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# Adapting a dynamic system model using life traits and local fishery knowledge - Application to a population of exploited marine bivalves (*Ruditapes philippinarum*) in a mesotidal coastal lagoon

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1 **Adapting a dynamic system model using life traits and local fishery knowledge -**  
2 **application to a population of exploited marine bivalves (*Ruditapes philippinarum*) in a**  
3 **mesotidal coastal lagoon**

4

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21 Keywords: system dynamic model, co-management, population dynamic, Arcachon Bay,  
22 *Ruditapes philippinarum*

23

24 **Abstract**

25 Effective planning and management strategies of the Manila clam (*Ruditapes*  
26 *philippinarum*) stock in Arcachon Bay rely on a co-management approach, involving  
27 scientific advice and the fishing industry. In order to strengthen this management process, a  
28 specific compartmental single-species model has been developed to assess different  
29 management strategies. Based upon a size structure of the population and built from the  
30 dynamic systems paradigm, the modelling involves selected environmental and fishery-  
31 related parameters for their impact on the population dynamics. Integration of newly available  
32 life traits data regarding the local population and better knowledge of the fishing activity and  
33 its control parameters have enabled a revision of the existing version including model  
34 parameters and integration of new formulations. Effect of food availability and total  
35 suspended matter on the production of newly settled juveniles, natural mortality, growth rates,  
36 and price, accounted for the bulk of the undertaken improvements. Model performance was  
37 evaluated by comparing simulation outputs to observed data from stock assessments (2003,  
38 2006, 2008, 2010, 2012, 2014 and 2018). In addition, a sensitivity analysis regarding  
39 uncertainty on parameters related to biological and environmental aspects was carried out to  
40 provide information about parameters that influence the outputs of the model the most. In  
41 particular, this highlighted that a deeper understanding of the processes related to the  
42 reproduction phase and its control parameters on biomass should be pursued. The  
43 improvements enable the calibration of the model with parameters that are as close as possible  
44 to the specificities of the stock considered. This adaptation permits use of the model to test  
45 various management strategies on the stock evolution and also to evaluate potential effects of

46 environmental or market fluctuations. It encompasses ecological and socio-economic  
47 valuations of the measures of impact. As long as those objectives are shared by the different  
48 entities involved at the regional scale, communication and management decisions should be  
49 facilitated.

50

## 51 **1. Introduction**

52 Management of coastal zones is considered globally as an important issue (Pastres et  
53 al., 2001) because it implies multiple–conflicting goals involving socio-economic and  
54 ecological considerations (Freire et al., 2002). This is particularly true for areas providing  
55 bivalve resources because they frequently enable the development of flourishing activities  
56 either for fishing or farming (Canu and Solidoro, 2018; Coelho et al., 2021; Vincenzi et al.,  
57 2006). Design and implementation of adaptive management system policies are vital to  
58 conciliate socio-economic activities and long-term sustainability of the natural environment  
59 (De Leo and Levin, 1997), especially considering resources where population dynamics are  
60 particularly sensitive to environmental variations. For this purpose, models constitute useful  
61 tools for guiding management of coastal waters (Mongruel et al., 2011), including the  
62 monitoring of exploited species that generate significant income for the fishing industries in  
63 coastal zones.

64 To reinforce the management of exploited species, several models have been designed.  
65 These include demographic models and increasingly combined ecophysiological and  
66 economic ones (Bertolini et al., 2021; Canu et al., 2011; Ferriera et al., 2009; Grant et al.,  
67 2007; Solidoro et al., 2003; Troost et al., 2010). The first model developed for Manila clams  
68 by Bald et al. (2009) was a compartmental single-species model driven by fixed parameters,  
69 which were based upon the size structure of the population and several dynamics of the  
70 species. This modelling approach belongs to the simulation modelling category, which was  
71 built from the dynamic systems paradigm developed in the 1950s by Forrester (1973). What is  
72 more, the interactions among variables and the evolution over time of the level variables  
73 (density and abundance expressed in numbers or mass) are mathematically represented by  
74 differential equations (the model being integrated continuously in time). Six weaknesses  
75 about this model were pointed out by Bald et al. (2009). Since more ecological data on the

76 Manila clam are now available and on-going studies in the Arcachon Bay are completed, a  
77 revision of the first version of the model parameters can be undertaken. This new information  
78 enabled an improvement of four identified weaknesses: effect of food availability, growth  
79 rates, indirect natural predation and effect of diseases (the one remaining concern is larval  
80 transport and settlement with spatial considerations). In addition, more realistic harvesting  
81 activities and economic considerations were integrated and the lack of consideration of socio-  
82 economic drivers highlighted during working groups (involving scientists and fishermen) has  
83 also been taken into account.

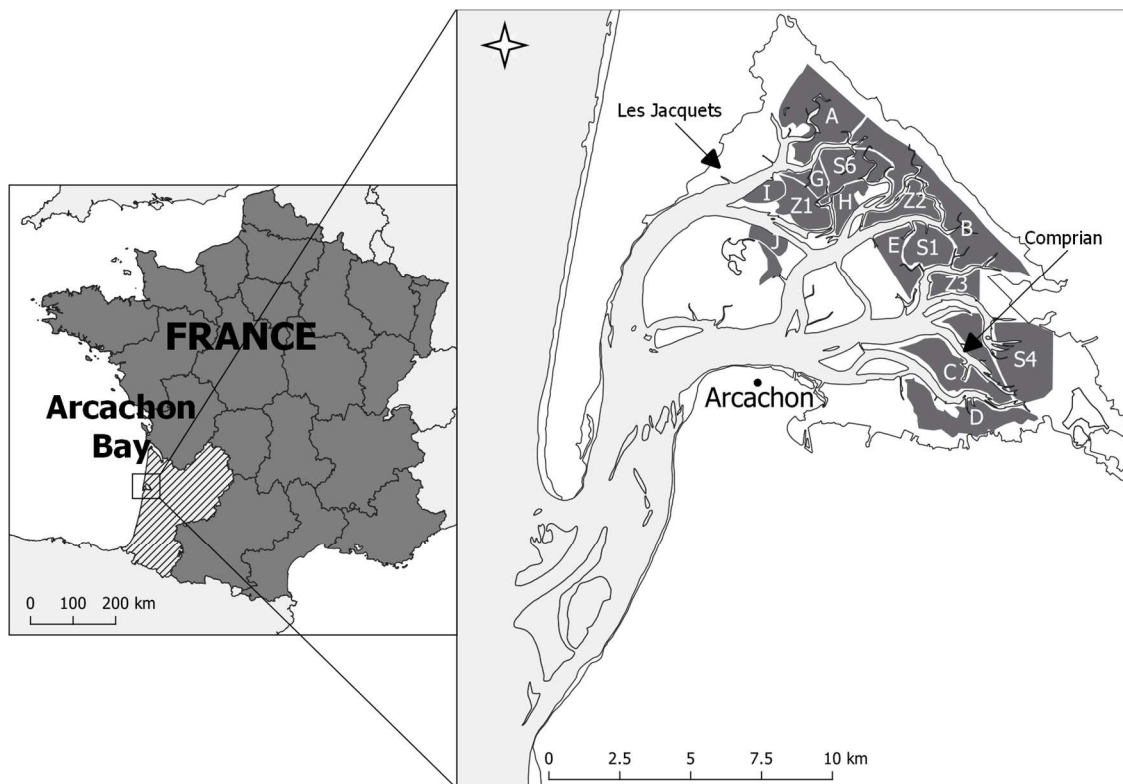
84 In this context the present paper 1) discusses the developments implemented since the  
85 first version of the model; 2) integrates a validation and a sensitivity analysis regarding  
86 uncertainty on a selection of parameters and 3) describes the evolution of the modeled  
87 biomass under various management, environmental and economic scenarios in order to  
88 provide decision making guidance.

## 89 **2. Study area and Manila clam population**

### 90 *2. 1. Study area*

91 Arcachon Bay is a 156 km<sup>2</sup> semi-sheltered lagoon in the southwest coast of France  
92 (Figure 1). Mostly composed of intertidal flats (110 km<sup>2</sup> within the inner lagoon which are  
93 colonized by vast *Zostera noltii* seagrass meadows), the composition of this mesotidal system  
94 ranges from mud to muddy sands. The tide is semi-diurnal and the bay is both influenced by  
95 oceanic (external neritic waters) and continental (principally from the Eyre River) inputs  
96 (Dang, 2009). The characteristics of these water masses as well as the slow renewal of water  
97 by tides (Plus et al., 2009) both influence salinity and temperature within the bay. Variations  
98 of these two parameters are important: seawater temperature ranges from 1.8 to 27.4 °C  
99 (mean value 15.4 °C) and salinity ranges from 15.4 to 35.4 (mean value 30.2) (Caill-Milly,

100 2012). According to the same database, chlorophyll a concentration varies from 0.4 to 30.8  
101  $\mu\text{g l}^{-1}$  (mean value  $2.6 \mu\text{g l}^{-1}$ ).



102

103 **Fig. 1.** Maps showing the studied site Arcachon Bay (France) (sources: ESRI, BD Carthage, Ifremer –  
104 M. Lissardy).

