategy of the Baltic cod (*Gadus morhua*) fishery including gear selectivity as
81 a state variable in a stochastic model. They showed that endogenous selectivity strongly
82 changes the MEY harvest pattern and increase substantially the profit obtained from the
83 fishery. They also highlighted that the stochastic solution can be accurately
84 approximated by the certainty equivalence principle.

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

² ICCAT Recommendation 17-07 (2017).

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

88 (2006) who based their analysis on an age-structured, multi-gear model which lead to
89 pulse fishing⁴ as an optimal solution. In the present research, we propose to update and
90 revisit their results by using a discrete age-structured population optimization model for
91 the EABFT in line with the framework used for the stock assessment by ICCAT. This
92 optimization framework based on the general age structured bio-economic model of
93 Tahvonen et al. (2013) uses directly annual harvest, total allowable catch (TAC) as an
94 optimized variable. We extend the model by including non-linear demand function
95 affected by the supply of the three Bluefin tuna species on the global market and stock-
96 dependent harvesting costs. Furthermore, we analyse the effects of considering different
97 recruitment levels according to ICCAT scenarios and different evolution of Bluefin tuna
98 supply levels. Finally, we determine the optimal management when selectivity pattern is
99 integrated as an endogenous variable in addition to the TAC in the model. Our work
100 suggests that adopting the MEY target meets both conservation and economic objectives
101 by keeping the stock to higher level than under the current MSY target and producing
102 higher benefits for the fishery. This result is exacerbated when selectivity is defined
103 endogenously, shifting to a more balanced fishing mortality over all age classes.
104 Finally, we deal with high stock estimation uncertainties⁵ underlying the EABFT stock
105 assessment. The uncertainty surrounding the assessment of the exploited fish stock is a
106 pervasive feature of fishery management. Uncertainties in EABFT stock assessment arise
107 from several sources: our understanding of EABFT biology and population dynamics; the ability
108 of assessment models to correctly reproduce population dynamics patterns and the
109 quality/quantity of the data used (detailed in Fromentin et al. 2014). Data used for the
110 assessment of highly migratory species suffer from a lack of independent observations
111 (i.e. not directly related to catches) to track down changes in stock abundance. The
112 fitting quality of the stock assessment relies on catch per unit of effort (CPUE) indices
113 produced by commercial activities which are, among other factors, affected by recent
114 regulatory measures of the rebuilding plan. The recent development of aerial fishing-
115 independent surveys is a good basis to improve abundance indices (Fromentin et al.

⁴ Periodic fishing.

⁵ Refers to observational uncertainty which arises when state variables cannot be directly observed (e.g. stock biomass).

116 2011). Based on the results from Tahvonen et al., (2017) we did not consider stochastic
 117 processes, but we fully acknowledge the presence of stock estimation uncertainty by
 118 extending the previous work of Sethi et al. (2005) to an age-structured framework
 119 specifying equilibrium assumptions. Using dynamic stochastic programming, our results
 120 indicate that stock estimation uncertainties strongly affect the optimal management of
 121 the EABFT fishery, resulting in a lower SSB steady state compared to the full information
 122 case.

123 2. Material and methods

124 2.1. The Age-Structured model

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

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

$$137 \quad x_{1,t} = \phi(ssb_t) \quad Eq 1$$

$$138 \quad ssb_t = \sum_{s=1}^n g_s \cdot w_s \cdot x_{s,t} \quad Eq 2$$

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

141 As Tahvonen et al., (2013), we assume that fishing activity takes place every year after
 142 recruitment but before natural mortality. We determine total catch (H_t) in biomass (kg)
 143 as the decision variable. Denoting $H_t = Fmax_t \cdot B_t^\chi$ with $B_t = \sum_{s=1}^n sel_s \cdot w_s \cdot x_{s,t}$ the

144 vulnerable biomass called ‘efficient biomass’ (Tahvonen et al., 2017), χ the catch-stock
 145 elasticity parameter and $Fmax_t$ the fishing mortality at maximum selectivity, we can
 146 write the age-structured population model as:

$$147 \quad x_{s+1,t+1} = \alpha_s \cdot (x_{s,t} - H_t \cdot G_{s,t}), \text{ for } s = 1, \dots, n-2, \quad Eq 3$$

$$148 \quad x_{n,t+1} = \alpha_{n-1} \cdot (x_{n-1,t} - H_t \cdot G_{n-1,t}) + \alpha_n \cdot (x_{n,t} - H_t \cdot G_{n,t}) \quad Eq 4$$

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

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

$$154 \quad U(H_t) = R(H_t) - C(H_t) \quad Eq 5$$

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

$$157 \quad C(H_t, B_t) = c \cdot H_t \cdot B_t^{-\div} \quad Eq 6$$

158 With c and \div the cost scale in euros and the schooling parameters respectively.

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

$$161 \quad R(H_t) = P(H_t) \cdot H_t \quad Eq 7$$

162 Finally, the optimization problem is:

$$163 \quad \max_{\{H_t\}} \sum_{t=0}^T U(H_t) \cdot \ddot{a}^t \quad Eq 8$$

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

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

$$167 \quad x_{s,0} \text{ given,}$$

168
$$x_{s,t} \geq 0, \text{ for } s = 1, \dots, n \text{ and } t = 1, \dots, T;$$

169
$$H_t \geq 0, \text{ for } t = 1, \dots, T.$$

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

172 Based on this model, we derive the equilibrium age structured population considering
173 the long term population under a constant fishing mortality F_{max} (Supplementary
174 materials, appendix 1). This leads to the definition of the MSY level which is the
175 management target of EABFT. The MSY level will be the basis for the comparison of the
176 optimal management, but it drastically depends on the selectivity pattern and the
177 recruitment function parameters estimation which is highly variable throughout time.
178 As ICCAT, we consider 3 recruitment levels corresponding to the fitting of the Beverton
179 and Holt relationship for a high recruitment period (1990-2010), a medium recruitment
180 period (1970-2010) which is our reference case and a low recruitment period (1970-
181 1980).

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

189 **2.2. The East Atlantic Bluefin tuna (EABFT) fishery**

190 The Eastern Atlantic Bluefin tuna has been an archetype of the overexploitation and
191 mismanagement of marine resources (Fromentin et al. 2014). Several countries, either
192 coastal or distant water fishing nations, have contributed to a high level of depletion
193 driven by the high market value of the tuna on the Japanese market. The decline in the
194 EABFT has raised considerable concerns about its management in the 2000s (Hurry et
195 al., 2008, ICCAT 2007, ICCAT 2009). Under the governance of ICCAT, a Regional Fishery
196 Management Organization (RFMO), the fish population has suffered, at the same time,

197 from its failure to follow scientific advice and a high level of illegal, unreported and
 198 unregulated (IUU) fishing. This situation occurred when the first management
 199 regulation based on quotas (TAC) appeared in 1999 and lasted until 2007 with the
 200 implementation of a recovery plan for the EABFT fishery. After 2009 and the strict
 201 management measures which have been implemented, the stock has showed signs of
 202 increase in the last years to peak a potential spawning stock biomass (SSB) value up to
 203 $610 \cdot 10^6$ t in 2015 (ICCAT 2017). A combination of a decrease in fishing pressure and
 204 potential high recruitment events resulted in a strong increase of the SSB. Presently, the
 205 stock is regarded as fulfilling the objective of the recovery plan ($F < F_{0.1}$ and $SSB > SSB_{0.1}$ ⁶),
 206 depending nonetheless on the assessment scenarios and assumptions. The magnitude of
 207 the SSB recovery appears to be very sensitive to slight changes in the input data (notably
 208 catch data) and technical assumptions (ICCAT 2017).

