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The potential impact of marine protected areas on the Senegalese sardinella fishery

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Abstract :

In the early 2000s, Senegal set up several Marine Protected Areas (MPAs) along its coastal zone with the purpose of biodiversity conservation and to support sustainable management of fisheries. However, the impact of MPAs may vary according to the type of fisheries. In Senegal, the sardinella fishery accounts for 70% of total catches. This fishery is of crucial importance for national food security and employment. Given this importance, it is necessary to evaluate the impact of MPAs, often being considered as a tool for fisheries management. An analytical, dynamic and spatial bio-economic model of sardinella fishery, considering fish and fisher migration, has been developed and scenarios over forty years have been analyzed. The results show that the fishery is economically overexploited and that Senegal could lose about 11.6 billion CFA over forty years of exploitation, i.e. 290 million CFA per year. To achieve an optimal level of exploitation, it would be necessary to halve the current fishing capacity. Implementing MPAs for 10, 20 and 30% of the Senegalese exclusive economic zone lead to slight increases in biomass (1%) and rent (5-11%). In addition, spatio-temporal closures can lead to increased exploitation in unclosed areas, due to the absence of enforcement. Achieving target 11 of the Aichi Convention, i.e., 10% of coastal and marine areas protected per country, will have a reserve effect on the resource but also only lead to weak improvements in economic indicators for the Senegalese fishery. Finally, because the sardinella resource is shared among many countries of the Sub-Regional Fisheries Commission (SRFC), a sub-regional cooperation is necessary for a sustainable management.

Highlights

► The *Sardinella* fishery is economically overexploited and that the society loses about 290 million CFA per year. ► To reach an optimal level of exploitation, the current fishing capacity should be halved. ► Spatio-temporal closure measures or MPAs lead inevitably to overcapacity in unclosed areas. ► The objective 11 of the Aichi Convention will have a reserve effect on the resource.

Keywords : Small scale fisheries, MPA, Bioeconomic modeling, Fishing capacity, Fishery management, *Sardinella aurita*, *Sardinella maderensis*, Aichi targets, West Africa

42 1 INTRODUCTION

43 The exploitation of sardinella (*Sardinella aurita* and *Sardinella maderensis*) has a long tradition in
44 Senegal. It expanded with the development of the artisanal purse seine fishery in the 1970s, following an
45 investment into the sector by an FAO project (Dème and Kébé, 2000). Today sardinella catches represent
46 70% of the total catch of the Senegalese artisanal fishery in volume (Thiaw et al., 2017) and contribute
47 mainly to the supply of the local and regional market (Dème et al., 2012; Ba, 2017; Ba et al., 2017).
48 *Sardinella* fisheries play a dual role in the Senegalese economy. Through its contributions to food security
49 and employment, it employs more than 25% of artisanal fishers (16 000 fishers) and provides about 70%
50 of Senegal's fish consumption (Ba, 2017).

51 The sustainability of this fishery is facing many challenges. The overexploitation of the stocks of small
52 pelagic fish is the main one (FAO, 2015; Baldé et al. 2018). In Senegal, the fishery on small pelagics is
53 mainly artisanal, open access and subsidized. Other types of exploitation may compete with artisanal
54 fishing and increased pressure on the resource. These include foreign industrial fishing and national
55 industrial small pelagic fishing. Recently, demand has increased with the establishment of fishmeal
56 industries but also with the opening of new export markets in the sub-region. This situation inexorably
57 contributes to the increase in fishing effort in the area ((Diankha et al., 2018). *Sardinella* stocks migrate
58 between different EEZs (Exclusive Economic Zone) and are shared between Senegal and its neighboring
59 countries (Morocco, Mauritania, Gambia and Guinea-Bissau). Fishing activity for each of the countries
60 therefore depends on the level of exploitation in other countries. In recent years the exploitation of
61 sardinella has intensified in the neighboring areas of Senegal, due to foreign investment for the
62 development of the national fishing or even the presence of international fleets, mainly Dutch and Russian
63 (Corten et al., 2012). According to the FAO, (2017) 2016 landings in countries sharing the resource is
64 around 125 552 tonnes for Senegal, 91 013 tonnes for Mauritania and 6929 tonnes for Gambia. This also
65 reflects the intensity of the fishing effort in the area.

66 In parallel with this dynamics, Senegal signed the International Convention on Biological Diversity in
67 1992 (Anonymous, 1992) and aims to achieve the Aichi biodiversity targets relating to the strategic plan
68 for biodiversity on a global scale for the period 2011-2020. Aichi target 11 calls for a protection of at least
69 10% of the coastal zone by 2020 (Anonymous, 2014; Thomas et al., 2014). Senegal is committed to setting
70 up a network of marine protected areas to preserve marine and coastal biodiversity, but also to ensure
71 sustainable development of fisheries (Anonymous, 2013). Since the beginning of the 2000s, several
72 coastal MPAs have been created, such as off Saint-Louis (496 km²), Kayar (171 km²), Joal (174 km²),
73 Sangomar (817 km²) and Abéné (119 km²) (Anonymous, 2004, 2002). The objective for the choice of
74 these areas is to protect nursery and spawning areas of species with socio-economic interest and also
75 vulnerable species. Most of these areas are located in coastal fishing areas and their implementation limits
76 the access of local artisanal fishers to these fishing areas.

77 Given the importance of the exploitation of sardinella for Senegal and the potential impact of the
78 establishment of MPAs on its sustainable development through reserve and "Spill over" effects (Harmelin-
79 Vivien et al., 2008), it would be useful to estimate the potential consequences of this management policy
80 on the fishery in the long-term. A bioeconomic model has then been developed and used to test different
81 management scenarios to analyze the dynamics of the fishery over the long term in response to different
82 management measures.

83 **2 Materials and methods**

84 Several data sources were used: (i) the database of the Oceanographic Research Center of Dakar Thiaroye
85 (CRODT) already described by several authors (Barry-Gérard, 1985; Laloë, 1985; Laloë and Samba,
86 1990; Thiao, 2009), for landing and effort data for purse seine and encircling gillnet fishing units, as well
87 as the ex-vessel prices of their target species; (ii) data on fixed and variable costs of fishing units were
88 obtained from previous studies (Ba et al., 2017); and (iii) data on the sizes and positions of MPAs
89 (Anonymous, 2004, 2014; Brochier et al., 2015).

90 2.1.1 Size and position of Marine Protected Areas of Senegal

91 The positions and dimensions (Table 1; Fig. 1) of the various MPAs are derived from "Decree No. 2004-
 92 1408 of 4 November 2004 on the creation of Marine Protected Areas" and the Management Plan for the
 93 Marine Protected Area. The area of these MPAs represents only 1% of the Senegalese EEZ (Brochier et
 94 al., 2015). To achieve the 10% protected area of the EEZ (i.e. Aichi target 11) a very significant increase
 95 in the number or size of MPAs is needed.

96 Table 1.

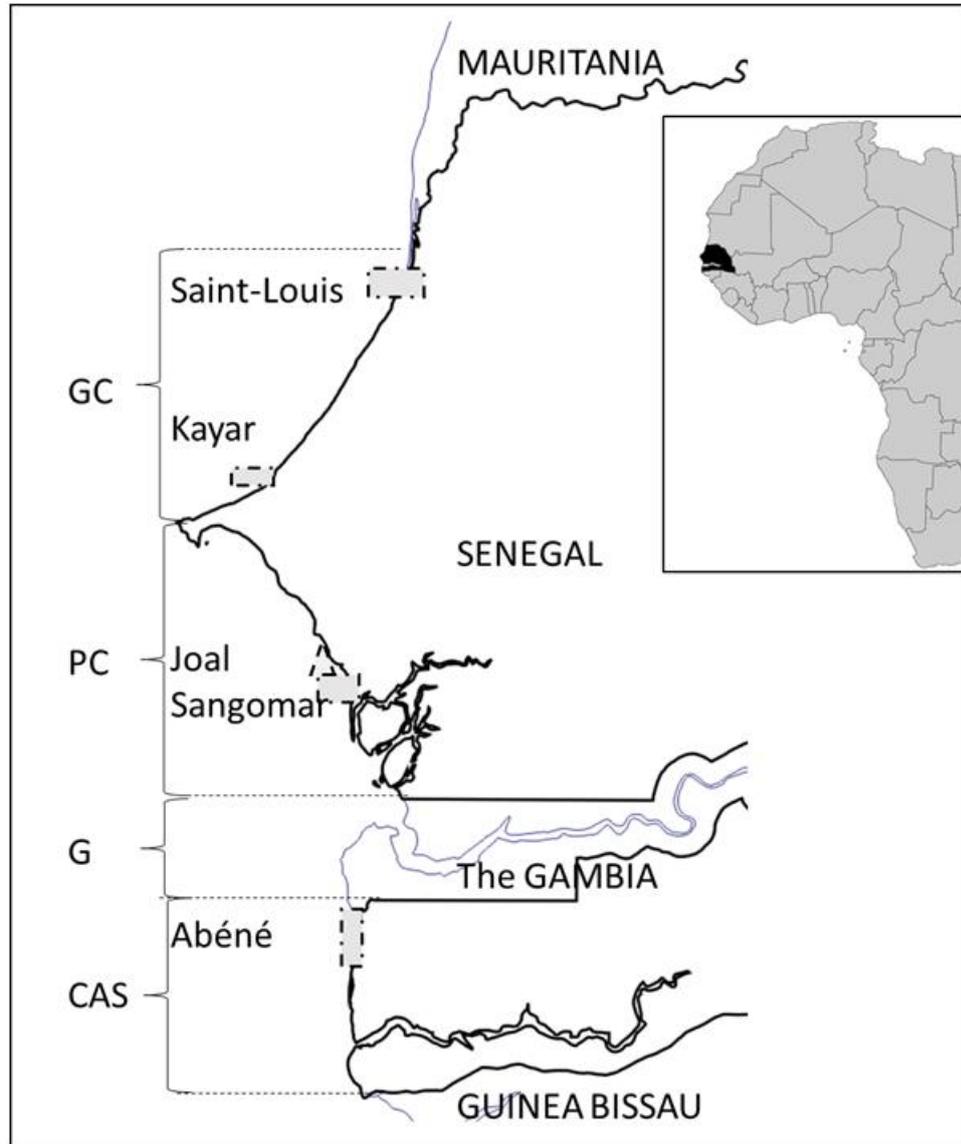
97 The geographical positions and surface areas of the five marine protected areas located along the
 98 Senegalese coastline.

99

Marine Protected Areas	Land positions		Sea Positions		Surface
	Latitudes	Longitudes	Latitudes	Longitudes	
Abéné	13° 02'.3N	16° 44'.5W	13° 02'.3N	16° 49'.5W	119 km ²
	12° 55'. 3N	16° 45'.3W	12° 55' .3N	16° 50' .3W	
Joal-Fadiouth	14 ° 04'.5 N	16 ° 46'.7 W	14 ° 04'.5 N	16 ° 51'.7 W	174 km ²
	14 ° 13'.0 N	16 ° 52'.2 W	14 ° 13'.0 N	16 ° 57'.2 W	
Kayar	14 ° 59'.1 N	17 ° 04'.8 W	15 ° 01'.6 N	17 ° 10'.8 W	171 km ²
	14 ° 53'.1 N	17 ° 10'.5 W	14 ° 55'.6 N	17 ° 16'.5 W	
Saint-Louis	15 ° 58'.5 N	16 ° 31'.5 W	15 ° 58'.5 N	16 ° 48'.5 W	496 km ²
	15 ° 50'.0 N	16 ° 31'.5 W	15 ° 50'.0 N	16 ° 48'.5 W	
Sangomar	14°03'36 N	16°58'48 W	14°03'36 N	16°46'12 W	817 km ²
	13°46'48 N	16°58'48 W	14°03'36 N	16°40'12 W	

100

101



103

104 Figure 1: Marine protected areas (grey area in dashed line) located off the coast of Senegal. The Saint-
 105 Louis and Kayar MPAs are on the Grande Côte (GC), the Joal and Sangomar MPAs are on the Petite Côte
 106 (PC) and the Abéné MPA is located in the Casamance area (CAS). Between the PC and CAS is Gambia
 107 (G) considered in the model as non-participating to the sardinella fishery.