105

## 106 2.2. Species description and stock evolution

107 Manila clam (*Venerupis philippinarum*) is an infaunal species inhabiting various  
108 substrates such as sandy, sandy-muddy and muddy bottoms. As a suspension-feeding bivalve,  
109 its dietary regime is dominated by phytoplankton (Kanaya et al., 2005; Kasai et al., 2004;  
110 Spillman et al., 2008; Yokoyama et al., 2005). Length class differentiation within the  
111 population is determined by valve length, which is defined as the longest distance from front  
112 edge to back edge (mm). For bivalves, fecundity is age-related (Gosling, 2003) and the  
113 Manila clam sexual maturity is considered effective from the second year, corresponding to  
114 clams above 20 mm in length (Holland and Chew, 1974). Two annual spawning periods occur

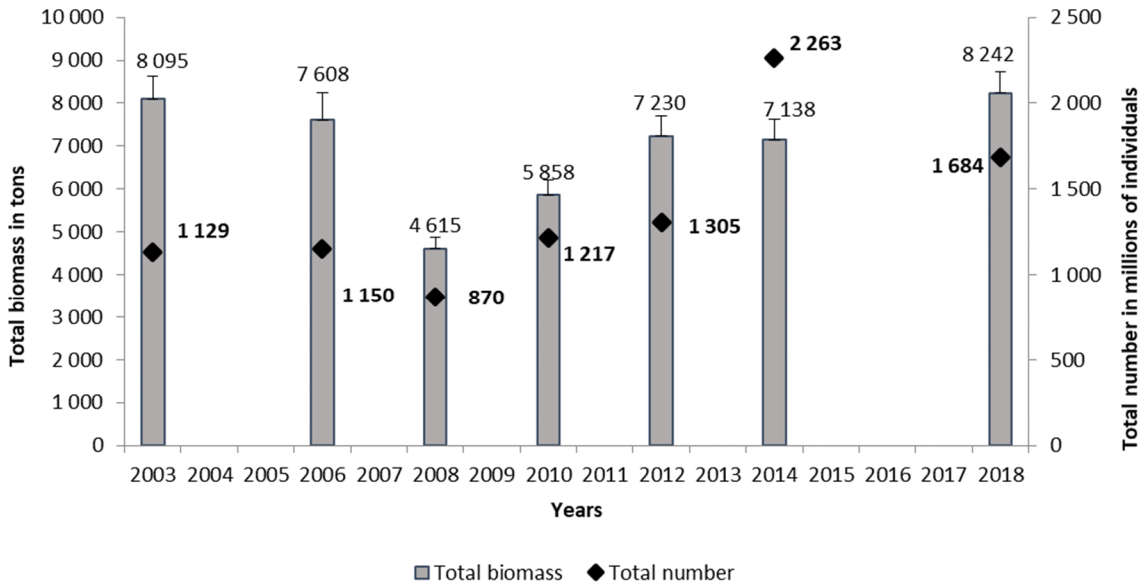
115 in Arcachon Bay: from April to June and from August to October, which are driven by  
116 increasing seawater temperatures between 15°C and 22°C (Dang et al., 2010).

117 Metamorphosis and settlement occur generally after a two-to-three-week period of  
118 pelagic larval stage. Then, the spatial distribution is of an aggregative type and the limited  
119 lateral displacements of individuals are reported to reach six meters per month (Tamura, 1970  
120 in Le Treut, 1986). Manila clam maximum lifespan is unknown (Dee Boersma et al., 2006);  
121 Gillespie et al. (1999) indicated that it rarely exceeds 10 years of age in fished populations.

122 Factors influencing natural mortality include natural predation (*Carcinus maenas*,  
123 *Ocenebra erinacea*, birds...), diseases (among others, Brown Muscle Disease, one of the most  
124 important) and aging. Pollution may also have an unfavorable role in the evolution of  
125 mortality (Paul-Pont, 2010).

126 The Manila clam resource in Arcachon Bay has been monitored through stock  
127 assessment campaigns. Surveys considering the total distribution area of Manila clam (~47  
128 km<sup>2</sup>) began in 2003 and have been carried out as much as possible every other year since  
129 2006 during late spring (the 2016 survey could not take place for financial reasons). Seven  
130 years of monitoring data (2003, 2006, 2008, 2010, 2012, 2014 and 2018) are currently  
131 available. These surveys provide a dataset of indicators such as abundance indices, length-  
132 frequency histograms, total abundance and biomass, fraction of juveniles (individuals  
133 measuring less than 17 mm), spawners (individuals measuring more than 25 mm) and  
134 exploitable stock (individuals measuring more than 35 mm), as well as their abundance and  
135 maps of clam densities (Sanchez et al., 2018; Caill-Milly et al., 2021). The stock assessments  
136 of these campaigns show a decrease of the population biomass until 2008, and then a recovery  
137 to a high level toward the end of the series (Figure 2).





138

139 **Fig. 2.** Evolution since 2003 of the total biomass (with its standard deviation) and of the total numbers  
 140 of Manila clams in Arcachon Bay (from Sanchez et al., 2018).

141

### 142 3. Fishing activity and management

143 Fishermen access fishing areas by boat and exploitation occurs at low tide. Clams are  
 144 extracted by hand, the sediment is scraped using a small tool. Catch fishing data from national  
 145 and regional databases are utilized to account for the exploitation (sources: CRTS La  
 146 Rochelle, SIH Ifremer, CRPMEM Nouvelle-Aquitaine). The first catch declarations were  
 147 recorded in 1992 (with 1 ton), production then grew quickly from 2001. After a peak in 2007  
 148 with 1000 tons landed, the production decreased to reach values comprised between 300 and  
 149 400 tons annually in recent years (Caill-Milly et al., 2021).

150 Whereas the minimum legal harvest size (40 mm prior to 2008, 35 mm since then) is set  
 151 by European legislation (EC Regulation CE n°40/2008), in addition specific local legislation  
 152 may be applied such as protected areas, limited fishing periods and a fixed number of  
 153 licenses. They vary over time in terms of location, duration, number, allocation rules and are

154 considered in the next sections of this paper. The local regulations are under the responsibility  
155 of industry organisations (like Comité Régional des Pêches Maritimes et des Élevages Marins  
156 de Nouvelle-Aquitaine) and involve regional administration (Frangoudes et al., 2020).

#### 157 **4. Existing model structure and components**

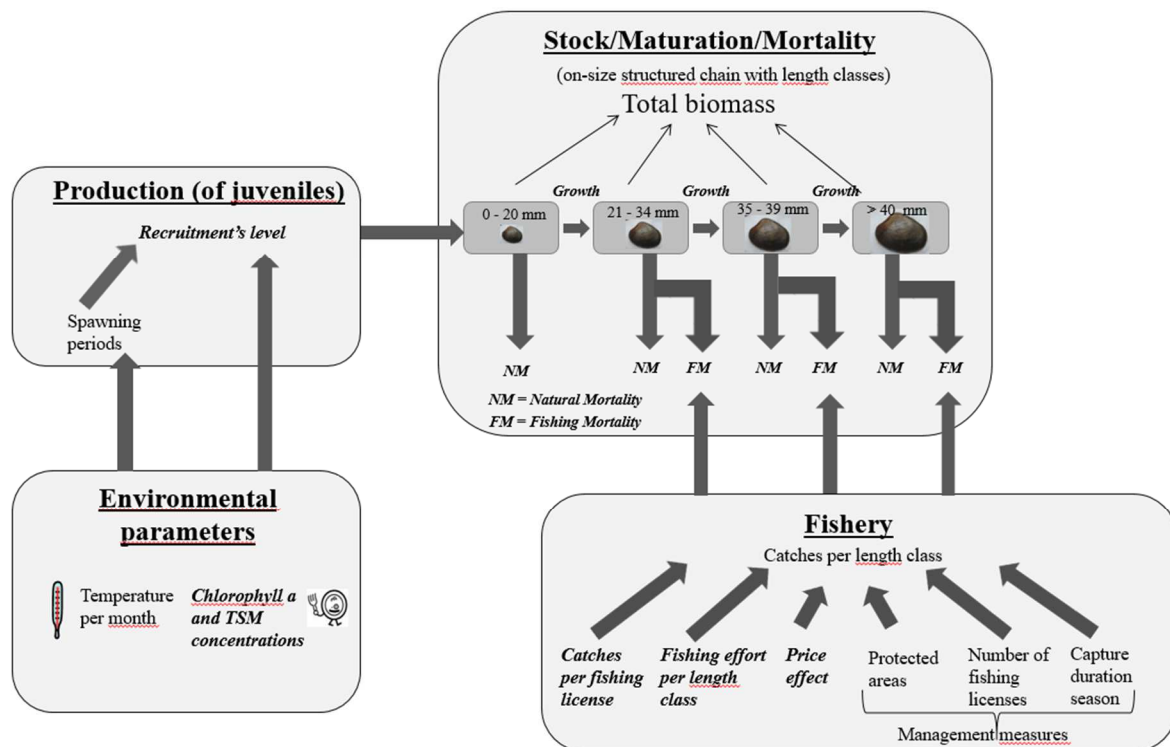
158 The existing model applied to Manila clam in Arcachon Bay was developed at the end  
159 of the 2000s. The model and all the simulations are performed using the object-oriented  
160 modelling framework Vensim ® DSS. This software is widely used to construct simulation  
161 models of business, scientific, environmental, and social systems. Specific dynamic models  
162 regarding exploited marine resources (by fishing and aquaculture) have been developed under  
163 various softwares such as Vensim, ExtendSim, Stella, Simile, etc. (Canu et al., 2011; Hawkins  
164 et al., 2002; Grant et al., 2007).