209 Following the standard stock assessment for the EABFT by ICCAT (2014), we consider
 210 10 age classes (n). Age-specific maturities (g_s) and survival rates ($\acute{a}_s = e^{-m_s}$, with m the
 211 natural mortality at age) which are directly taken from the (ICCAT 2017) assessment
 212 report. For the age-specific weights (w_s in kg per individual), we use the mean values of
 213 the period 2011-2014 (Table 1). Selectivities (sel_s) are estimated by the catch curve
 214 analysis method for the purse seiner (Kell et al., 2013) for the period 2011-2015 and
 215 equal to 1 for the oldest age class by normalization. Recruitment is assumed to follow
 216 the Beverton and Holt (1957) recruitment function:

$$217 \quad x_{1,t} = \phi(ssb_t) = \frac{\phi_{1,ssb_t}}{\phi_{2+ssb_t}} \quad Eq \ 9$$

218 We use ICCAT (2017) data on spawning stock biomass and recruitment for the years
 219 1970 to 2010 (corresponding to the medium recruitment scenario of ICCAT), and we
 220 estimate the parameters by maximizing the likelihood function assuming a lognormal
 221 error structure with the Fisheries library R ('FLSR' package in FLCore 3.0, Kell et al.

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

222 2007). We constrained the estimation by setting the steepness⁷ at 0.99 following ICCAT
 223 (2017) parametrisation in order to specify a quasi-constant recruitment level. This
 224 yields the estimates of the asymptotic recruitment $\phi_1 = 2,230,398$ recruits (standard
 225 deviation 12,672 individuals) and the SSB needed to produce the half of the asymptotic
 226 recruitment $\phi_2 = 1,155,983$ kg (standard deviation 5,403 kg).

227 *Table 1 Parameters used in the model.*

Age-class [year]	Survival rate \acute{a}	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

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

235 EABFT is a large highly migratory schooling species which is the main target for purse
 236 seine commercial fisheries in the Mediterranean Sea. The low TAC level of the early
 237 2010s as well as the good knowledge of seasonal migration and concentration patterns
 238 in the Mediterranean (Fromentin & Powers 2005), in combination with technology-
 239 based information on the fishing activities and prospecting equipment, result in minor

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

240 search costs within a short fishing period (usually less than a month, the purse-seiners
 241 remaining idle at ports for the rest of the year). We estimate the generalized cost
 242 function by mean of non-linear least square method (R package 'stats'). Using data on
 243 catch, efficient biomass and variable costs, we estimate the cost parameter (c) and the
 244 catch-stock elasticity parameter (\div) following the relationship:

$$245 \quad c_t = c \cdot H_t \cdot B_t^{-\div} + \epsilon_t, \text{ with } \epsilon_t \sim IIDN(0, \sigma^2)$$

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

252 The EABFT purse fishery is driven by the rising Japanese demand for fatty tuna intended
 253 to high-quality sushi/sashimi market. The quasi totality of EABFT caught by purse
 254 seiners is sold to fattening farms in the Mediterranean Sea (Mylonas et al., 2010). Since
 255 the 1990s selectivity mainly shifts toward large tuna caught in the Western
 256 Mediterranean (Fromentin & Bonhommeau., 2011). Tunas are fattened during a 3-5
 257 month period and sold on the Japanese sashimi market when domestic demand is high
 258 (usually at the end of the year). Fattened EABFT is mainly sold frozen to the Japanese
 259 market, representing more than 80% of the market since 2006 (Mylonas et al., 2010). In
 260 the Eastern Mediterranean, a smaller part of EABFT are caught by Croatian purse
 261 seiners, generally smaller individuals (less than 60 kg), and reared for longer periods
 262 (around 2 years) during which initial weight can be doubled (Mylonas et al., 2010).

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

$$268 \quad P(H_t) = p \cdot (H_t + Hbft_t)^{-\delta} \text{ Eq 10}$$

269 With p the theoretical price of the first sold kilos of Bluefin tuna, the price scale
270 flexibility parameter and $Hbft_t$ is defined as the aggregated supply of all other Bluefin
271 tuna species (including Pacific and Southern Bluefin tuna) which are considered as close
272 substitutes on the sashimi-grade tuna market (Sun et al., 2017). Using catch data from
273 the different RFMOs (ICCAT, IATTC, ISC, and CCSBT, Supplementary materials, appendix
274 3) in charge of the management of Bluefin tuna species and purse seine ex-vessel price
275 from STECF we estimate the price parameter $p = 91,983,194$ € (standard deviation
276 8,947,638) using non-linear least square method.

$$277 \quad p_t = p \cdot (H_t + Hbft_t)^{-\phi} + \epsilon_t, \text{ with } \epsilon_t \sim IIDN(0, \sigma^2)$$

278 As Japan is the main market for Bluefin tuna products, we integrate the price scale
279 flexibility parameter $\phi=0.91$ (standard deviation 0.034) estimated by Sun et al., (2017)
280 from an inverse demand analysis of Bluefin tuna auction price. This estimate is based on
281 frozen Bluefin tuna (Pacific and Atlantic) products pricing on the wholesale market
282 (Tsukiji) in Japan. The recent increase of TAC (from 13,500 tons in 2014 to 19,296 tons
283 in 2016, i.e. an increase of 43%) has negatively impacted the global frozen BFT price
284 (11% decrease, Sun et al., 2017) through the auction market in Japan which represents
285 more than 80% of the Bluefin tuna sashimi market in the world (fresh and frozen, Sun et
286 al., 2017). The effect of the EABFT supply on the global sashimi tuna product price is
287 crucial in the analysis of the optimal management. In a near future, only the supply of
288 EABFT is about to vary with an adjustment of the quotas (TAC) after the success of the
289 recovery plan. Thus, we consider in our model a constant supply of BFT (Southern and
290 Pacific Bluefin tuna) substitutes corresponding to the mean harvest from 2008-2015, i.e.
291 34,636 tons.