108

109 2.1.2 Principle of the model

110 The bioeconomic model of the small pelagic fishery proposed here is multispecies, multi-fleet and
111 spatially explicit. The resource is composed of *Sardinella aurita* and *S. maderensis*, aggregating in large
112 fish schools (Brehmer et al., 2007), and the fleets targeting these schools are composed of two types of
113 artisanal fishing units called "purse seine (PS)" and "encircling gillnets (EG)". The modeled fishing zone
114 is the Senegalese coastal area where these fishing units operate. It is divided into Grande Côte (GC), Petite
115 Côte (PC) and Casamance (CAS) (Fig. 1). Fishing areas outside the Senegalese EEZ, where part of the
116 resource is seasonally present, are Mauritania (Nordex), Gambia (G) and Guinea Bissau (Sudex). The
117 exploitation of the resource outside Senegal's waters is not explicitly modeled but determined through a
118 fishing mortality rate defined in the initial simulation parameters. The model has monthly time steps and
119 allows for long-term simulations (up to 40 years).

120 The biological component of the model is analytical, based on a simulation of monthly cohorts, the size
121 of which depends on initial recruitment, and natural and fishing mortalities. Fishing mortality is
122 determined by the dynamics of fishing effort, which is itself a function of past economic performance,
123 technological change and management measures. The exogenous parameters of the model (price, costs,
124 recruitment, growth and natural mortality) are either determined before the start of the simulation or
125 redefined during simulation as specified from a parameter file.

126 Fishing effort, catch and price data used for the parameterization of the model are collected using a
127 sampling protocol, detailed in several works (Laloë and Samba, 1990; Pech et al., 2001; Thiao, 2009).
128 The stratified random sampling has been constantly improved since the 1970s (Thiao, 2012; Thiao et al.,
129 2012) and is conducted regularly in the main landing sites along the Senegalese coast where more than
130 90% of the catches are landed. The main landing centers are: Saint-Louis, Kayar, Yoff, Soumbédioune,
131 Hann, Mbour and Joal. The data were structured by months, landing site and fishing gear. The model is
132 developed on the Vensim[®] modeling platform.

133 2.1.3 A multi-species, multi-fleet and spatially explicit model

134 The model is an analytical age-structured, multi-cohort model. The model is inspired by the pioneering
135 work of Thompson and Bell (Thompson and Bell, 1934), Beverton and Holt (Beverton and Holt, 1957)
136 and Laurec and Le Guen (Laurec and Le Guen, 1981). Biological parameters for both *Sardinella* species
137 were obtained from Fréon (1988) and Camarena Luhrs (1986).

138 Both exploited *Sardinella* stocks are analytically modeled with monthly cohorts and the biological part of
139 the model is presented as “supplementary material” in annex 1.5. The fishing effort dynamics is
140 determined through functions of outputs from the economic module. The choice of this type of model was
141 motivated firstly by the migratory behaviors of the species and the fleets but also by the aim of testing
142 different management scenarios such as spatial and temporal closures.

143 The dimensions and the parameters of the model are detailed in the supplementary material (annex 2, 3,
144 4).

145

146

147 2.1.4 Fishing effort dynamics

148 Fleets spatiotemporal dynamics is determined by the availability of the resource in time and space and
149 endogenous economic results. Fleet dynamics is the result of different phenomena. First of all, the
150 determination of the yearly fishing capacity, *i.e.* the total number of boats in the fleets and the fishing
151 effort.

152 2.1.4.1 Determination of the capacity of fishing

153 The fishing capacity ‘*UP*’, which is constant within each annual interval is considered endogenous
154 because of the open access characteristics of the artisanal fishery.

155 The endogenous effort depends on the investment and the disinvestment at the end of each year.
 156 Investment depends on the profit obtained during the past year. At the end of each year 'a', a fixed
 157 proportion of the total profit is reinvested in the form of new fishing units 'NUP' for each fleet 'e'. In the
 158 case of a negative profit 'NUP' will be negative and will correspond to an exit of fishing units. The amount
 159 invested 'IVT' at the end of the year is calculated as follows (equation number is set according to biologic
 160 component equations presented in:

161

$$162 \begin{cases} IVT_{e,a} = PROF_{ea} \cdot txi & PROF_{ea} \geq 0 \\ IVT_{e,a} = PROF_{ea} \cdot txi1 & PROF_{ea} < 0 \end{cases} \quad \text{Equation 1}$$

163 'txi' is the investment rate (reinvested positive profit share) and 'txi1' the disinvestment rate in case of a
 164 negative profit. Given the price of a new fishing unit 'PrUP', the number of new units is then obtained
 165 for each fleet 'e' and year 'a':

166

$$167 NUP_{e,a} = IVT_{e,a} / PrUP_e \quad a = a1, a2, \dots, a40 \quad \text{Equation 2}$$

168

169 The number of 'UP' fishing units per fleet 'e' and for year 'a' will be:

170

$$171 UP_{e,a} = UP_{e,a-1} + NUP_{e,a-1} \quad a = a1, a2, \dots, a40 \quad \text{Equation 3}$$

172

173 2.1.4.2 Spatial distribution of fleets

174 To represent the spatial redistribution of fishing units over time in Senegal, a distribution function guided
 175 by the attractiveness of fishing zones is constructed. The latter is equal to the average biomass of each

176 zone in relation to the total average biomass ‘*BIZS*’ in $t-1$ and $t-12$, for each species and zone ‘*zsen*’. The
 177 average abundance of each zone is multiplied by the closure variable of zone ‘*Ferm*’ (equal to 0 when
 178 closed and to 1 when opened) so that the closed zones (MPA) (thus zero attractiveness), are not targeted
 179 by the fisheries.

$$180 \quad ATRZ_{zsen, t} = \frac{\sum_i [(BIZS_{i, zsen, t-1} + BIZS_{i, zsen, t-12}) * Ferm_{zsen, t}]}{\sum_{i, zsen, t} [(BIZS_{i, zsen, t-1} + BIZS_{i, zsen, t-12}) * Ferm_{zsen, t}]} \quad \text{Equation 4}$$

181 The fleet ‘*UPZ*’ per zone ‘*zsen*’ and fishing type ‘*e*’ can then be determined:

$$182 \quad UPZ_{e, zsen, t} = UP_{e, t} \cdot ATRZ_{zsen, t} \quad \text{Equation 5}$$

183 2.1.4.3 Determination of the active fleet

184 A distinction is made between present fleet (fishing capacity) and active fleet ‘*Fla*’ (nominal fishing
 185 effort). To move from the first to the second, it is necessary to use the rate of activity ‘*txact*’ per fleet,
 186 determined by the short-term profitability of the activity (relative margin on the variable cost).

187

$$188 \quad Fla_{e, zsen, t} = UPZ_{e, zsen, t} \cdot txact_{e, zsen, t} \quad \text{Equation 6}$$

189

190 2.1.5 Economic module of the bioeconomic model

191 2.1.5.1 Fixed and variables costs

192 Two types of costs are considered. The fixed costs ‘*CFTOT*’ are independent of the activity rate of the
 193 fleet but proportional to the fishing capacity (constants inputs, depreciation, maintenance of equipment
 194 and insurance). The variable costs ‘*CVTOT*’ are proportional to the active fleet but are also be related to
 195 landed quantities

196

$$197 \quad CFTOT_{e, zsen, t} = parCF_e \cdot UPZ_{e, zsen, t} \quad \text{Equation 7}$$

198

199 Where ' $parCF$ ' are the annual fixed costs per fishing unit.

200 The cost of landing, which is part of the variable costs, is proportional to the quantity of landings ' CFT '.

201 ' $ParCV$ ' is the amount of other variable costs per fishing unit and per month.

202

203
$$CVTOT_{e, zsen, t} = Fla_{e, zsen, t} \cdot parCV_e + CDEB_{e, zsen, t} \quad \text{Equation 8}$$

204

205 *2.1.5.2 Labor remuneration*

206 In the fishing sector, the remuneration of labor is generally based on a system with a "pure" or "mixed"

207 share. The first system is the one generally observed in the Senegalese artisanal fishery. In this model, the

208 crew remuneration ' LA ' is obtained from the balance to be shared, obtained by the difference between

209 turnover ' REV ' and variable costs ' $CVTOT$ ', and that is multiplied by the relative share going to the crew

210 ' $paramPartPa$ '. The annual remuneration by type of fishing ' e ' is obtained from the following equation

211 (where ' $tdeb_a$ ' and ' $tfin_a$ ' are the limits of each annual time interval ' a ').

212
$$LA_{e, a} = \sum_{t=tdeb_a}^{tfin_a} \sum_{zsen} \left((REV_{e, zsen, t} - CVTOT_{e, zsen, t}) \cdot paramPartPa \right) \quad \text{Equation 9}$$

213
$$\text{with } a = a1, a2, \dots, a40$$

214

215 *2.1.5.3 Vessel owners' profit*

216 The profit ' $PROFC$ ' is the remuneration of private investors (vessel owners). It is equal to turnover REV

217 minus the variable costs ' $CVTOT$ ' (common costs shared between crew and owner), fixed costs ' $CFTOT$ '

218 and labor remuneration ' L .' The cumulative profit per year ' a ' and fleet ' e $PROFC$ ' is obtained by

219 summing the profit on each annual time interval:

220

221 $PROFC_{e,a} = \sum_{t=tdeb_a}^{tfin_a} (\sum_{zsen} (REV_{e,zsen,t} - CVTOT_{e,zsen,t} - CFTOT_{e,zsen,t} -$
 222 $L_{e,zsen,t}))$ Equation 10

223 With $a = a1, a2, \dots, a40$

224

225 *2.1.5.4 The economic rent of the fishery*

226 The economic ‘*RENT*’ corresponds to the private profit corrected for the net transfers between the state
 227 and the fishery (taxes ‘*RED*’ less subsidies ‘*SUB*’). The economic rent is estimated per fleet ‘*e*’ at the end
 228 of each annual interval ‘*a*’.

229

230 $RENT_{e,a} = PROFC_{e,a} + (RED_{e,a} - SUB_{e,a})$ Equation 11

231 The discounted economic rent ‘*RENTACT*’ is the sum of the current economic rent multiplied by the
 232 discount factor ‘*FACT*’, obtained from the annual discount rate ‘*TxActu*’.