165 For Arcachon Bay, the processes are modelled at the bay scale (not spatialized at a finer  
166 scale) and the time frame is monthly, with the exception of temperature (daily). The model is  
167 structured into basic component parts corresponding to four interrelated so-called blocks:  
168 Production, Stock/Maturation/Mortality, Environmental parameters and Fishery (see Figure 3  
169 and Bald et al., 2009 for details including structuration and equations of the first version). The  
170 production of juveniles (**Production block**) is controlled by the quantity of spat arriving in  
171 the system after the spawning period, the larval development and the settlement (after a  
172 pelagic phase of three weeks, Le Treut, 1986). Because those phases of the life cycle are well-  
173 known to be highly influenced by the environment [Holland and Chew (1974), Mann (1979),  
174 Ohba (1959), Park and Choi (2004), Robinson and Breese (1984) and Emmett et al. (1991)], a  
175 control block integrating environment drivers (**Environment parameters block**) acts on the  
176 Production block. In the Environment parameters block, seawater temperature was simulated  
177 using the sinusoidal function proposed by Melià et al. (2004) and adjusted to Arcachon Bay

178 conditions by Bald et al. (2009). In the **Stock/Maturation/Mortality** block, the Manila clam  
 179 population in Arcachon Bay is divided into four sub-populations according to their length. For  
 180 the population dynamics model, several authors (De Leo and Gatto, 2000; Solidoro et al.,  
 181 2003) underlined the importance of length class differentiation to take into account  
 182 differences in vital rates such as fertility, mortality, and respiration (Flye-Sainte-Marie et al.,  
 183 2007). Therefore, they correspond to: juvenile size class (from 0 to 20 mm), adult under the  
 184 minimum current harvest size class (from 21 to 34 mm) and two adult size classes above the  
 185 minimum current harvest size (from 35 to 39 mm and upper 40 mm). Thereby the chosen  
 186 endpoints of those classes depend on biological and exploitation considerations. The rules of  
 187 evolution over time of the number of clams in each class are controlled by specific growth,  
 188 natural and fishing mortality parameters and are described in detail in Bald et al. (2009). In  
 189 addition, the initial condition is controlled by the production of juveniles in the first class.  
 190 This compartment gives at the end the main result, which is the total biomass.

191

192



193

194 **Fig. 3.** Diagram of the Manila clam model illustrating the four blocks and the interactions among  
195 them. Improvements made since the first version of the model regarding blocks are in bold italics.

196

197 The **Fishery Block** includes the parameters that control the fishing mortality required  
198 for the Stock/Maturation/Mortality Block (e.g. fishing effort per clam length class, capture  
199 duration season, number of delivered fishing licenses, catches volume per license, protected  
200 area surface....). To convert the volume of catches per length class to effective per length  
201 class, a length-weight relationship for the Manila clam population was established using the  
202 2003 survey campaign (see Appendix 1).

203 All the formulations of this existing model are detailed in Bald et al. (2009). Starting  
204 from this existing version, both the integration of newly and specific available life traits data,  
205 and the adjustment of the fishing activity and its control parameters allow for a revision of the  
206 model, which includes model parameters and the integration of new formulations.

## 207 **5. Model revision**

### 208 *5.1. Integration of real data to simulate seawater temperature*

209 In the first version of the model, seawater temperature T (Environment parameters  
210 block) was simulated using the sinusoidal function (Bald et al., 2009). In order to be closer to  
211 the real variations of temperature inside the Bay, this equation was replaced by real weekly  
212 temperature data coming from the ARCHYD network<sup>2</sup>. Regarding the Manila clam  
213 distribution, two stations - Comprian and Les Jacquets (see Figure 1 for location) - were  
214 selected to calculate mean temperature (*T<sub>real</sub>*) per month from 2003 to 2019. For subsequent  
215 years, the attributed value per month *m* is equal to the average mean over three years for a

---

<sup>2</sup> The hydrological network of observation and monitoring dedicated to Arcachon Bay  
(<https://sextant.ifremer.fr/record/dde63586-6a51-4e9b-8630-b7648cda86a0/>)

216 given month ( $T_{am}$ ) with the addition of a parameter temperature variation ( $\Delta T$ ) to have the  
217 possibility to test the hypothesis of an increase or decrease of the monthly temperature.

$$218 \quad T(m) = \begin{cases} T_{real}(m) & \text{from 2003 to 2019} \\ T_{am}(m) + \Delta T & \text{from 2020 to 2029} \end{cases}$$

219 Due to this modification, the time frame for the seawater parameter changed from daily  
220 to monthly. Using real data is considered preferable notably to work on hindcasts.

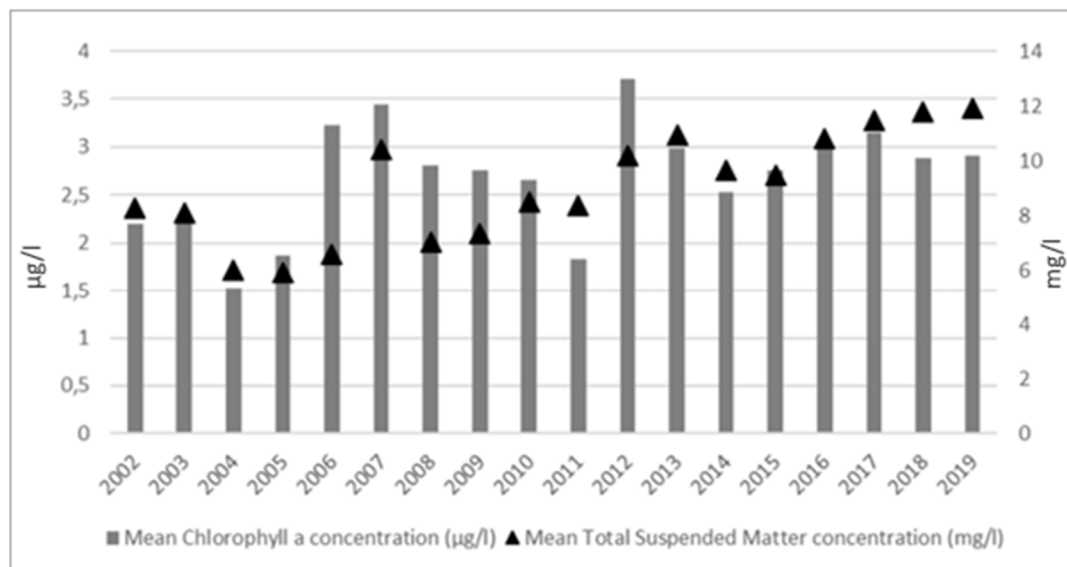
## 221 *5.2. Integration of specific available life traits data*

### 222 *5.2.1. Recruitment (Production and environmental parameters blocks)*

223 In the first version of the model, an iterative modeling was used to fix the recruitment  
224 level and the period of arrival of juveniles in the Stock/Maturation/Mortality block was  
225 controlled by the seawater temperature conditions (Environment parameters block) (Bald et  
226 al., 2009). Regarding Manila clam, temperature, photoperiod and food availability are the  
227 three main factors contributing to the reproduction phase (from gametogenesis to spawning)  
228 (Delgado and Pérez-Camacho, 2007; Devauchelle, 1990; Holland and Chew, 1974; Le Pennec  
229 and Benninger, 2000; Mann, 1979; Ohba, 1959; Soudant et al., 2004; Toba and Miyama,  
230 1995). To a lesser extent, a possible effect of salinity has also been described by Park and  
231 Choi (2004) and Dang et al. (2010). For the Arcachon Bay population and using stock status  
232 indicators and environmental parameters, Caill-Milly (2012) highlighted both the importance  
233 of temperature during the reproduction phase (interaction already taken into account in the  
234 model) and the trophic conditions associated to total suspended matter (TSM) for young  
235 stages. High proportions of juveniles were related to high chlorophyll a and low TSM values.

236 Graphically, mean chlorophyll a concentration is the lowest in 2004 and TSM  
237 concentration is lowest in 2005. Conversely, mean chlorophyll a concentration and TSM  
238 concentration are highest in 2012 and in 2019 respectively. Regarding the trends of these two

239 data sets over the 2002-2019 period, they seem to display a break in the data series between  
 240 2009 and 2010 (with significant differences for TSM) (Figure 4).



241

242 **Fig. 4.** Evolution of chlorophyll a and Total Suspended Matter over the 2002-2019 period.