292 **2.3. Numerical analysis**

293 We numerically analyze optimal management in a setting of no uncertainty by solving
294 the dynamic optimization model as an open-loop⁸ nonlinear programming problem. This
295 is performed using the COBYLA algorithm of the NLOpt optimization package (Johnson,
296 2017) with R (R core team 2017).

297 We also perform the optimization problem by integrating stock estimation
298 uncertainties. Stock estimation uncertainties represent an important feature of fishery
299 management. To analyze the effects of stock estimation uncertainty on management, we
300 consider a stylized representation where a uniformly distributed noise Z_t with different
301 errors level σ_m (0, 0.3, 0.6, 0.9 and 1.2) alters information on stock levels. The solution of
302 this problem requires to solve the stochastic program in closed-loop formulation by
303 backward recursion of Bellman's equation. Bellman's (1957) principle of optimality
304 implies that the optimal policy must satisfy the functional equation:

305
$$V_t(X_t) = \max_{0 \leq H_t, \dots, T \leq B_t, \dots, T} \{ U(H_t, X_t) + \bar{\alpha} \cdot \sum_t^T P(X_{t+1} | H_{t+1}, X_t) \cdot V_{t+1}(X_{t+1}) \} \quad Eq 11$$

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

315 For computational effort reasons, we simplify the optimization problem by taking the
316 equilibrium age structure $x_{s,t}$ for each value of the state X_t considering a constant fishing

⁸ In open-loop optimisation, once the optimal path has been defined the control action from the manager is independent of the resource state.

317 mortality F_{max} (Supplementary materials, appendix 1 following the specification of
318 Tahvonen et al. 2009).

319 We include a random variable underpinning the uncertainty in period t , Z_t , which affects
320 stock estimation. This random variable is independent and identically distributed (IID)
321 over years. Integrating a stock estimation uncertainty implies to define an observation
322 variable of the stock X_{obs_t} , which is defined as follow:

$$323 \quad X_{obs_t} = Z_t \cdot X_t \quad Eq\ 12$$

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

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

336 We solve this problem on a finite time horizon $T = 80$ years using value iteration
337 algorithm (following the methodology of Boettiger et al., 2016), but we consider only the
338 50 first projection years for analysis. We also discretize the state and decision variable
339 space over a regular sequence of a length out of 1000 steps from 0 to $12 \cdot 10^6$ individuals.
340 We simulate 500 times the optimal path following the optimal policy obtained from the
341 solution to Bellman's equation (Equation 11) under the different uncertainty levels. The
342 optimal solution of the deterministic closed-loop formulation has to be expressed as a
343 feedback policy, which could refer to a harvest-control rule in fishery management. The
344 feedback policy indicates the optimal harvest quantity H_t as a function of the state of the
345 fishery X_t . As mentioned above, we simplified the optimization problem by assuming an
346 n age structured population at equilibrium at each discretized state space. Despite this

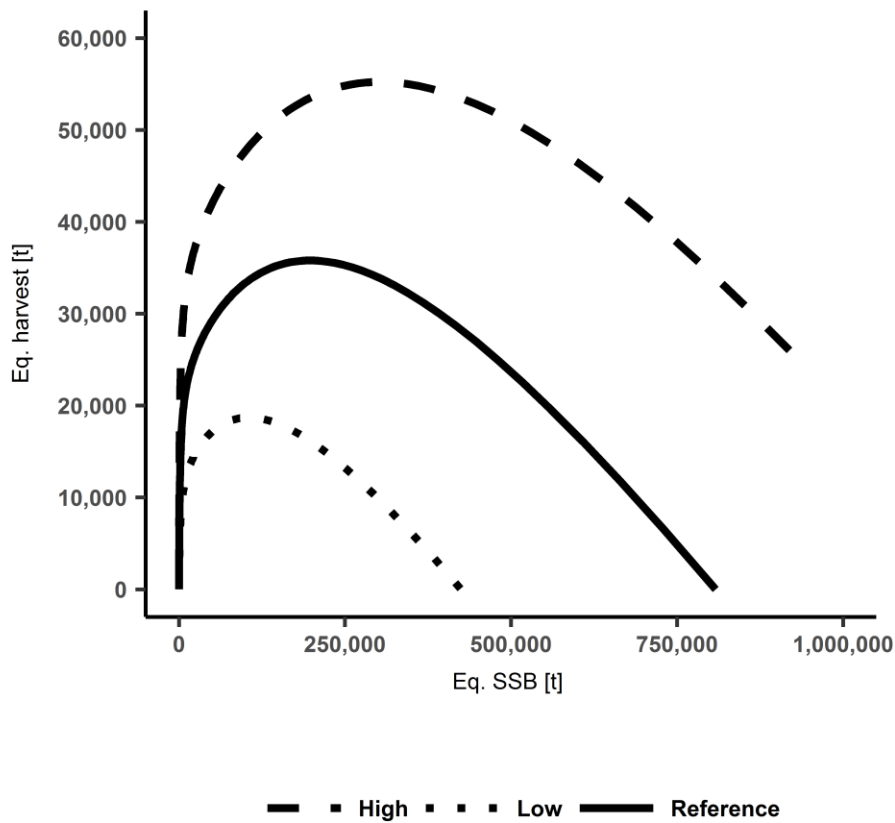
347 assumption, we control that the solution of the closed-loop formulation is close to the
348 solution of the open-loop formulation. This shows that the approximation to discretize
349 the state space and considering the age structure of the stock at the equilibrium leads to
350 reasonably good results on the aggregated indicators level (Supplementary materials,
351 appendix 4).