233 $FACT_a = \frac{1}{(1+TxActu)^a}$ Equation 12

234

235 $RENTACT = \sum_a (\sum_e RENT_{e,a} \cdot FACT_a)$ Equation 13

236

237 *2.1.5.5 Added value*

238 Gross added value (*GVA*) is the difference between the value of landings and intermediate consumption
 239 inputs (all goods and services used during the production process). Net value added (*NVA*) is equal to
 240 gross value added less depreciation ‘*ParAmt*’ and subsidies ‘*SUB*’. It is also equal to the sum of the net
 241 remuneration of production factors (private profit and labor remuneration) plus the net income of the

242 State. Gross added value is an indicator of wealth creation by the fishery (contribution to the national
 243 Gross Domestic Product). Unlike rent, it integrates labor remuneration, an important element for poverty
 244 reduction, which is part of Senegal's fisheries management objectives (Anonymous, 2002). If the focus of
 245 the management of the small scale sector is the social dimension then value added seems to be a more
 246 relevant objective than economic rent.

247 The actual net value added, which can be considered, in a similar way to the actual rent, as an objective
 248 function (to be maximized) in long-term management, is obtained by using the actual factor *FACT*:

249

$$250 \quad VANACT = \sum_a (\sum_e (\sum_{t=tdeb_a}^{tfin_a} (VAB_{e,t} - ParAmt_e) - SUB_{e,a}) \cdot FACT_a) \quad \text{Equation 14}$$

251 2.2 Management scenarios

252 As a first step, the dynamics of the Sardinella fishery has been simulated over forty years, using parameters
 253 based on the current fishery situation, to test the consequences of a long-term *status quo* on it. As a second
 254 step, the response of the fishery to an increase of fishing capacity (using a fishing capacity multiplier) has
 255 been simulated to determine economic and biological optima. Then, the dynamics of the fishery is
 256 simulated according to different closures options (size of the MPAs) in the current situation management
 257 scenario and in an overexploitation scenario

258 3 Results

259 The dynamics of biomass, active fleets, rent, total cost, income, profit, net added value and labor income
260 are used to compare different scenarios. The economic results are evaluated over the long term (40 years)
261 on the basis of their final discounted value (at a discount rate of 5%).

262 3.1 Consequence of a 40-year *status quo* on Sardinella fishery in Senegal

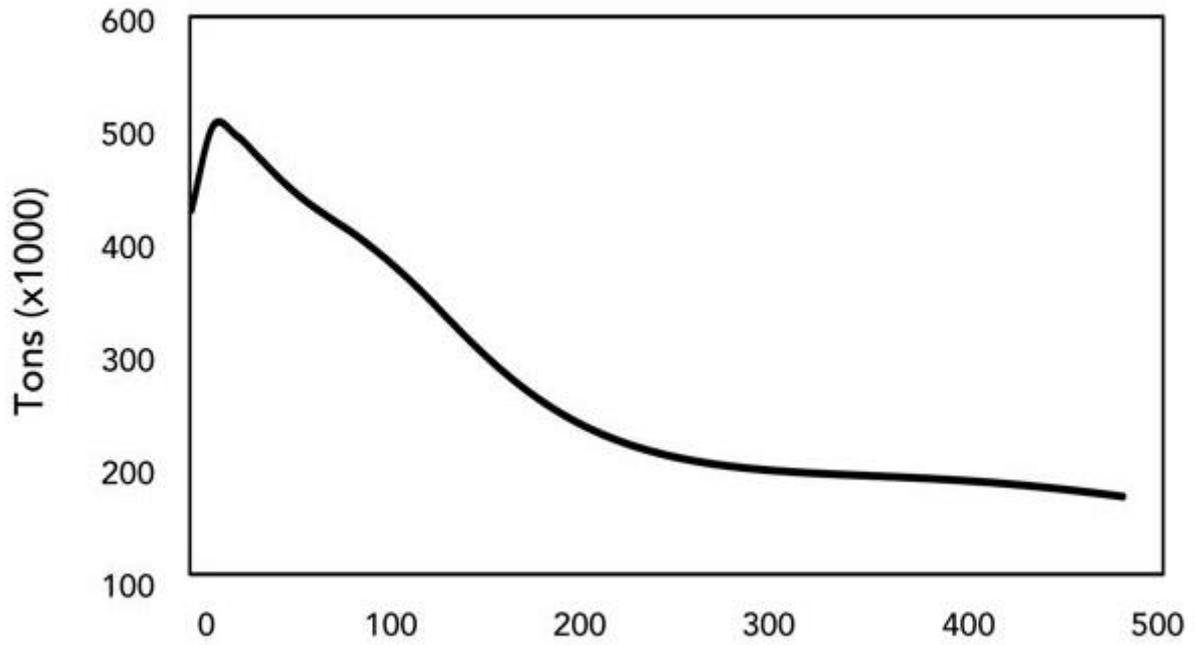
263 This scenario is used to show the dynamics of the fishery if current conditions, including free access to
264 the resource and subsidies of fishery, were maintained over the next forty years.

265

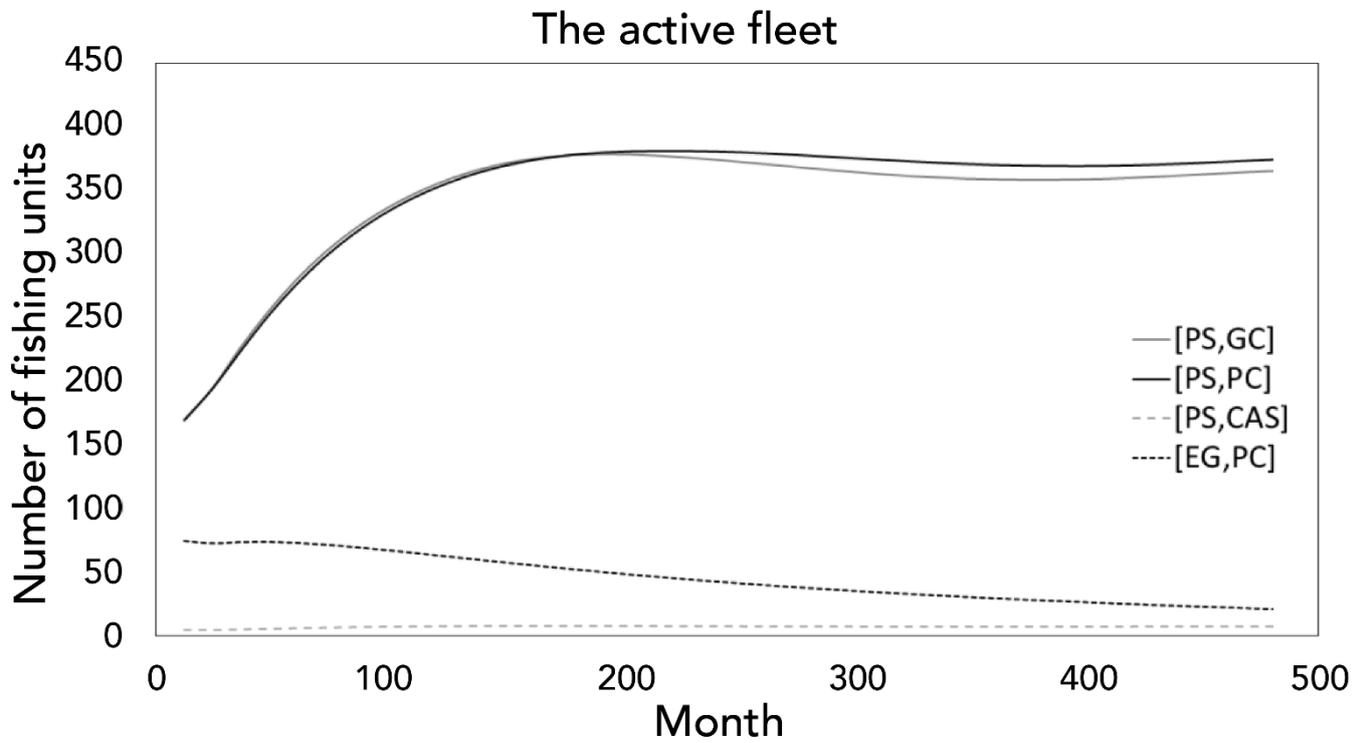
266 3.1.1 Effect of the *status quo*: on the biomass and the active fleet

267 After an initial small increase, the biomass is decreasing over the simulation period, and at the end of the
268 simulation 68% of the biomass is lost (Fig. 2). This decline is faster during the first 20 years, with a 60%
269 biomass decrease. This is mainly due to the increase of the artisanal fleet capacity (Fig. 3). The number
270 of purse seine fishing units is doubling over the total simulation period. For encircling gillnet fishing units,
271 we observe a decrease in their activity over time and their number is divided by more than six at the
272 simulation end.

273



274
 275 Figure 2: Dynamics of the total biomass of sardinella over the forty years according to the reference
 276 situation.



277
 15

278 *Figure 3: Dynamics of the Senegalese active fleets in the different zones. Black curve = Purse seine (PS)*
279 *on the Grande Côte (GC); gray curve = Purse seine on the Petit Côte (PC); dotted gray = Purse seine in*
280 *Casamance (CAS); dotted black = Encircling gillnets (EG) on the Petite Côte (PC).*

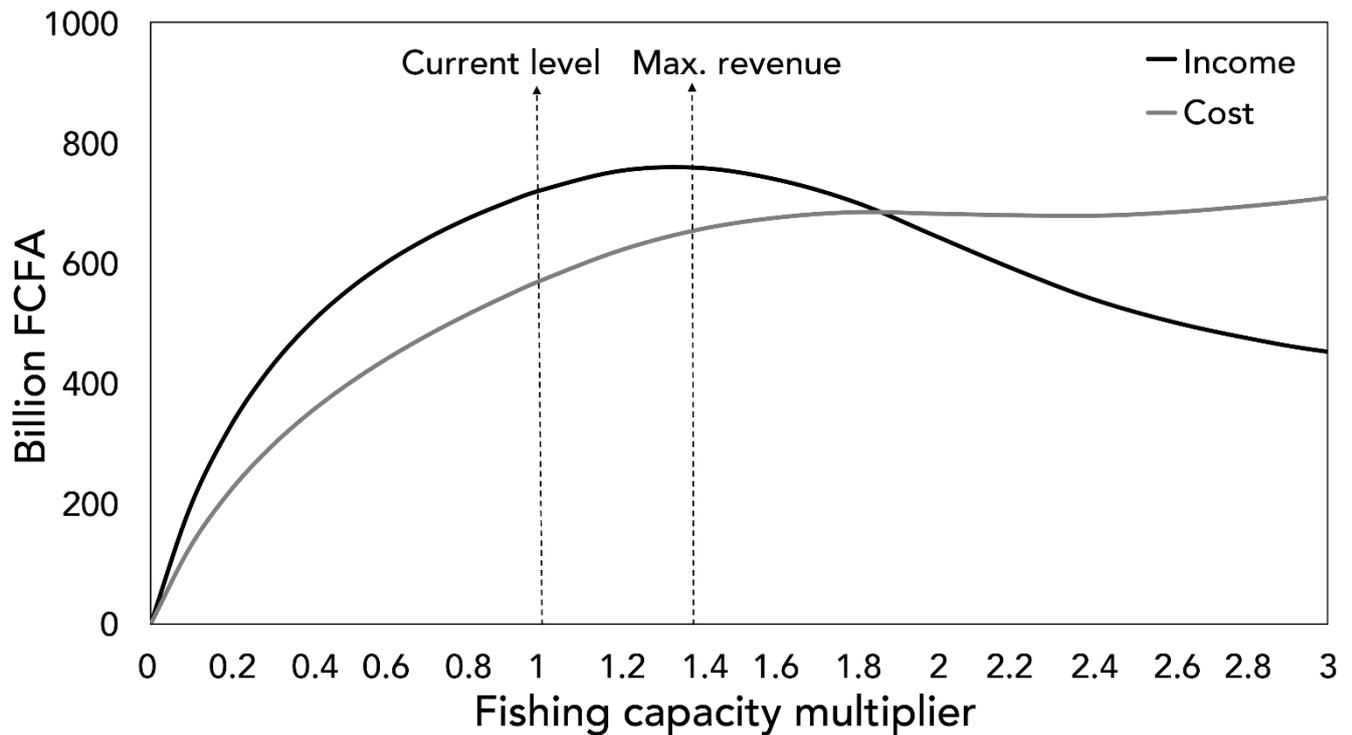
281

282 3.1.2 Response of economic indicators to different levels of fishing capacity

283 Different fishing capacity scenarios were explored, with different initial fishing capacity (using a
284 multiplier), and taking this values constant until simulation end. A multiplier value equal to 1 corresponds
285 to the fishing capacity level in 2013, i.e., 593 purse seine and 128 encircling gillnets fishing units. The
286 discounted values, over the entire simulation period, for the main economic indicators were obtained as a
287 function of the fishing capacity multiplier in order to determine the different optima according to this
288 control variable.