243

244 Current understanding of the impact of these two conditions on recruitment suggests a  
 245 positive effect of high chlorophyll a and low TSM. As these two factors show a break  
 246 between 2009 and 2010, the recruitment level proposed by Bald et al. (2009) - *JPm* - was  
 247 modulated from 2010 using a combination of evolution rates of those two factors acting with  
 248 opposite effects. To do so, chlorophyll a and TSM evolution rates were calculated between  
 249 2002-2009 and 2010-2019 and combined (considering positive effect for chlorophyll a and  
 250 negative effect for TSM to estimate the  $\Delta JPm(m)$  from 2010 (Table 1).

251 **Table 1:** Applied rules to estimate the combined effects of Chlorophyll a and TSM concentrations on  
 252 *JPm* from 2010.

253

Factors	Mean concentration	Mean concentration	Evolution	Estimated type	Estimated
	2002-2009	2010-2019	rate	of effect	combined
			between	<i>JPm</i>	effects to

			2002-2019		apply on
			and 2010-		JPm from
			2019		2010
					( $\Delta JPm$ )
Chlorophyll a	2.51 $\mu g/l$	2.84 $\mu g/l$	13%	Positive	
TSM	7.46 mg/l	10.31 mg/l	38%	Negative	-25%

254

255  $\Delta JPm(m)$  is thus set at 0% between 2003 and 2009 and at -25% from 2010. As a  
 256 result, from 2003 to 2009,  $JPm$  is 3.3 ind.m<sup>2</sup>.month<sup>-1</sup> and 2.5 ind.m<sup>2</sup>.month<sup>-1</sup> from 2010.

257 Due to this reformulation, the juvenile production per surface unit and per month  
 258  $JP(m)$  is:

259 
$$JP(m) = [JPm(m) \times [1 + \Delta JPm(m)]] \times SP(m)$$

260 with  $JPm$  = the juvenile production per spawning month fixed by Bald et al. (2009);  $\Delta JPm$  =  
 261 Combined chlorophyll a and TSM effects on juveniles production and  $SP$  = Spawning  
 262 occurrence for a given month.

263 The model now includes not only the effect of temperature (spawning triggering) but  
 264 also of chlorophyll a and TSM on recruitment.

265

### 266 5.2.2. Growth (Stock/Maturation/Mortality block)

267 In the first version of the model, the growth rates were calculated following the growth  
 268 model developed by Melià et al. (2004) for the Sacca di Goro Lagoon (Italy) (Bald et al.,  
 269 2009).

270 Between 2005 and 2007, Dang et al. (2010) undertook enclosure field experiments  
 271 within Arcachon Bay that allow defining the Von Bertalanffy Growth Function (VBGF)  
 272 parameters related to the Bay. These ecological data led to the reassessment of realistic  
 273 growth rate estimates, namely 0.361, 0.245 and 0.227 (dimensionless) for length classes 0-20,

274 21-34 and 35-39 mm respectively. For example, this means that each month, the number of  
 275 clams entering the 21-34 mm class from the previous class (0-20 mm) is obtained by  
 276 multiplying the number of clams in the 0-20 mm class from the previous month by 0.361.

277

### 278 5.2.3. Natural mortality (Stock/Maturation/Mortality block)

279 In the first version of the model, natural mortality was defined by the relationship  
 280 established by Solidoro et al (2000) and Solidoro et al. (2003). It integrated sea water  
 281 temperature and was based on studies on Northern Adriatic lagoons.

282 Also in this case, the enclosure field experiments undertaken by Dang et al. (2010)  
 283 were useful to integrate more realistic values related to Arcachon to adjust the model. They  
 284 allow to draw a direct assessment of this source of mortality. They were established at 6.9%,  
 285 3.9%, 1.8% and 1.2% respectively for length classes 0-20, 21-34, 35-39 and > 40 mm  
 286 (deduced from Dang et al., 2010). On the same principle as for growth, this means, for  
 287 example, that each month the number of clams in the 0-20 mm class that died of natural  
 288 causes is obtained by multiplying the number of clams in the 0-20 mm class in the previous  
 289 month by 6.9%. A feedback loop was also added from the stock variable in order to model a  
 290 "trophic competition" effect on natural mortality (the rule applied is: if the stock is higher than  
 291 20000 t, natural mortality is doubled for each size class) – for equation, see Figure 5.

292 The updated information regarding growth and natural mortality enables describing  
 293 the clam effective evolution per month  $m$  and per class  $i$  (1 to 4) and due to natural processes  
 294 only as:

$$\begin{array}{l}
 \text{For } i = 1 \\
 \begin{array}{ll}
 JP(m) - Z_1(m) - G_1(m) & \text{if } S < 20000 \text{ t} \\
 JP(m) - Z_1(m) \times 2 - G_1(m) & \text{else}
 \end{array} \\
 \text{For } i \geq 2 \\
 \begin{array}{ll}
 LC_{i-1}(m) \times GR_{i-1}(m) - Z_i(m) - LC_i(m) \times GR_i(m) & \text{if } S < 20000 \text{ t} \\
 LC_{i-1}(m) \times GR_{i-1}(m) - Z_i(m) \times 2 - LC_i(m) \times GR_i(m) & \text{else}
 \end{array}
 \end{array}$$

296



297 *5.2. Adjustment of fishing activity and its control parameters*

298 This new work on the model was an opportunity to review some of the fishery-related  
299 parameters and to take into account other economic factors. This information includes annual  
300 fishing declarations of Manila clam within Arcachon Bay and was extracted from two  
301 complementary databases: the national statistic database of the “Système d’Informations  
302 Halieutiques” (for data between 2003 and 2008); the regional database - the “Base Pêche  
303 Aquitaine” (CRPMEM, unpublished data) (for data subsequent to 2009). Combined with the  
304 annual number of active fishing licenses (coded NFL - values in Table 2), the total annual  
305 volumes of catches declared by fishermen allow the calculation of mean catches volume per  
306 fishing license each month (coded CVL).

307 With respect to the fishing mortality per length class and because clams below the  
308 legal harvest size are known to be exploited (anonymous catch reports and authority controls),  
309 the fishing effort (FE) was reallocated on the whole length classes: 21-34 mm, 35-39 mm and  
310 > 40 mm length classes, which were estimated at 40%, 50% and 10 % respectively. This took  
311 into account higher fishing pressure on clams below the minimum legal size, which is more  
312 realistic.

313 In regard to the impact of the protected areas on catches, the Bald et al. (2009) model  
314 considered the percentage of exploitable stock and the percentage of reserve area to  
315 parametrize this variable (Dang, 2009). In the last version of the model, a reformulation was  
316 undertaken: the exploitable stock was considered using the fishing effort applied to each class  
317 above the minimum legal size and the total applicable protected area(s) surface (expressed in  
318 m<sup>2</sup>) according to local legislation became a control variable.

319 In addition, a price effect was included as a control parameter of the fishing activity.  
320 This aims to fill a gap in the model regarding socio-economic drivers which was picked up on  
321 by stakeholders. Following interviews with professionals, the applied rules follow a linear

322 response of catches to any price increase from a reference price (*Pref*) fixed at 3.5 euros per  
 323 kilogram (considered by fishermen as a mean selling price for Manila clam from Arcachon  
 324 Bay). In other words, if the difference between the effective price (*Pr*) and the reference price  
 325 (*Pref*) is one euro, the catches increase by 10%; if the difference is two euros, the catches  
 326 increase by 20% and so on.

327 All this updated information mentioned above led to the reformulation of the temporal  
 328 fishing catches evolution per month *m* and per class *i* (1 to 4) denoted  $FM(m) \times Capt_i(m)$ ,  
 329 which was expressed in effective per surface unit each month ( $\text{ind.m}^{-2}.\text{month}^{-1}$ ), according to  
 330 the following equations:

$$331 \quad FM(m) = \begin{cases} 1 & \text{if } OFM \leq m \leq OFM + CDS \\ 0 & \text{else} \end{cases}$$

332 with *FM* = Fishing Month, *OFM* = Open Fishing Month (month number), *CDS* = Capture  
 333 Duration Season (in month).

$$334 \quad Capt_i(m) \\ 335 \quad = \\ 336 \quad = \begin{cases} \frac{NFL(m) \times CVL(m) \times 10^6 \times FE_i(m)}{ABS \times MW_i} \times \frac{ABS - PAS(m)}{ABS} \times \left[ 1 + \frac{Pr(m) - Pref}{10} \right] & \text{if } Pr(m) > Pref \\ \frac{NFL(m) \times CVL(m) \times 10^6 \times FE_i(m)}{ABS \times MW_i} \times \frac{ABS - PAS(m)}{ABS} & \text{else} \end{cases}$$

337 with *NFL* = Number of Fishing Licenses each month, *CVL* = Catches Volume per fishing  
 338 License each month (t), *FE<sub>i</sub>* = Fishing Effort allocated for class *i* each month (in %), *ABS* =  
 339 Arcachon Bay Surface ( $\text{m}^2$ ), *PAS* = Protected Area Surface each month ( $\text{m}^2$ ), *MW<sub>i</sub>* = Mean  
 340 Weight for class *i* (g), *Pr* = Effective price each month ( $\text{€}.\text{kg}^{-1}$ ), *Pref* = Reference price fixed  
 341 at 3.5 euros per  $\text{kg}^{-1}$ . The first fraction of the last equation reported the catch as a function of  
 342 the number of licenses, the catch per license and the mortality of the class considered in  
 343 Arcachon Bay. The second fraction accounts for the fishing reserve effect. When the selling

344 price was greater than 3.5 €·kg<sup>-1</sup>, the third fraction reflected a price effect with a linear  
345 response.