352 **3. Results**

353 **3.1. Optimal management of Eastern Atlantic Bluefin tuna (EABFT)**

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

360



361

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

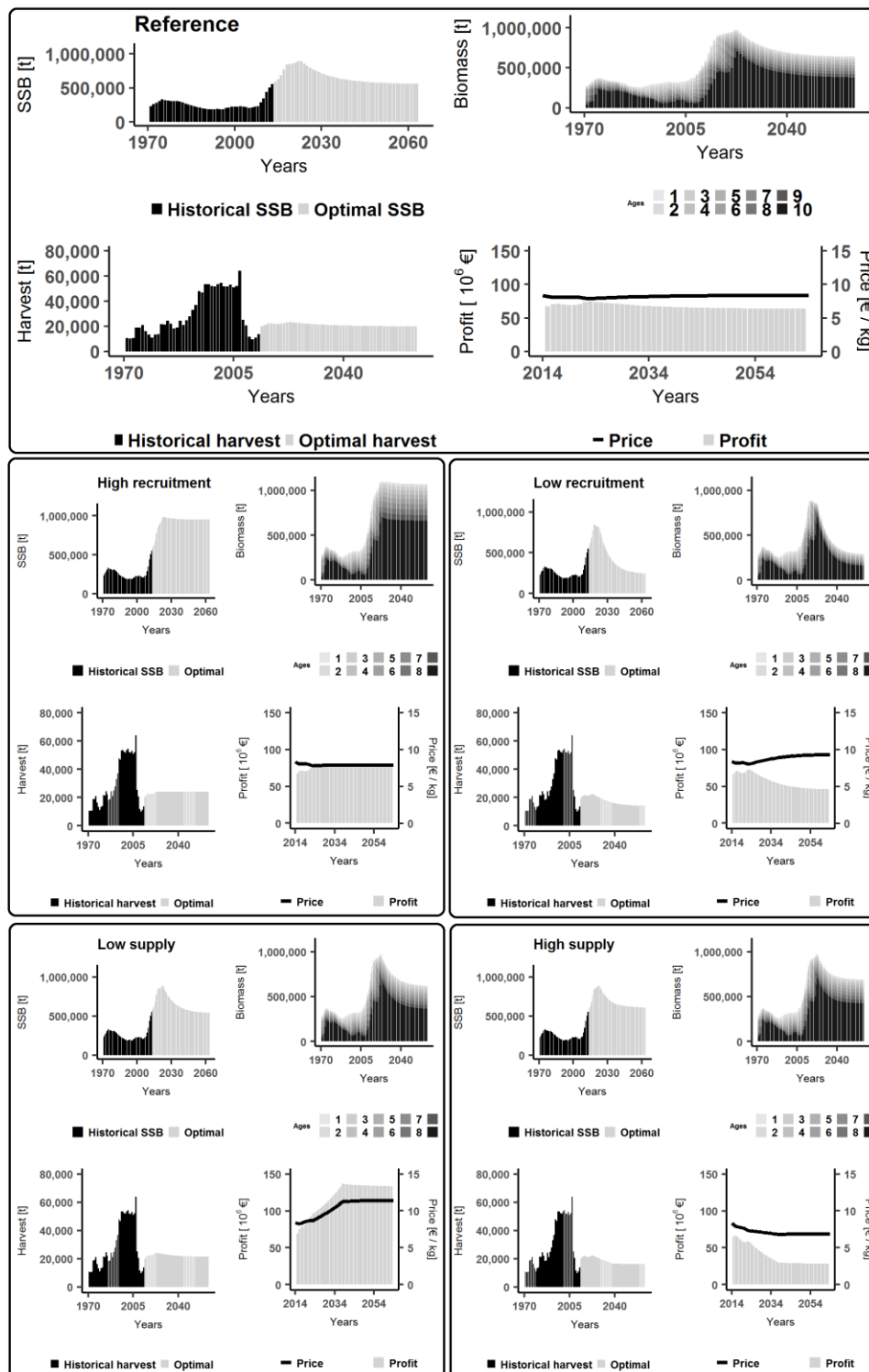
369 The optimal management of the EABFT targets the biomass level that maximizes the
 370 sum of the discounted (net present) values (NPV) from fishing (Equation 8), this level
 371 being called the B_{MEY} . The program is solved in the deterministic open-loop formulation
 372 which displays a smooth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

374 564,600 tons (mean over the period 2055 to 2065), much higher than the SSB at MSY
375 level representing only 35% of the steady state level⁹. Furthermore, this level is higher
376 than the mean SSB level from 1970 to 2009 while the steady state harvest of around
377 20,100 tons (mean over the period 2055 to 2065) which is quite lower than the mean
378 level of the 'over-harvested' period from 1999 to 2009. Moreover, the catch level during
379 this period is likely to be higher than the reported catch because of IUU fishing (ICCAT
380 2014). Available information on fishing capacity showed that catches EABFT were
381 under-reported from 1998 to 2007. Under the reference recruitment level, the steady
382 state harvest, representing 56% of the MSY level, is reached after a short period of
383 slightly higher harvest intensity and creates an annual profit of 64 million euros with a
384 high proportion of old age class fish. Along the smooth transition to the steady state, the
385 harvest level gradually decreases while the profit stay quasi-constant, as the market price
386 stays around 8.3 € per kg of fish. However, this result is very sensitive to the cost function
387 parameters. Schooling and cost scale parameters fully determine if the MEY level is
388 determined with a higher SSB and lower catch than MSY or on the contrary if the MEY
389 converge to a level slightly above MSY for the catch and below for the SSB for lower cost
390 and/or lower schooling behavior (χ tends to 1 and/or c tends to 0, see Supplementary
391 materials appendix 5).

392 The optimal management of the EABFT could be also affected by an exogenous change of
393 global Bluefin tuna supply. A 50% increase of overall Bluefin tuna supply negatively
394 impacts the price from 8.4 to 6.8 € per kg and reduces the profitability of the fishery by
395 37.4% while a decreasing supply of substitutes increases the price to 11.4 € per kg and
396 raises the profitability by 65.0 % (Figure 2). Furthermore, the recruitment levels affect
397 the productivity of the stock and modify the equilibrium estimation (Figure 1).
398 Assuming a low recruitment level drastically reduces the profit from the fishery with a
399 lower sustainable harvest level of 14,200 tons, increasing the price to 9.26 € per kg. On
400 the contrary, a high recruitment level raises the profit expected from higher harvest
401 level of 24,000 but lowered the price to 7.8 € per kg (Figure 2).

⁹ Refer to the supplementary materials appendix 5 for a sensitivity analysis of the key economic and biological parameters of an optimal policy.

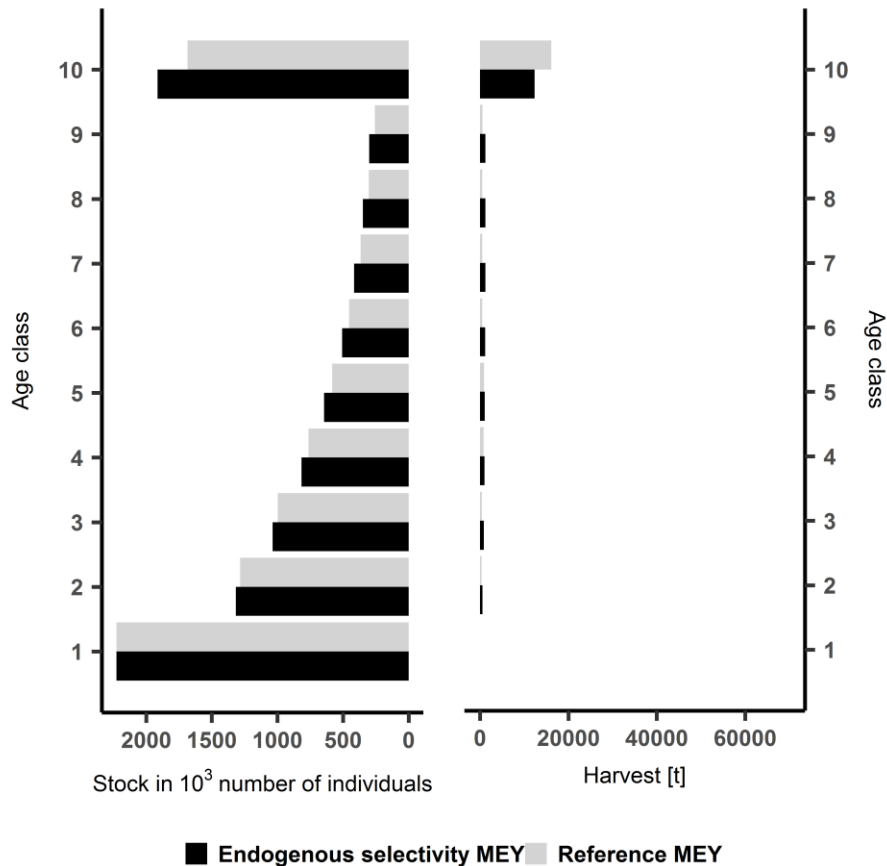
402 Including selectivity as an endogenous variable in the optimization produces optimal
403 steady states very close to the current selectivity pattern. Considering a perfect and
404 costless selectivity, the steady state harvest level stays around 20,000 tons with a more
405 balanced fishing mortality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