289 The discounted income obtained in the reference scenario (i.e. for a fishing capacity multiplier equal to
290 1) is equal to 722 billion FCFA, corresponding to an annual catch level of 313 200 tons. This is clearly
291 less than the achievable maximum (758 billion FCFA) corresponding to a capacity multiplier equal to 1.4
292 (Fig. 4). In the current fishing capacity situation, the fishery does not reach its maximum sustainable yield
293 (MSY) and is not be biologically overexploited.

294 In the same simulation (fishing capacity multiplier equal to 1) for economic rent, profit and net value added
295 (NVA), the fishery is not in a state of total dissipation of economic wealth (i.e. these indicators still stay
296 positive). The profit equal zero when the capacity multiplier is set to 1.85, and the 'NVA' equal zero when
297 the capacity multiplier equals to 1.9.



298

299 Figure 4: Responses of cost (gray curve) and income (black curve) to different fishing capacity multiplier

300 values

301

302 To achieve the level of fishing capacity corresponding to the maximum profit (162 billion FCFA) the

303 current effort has to be decreased by 30%. However, the discounted profit still remains positive (150

304 billion FCFA) for the current fishing capacity level. An open access equilibrium leading to zero profit is

305 therefore not yet reached.

306 However, the fishery is currently economically overexploited. The discounted rent (100.5 billion) is lower

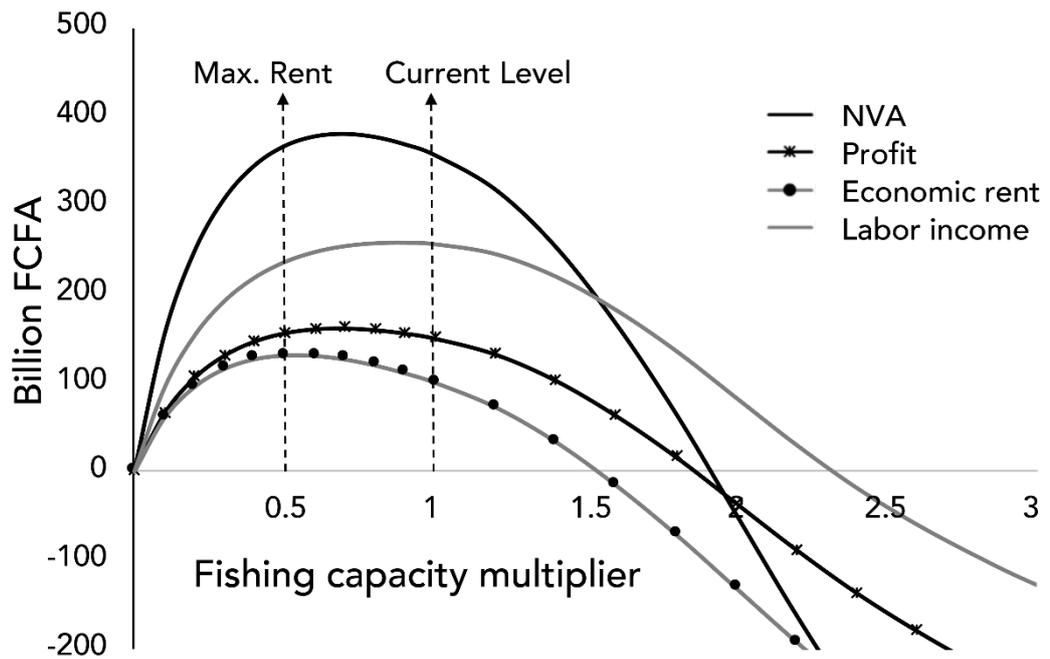
307 than the discounted maximum economic yield (MEY) (131.4 billion FCFA), obtained for a fishing

308 capacity equal to the half of the reference capacity level (Fig. 5). The contribution of the fishery to the

309 national economy, the net added value (NAV), achieves its maximum (381.7 billion FCFA) when the

310 fishing capacity is decreased by 30%. (Fig. 5).

311



312
 313 Figure 5: Responses of the main economic indicators to the increase of fishing capacity. Black curve:
 314 NVA (Net value added); gray curve: labor income; black curve with cross: profit; gray curve with circle:
 315 economic rent.

316
 317 The discounted labor income (wages of crew members) is maximized with a 10% reduction in fishing
 318 capacity (Fig. 5). Thus, if the objective is to guarantee maximal remuneration for fishermen, fishing
 319 capacity should thus only be reduced by 10%, still ensuring a positive, but sub-optimal profit for vessel
 320 owners. This situation, however, is not optimal for the whole national economy due to a government
 321 revenue loss equal to 50 billion FCFA. On the other hand, if one seeks to maximize the contribution of
 322 the sector to the national wealth r (discounted NPV), it is necessary to reduce the fishing capacity by 30%.
 323 Finally, if the objective is to guarantee maximum remuneration for private investors (vessel owners) a
 324 same reduction of 30% would fulfil this objective.

325

326 3.2 Consequences of MPA implementation

327 In the current fishery (including open access in the fishery), closure rates of 10%, 20% and 30% for all
328 fishing areas lead to an insignificant increase in final total biomass of 1%. A closure of 30% of the Petite
329 Côte alone, does not lead to an increase in total biomass (Fig. 6a, b, and c).

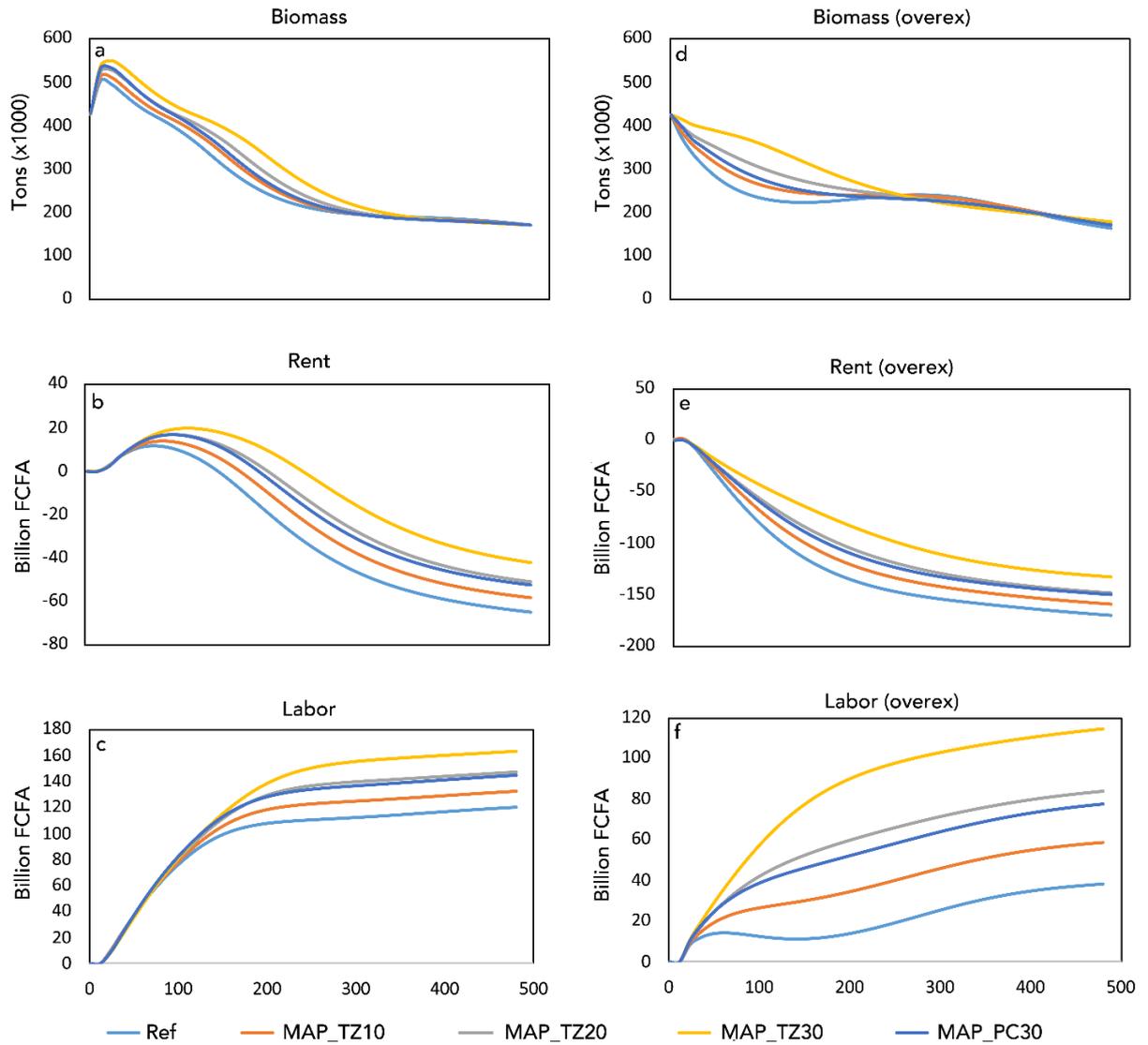
330 For discounted economic rent, closure rates of 10%, 20% and 30% of all fishing zones result in an increase
331 of 10%, 21% and 35%, respectively. The closure of 30% of the Petite Côte only leads to 18% increase in
332 economic rent (Fig. 6a, b, and c).

333 Concerning labor income, closures of 10%, 20% and 30% of all fishing areas result in increases of 10%,
334 22% and 36% respectively. The closure of 30% of the Petite Côte only leads to an increase in labor income
335 equivalent to that of a closure of 26% of all fishing areas (Fig. 6a, b, and c).

336 With overcapacity in the fishery (current fishing capacity multiplied by three), closure rates of 10%, 20%
337 and 30% respectively lead to an increase of 3%, 7% and 9% at the end of the simulation period compared
338 to the reference biomass (capacity multiplier equal to 1) (Fig. 6d, e, and f). An implementation of marine
339 reserves of 30% of the Petit Côte leads to a 5% increase in biomass. In addition, the trajectory taken by
340 biomass in both cases (overcapacity and current situation) shows that the establishment of MPAs produces
341 a slight reserve effect in the case of *Sardinella* exploitation.