346 Equation formulations for each process [including those not modified from the Bald et  
347 al. (2009) version and their parametrization are presented in detail in Figure 5 and Table 2.  
348 Figure 5 distinguishes the known parameters or fixed by the user from those estimated by  
349 equations within the model. Table 2 provides details regarding the latest parametrization. The  
350 output variable is the total biomass (S) since it constitutes the current indicator shared  
351 between scientists and managers to discuss the responses of the system to different scenarios.

## Environment and Production of juveniles blocks

$T(m)$ : Temperature at month  $m$   
 $\Delta T(m)$ : Temperature variation  
 $T_{smin}$ ,  $T_{smax}$ : temperature for spawning  
 $JPm(m)$ : Juveniles Production per spawning month fixed by Bald et al. (2009)  
 $\Delta JPm(m)$ : Combined chlorophyll a and TSM effects

$SP(m)$ : Spawning occurrence for a given month  
 $JP(m)$ : Juvenile Production per surface unit and per month

$$SP(m) = \begin{cases} 1 & \text{if } T_{smin} < T(m) + \Delta T(m) < T_{smax}(m) \\ 0 & \text{else} \end{cases}$$

$$JP(m) = [JPm(m) \times [1 + \Delta JPm(m)]] \times SP(m)$$

## Stock/Maturation/Mortality block

$Z_i(m)$ : Natural mortality evolution per surface unit and per month for a generic  $i^{th}$  length class  
 $M_i(m)$ : Effective per surface unit of the  $1^{st}$  class length having died per month  
 $G_i(m)$ : Effective per surface unit of the  $1^{st}$  length class having grown to achieve the next length class in a month  
 $GR_i(m)$ : Growth rate of the  $i^{th}$  length class per month

$M_i(m)$ : Mortality evolution per surface unit and per month for a generic  $i^{th}$  length class  
 $LC_i(m)$ : Clam effective evolution per surface unit and per month for a  $i^{th}$  length class

$$M_i(m) = \begin{cases} Z_i(m) + FE_i(m) \times FM(m) \times Capt_i(m) & \text{For } i = 1 \text{ to } 4 \\ Z_i(m) \times 2 + FE_i(m) \times FM(m) \times Capt_i(m) & \text{if } S < 20000 \text{ t} \\ & \text{else} \end{cases}$$

$$LC_i(m) = \begin{cases} JP(m) - M_i(m) - G_i(m) & \text{For } i = 1 \\ LC_{i-1}(m) \times GR_{i-1}(m) - M_i(m) - LC_i(m) \times GR_i(m) & \text{For } i \geq 2 \end{cases}$$

## Fishery block

$OFM$ : Opening Fishing Month  
 $CDS$ : Capture Duration Season (month)  
 $NFL(m)$ : Number of Fishing Licenses  
 $CVL(m)$ : Catches Volume per fishing License each month  
 $FE_i(m)$ : Fishing Effort expressed in percentage of the total fishing effort all length class considered applied to class 1 to 4 each month  
 $ABS$ : Arcachon Bay Surface ( $m^2$ )  
 $MW_i$ : Mean Weight of the  $i^{th}$  length class (g)  
 $PAS(m)$ : Protected Area Surface  
 $Pr(m)$ : Selling price  
 $Pref$ : Reference price

$FM(m)$ : Fishing Month  
 $Capt_i(m)$ : Fishing catches evolution expressed in effective per surface unit and per month for a generic  $i^{th}$  length class

$$FM(m) = \begin{cases} 1 & \text{if } OFM \leq m \leq OFM + CDS(m) \\ 0 & \text{else} \end{cases}$$

$$= \begin{cases} \frac{NFL(m) \times CVL(m) \times 10^6 \times FE_i(m)}{ABS \times MW_i} \times \frac{Capt_i(m)}{ABS - PAS(m)} \times \left[ 1 + \frac{Pr(m) - Pref}{10} \right] & \text{if } Pr(m) > Pref \\ \frac{NFL(m) \times CVL(m) \times 10^6 \times FE_i(m)}{ABS \times MW_i} \times \frac{ABS - PAS(m)}{ABS} & \text{else} \end{cases}$$

$S(m)$ : Total biomass

$$S(m) = \sum_{i=1}^4 LC_i(m) \times MW_i \times ABS$$

352

353 **Fig. 5.** Equation formulations for each process from the starting point S (biomass) - in blue: known parameters or fixed by the user; in green: estimated by the  
 354 model.

355 **Table 2:** Fixed or known parameters used for the parametrization of the differential equations.

Blocks	Parameter sets (units)	Values of parametrization	References
Environment and Production (of juveniles)	T: temperature per month (°C) Defined by f, h and g: coefficients of the sea water temperature with f : half of the maximum temperature variation h: phase g: mean annual temperature	From 2003 to 2019: real data From 2020: moving average over three years calculated on each month	ARCHYD network on two stations (Comprian and Les Jacquets)
	$\Delta T$ : temperature variation (°C)	From 2003 to 2019: 0 From 2020: see part 7 for retained values according to scenarios	Parameter added to simulate environmental scenario from 2020.
	Tsmin: minimum temperature for spawning (°C)	15	Literature (Beninger and Lucas, 1984; Rodríguez-Moscoso et al., 1992; Solidoro et al., 2003)
	Tsmax: maximum temperature for spawning (°C)	22	Literature (Rodríguez-Moscoso et al., 1992; Solidoro et al., 2003)
	JPm: juveniles production per spawning month (ind m <sup>-2</sup> month <sup>-1</sup> ) fixed by Bald et al. (2009)	3.3	Bald et al., 2009
	$\Delta JPm$ : Combined chlorophyll a and TSM effects on juveniles production (%)	From 2003 to 2009: 0 From 2010 to 2019: -25 From 2020: see part 7 for retained values according to scenarios	Caill-Milly (2012), ARCHYD network on two stations (Comprian and Les Jacquets)
Stock/Maturation/ Mortality/Fishery	ABS: Arcachon Bay Surface (m <sup>2</sup> )	46,4 x 10 <sup>6</sup>	Bald et al., 2009
$S_t^o$	GR <sub>1</sub> to GR <sub>4</sub> : growth rates of length class 1 to	[0-20]: 0.361	Assessed from enclosure field experiments undertaken by

	4 (dimensionless)	[21 – 34]: 0.245 [35 – 39]: 0.227 > 40: /	Dang et al (2010)
	MW <sub>1</sub> to MW <sub>4</sub> : mean weight of length class 1 to 4 (g)	[0-20]: 0.992 [21 – 34]: 6.624 [35 – 39]: 11.662 > 40: 18.288	Calculated using relation length-weight (see Appendix 1)
	Z <sub>1</sub> to Z <sub>4</sub> : natural mortality evolution per surface unit for class 1 to 4 (%)	[0-20]: 6.9 [21 – 34]: 3.9 [35 – 39]: 1.8 > 40: 1.16	Assessed from enclosure field experiments undertaken by Dang et al (2010)
	FE <sub>1</sub> to FE <sub>4</sub> : fishing effort expressed in percentage of the total fishing effort all length class considered applied to class 1 to 4 (%)	[0-20]: 0 [21 – 34]: 0.4 [35 – 39]: 0.5 > 40: 0.1	Estimated from anonymous catches reports and authority controls
	OFM: opening fishing month	July	From Bald et al., 2009
	CDS: capture duration season	2003: 6 2004 to 2008: 12 2009 to 2012: 10.3 2013 to 2019: 12	Local regulation (Sanchez et al., 2018 ; Caill-Milly et al., 2021)
Fishery	NFL: number of fishing licenses	2003 to 2008: 70 2009: 66 2010: 57 2011: 57 2012: 60 2013: 55 2014: 56 2015: 52 2016: 44 2017: 49 2018: 47 2019: 46	Local regulation (Caill-Milly et al., 2021)
	PAS: protected area surface (x 10 <sup>6</sup> m <sup>2</sup> )	2003 to 2005: 2.37 2006 to 2007: 0.96	Local regulation (Sanchez et al., 2018 ; Caill-Milly et al., 2021)

---

	2008: 9.10	
	2009 to 2012: 4.3	
	2013: 4.3 and 5.4	
	2014: 5.4 and 0	
	2015: 0 and 9.6	
	2016: 0, 9.6 and 4.9	
	2017 to 2019: 4.9	
Pr: Effective price (€.kg <sup>-1</sup> )	From 2003 to 2019: 3.5	Based on interviews with fishermen
Pref: Reference price (€.kg <sup>-1</sup> )	3.5	Based on interviews with fishermen
CVL: catches volume per fishing license each month (t.month <sup>-1</sup> )	2003: 0.47 2004: 0.67 2005: 0.46 2006: 1.06 2007: 1.22 2008: 0.85 2009: 0.82 2010: 0.73 2011: 0.90 2012: 0.68 2013: 0.75 2014: 0.51 2015: 0.50 2016: 0.64 2017: 0.75 2018: 0.88 2019: 0.74	Calculated from fishermen declarations (SIH, unpublished data and CRPMEM, unpublished data; Sanchez et al., 2018; Caill-Milly et al., 2021).