410

411 *Figure 2 Historical and optimal management of Eastern Atlantic Bluefin tuna (EABFT)*
 412 *with a 2% discount rate for each recruitment level and supply scenarios. Historical data*
 413 *are collected from ICCAT (2017) for the period 1970–2014. Each panel presented the*
 414 *optimal economic management of the EABFT for 5 different scenarios: reference, high and*

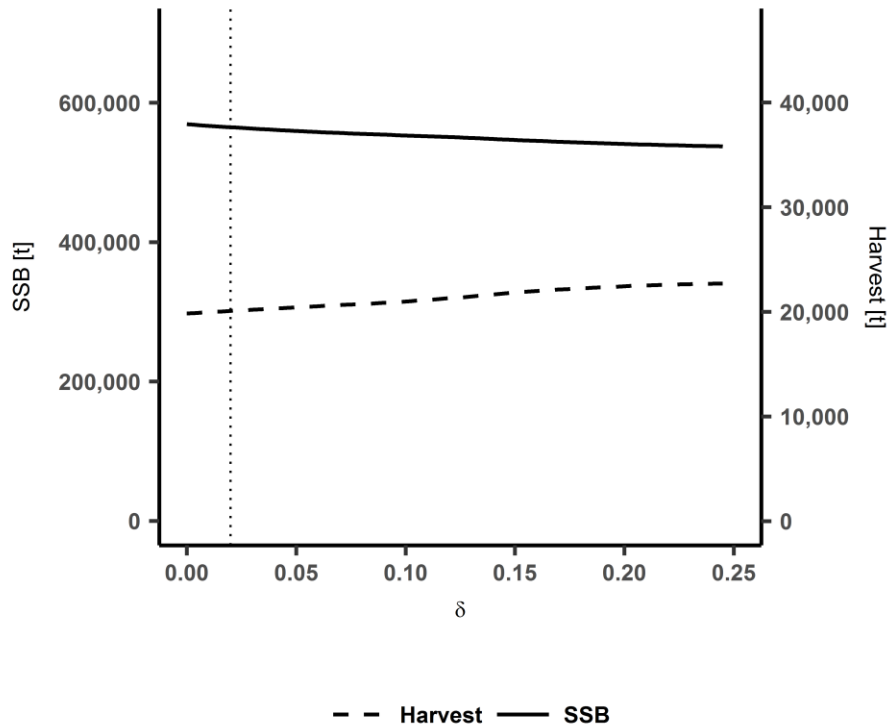
415 *low recruitment, low and high supply scenarios. For each scenario, the optimal SSB path*
 416 *under the optimal harvest selected for the period 2014-2064 and the resulting biomass*
 417 *(tons), profit (€) and price (€/Kg) from the fishery are shown.*



418

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

421 The optimal exploitation of fish populations also depends on interest rate levels (Clark
 422 1973). The effect of increasing the discount rate up to 25% does not affect too much the
 423 optimal steady state. SSB steady state only decreases by 7% (Figure 4) while the steady
 424 state harvest increase of about 18%. Finally, it is worth noticing that the steady state SSB
 425 remains higher than MSY level even with high discounting.