342 In the context of an overexploitation, closures of fishing areas lead to an increase in discounted economic
343 rent (Fig. 6d, e, and f). The closures of 10%, 20% and 30% of all fishing zones result in increases of 6%,
344 13% and 21% of discounted rent, respectively. A closure of 30% of the Petit Côte alone leads to an 11%
345 increase.

346 The closure of fishing areas leads to a sharp increase in discounted labor income under overexploitation
347 (Fig. 6d, e, and f). Closures of 10%, 20% and 30% of all fishing areas lead to a 53%, 119% and 199%
348 increase in discounted labor income, respectively. A reserve of 30% of the Petit Côte allows a 104%
349 increase.



350

351 Figure 6: Responses of the biological and economic indicators of the sardinella fishery to closure rates in
 352 the current exploitation context (a, b, and c) and in a context of overexploitation of the resource (d, e, and
 353 f). ‘Ref’ = current state; ‘MPA_TZ’ = Closure all zones (PC, GC, CAS); ‘MPA_PC’ = Closure ‘Petite
 354 Côte’ only; 10%, 20%, 30% = closing rates of fishing areas. ‘Overex’ (overexploited), ‘TZ’ (All Zones),
 355 ‘GC’ (Grande Côte), ‘PC’ (Petite Côte), ‘CAS’ (Casamance), ‘G’ (Gambia) and ‘MPA’ (Marine Protected
 356 Area). The abscissas are in months.

357

358

359 **4 Discussion**

360 4.1 On the state of the Sardinella fishery in Senegal

361 The analysis of the reference scenario shows that the Sardinella fishery is currently economically
362 overexploited. Compared to the optimal situation, the society loses about 11.6 billion FCFA over 40 years,
363 or 290 million FCFA per year. This is mainly due to the open access regime leading to fleet overcapacity,
364 i.e the capital required to optimize economic indicators, with the exception of labor income, is largely
365 exceeded in the Senegalese Sardinella fishery. These results are consistent with the findings of several
366 authors (Pech et al., 2001; Greboval and Catanzano, 2005; Pauly, 2006, 2007; Teh and Sumaila, 2007;
367 Thiao et al., 2012) which show how open access or chronic subsidies lead to overcapacity, economic
368 losses and a reduction in the exploited natural capital.

369 This overcapacity was also empirically confirmed by the emigration of purse seine fishing units from
370 Senegal to Mauritania (Corten et al., 2012), in search of more profitable fishing grounds. These migrations
371 were legally permitted through a bilateral fishing agreement (400 fishing licenses for Senegalese purse
372 seine units) between Senegal and Mauritania. This agreement allowed purse seine fishing units to follow
373 the natural migration of sardinella but also contributed to the reduction of overcapacity in Senegalese
374 waters. This fishing agreement was not renewed in 2017, so the Senegalese fishing units returned to
375 Senegal, then increasing overcapacity again.

376 Sardinella catch has not yet reached the maximum sustainable yield (MSY) and thus can still be increased.
377 But an increase in fishing effort will also be accompanied by an increase in costs difficult to sustain by
378 the artisanal fishery. These findings suggest that the fishery is not biologically overexploited, being in
379 contradiction with the assessments made by CECAF (Fishery Committee for the Eastern Central Atlantic)
380 between 2001 and 2015 (FAO, 2001, 2015).

381 This difference in results could be explained by several factors including the assessment method used, the
382 spatial coverage of the model and the difficulty of having heterogeneous data in the countries sharing the

383 sardinella stocks. Indeed, the CECAF estimates consider the sardinella stocks from Mauritania to Senegal
384 whereas the model utilized in this study uses only the data available in the Senegalese economic exclusive
385 zone. CECAF also uses a global Gordon-Schaefer model over the entire Senegal-Mauritanian zone, while
386 an analytical model applied on the Senegalese zone is used in this study. However, the scenarios carried
387 out in this study are likely optimistic scenarios, i.e. underestimating effort and harvest, as they did not
388 consider the possibility of an increase in fishing effort in the neighboring countries of Senegal.

389

390 4.2 The effect of MPAs on the sardinella fishery

391 Most studies address the behavior of fishing effort and abundance in pelagic and mobile species
392 (Mesnildrey et al., 2013). This study does not only address these aspects, but also shows the economic
393 efficiency that could be achieved by establishing spatiotemporal closures in an open access small pelagic
394 fishery.

395 In the current state of the fishery, closures lead to a slight increase in biomass and economic gains in rent
396 and labor income. These results are mainly due to the current overcapacity in the fishery. Indeed, the
397 closure of fishing areas indirectly leads to the decline of fishing capacity in closed areas. In the case of
398 the closure of a single fishing zone, this policy results in a displacement of the fishing capacity into areas
399 open to fishing and subsequently to poor biological and economic results.

400 This particularity is essentially linked to the very high mobility of the resource and the fleet. The effect of
401 the MPA on the fishing capacity in a single fishing zone is therefore limited by the mobile nature of the
402 resource and the fleet. This consequence of a closure has also been shown in other fisheries (Hilborn et
403 al., 2004; Garcia et al., 2013; Lehuta et al., 2013; Mesnildrey et al., 2013; Ba, 2017). In order to have a
404 positive effect on both biomass and economic indicators, MPAs should be combined with a limitation of
405 fishing effort, which is not yet the case in Senegal (Ba, 2017). In a more in-depth framework, it appears
406 that the effects of spatiotemporal closures on the resource and on economic indicators are more evident

407 when fishing is in a state of overexploitation. In this case a reduction in effort or fishing capacity can
408 contribute to the increase in total biomass but also an improvement in economic indicators.

409 In line with target 11 of the Aichi Convention which suggests a closure of 10% of the coastal zone, the
410 model shows that this objective leads to a slight increase in the total biomass of sardinella. Under the
411 assumption of full or overexploitation, this closure rate would lead to an increase in biomass and economic
412 gains. Given that the Sardinella fishery is economically overexploited, any closure of the area necessarily
413 leads to a decline in fishing capacity and therefore an improvement in biological and economic indicators.

414 One caveat is that in these scenarios, no illegal fishing is assumed to happen in the regulated or protected
415 marine areas. In Senegal since the beginning of the 2000s, several MPAs have been created (e.g., Kayar
416 on the Grande Côte and Joal on the Petite Côte), but without clear effect on the dynamics of the fleet. The
417 number of fishing units, especially purse seine, has not declined in these areas and thus these MPAs seem
418 to be not very effective because of the high mobility of the resources and wide distribution of fishing
419 units. Illegal, unreported and unregulated fishing “IUU” is not considered in this study even though a
420 significant activity in the West African region could be assumed, with a high number of foreign industrial
421 vessels operating in Senegal, neighboring countries and the region in general. Their inclusion in the model
422 will likely increase the assessment of overcapacity of the fisheries. Therefore, we can assume that the
423 results on overcapacity are an underestimation and recommendations regarding the overcapacity are
424 reinforced.

425

426 The observation of the weak effect of MPA on the small pelagic fishery in Joal is in agreement with
427 Hilborn and al. (Hilborn et al., 2004) who argue that marine reserves provide few advantages over
428 conventional fishing management tools for fisheries that target a single highly mobile species with little
429 or no by catch. This low impact of MPAs in small pelagic fisheries has also been reported in the pelagic

430 fishery of the Bay of Biscay (Lehuta, 2010; Lehuta et al., 2013). In addition, the closure zone must be
431 large enough to protect breeding stocks of mobile species and to have spillover effects (Hannesson, 1998).
432 In our case, the number and size of closed areas (MPA size) seems enough to provide positive results on
433 biomass. The results are better than those of the *status quo* but this difference is explained by the fact that
434 in the model, the fishing ban is completely enforced in the closed zone. The increase in fishing costs due
435 to the establishment of MPAs reported by several authors (Hilborn et al., 2004; Boncoeur, 2005;
436 Mesnildrey et al., 2013; Chaboud, 2014) is less obvious in this fishery due to the seasonal migration of
437 fishers and especially because they can change their home port.

438 Another point is the cost of implementation and monitoring which can be quite high for large MPAs. This
439 cost should have been taken in account to estimate the economic return obtained for the national economy.
440 Due to the absence of data on these MPAs costs, there were not included in our model. Then effective
441 returns to national economy should be slightly less than those obtained in simulations.

442

443 **5 Conclusion**

444 The available scientific knowledge on the Senegalese artisanal fishery for small pelagic fish has allowed
445 to build a bio-economic model, and to simulate its dynamics over several decades and then to test the
446 impact of different spatial closure options on biological and also economic indicators.

447 Sardinella fishery is, from an economic point of view, overexploited in Senegal. To reach an optimal level
448 of exploitation, it would be necessary to significantly reduce the fishing capacity. However, this solution
449 remains difficult to implement because it requires fishermen acceptance and compensation for those who
450 agree to leave fishery, as it is the case for fleet decommissioning plans (OECD, 2009). Moreover, the
451 introduction of such measures will likely run up against the cultural nature of small-scale fisheries in

452 Senegal, which consists mainly of family businesses in small communities where fishing plays an
453 important identity building role.

454 The spatiotemporal closure measures lead to a decrease in capacity in closed areas. However, in the current
455 context of open access and high sub regional mobility of resources and fleets, this measure leads to a
456 concentration of fishing capacity and effort in areas remaining open to fishing. Thus, Senegal's compliance
457 with target 11 of the Aichi will not have a highly significant effect on the sardinella fisheries.

458 For the establishment of spatiotemporal closures to have a significant impact on the fishery, closed areas
459 should be large enough to cover an entire breeding area (Hannesson, 1998). This measure is difficult to
460 take because the breeding areas are often very large, sometimes shared between two states and often
461 overlay with fishing grounds. To ensure the sustainability of the exploitation of this resource, the countries
462 concerned should have a common management plan within the maritime zones under the jurisdiction of
463 the Sub-Regional Fisheries Commission (SRFC) member States.

464 In the event that a *status quo* situation persists, and that the States remain on unilateral or bilateral positions
465 in the negotiations of fishing agreements and the establishment of a common concerted policy, sardinella
466 fishery will always be subject to overexploitation and perhaps even collapse. The absence or weak
467 coordination in the management of resources shared between the different countries will continue to lead
468 to a "race for fish" and thus to the tragedy of common goods (Gordon, 1954; Hardin, 1968; Clark and
469 Munro, 1975; McWhinnie, 2009). It is therefore important to remember that decision-making on this
470 fishery must be sub-regional to be efficient because of the shared nature of the resource.

471 This work allows to inform decision-making in a sub-regional context by providing scenario of the impact
472 of different regulatory scenarios, playing with the types of fishing units, considering the effort and the
473 dynamics of the fishery in the other countries sharing the same resource. This opportunity would require
474 the standardization of data in all countries sharing the resource. Thus, the natural perspective of our work
475 of interest in terms of fishery management, is to extend our modeling work on the distribution area of both

476 sardinella stocks and thus foster sub-regional collaboration providing to sub-regional and state
477 institutions a management tool built on socio-economic bases and incorporating ecological and marine
478 criteria.