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## 357 6. Validation and sensitivity analysis

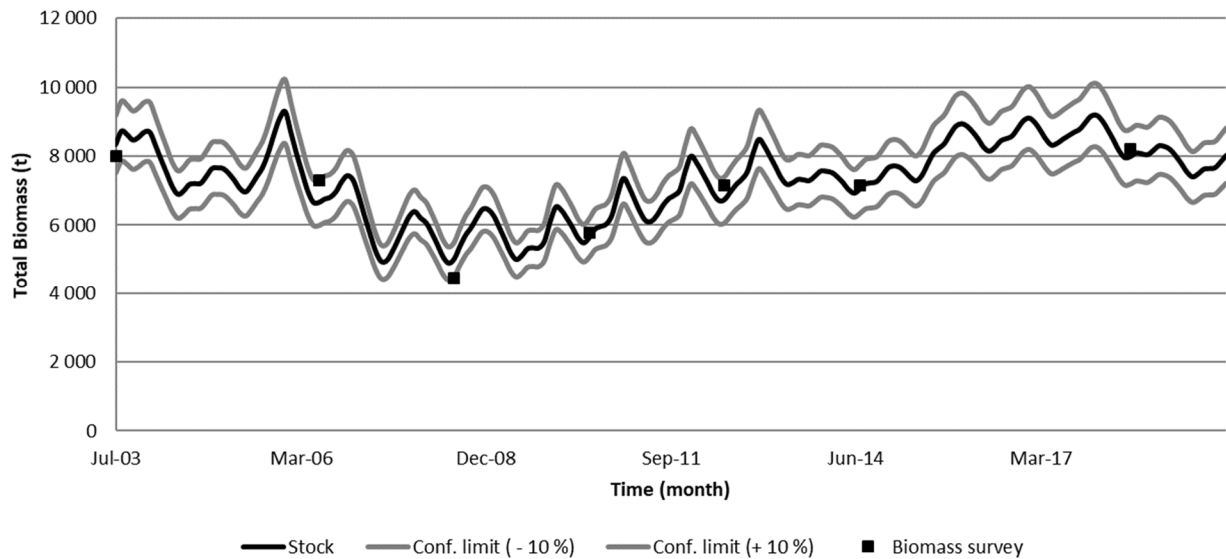
### 358 6.1. Goodness of fit of the model

359 The first available dataset on size distribution of the population within the bay (Caill-  
360 Milly et al., 2003) determines the initial time of the model and is available for July 2003.  
361 Starting from this date, the model was calibrated with the aforementioned recent population,  
362 ecological and fishery data. This “historical” reconstitution ended in December 2019. It traced  
363 the stock evolution before testing new management strategies.

364 Model validation was performed on this hindcast using the subsequent stock  
365 assessments (2003, 2006, 2008, 2010, 2012, 2014 and 2018). Those observed data (learning  
366 samples) were compared to the predicted data given by the model. The model efficiency,  
367 which is the calibration step, was evaluated by the percentage of deviation between observed  
368 and predicted data sets. The criterion of a maximum deviation percentage (set to 10 %) was  
369 retained according to previous works (Bald et al., 2006, 2009). The model output for the July  
370 2003 to December 2019 period is illustrated in Figure 6 and presents a first period  
371 characterized by a global decrease of the total biomass up to 4,883 tons mid-2008 and a  
372 second period displaying a recovery of the stock (with a maximum at 9,188 tons early 2018).  
373 At the end of the period, the total biomass is around 8,000 tons.

374 For this historical reconstitution, the model outputs fits quite well with the real data  
375 since the percentage of deviation (in absolute terms) between observed and predicted data  
376 were respectively 4% in 2003, 10% in 2006, 11% in 2008, 3% in 2010, 6% in 2012, 1% in  
377 2014 and 3% in 2018 (Figure 6) (average of the absolute values of this percentage equal to  
378 5.3%). Those values meet the criterion of a maximum deviation percentage set at 10% except  
379 for 2008 with 11%.





380 **Fig. 6.** Total biomass (in t) simulated between July 2003 and December 2019 (“historical”  
 381 reconstitution).  
 382

### 383 6.2. Model sensitivity

#### 384 6.2.1. Retained methodology

385 Parameters of system dynamics models are subject to uncertainty, which propagates  
 386 throughout the model, and lead to variability of its outputs. In this context, sensitivity analysis  
 387 can provide an answer to various issues such as improvement of the model formulation  
 388 including simplification by eliminating non-essential components, model robustness  
 389 assessment, identification of the parameters that have the greatest influence of chosen target  
 390 variables, etc. (Banos-Gonzalez et al., 2018; Norton, 2015; Pianosi and Wagener, 2018). In  
 391 this paper, the effect of variations in assumed information on the model output is considered.  
 392 It enables identification of the most influential parameters.

393 In this context, uncertainty of the control parameters used in the model were  
 394 considered; they are related to biological and environmental aspects. For each parameter, an  
 395 arbitrarily selected range of 25% variation around the default parameter value was applied  
 396 (Banos-Gonzalez et al., 2018), unless available assessment of uncertainty was already  
 397 available. This was the case for natural mortality, spawning minimum and maximum

398 temperature, mean length weight. For natural mortality, the standard deviation of calculated  
 399 values established from Dang (2009) was employed as the uncertainty measure ( $\pm 3.3$ ,  $\pm 1.5$   
 400 and  $\pm 1.1\%$  for the 0-20 mm, 20-35 mm and 35-40 mm length classes respectively). In the case  
 401 of spawning minimum and maximum temperature, few works established a threshold  
 402 (Delgado and Pérez-Camacho, 2007; Holland and Chew, 1974; Mann, 1979; Obha, 1959;  
 403 Toba and Miyama, 1995), which challenged us to consider a possible difference of  $\pm 0.5^\circ\text{C}$ .  
 404 For mean length weight, the standard deviation calculated by Bald et al. (2009) was used as  
 405 the uncertainty measure ( $\pm 0.67$ ,  $\pm 0.21$ ,  $\pm 0.41$  and  $\pm 1.12\%$  for the 0-20 mm, 20-35 mm, 35-39  
 406 mm and above 40 mm length classes respectively) (Table 3).

407 **Table 3.** Parameters' uncertainty applied in the model to assess the sensitivity analysis using  
 408 Monte Carlo simulations.  
 409

Parameters	Uncertainty applied	Percentage of variation around the default parameter value
Natural mortality evolution (%)	0-20 mm: $\pm 3.3$	48%
	21-34 mm: $\pm 1.5$	38%
	35-40 mm: $\pm 1.1$	61%
	> 40 mm : $\pm 0.3$	25%
Spawning minimum temperature ( $^\circ\text{C}$ )	$\pm 0.5$	7%
Spawning maximum temperature ( $^\circ\text{C}$ )	$\pm 0.5$	5%
Mean length weight (g)	0-20 mm: $\pm 0.670$	68%
	21-34 mm: $\pm 0.210$	3%
	35-40m: $\pm 0.410$	3%
	> 40 mm: $\pm 1.120$	6%
Growth rates of the length (dimensionless)	0-20 mm: $\pm 0.090$	25%
	21-34 mm: $\pm 0.061$	25%
	35-40 mm: $\pm 0.057$	25%
Juveniles production per spawning month ( $\text{ind month}^{-1}$ )	$\pm 0.6$	25%

410  
 411 On a first step, each parameter was studied separately to test for the variability of the  
 412 estimated biomass (S) using thousand Monte Carlo simulations (Univariate Sensitivity  
 413 Analysis) with a random uniform distribution of probability. This approach corresponded to  
 414 the One-Factor-At-A-Time analysis where the initial values of the parameters were modified

415 in a range that account for ecological reality or in a range of +/- 25%. For December 2029, a  
416 sensitivity index (Banos-Gonzalez et al., 2018) was calculated for each parameter.

$$417 \quad Sensi_i = \left( \frac{SMax - SMin}{SVal} \right) \div \left( \frac{PMax - PMin}{PVal} \right) \times 100$$

418 where  $Sensi_i$  represents the sensitivity index of the biomass in relation to the parameter  $i$ ;  
419  $SMax$  and  $SMin$  are the maximum and minimum values, respectively, of the biomass at time  
420 December 2029;  $SVal$  represents the status quo model value of the biomass at time December  
421 2029;  $PMax$  and  $PMin$  represent the maximum and minimum values of the  $i$ th parameter,  
422 respectively; and  $PVal$  is the status quo model value of the  $j$ th parameter.