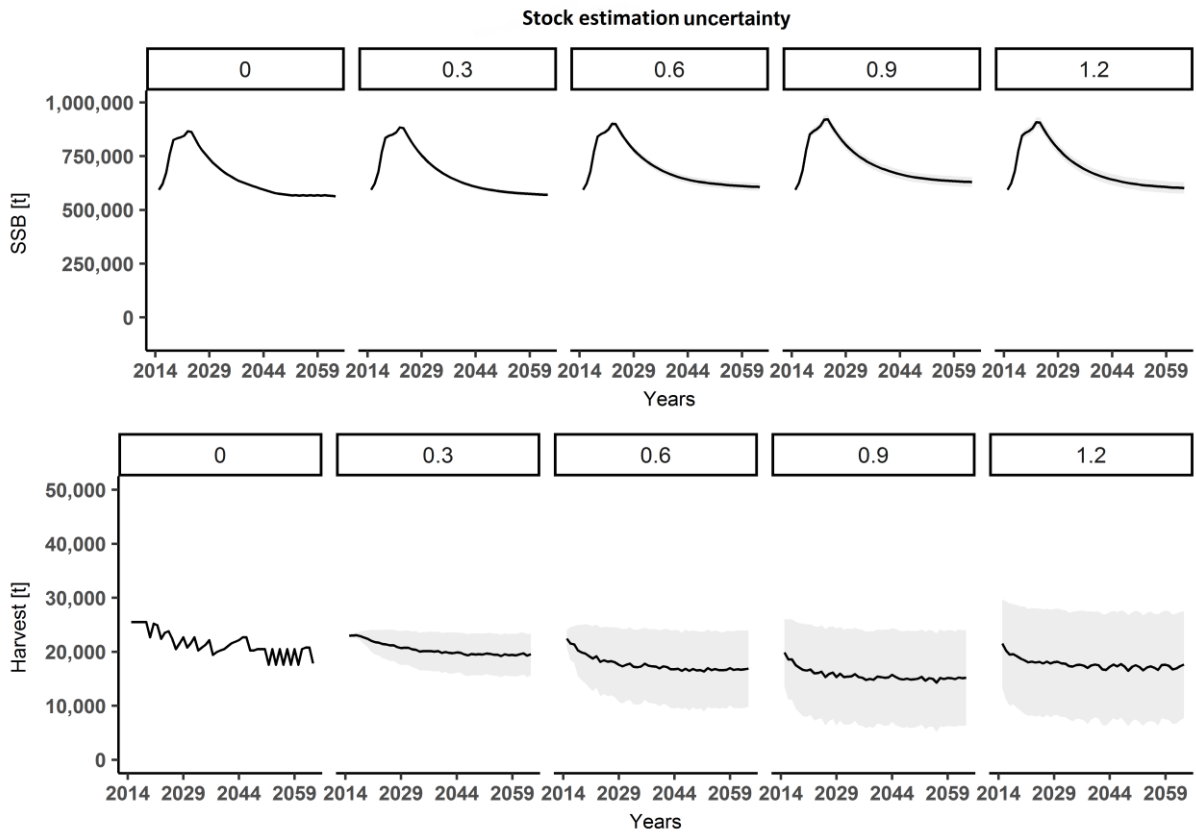


426

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

430 **3.2. Effect of stock estimation uncertainties**

431 We observe that stock estimation uncertainty has an insignificant effect on the optimal
 432 harvest path even when the uncertainty level becomes high (Figure 5). The accuracy of
 433 information about the resource level does not affect the capacity of a manager to define
 434 a TAC-based policy. The MEY policy defined by a low harvest rate and a high population
 435 level is robust to stock estimation uncertainties. This result is also sensitive to the cost
 436 and schooling parameters. As the MEY becomes close to the MSY level, stock estimation
 437 uncertainties increase.



438

439 *Figure 5 Results of 500 independent simulations of the closed-loop optimization model*
 440 *with different level of uniformly distributed stock estimation uncertainties ($\delta_m =$*
 441 *0; 0.3; 0.6; 0.9 and 1.2). On the top charts, the optimal path of spawning stock biomass*
 442 *(SSB in tons) from 2014 to 2064. On the bottom charts, the optimal path of harvest (in*
 443 *tons) from 2014 to 2064. The grey shaded region represents the standard deviations.*

444 **4. Discussion**

445 This study provides a bioeconomic model of the EABFT fishery in line with the ICCAT
 446 stock assessment procedure. This work updates previous analysis of Bjorndal & Brasao
 447 (2006) which found out pulse fishing as optimal management. We outline the optimal
 448 dynamic exploitation of the EABFT fishery by setting directly the harvest level as a
 449 fishing quota (TAC) and considering an age structured model which explicitly takes into
 450 account the schooling behavior of Bluefin tuna. Our model integrates the effect of the
 451 global supply of EABFT close substitutes on the price, analyses the effects of different
 452 recruitment levels and selectivity as an optimized variable. Using actual economic data

453 of the European purse seine fishery, the model has been applied to determine the
454 optimal economic policy for EABFT fishery.

455 **4.1. Toward a new management target**

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

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

483 should smooth potential errors in the stock estimation and the productivity of the
484 EABFT.

485 **4.2. Fishing selectivity**

486 When harvesting selectivity is costless and perfectly adjusted, the optimal path keeps
487 the same qualitative property but harvest is balanced over all age classes. Under the
488 assumption of a constant price per age class, this new selectivity pattern results in a
489 slightly higher harvest in term of biomass and consequently a higher profit. Selective
490 gear such as purse seine could potentially detect and select schools of tuna which are
491 often organized according to their size (Newlands et al., 2006; Ottolenghi, 2008; Bauer et
492 al., 2015). However, at low fishing mortality a balanced harvesting selectivity is
493 economically promoted, and serves both conservation and economic performance of the
494 fishery, ensuring in the long run higher profits than the current selectivity pattern and
495 conservation objective by maintaining stock levels above the MSY limit even if
496 productivity is uncertain. The demographic structure of stocks is an important factor
497 affecting the resilience of a population facing environmental variability (Perry et al.
498 2010). Maintaining a high proportion of old individuals which potentially contribute the
499 most to reproduction is also an important factor to decrease fluctuations in population
500 abundance (Anderson et al., 2008). In addition, fishing alters life-history traits with an
501 evolutionary side effect, affecting maturity, growth and leads to a loss of genetic
502 diversity and sub-populations (Planque et al. 2010, Garcia et al., 2012). In an ecosystem
503 context, under the synergic effect of fishing activity and climate change, community
504 structure can shift toward new states with lowest productivity rates. Some
505 Mediterranean fish stocks, hakes and small pelagic fishes, have already undergone such
506 shifts (Hidalgo et al., 2011; Saraux et al., 2017). Our results support the new paradigm of
507 balanced harvesting instead of the current increased selectivity objective. At the
508 ecosystem level, balanced harvesting have been shown to produce better conservation
509 result regarding both exploited and unexploited species which structured the
510 ecosystem. Removing parts of the ecosystem can lead to unintended consequences even
511 for exploited species managed under the MSY policy.

512 **4.3. Global supply and international market**

513 The supply on the global Bluefin tuna market also plays a critical influence on the price
514 and the profit of the EABFT fishery. The 50-year horizon net present value is increased
515 by 20% when the supply of EABFT substitutes is reduced by 50% over the period. Even
516 if the price flexibility does not qualitatively affect the optimal management, the price
517 responsiveness substantially affects the profitability of the fishery. The scale flexibility
518 smaller than unity evaluated by Sun et al., (2017) creates an incentive from the EABFT
519 fishery to maintain high catch level. The potential increase of the EABFT TAC under the
520 optimal management path will negatively affect other BFT fisheries and justify
521 coordination and a consistent management across RFMOs (Allen et al., 2010; Sun et al.,
522 2017). In our modeling framework, we exclude investment, technical change and
523 overcapacity management issues which are nevertheless important in a fishery which
524 has undergone an over 50% reduction of its activity within a couple of years. Selecting a
525 smooth pathway strategy toward the MEY or MSY objective is a preferable option for
526 managers to ensure a safe investment context, keeping the supply chain unchanged,
527 avoiding overcapacity, maintaining confidence in the future and holding low discount
528 rate values to avoid a detrimental "race to fish" (Armsworth & Roughgarden 2003;
529 Patterson et al., 2007; Boettiger et al., 2016).

530 **4.4. Stock estimation uncertainties**

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

542 **5. Conclusion**

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

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

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745

746 **8. Supplementary materials**

747 Appendix 1 Equilibrium age structured relationship.

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

749
$$x_{s+1,\infty} = x_{s,\infty} \cdot \lambda_s \quad Eq A1$$

750 With $\lambda_s = a_s \cdot (1 - sel_s \cdot Fmax)$, for $s = 1, \dots, n-2$ and $\lambda_{n-1} = \frac{a_{n-1} \cdot (1 - sel_{n-1} \cdot Fmax)}{1 - a_n + a_n \cdot sel_n \cdot Fmax}$

751 Considering $h_s = x_s \cdot sel_s \cdot Fmax$, the equilibrium age structure for $s=2, \dots, n$ can be written
752 as:

753
$$x_{s,\infty} = \ddot{o}_s \cdot x_{1,\infty} \quad Eq A2$$

754
$$\ddot{o}_s = \prod_{i=1}^{s-1} \lambda_i, \quad s=2, \dots, n \quad Eq A3$$

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

756
$$x_{1,\infty} = \frac{\phi_1 \cdot D \cdot x_{1,\infty}}{\phi_2 + D \cdot x_{1,\infty}} \quad Eq A4$$