479

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489

490 **REFERENCES**

- 491 Anonymous, 2014. Cinquième rapport national sur la mise en œuvre de la convention internationale sur la
492 diversité biologique (Rapport technique). Ministère de l'Environnement et du Développement Durable,
493 République du Sénégal, Dakar. <https://www.cbd.int/doc/world/sn/sn-nr-05-fr.pdf>
- 494 Anonymous, 2013. Stratégie Nationale pour les Aires Marines Protégées du Sénégal (Rapport technique).
495 République du Sénégal, Dakar. <http://extwprlegs1.fao.org/docs/pdf/sen160731.pdf>
- 496 Anonymous, 2004. DECRET n° 2004-1408 du 4 novembre 2004 portant création d'Aires Marines Protégées. J. Off.
497 Sénégal 3. <http://www.jo.gouv.sn/spip.php?article6753>
- 498 Anonymous, 2002. Document de Stratégie de Réduction de la Pauvreté (Rapport technique). République du
499 Sénégal, Ministère de l'économie et des finances, Dakar.
500 <http://www.bameinfopol.info/IMG/pdf/DSRP.pdf>
- 501 Anonymous, 1992. Convention sur la Diversité Biologique (Rapport juridique). Nations Unis, Rio de Janeiro.
502 <https://www.cbd.int/doc/legal/cbd-fr.pdf>
- 503 Ba, A., 2017. Analyse microéconomique et modélisation bioéconomique de la pêche artisanale de sardinelles
504 au Sénégal (Thèse de doctorat en Sciences Halieutiques). Université Cheikh Anta Diop de Dakar, Dakar.
- 505 Ba, A., Schmidt, J., Dème, M., Lancker, K., Chaboud, C., Cury, P., Thiao, D., Diouf, M., Brehmer, P., 2017.
506 Profitability and economic drivers of small pelagic fisheries in West Africa: A twenty year perspective.
507 *Mar. Policy* 76, 152–158. <https://doi.org/10.1016/j.marpol.2016.11.008>
- 508 Barrowman, N.J., Myers, R.A., 2000. Still more spawner-recruitment curves: the hockey stick and its
509 generalizations. *Can. J. Fish. Aquat. Sci.* 57, 665–676. <https://doi.org/10.1139/f99-282>
- 510 Barry-Gérard, M., 1985. Contribution à la connaissance de la pêche artisanale sur la Petite Côte : description et
511 étude critique du système d'enquête à Mbour et à Joal (Document scientifique No. 137), Archive-CRODT.
512 CRODT, Dakar.
- 513 Beverton, R.J.H., Holt, S.J., 1957. *On the Dynamics of Exploited Fish Populations*, Fisheries Investigation. ed.
514 Springer Science & Business Media, Londres, Grande Bretagne.
- 515 Boncoeur, J., 2005. Activités halieutiques et activités récréatives dans le cadre d'un espace à protéger : le cas du
516 Parc National de la Mer d'Iroise. (Projet No. R-06-2005). UBO-CEDEM, Brest France.
- 517 Brehmer, P., Gerlotto, F., Laurent, C., Cotel, P., Achury, A., Samb, B., 2007. Schooling behaviour of small pelagic
518 fish: phenotypic expression of independent stimuli. *Mar. Ecol. Prog. Ser.* 334, 263–272.
- 519 Brochier, T., Auger, P., Thiam, N., Sow, M., Diouf, S., Sloterdijk, H., Brehmer, P., 2015. Implementation of artificial
520 habitats: Inside or outside the marine protected areas? Insights from a mathematical approach. *Ecol.*
521 *Model.* 297, 98–106. <https://doi.org/10.1016/j.ecolmodel.2014.10.034>
- 522 Brochier, T., Ecoutin, J.M., Morais, L.T. de, Kaplan, D.M., Lae, R., 2013. A multi-agent ecosystem model for
523 studying changes in a tropical estuarine fish assemblage within a marine protected area. *Aquat. Living*
524 *Resour.* 26, 147–158. <https://doi.org/10.1051/alr/2012028>
- 525 Camarena Luhrs, T., 1986. La croissance de *Sardinella maderensis* (Lowe, 1841) au Sénégal. *Océan. Trop.* 2.
526 Chaboud, C., 2014. Economie des pêches, in: Monaco, A., Prouzet, P. (Eds.), *Valorisation et économie des*
527 *ressources marines*, Mer et Océan. ISTE, Londres, pp. 277–344.
- 528 Clark, C.W., Munro, G.R., 1975. The economics of fishing and modern capital theory: A simplified approach. *J.*
529 *Environ. Econ. Manag.* 2, 92–106. [https://doi.org/10.1016/0095-0696\(75\)90002-9](https://doi.org/10.1016/0095-0696(75)90002-9)
- 530 Corten, A., Mendy, A., Diop, H., 2012. La sardinelle d'Afrique du Nord-Ouest : Pêches, évaluation des stocks et la
531 gestion (Rapport technique). CSRP, Dakar Sénégal.
- 532 Cury, P., 1991. Les contraintes biologiques liées à une gestion des ressources instables, in: Cury, P., Roy, C. (Eds.),
533 *Pêcheries Ouest Africaines : Variabilité, Instabilité et Changement*. ORSTOM, Paris, pp. 506–518.
- 534 Dème, M., Kébé, M., 2000. Revue sectorielle de la pêche au Sénégal: aspects socio-économiques (Rapport
535 technique). CRODT/ISRA, Dakar.
- 536 Dème, M., Thiao, D., Sow, F.N., Sarre, A., Diadhiou, H.D., 2012. Dynamique des Populations de Sardinelles en
537 Afrique du Nord-Ouest: Contraintes environnementales, biologiques et socio-économiques. University of
538 Rhode Island, USAID COMFISH Project, Dakar.

539 Diankha, O., Ba, A., Brehmer, P., Brochier, T., Sow, B.A., Thiaw, M., Gaye, A.T., Ngom, F., Demarcq, H., 2018.
540 Contrasted optimal environmental windows for both sardinella species in Senegalese waters. *Fish.*
541 *Oceanogr.* 27, 351–365. <https://doi.org/10.1111/fog.12257>

542 FAO, 2017. Rapport du Groupe de travail de la FAO sur l'évaluation des petits pélagiques au large de l'Afrique
543 nord-occidentale. Nouadhibou, Mauritanie, 22-27 mai 2017. (technique No. 1221). FAO, Nouadhibou.

544 FAO, 2015. Rapport de septième session du sous-comité scientifique du comité des pêches pour l'atlantique
545 centre-Est à tenerife, Espagne, 14-16 octobre 2015 (Rapport technique No. 1128). Rome.

546 FAO, 2001. Rapport du Groupe de travail de la FAO sur l'évaluation des petits pélagiques au large de l'Afrique
547 nord-occidentale. Nouadhibou, Mauritanie, 24-31 mars 2001. (Rapport technique No. 657). FAO,
548 Nouadhibou, Mauritanie.

549 Fréon, P., 1988. Réponses et adaptations des stocks de cupléidés d'Afrique de l'ouest à la variabilité du milieu et
550 de l'exploitation: analyse et réflexion à partir de l'exemple du Sénégal (Thèse de doctorat en Sciences
551 naturelles). Université Aix-Marseille 2, Marseille, Marseille France.

552 Fréon, P., Stéquert, B., Boëly, T., 1978. La pêche des poissons pélagiques côtiers en Afrique de l'Ouest des îles
553 Bissagos au Nord de la Mauritanie : description des types d'exploitation. *Cah. ORSTOM Sér. Océan.* 209–
554 228.

555 Garcia, S.M., Gascuel, D., Henichart, L.M., Boncoeur, J., Alban, F., Monbrison, D.D., 2013. Les aires marines
556 protégées dans la gestion des pêches. (Rapport technique). CSRP, Dakar Sénégal.

557 Gordon, H.S., 1954. The Economic Theory of a Common-Property Resource: The Fishery. *J. Polit. Econ.* 62, 124–
558 142.

559 Greboval, D., Catanzano, J., 2005. Rapports et documents de l'atelier de réflexion sur le contrôle et la réduction
560 des capacités de pêche en Afrique de l'Ouest (Rapport technique No. 756). FAO, Rome.

561 Hannesson, R., 1998. Marine Reserves: What Would They Accomplish? *Mar. Resour. Econ.* 13, 159–170.

562 Hardin, G., 1968. The Tragedy of the Commons. *J. Nat. Resour. Policy Res.* 1, 243–253.
563 <https://doi.org/10.1080/19390450903037302>

564 Harmelin-Vivien, M., Le Diréach, L., Bayle-Sempere, J., Charbonnel, E., García-Charton, J.A., Ody, D., Pérez-Ruzafa,
565 A., Reñones, O., Sánchez-Jerez, P., Valle, C., 2008. Gradients of abundance and biomass across reserve
566 boundaries in six Mediterranean marine protected areas: Evidence of fish spillover? *Biol. Conserv.* 141,
567 1829–1839. <https://doi.org/10.1016/j.biocon.2008.04.029>

568 Hilborn, R., Stokes, K., Maguire, J.-J., Smith, T., Botsford, L.W., Mangel, M., Orensanz, J., Parma, A., Rice, J., Bell, J.,
569 Cochrane, K.L., Garcia, S., Hall, S.J., Kirkwood, G.P., Sainsbury, K., Stefansson, G., Walters, C., 2004. When
570 can marine reserves improve fisheries management? *Ocean Coast. Manag.* 47, 197–205.
571 <https://doi.org/10.1016/j.ocecoaman.2004.04.001>

572 Laloë, F., 1985. Contribution à l'étude de la variance d'estimateurs de biomasse de poissons obtenus par
573 échantillonnage. *Oceanogr. Trop.* 20, 163–167.

574 Laloë, F., Samba, A., 1990. La pêche artisanale au Sénégal. Ressources et stratégies de pêche (Thèse de doctorat
575 en Sciences de la Vie). Université de Paris Sud (Orsay), Paris.

576 Laurec, A., Le Guen, J.-C., 1981. Dynamique des populations marines exploitées. Tome 1. Concepts et méthodes
577 (Rapport scientifique et technique No. 45–1981). CNEXO/Centre Océanologique de Bretagne, Brest,
578 France.

579 Lehuta, S., 2010. Impact des mesures de gestion sur la dynamique de la pêcherie pélagique du golfe de
580 Gascogne : Quelles certitudes ? Quels descripteurs ? (Thèse de doctorat en Sciences Halieutiques).
581 Université Européenne de Bretagne, Agrocampus-ouest.

582 Lehuta, S., Mahévas, S., Le Floc'h, P., Petitgas, P., 2013. A simulation-based approach to assess sensitivity and
583 robustness of fisheries management indicators for the pelagic fishery in the Bay of Biscay. *Can. J. Fish.*
584 *Aquat. Sci.* 70, 1741–1756. <https://doi.org/10.1139/cjfas-2013-0066>

585 McWhinnie, S.F., 2009. The tragedy of the commons in international fisheries: An empirical examination. *J.*
586 *Environ. Econ. Manag.* 57, 321–333. <https://doi.org/10.1016/j.jeem.2008.07.008>

587 Mesnildrey, L., Gascuel, D., Pape, O.L., 2013. Integrating Marine Protected Areas in fisheries management
588 systems: some criteria for ecological efficiency. *Aquat. Living Resour.* 26, 159–170.
589 <https://doi.org/10.1051/alr/2013056>

590 OECD, 2009. Réduction de la capacité de pêche Bonnes pratiques en matière de plans de sortie de flotte: Bonnes
591 pratiques en matière de plans de sortie de flotte. OECD Publishing.