423 The sensitivity index values are visualized on an ordered bar chart (Pianosi et al.,  
424 2016). Using this index, the parameters can be classified into five categories: insensitive ( $Si =$   
425  $0\%$ ), low sensitivity ( $Si < 10\%$ ), moderate sensitivity ( $10\% < Si < 50\%$ ), high sensitivity ( $50\%$   
426  $< Si < 100\%$ ), and very high sensitivity ( $Si > 100\%$ ). In addition, confidence bounds of the  
427 biomass were plotted for the variation of each parameter. In relation to the corresponding  
428 relative variation of the input parameter, the index and the graphical representation provided  
429 information about the parameters, which influenced the system the most.

430 In a second step, the sensitive parameters ( $Si > 50\%$ ) were considered together  
431 (general sensitivity analysis) to quantify the effects of their simultaneous variations on the  
432 biomass. In this case, one thousand Monte Carlo simulations were generated with Latin  
433 Hypercube sampling. For this, it is common practice to constrain the parameter variations to  
434 acceptable ranges in order to have realistic levels (Banos-Gonzalez et al., 2018). In the  
435 absence of additional information, the percentages of variation were here identical to those of  
436 step one. With Latin Hypercube sampling, the full range of each parameter was thus explored  
437 using a reasonable number of runs (Banos-Gonzalez et al., 2018) and provided sufficient  
438 information about the distribution in the outcome (Ford and Flynn, 2005). It can be efficient

439 in order to reveal non-linearities, principally if one or two parameters dominate (Manache and  
440 Melching, 2008).

441 A variation coefficient ( $VC$ ) (Banos-Gonzalez et al., 2018) of the biomass shown by  
442 the Monte Carlo simulations was calculated for December 2029.

$$443 \quad VC = \left( \frac{SMax95 - SMin95}{\bar{S}} \right) \times 100$$

444 where  $VC$  is the relative variation of the biomass ( $S$ ) with respect to its mean value using 95%  
445 confidence bounds;  $SMax95$  and  $SMin95$  are the maximum and minimum values of the  
446 biomass in December 2029, using the 95% confidence bound; and  $\bar{S}$  is the mean value of  
447 biomass.

448 This coefficient was set in one of the three following categories: low response ( $VC <$   
449  $50\%$ ), moderate response ( $50\% < VC < 100\%$ ) and high response ( $VC > 100\%$ ).

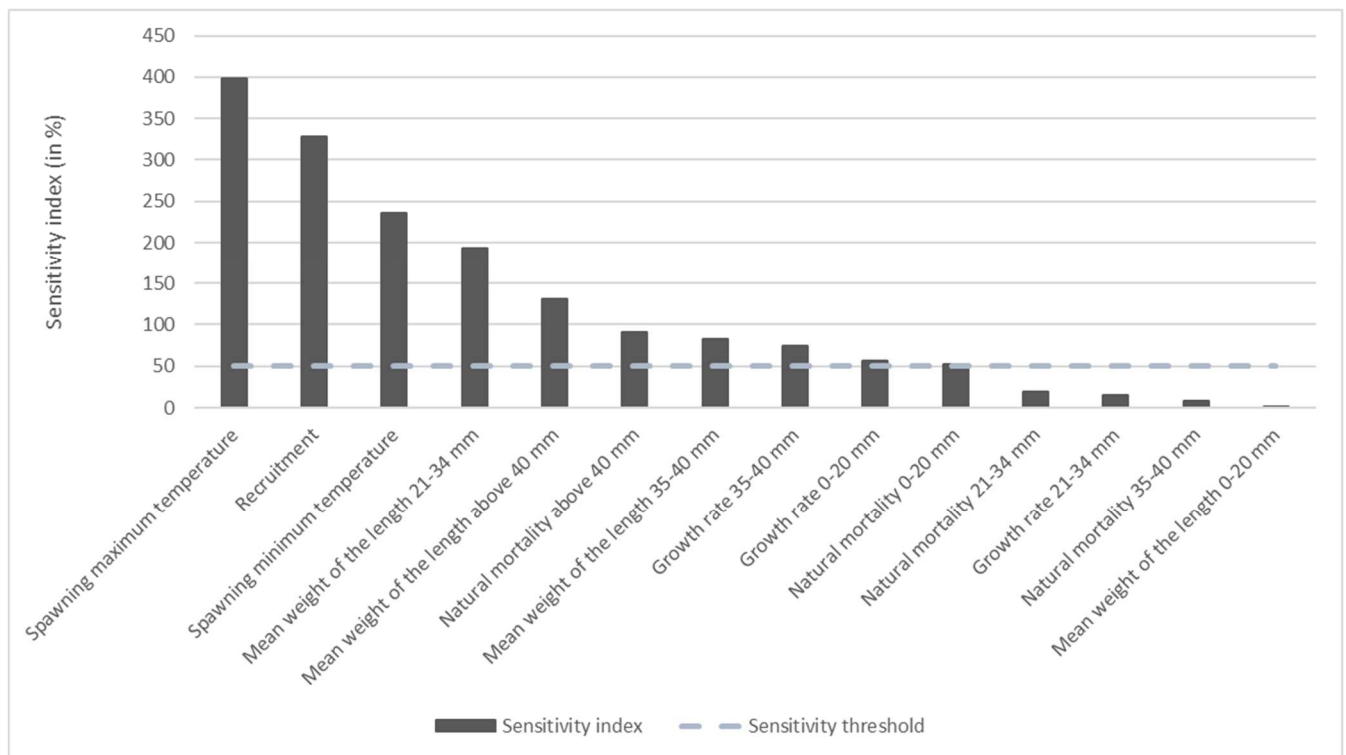
450 For the two steps, Monte Carlo simulation is appropriate since the model may generate  
451 interactions between factors or have non-linear outputs as stated by Lesnoff et al. (2012). The  
452 time-frame has two parts: from July 2003 to December 2019 – historical reconstitution; from  
453 January 2020 to December 2029 – projection with historical trends of environmental data and  
454 application of the same management measures as for 2019.

455

#### 456 6.2.2. Sensitivity analysis results

457 For the control parameters tested, the values of the sensitivity index are comprised  
458 between 1 and 399%, which means that the model is from low sensitive to high sensitive  
459 regarding those parameters. The highest indexes are obtained with parameters regarding or  
460 influencing young stages of the population: spawning maximum temperature, recruitment and  
461 spawning minimum temperature (Figure 7). The following are related to mean length weight  
462 21-34 mm, mean length weight above 40 mm and to a lesser extent natural mortality above 40

463 mm. The lowest indexes are related to mean length weight for 0-20 mm to natural mortality of  
 464 35-40 mm, to growth rate 21-34 mm and to natural mortality 21-34 mm.



465  
 466 **Fig. 7.** Value of the sensitivity index for the control parameters used as input factors.

467  
 468 Ten out of fourteen parameters are associated to the sensitive index. The confidence  
 469 bounds of the biomass according to their respective variation are plotted for each of those  
 470 parameters (Appendix 2).

471 Those ten parameters were used to run one thousand Monte Carlo simulations with  
 472 Latin Hypercube sampling. The variation coefficient is 173%, which means that the model  
 473 displays a high response of the biomass to those parameters.

474  
 475 **7. Application of various scenarios**

476 *7.1. Simulations of several management strategies*

477 Since the outcome of the model was to be used as a decision-making tool, case studies  
478 were defined to observe the simulated evolution of the total biomass according to various  
479 strategies relying on different types of measures (reducing fishing effort, technical measures  
480 and limitation of catches) (Table 4).

481 Forecasts from January 2020 to December 2029 resulting from the introduction of  
482 different management options were undertaken. The eight scenarios **related to management**  
483 **strategies** and retained for this paper were the following:

- 484 - Scenario 1 (status quo) corresponded to maintenance of the management measures  
485 in similar levels than those applied in 2019 ( $CVL = 0.74 \text{ t month}^{-1} \text{ license}^{-1}$ ,  $CDS =$   
486  $12 \text{ months}$ ,  $PAS = 4.9 \times 10^6 \text{ m}^2$ ,  $NFL = 46$ );
- 487 - Scenario 2 doubled the protected area surface, the other parameters remaining the  
488 same as for status quo ( $CVL = 0.74 \text{ t month}^{-1} \text{ license}^{-1}$ ,  $CDS = 12 \text{ months}$ ,  $PAS =$   
489  $9.8 \times 10^6 \text{ m}^2$ ,  $NFL = 46$ );
- 490 - Scenario 3 reduced the fishing period (equivalent to one day per week off) ( $CVL =$   
491  $0.74 \text{ t month}^{-1} \text{ license}^{-1}$ ,  $CDS = 10.3 \text{ months}$ ,  $PAS = 4.9 \times 10^6 \text{ m}^2$ ,  $NFL = 46$ );
- 492 - Scenario 4 simulated a decrease of the number of fishing licenses ( $CVL = 0.74 \text{ t}$   
493  $\text{month}^{-1} \text{ license}^{-1}$ ,  $CDS = 12 \text{ months}$ ,  $PAS = 4.9 \times 10^6 \text{ m}^2$ ,  $NFL = 40$ );
- 494 - Scenario 5 simulated a decrease of the catches per fishing licenses ( $CVL = 0.6 \text{ t}$   
495  $\text{month}^{-1} \text{ license}^{-1}$ ,  $CDS = 12 \text{ months}$ ,  $PAS = 4.9 \times 10^6 \text{ m}^2$ ,  $NFL = 46$ );
- 496 - Scenario 6 combined three measures – slight decrease of the catches per fishing  
497 licenses, decrease of the capture duration season and increase of the protected area  
498 surface ( $CVL = 0.70 \text{ t month}^{-1} \text{ license}^{-1}$ ,  $CDS = 11 \text{ months}$ ,  $PAS = 7.35 \times 10^6 \text{ m}^2$ ,  
499  $NFL = 46$ );
- 500 - Scenario 7 also combined three measures – slight decrease of the catches per  
501 fishing licenses, decrease of the capture duration season and of the number of