757
$$x_{1,\infty} = \phi_1 - \frac{\phi_2}{D} \quad Eq A5$$

758 With ϕ_1, ϕ_2 the Beverton & Holt stock recruitment parameters and $D = \sum_{s=1}^n w_s \cdot g_s \cdot \ddot{o}_s$,
759 the equilibrium spawning stock biomass becomes:

760
$$ssb_{\infty} = x_{1,\infty} \cdot \sum_{s=1}^n w_s \cdot g_s \cdot \ddot{o}_s \quad Eq A6$$

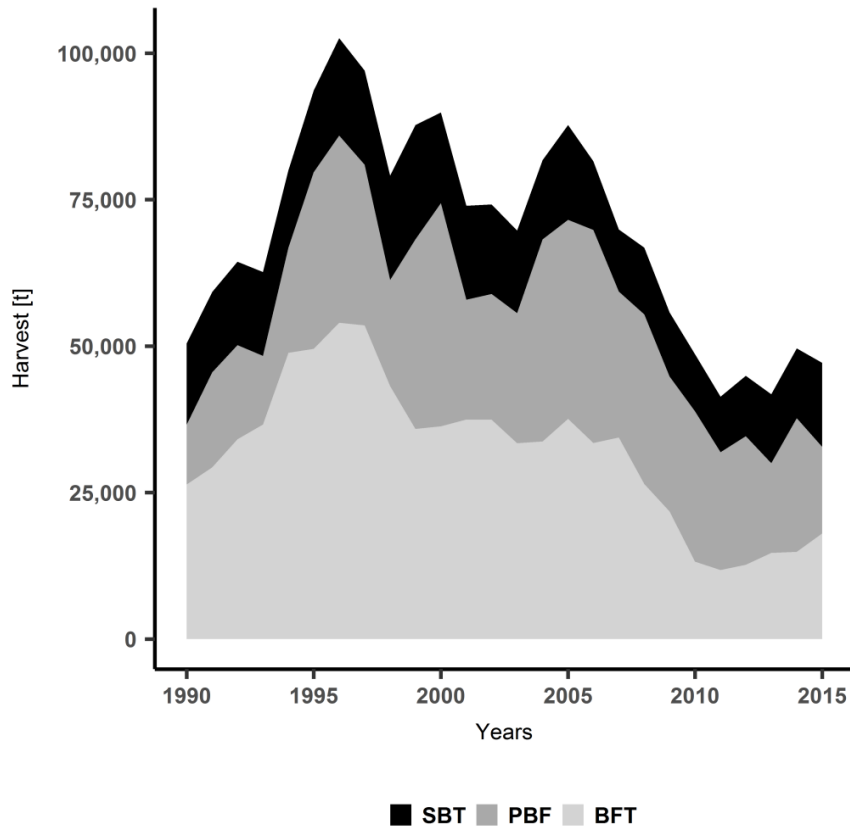
761

762 Appendix 2 Data on East Atlantic Bluefin tuna (EABFT) French and Italian purse seine
 763 fishery from statistics of the Scientific, Technical and Economic Committee for Fisheries
 764 (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

765

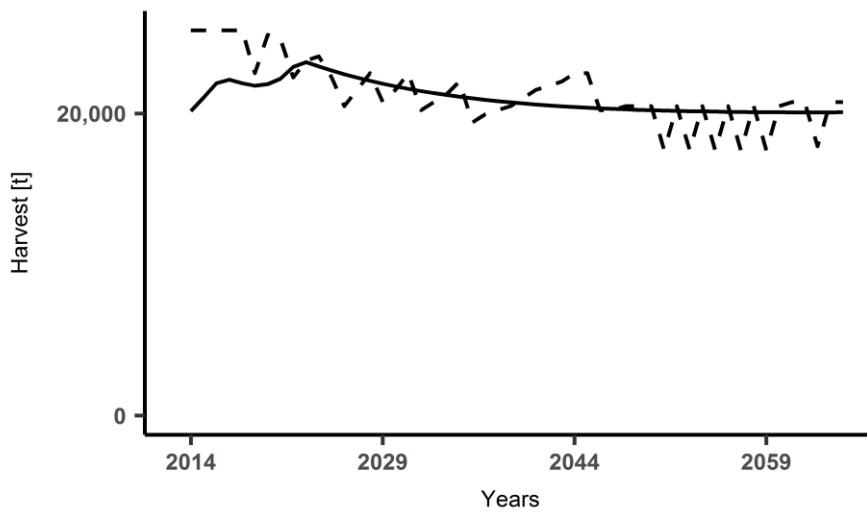
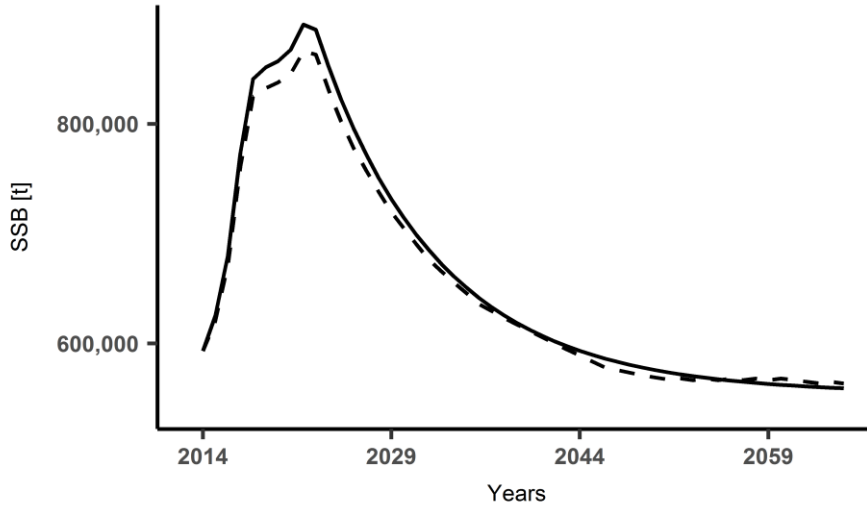
766 Appendix 3 Cumulative annual supply of the global Bluefin tuna by species. In dark the
767 historic of Southern Bluefin tuna (SBT, data from the CCSBT catch data base), in dark
768 grey the catch of Pacific Bluefin tuna (PBF, data from the IATTC and ISC catch data base)
769 and in light grey the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