592 Pauly, D., 2007. Small but mighty: elevate the role of small-scale fishers in the world market. *Conserv. Mag.* 8, 24.

593 Pauly, D., 2006. Major trends in small-scale fisheries, with emphasis on developing countries and some
594 applications for the social sciences. *Marit. Stud.* 4, 7–22.

595 Pech, N., Samba, A., Drapeau, L., Sabatier, R., Laloë, F., 2001. Fitting a model of flexible multifleet–multispecies
596 fisheries to Senegalese artisanal fishery data. *Aquat. Living Resour.* 14, 81–98.
597 [https://doi.org/10.1016/S0990-7440\(01\)01108-1](https://doi.org/10.1016/S0990-7440(01)01108-1)

598 Sadio, O., Simier, M., Ecoutin, J.-M., Raffray, J., Laë, R., Tito de Morais, L., 2015. Effect of a marine protected area
599 on tropical estuarine fish assemblages: Comparison between protected and unprotected sites in Senegal.
600 *Ocean Coast. Manag.* 116, 257–269. <https://doi.org/10.1016/j.ocecoaman.2015.08.004>

601 Teh, L., Sumaila, U.R., 2007. Malthusian overfishing in Pulau Banggi? *Mar. Policy* 31, 451–457.
602 <https://doi.org/10.1016/j.marpol.2007.01.001>

603 Thiao, D., 2012. Bioécologie et exploitation des petits pélagiques au Sénégal (Rapport CSRP). CSRP, Dakar.

604 Thiao, D., 2009. Un système d’indicateurs de durabilité des pêcheries côtières comme outil de gestion intégrée
605 des ressources halieutiques sénégalaises (Thèse de doctorat en Sciences Economiques). Université de
606 Versailles Saint-Quentin-en-Yvelines, Ecole Doctorale SOFT (Société du Futur), Sète, France.

607 Thiao, D., Chaboud, C., Samba, A., Laloë, F., Cury, P.M., 2012. Economic dimension of the collapse of the ‘false
608 cod’ *Epinephelus aeneus* in a context of ineffective management of the small-scale fisheries in Senegal.
609 *Afr. J. Mar. Sci.* 34, 305–311. <https://doi.org/10.2989/1814232X.2012.725278>

610 Thiaw, M., Auger, P.-A., Ngom, F., Brochier, T., Faye, S., Diankha, O., Brehmer, P., 2017. Effect of environmental
611 conditions on the seasonal and inter-annual variability of small pelagic fish abundance off North-West
612 Africa: The case of both Senegalese sardinella. *Fish. Oceanogr.* 26, 583–601.
613 <https://doi.org/10.1111/fog.12218>

614 Thomas, H.L., Macsharry, B., Morgan, L., Kingston, N., Moffitt, R., Stanwell-Smith, D., Wood, L., 2014. Evaluating
615 official marine protected area coverage for Aichi Target 11: appraising the data and methods that define
616 our progress. *Aquat. Conserv. Mar. Freshw. Ecosyst.* 24, 8–23. <https://doi.org/10.1002/aqc.2511>

617 Thompson, W.F., Bell, F.H., 1934. Biological statistics of the Pacific halibut fishery (Rapport scientifique No. 8). The
618 International Fisheries Commission, Seattle, Washington.

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Supplementary material

Annex 1

Biological module of the bio-economic model

Change in the number of a cohort

The variable t is the time of the simulation, i.e. $t = 1, 2 \dots, 480$. The abundance N of a cohort decreases exponentially according to the total mortality rate Z :

$$N_{t+1} = N_t * e^{(-Zt)} \quad \text{Equation 1a}$$

The exploited stock for each species i is composed of cohorts ' c ' appearing at each simulation period t (month). The initial size of a cohort c in each zone z is equal to the recruitment $R_{i,c,z}$, obtained from the parameter 'ParamR' at the beginning of the simulation. A stock recruitment relationship has never been demonstrated for small pelagics in the Senegal-Mauritania area (Fréon et al., 1978). However, it seems likely that their recruitment may be affected by a reduction of the spawning biomass (spawners) below a critical threshold. Examples such as Peruvian anchovy and California sardine have highlighted the possibility of significant falls in biomass and recruitment (Cury, 1991).

To take this possibility into account, the threshold critical biomass 'Blimi' must first be defined, below which recruitment will be affected by a decline in biomass. The threshold of critical biomass is a proportion 'PartBv' (defined as parameter) of virgin biomass 'Bv'. The latter is considered here as a parameter, estimated by simulation in the absence of exploitation of the two sardinella species. The "hockey stick" model is used to take into account the effect of fishing on recruitment. The results of these type of models are considered biologically more plausible than those of the Beverton-Holt recruitment model (Barrowman and Myers, 2000). The value of PartBv used in this study is 0.5.

$$Blim_i = Bv_i . PartBv_i \quad \text{Equation 2a}$$

When biomass ' BI ' is less than ' $Blim$ ', recruitment ' R ' tends linearly to 0 when ' BI ' tends to 0.

$$\begin{cases} R_{i,c,z} = ParamR_{i,c,z} & si BI_i \geq Blim_i \\ R_{i,c,z} = ParamR_{i,c,z} \cdot \left(\frac{BI_{i,t}}{Blim_i} \right) & si BI_i < Blim_i \text{ et } a_{i,c,t} = 0 \end{cases} \quad \text{Equation 3a}$$

Where $a_{i,c,t}$ is the age of the cohort and is by convention equal to 0 at the time of recruitment.

650 The size of a cohort 'c' at $t > tr$ (the time at which the cohort is recruited) in each zone z is denoted $N_{i,c,z,t}$. It is equal
 651 to the population in the same area in $t-1$ $N_{i,c,z,t-1}$, minus the total mortality in number $D_{i,c,z,t-1}$ and the $X_{i,c,z,t-1}$
 652 export of individuals to other areas and increased the import $M_{i,c,z,t-1}$ of individuals from other areas.

$$653 \begin{cases} N_{i,c,z,t} = 0 & t < tr_c \\ N_{i,c,z,t} = R_{i,c,z} & t = tr_c \\ N_{i,c,z,t} = N_{i,c,z,t-1} - D_{i,c,z,t-1} + M_{i,c,z,t-1} - X_{i,c,z,t-1} & t > tr_c \end{cases} \quad \text{Equation 4a}$$

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 655 The mortality in number $D_{i,c,z,t}$ is obtained from the following equation where Z is the total mortality rate:

$$656 \quad 657 \quad D_{i,c,z,t} = N_{i,c,z,t} \cdot (1 - e^{-Z_{i,c,z,t}}) \quad \text{Equation 5a}$$

658

659 The total mortality rate Z is the sum of the mortality rate $Mortn$ (constant) and the fishing mortality rate F , the
 660 calculation of which will be explained below.

$$661 \quad 662 \quad Z_{i,z,t} = F_{i,z,t} + Mortn_i \quad \text{Equation 6a}$$

663

664 For the fishing zones of the Senegalese EEZ 'zsen' the fishing mortality will be determined endogenously (linked to
 665 the spatio-temporal dynamics of the fleets) for the outer zones (Nordext, G, Sudext) it will take exogenous values
 666 'Ffix' (defined before simulation).

667
 668 The fishing mortality F is the sum of the fishing mortalities exerted by each fleet Ff .

$$669 \quad 670 \quad \begin{cases} F_{i,zsen,t} = \sum_e Ff_{i,e,zsen,t} & z \in \{GC, PC, CAS\} \\ F_{i,z,t} = \sum_e Ffix_z & z \in \{Nordext, G, Sudext\} \end{cases} \quad \text{Equation 7a}$$

671
 672 Fishing mortality per fleet is the product of the active fleet Fla , of the catchability q and the possibility of fishing in
 673 an area or not ($Ferm_{zsen,t}$). Catchability is defined by species i and type of fishing e . It is also a function of the age
 674 of the individuals $a_{i,c,t}$. The parameter $Ferm_{zsen,t}$ is used to indicate the closing rate of a zone. The possibility of
 675 seasonal fishing closures affecting the Senegalese fishing zones is foreseen in accordance with the conservation
 676 and / or storage policies of certain parts of the exploited areas. The variable $Ferm$ is then between 0 (total closure)
 677 and 1 (full opening).

$$678 \quad 679 \quad Ff_{i,c,e,z,t} = Fla_{e,z,t} * q_{e,i,c,t} * Ferm_{zsen,t} \quad \text{Equation 8a}$$

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681 Evolution in weight of a cohort

682 W The growth of individuals in each cohort is a function of their age. The individual length L is calculated by means
683 of the von Bertalanffy function, L_{inf} is the asymptotic length, k is the growth parameter and t_0 is the theoretical age
684 for which the length is zero.

685 The individual weight W is then obtained by applying a weight-length relation (parameters α and β). Growth is
686 considered to be identical for all zones:

687

$$688 \quad L_{i,t} = L_{inf} \cdot [1 - e^{-k_i \cdot (a_{i,t} - t_{0i})}] \quad \text{Equation 9a}$$

$$689 \quad W_{i,t} = \alpha_i \cdot L_{i,t}^{\beta_i} \quad \text{Equation 10a}$$

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691 It is then easy to calculate the total biomass per species BI by summing the weight of all the individuals for every
692 ‘’ cohort.

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695 Spatial aspects of the resource

696 In order to simulate the migration of sardinella, at each time step, the stocks are redistributed between the
697 different spatial cells (different zones) of the model. The stocks are distributed in 6 zones, including three
698 in Senegal (GC, PC and CAS) and three outside (Nordext, G, and Sudext) (Fig. 1).

699 The monthly migration scheme is introduced by the parameter "*ParamMigr*" which indicates, by species
700 and by month, the emigration rate of the stock present in each zone of origin "*ori*" to each of the possible
701 destination zones "*dest*". The monthly CPUEs for each zone was used as a monthly local abundance index
702 to inform the matrix. The use of monthly parameters requires creating a monthly variable between 1 and
703 12 which allows to redistribute the seasonal parameters (indexed by "*nmois*") within each year. The flux
704 of monthly migrations "*FMM*" between zones is obtained from the following equation:

705

$$\begin{aligned}
& FMM_{i,c,ori,dest,nmois,t} = N_{i,c,z,t} \cdot ParamMigr_{i,ori,dest,nmois} && \text{if } t \geq tr_c \\
706 \quad & FMM_{i,c,ori,dest,nmois,t} = 0 && \text{if } t < tr_c \\
& nmois = mois1, mois2 \dots, mois12 && \text{if } mois = 1, 2, \dots, 12
\end{aligned}
\tag{Equation 151a}$$

707

708

709 Where $N_{i,c,z,t}$ is the size of a cohort, ‘ i ’ the species and ‘ c ’ the cohort.

710 It is then possible to calculate the immigration and the emigration by zone (it is important to underline

711 here that the elements of the indices ‘ z ’, ‘ ori ’ and ‘ $dest$ ’ are the same, which makes it possible to establish

712 a correspondence between these indices):

713

$$714 \quad X_{i,c,z} = \sum_{dest} FMM_{i,c,ori,dest} \quad (\text{nb: } z \text{ corresponds to } ori) \quad \text{Equation 12a}$$

$$715 \quad M_{i,c,z} = \sum_{ori} FMM_{i,c,ori,dest} \quad (\text{nb: } z \text{ corresponds to } dest) \quad \text{Equation 13a}$$

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717 The catch dynamics

718 Catches are only calculated in areas of the Senegalese EEZ, so the ‘ $zsen$ ’ index is used instead of ‘ z ’ (the

719 ‘ $zsen$ ’ elements are a subset of z). The number of deaths due to fishing is equal to the share of fishing

720 mortality ‘ F ’ in total mortality ‘ Z ’, multiplied by the number of total deaths ‘ D ’. The instantaneous catches

721 in weight ‘ C ’ are obtained by multiplying catches in number by weight individual ‘ W ’:

$$722 \quad C_{i,zsen,t} = \left(\frac{F_{i,zsen,t} \cdot D_{i,zsen,t} \cdot W_{i,t}}{Z_{i,zsen,t}} \right) \quad \text{Equation 14a}$$

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724 The instantaneous catch by species is obtained by summing the catch C by cohort and area.