771

772

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



-- deterministic open-loop — deterministic closed-loop

776

777

778

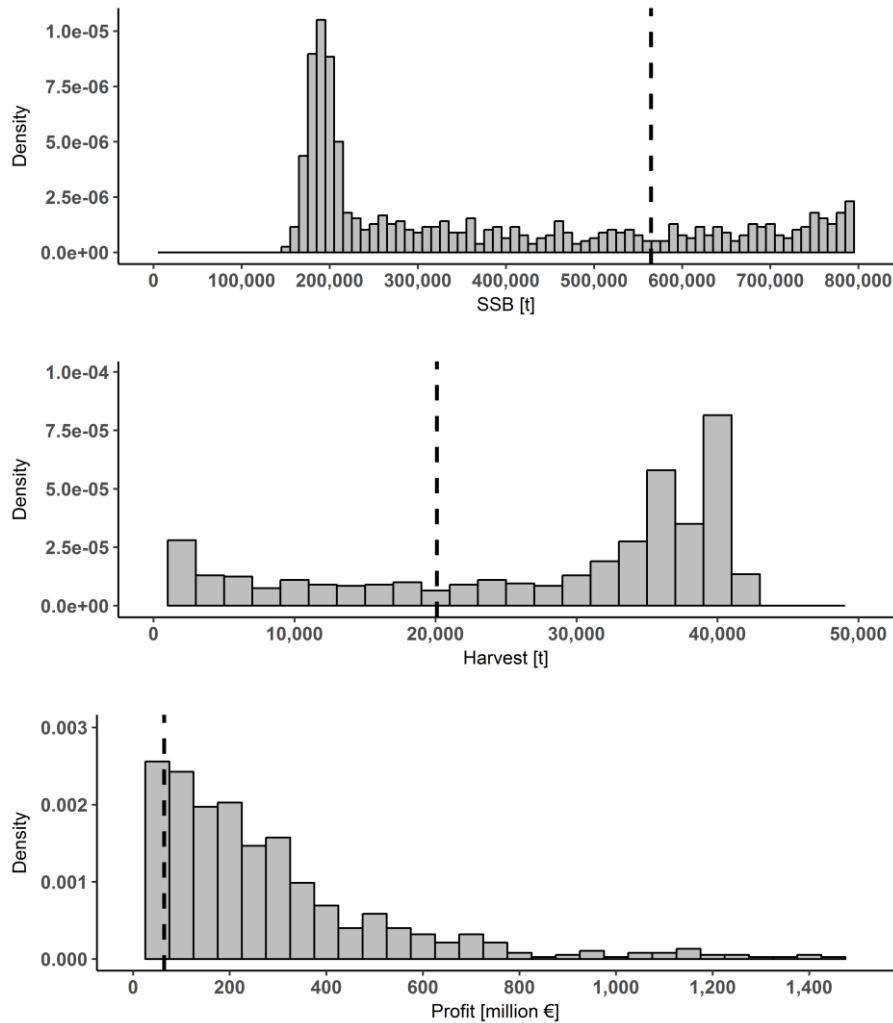
779 Appendix 5 Sensitivity analysis.

780 We assess the effect of key parameters uncertainties on the steady state optimal levels
781 based on the open-loop formulation of the model. For each parameter set, we generate
782 1000 observations assuming normal distributions with means given by their estimates
783 and standard deviation derived from the estimation. We carry out the sensitivity
784 analysis using the latin hypercube sampling (LHS) method from the 'pse' package in R
785 (Chalom et al., 2017).

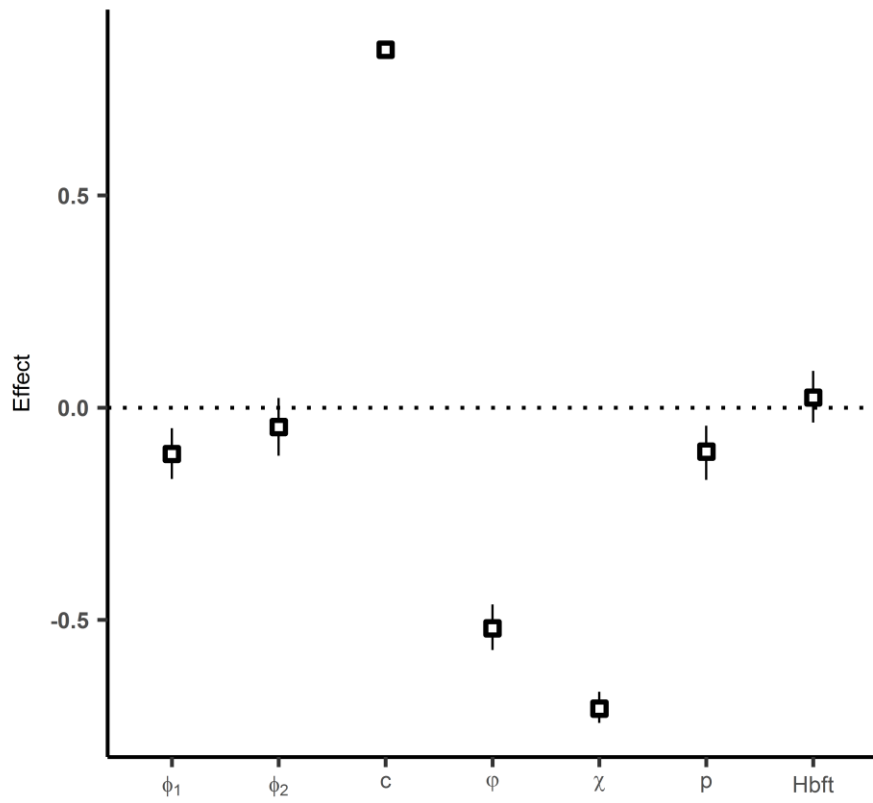
786 An important drawback of age structured population model is the necessity to specify a
787 stock-recruitment relationship. Stock recruitment models are low explanatory because
788 of the low availability of recruitment data and the variability of the recruitment process
789 independently of the spawning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

804 The optimal SSB steady state is very sensitive to economic parameters variations and
805 shows a skewed right distribution with a peak centered on 190,000 tons slight below
806 the SSB at MSY level (Figure A4.1). We observe the inverse pattern for the optimal
807 harvest steady state which shows a long tail to the left of a mode centered on the steady
808 state of 40,000 tons slightly above the MSY level. However, the optimal steady state
809 profit shows large variations on the right of its optimal steady state. The partial rank
810 correlation coefficients (PRCCs, Figure A4.2) measure how strong the linear associations

811 between the optimal steady state SSB and the cost, price and recruitment function
 812 parameters are, after removing the linear effect of the other parameters. PRCCs show
 813 strong negative effects of the stock elasticity parameter (\div) and the price flexibility
 814 parameter (φ) on the optimal SSB steady state. We also notice a strong positive
 815 relationship between the cost scale parameter (c) on the SSB steady state. The dynamic
 816 MEY is fully determined and very sensitive to economic parameters.



817
 818 Figure A4.1 Histogram of the effects of stock recruitment and cost function on optimal
 819 steady-state spawning stock biomass (SSB in tons), harvest (tons) and profit (10^6 €) for
 820 1000 randomly drawn parameter sets. The dotted line represents the optimal steady
 821 state for the selected model parameters.



822

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

825