725 The cumulative annual catch per species is obtained by summing the instantaneous catches in each of the

726 annual time intervals.

727 The instantaneous catch by fleet CF is calculated by multiplying the daily catch weight C by the ratio of

728 fishing mortality of each fleet Ff in the total fishing mortality F :

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$$730 \quad CF_{i,c,e,zsen,t} = (Ff_{i,c,e,zsen} / F_{i,c,zsen}) \cdot C_{i,c,zsen,t} \quad \text{Equation 16a}$$

731 Annex 2

732 The dimensions of the model (subsripts)

Nature	Symbol	values
Type of fishing	<i>e</i>	ST, IND, FME
Areas (total)	<i>z</i>	Nordext, GC, PC, G, CAS, Sudext
Areas (Sénégal)	<i>zsen</i>	GC, PC, CAS, CAS
Species	<i>i</i>	Sr ,sp
Cohorts	<i>c</i>	c1, c2..., c492
Years	<i>a</i>	a1, a2,... ,a40
Months of the year	<i>nmois</i>	mois1, mois2,... ,mois12
Origin area of fish migrations	<i>ori</i>	Nordext, GC, PC, G, CAS, Sudext
Destination area for fish migrations	<i>dest</i>	Nordext, GC, PC, G, CAS, Sudext

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744 Annex 3

Model parameters and their values

Parameter	Meaning	Subscripts	Unit	Value in the reference simulation
<i>ParamR</i>	Initial recruitment of a monthly cohort of species <i>i</i> , in a zone <i>c</i>	<i>i,z,c</i>	individual	Defined in the parameter file
<i>t_r</i>	Date of recruitment of cohort <i>c</i>	<i>c</i>	time	
<i>k</i>	Growth parameter of the von Bertalanffy function	<i>i</i>	time	S. ronde : 0.100833 S. plate : 0.040833
<i>t₀</i>	Fictitious "date of birth" corresponding to the time when the size would be zero.		time	S. ronde : -0.72 S. plate : -7.08
<i>α</i>	Parameter of the weight-length relationship	<i>i</i>		S. ronde : 0.006392 S. plate : 0.0098535
<i>β</i>	Parameter of the weight-length relationship	<i>i</i>		S. ronde : 3.274 S. plate : 3.1676
<i>txi</i>	Investment rate	<i>e</i>	%	0.3
<i>txi1</i>	Disinvestment rate	<i>e</i>	%	0.1
<i>parCV</i>	Variable cost	<i>e</i>	FCFA/month	ST : 3.449 million FCFA FME : 1.171 million FCFA
<i>parLIC</i>	Amount of fishing license (permit)	<i>e</i>	FCFA / year	ST : 25 000 FCFA FME : 25 000 FCFA
<i>parCF</i>	Fixed cost	<i>e</i>	FCFA / year	ST : 372 605 FCFA FME : 324 690 FCFA
<i>parCDEB</i>	Landing cost		FCFA /t	1000 FCFA
<i>Ffix</i>	Fishing mortality in areas outside the Senegalese EEZ	$z \in \{Nordext, G, Sudext\}$		0.08 ; 0..08 ; 0.08
<i>TxActu</i>	Discount rate		%	5
<i>PR</i>	Price per species	<i>i</i>	FCFA /t	Sr : 130995 FCFA Sp : 103670 FCFA
<i>ParCiF</i>	Fixed intermediate consumption	<i>e</i>	FCFA/month	ST : 126 573 FCFA FME : 153 207 FCFA
<i>ParCiv</i>	Variable intermediate consumption	<i>e</i>	FCFA/month	ST : 3 448 629 FCFA FME : 1 170 857 FCFA
<i>Ferm</i>	Closure of fishing areas	<i>zsen</i>		Defined according to the scenarios
<i>FinalTime</i>	Final time of the simulation		month	480

<i>ParEquip</i>	Crew size by fleet type	<i>e</i>	person	ST : 20 : FME : 10
Parameter	Meaning	Symbol	Unit	Value in the reference simulation
<i>TxCaptAccess</i>	Bycatch rate by value	<i>e</i>	%	ST : 0.24 IND : 0 FME : 0.32
<i>TxCroisCapt</i>	Annual growth rate of fishing power	<i>e</i>	%	ST : 0.02. IND : FME : 0.01
<i>ParCicarbTTC</i>	Monthly consumption of fuel ATI	<i>e</i>	FCFA	ST : 3150000 FCFA FME : 1013000 FCFA
<i>ParCicarbHT</i>	Monthly consumption of fuel ET	<i>e</i>	FCFA	ST : 3706000 FCFA FME : 1191000 FCFA
<i>ParDetaxMot</i>	Annual engine tax exemption, per fishing unit	<i>e</i>	FCFA	ST : 415666 FCFA FME : 268333 FCFA
<i>ParDetaxEng</i>	Annual exemption of fishing gear taxes, by fishing unit	<i>e</i>	FCFA	ST : 360000 FCFA FME : 97200 FCFA

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751 Annex 4

752 Catchability of both sardinella

Fish Age (month)	Catchability <i>Sardienlla aurita</i>
4 - 6	4.2247E-06
7 - 9	1.1574E-05
10 - 12	2.7162E-05
11 - 15	1.5477E-05
16 - 18	6.4401E-05
19 - 21	5.9776E-05
22 - 24	6.6904E-05
25 - 27	6.1756E-05
28 - 30	6.7922E-05
31 - 33	4.677E-06
34 - 36	1.9845E-06
37 - 39	1.7133E-06
>39	1.6992E-05

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Fish Age (month)	Catchability <i>Sardinella maderensis</i>
7 - 9	1.1362E-07
10 - 12	9.9849E-07
11 - 15	3.3935E-06
16 - 18	1.4198E-06
19 - 21	9.4787E-06
22 - 24	1.1746E-05
25 - 27	1.3759E-05
28 - 30	7.5257E-06
31 - 33	7.1591E-06
34 - 36	1.4042E-05
37 - 39	7.6991E-06
40 - 42	7.1011E-06
43 - 45	3.2785E-06
46 - 48	5.1656E-06
49 - 51	3.4174E-06
>51	2.2283E-06

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756 **Annex 5**

757 Monthly migration matrices for *Sardinella aurita*. Share of the number of fish migrating from a origin
 758 area to other areas. The diagonal of each matrix must remain equal to 0. ORI (origin), DEST
 759 (destination), GC (Grande Côte), PC (Petite Côte), CAS (Casamance), G (Gambia), sudex (Guinea
 760 Bissau) and nordex (Mauritania).

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<i>S. aurita</i>															
January		DEST						July		DEST					
		Next	GC	PC	G	Cas	Sudext			Next	GC	PC	G	Cas	Sudext
ORI	Next	0	0.7	0	0	0	0	ORI	Next	0	0	0	0	0	0
	GC	0	0	0.1	0	0	0		GC	0.5	0	0	0	0	0
	PC	0	0	0	0.1	0	0		PC	0	0.3	0	0	0	0
	G	0	0	0	0	0.07	0		G	0	0	0.5	0	0	0
	Cas	0	0	0	0	0	0		Cas	0	0	0	0.1	0	0
	Sudext	0	0	0	0	0	0		Sudext	0	0	0	0	0	0
February		DEST						August		DEST					
		Next	GC	PC	G	Cas	Sudext			Next	GC	PC	G	Cas	Sudext
ORI	Next	0	0.3	0	0	0	0	ORI	Next	0	0	0	0	0	0
	GC	0	0	0.05	0	0	0		GC	0	0	0	0	0	0
	PC	0	0	0	0.1	0	0		PC	0	0.1	0	0	0	0
	G	0	0	0	0	0.07	0		G	0	0	0.2	0	0	0
	Cas	0	0	0	0	0	0		Cas	0	0	0	0.1	0	0
	Sudext	0	0	0	0	0	0		Sudext	0	0	0	0	0	0
March		DEST						September		DEST					
		Next	GC	PC	G	Cas	Sudext			Next	GC	PC	G	Cas	Sudext
ORI	Next	0	0	0	0	0	0	ORI	Next	0	0	0	0	0	0
	GC	0	0	0.05	0	0	0		GC	0	0	0	0	0	0
	PC	0	0	0	0.005	0	0		PC	0	0.1	0	0	0	0
	G	0	0	0	0	0.7	0		G	0	0	0.2	0	0	0
	Cas	0	0	0	0	0	0		Cas	0	0	0	0.1	0	0
	Sudext	0	0	0	0	0	0		Sudext	0	0	0	0	0	0
April		DEST						October		DEST					
		Next	GC	PC	G	Cas	Sudext			Next	GC	PC	G	Cas	Sudext
ORI	Next	0	0	0	0	0	0	ORI	Next	0	0.6	0	0	0	0
	GC	0	0	0.05	0	0	0		GC	0	0	0	0	0	0
	PC	0	0	0	0.05	0	0		PC	0	0	0	0	0	0
	G	0	0	0	0	0	0		G	0	0	0	0	0	0
	Cas	0	0	0	0	0	0		Cas	0	0	0	0	0	0
	Sudext	0	0	0	0	0	0		Sudext	0	0	0	0	0	0
May		DEST						November		DEST					
		Next	GC	PC	G	Cas	Sudext			Next	GC	PC	G	Cas	Sudext
ORI	Next	0	0	0	0	0	0	ORI	Next	0	0.6	0	0	0	0
	GC	0.4	0	0	0	0	0		GC	0	0	0.05	0	0	0
	PC	0	0.2	0	0	0	0		PC	0	0	0	0	0	0
	G	0	0	0.2	0	0	0		G	0	0	0	0	0	0
	Cas	0	0	0	0.2	0	0		Cas	0	0	0	0	0	0
	Sudext	0	0	0	0	0	0		Sudext	0	0	0	0	0	0
June		DEST						December		DEST					
		Next	GC	PC	G	Cas	Sudext			Next	GC	PC	G	Cas	Sudext
ORI	Next	0	0	0	0	0	0	ORI	Next	0	0.7	0	0	0	0
	GC	0.7	0	0	0	0	0		GC	0	0	0.1	0	0	0
	PC	0	0.2	0	0	0	0		PC	0	0	0	0.005	0	0
	G	0	0	0.5	0	0	0		G	0	0	0	0	0.07	0
	Cas	0	0	0	0.5	0	0		Cas	0	0	0	0	0	0
	Sudext	0	0	0	0	0	0		Sudext	0	0	0	0	0	0

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