502 fishing licenses ( $CVL = 0.70 \text{ t month}^{-1} \text{ license}^{-1}$ ,  $CDS = 11 \text{ months}$ ,  $PAS = 4.9 \times$   
503  $10^6 \text{ m}^2$ ,  $NFL = 40$ );  
504 - Finally, Scenario 8 combined two measures – decrease of the catches per fishing  
505 license and decrease of the capture duration season ( $CVL = 0.60 \text{ t month}^{-1} \text{ license}^{-1}$ ,  
506  $CDS = 10.3 \text{ months}$ ,  $PAS = 4.9 \times 10^6 \text{ m}^2$ ,  $NFL = 46$ ).

507 When a parameter was not listed above, it means that the applied value was the same  
508 as for the last year of the “historical” reconstitution.

509 To undertake comparisons between these management scenarios, evolution of the total  
510 biomass trend was compared between the chosen scenarios and the continuation of the active  
511 management measures in 2019 (Scenario 1 - status quo) (Table 4).

512 **Table 4.** Description of the eight tested management scenarios integrated in the model from  
513 2020 to 2029. Relative differences of each management measure applied in Scenarios 2 to 8 are  
514 compared to Scenario 1 (status quo) management measure values using the following codification =  
515 no changes, ↗ increase comprised between 1 and 10%, ↗↗ increase (strictly) superior to 10%, ↘  
516 decrease comprised between 1 and 10%, ↘↘ decrease (strictly) superior to 10%.

517 Key:  $NFL$  = number of fishing licenses,  $CVL$  = catches volume by license ( $\text{t month}^{-1} \text{ license}^{-1}$ ),  $CSD$  =  
518 capture season duration (month),  $PAS$  = Protected area surface ( $\times 10^6 \text{ m}^2$ ).  
519  
520

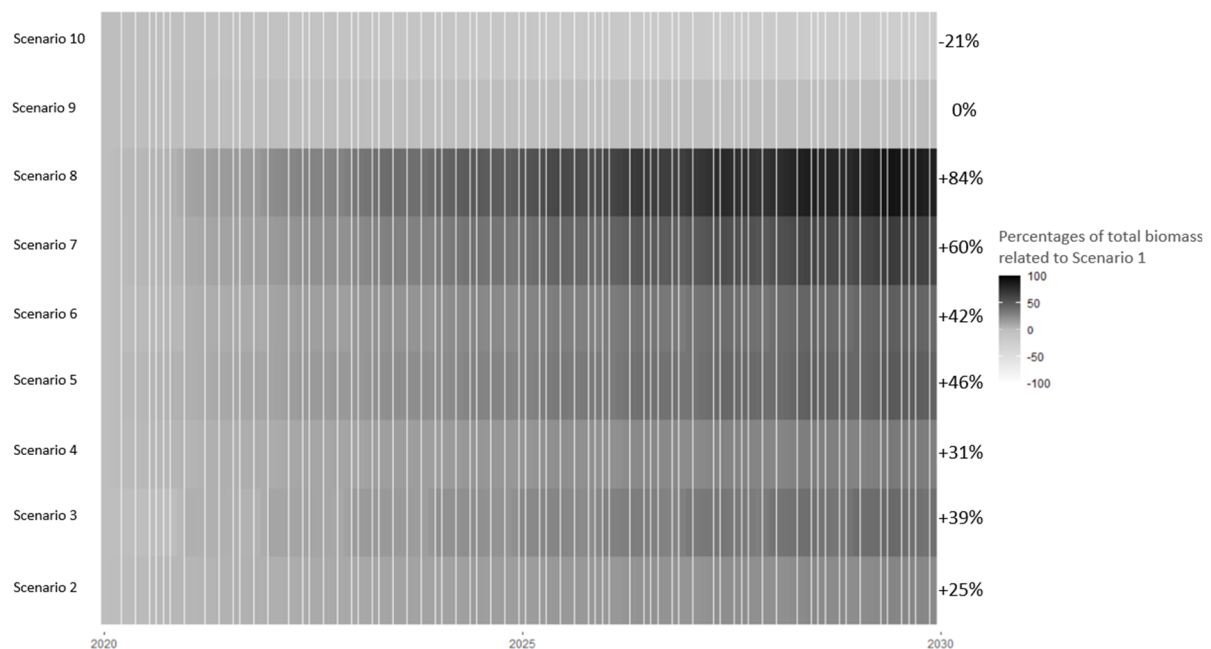
	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8
Types of measures differing from status quo	/	Technical measures,	Technical measures	Reducing fishing effort	Limitation of catches	Limitation of catches, technical measures	Limitation of catches, technical measures, reducing fishing effort	Limitation of catches, technical measures
$NFL$	46	=	=	↘↘	=	=	↘	=
$CVL$	0.74	=	=	=	↘↘	↘	↘	↘↘
$CDS$	12	=	↘↘	=	=	↘	↘	↘↘
$PAS$	4.9	↗↗	=	=	=	↗↗	=	=

521  
522 The total biomass according to the eight management strategies (from January 2020 to  
523 December 2029) displayed in any case an improvement in the stock level. The results were  
524 summarized in the two following categories (single measures and multiple measures, see  
525 Table 5):

- 526 - Among the single measures, the gain between the scenarios 2 to 5 and scenario 1  
 527 (status quo) is comprised between 25% and 46% at the end of 2029. The lowest  
 528 gain is obtained with technical measures (*PAS*); the highest gain is obtained with  
 529 the limitation of catches (*CVL*);
- 530 - Among the multiple measures, the gain between the scenarios 6 to 8 and scenario 1  
 531 (status quo) is comprised between 42% and 84% at the end 2029. The highest gain  
 532 is obtained with the limitation of catches (*CVL*) combined with technical measures  
 533 (*CDS*).

534 These results highlighted the relevance of combining selected management measures to  
 535 improve the stock level.

536 **Table 5.** Relative differences expressed in percentages between the total biomass estimated for each  
 537 Scenario [Scenarios 2 to 8 (management strategies); Scenarios 9 to 10 (potential effects of  
 538 environmental or market modifications)] and the total biomass estimated for Scenario 1 (status quo)  
 539 from January 2020 to December 2029. The gains or losses at the end of 2029 are displayed on the right  
 540 of the table.  
 541





542 7.2. Simulations of environmental and market modifications

543 Two other scenarios were defined to consider the **potential effects of environmental**  
544 **or market modifications** to the stock evolution in addition to *status quo* management  
545 measures. For these scenarios, the management measures applied were the same as those  
546 selected for Scenario 1 (*status quo*) on which the additional hypotheses were applied from  
547 2020:

- 548 - Scenario 9 simulated an increase of the seawater temperature. To define this  
549 augmentation, the last report of the GIECC (IPCC, 2019) was used. Considering  
550 the projected change in sea surface temperature between the recent past (1986–  
551 2005) and the near term (2031–2050) under scenario RCP8.5, an increase of  
552 0.04°C per year was tested. It was applied to all the months of the same year. This  
553 value is consistent with regional forecasts given by Chust et al. (2014) for the Bay  
554 of Biscay for the end of the century. This modification was applied between 2020  
555 and 2029;
- 556 - Scenario 10 considered the increase of the selling price from 3.5 euros per kg to  
557 4.5 euros per kg. As mentioned above, this resulted in an increase in catches of  
558 10%.

559 Regarding scenario 9 (slight increase of temperature applied in addition to *status quo*  
560 management measures), the total biomass exhibited the same evolution as for the *status quo*  
561 scenario (Table 5). Over the period 2020-2029, the number of months favorable to the  
562 realization of spawning was not modified. When modelling is continued with the same  
563 assumption (+ 0.04°C per year), a change is observed in 2037. All other things being equal, at  
564 the end of 2040, the biomass would be 24% higher than with scenario 1 (Appendix 3).

565 For scenario 10, the simulated price per kilo increase results in a gradual decrease in  
566 the total biomass over the period 2020-2029 (Table 5). At the end of the period, the difference  
567 reaches -21% compared to the level obtained for the status quo.

568

## 569 **8. Discussion and conclusion**

570 Considering the initial assumptions listed in Bald et al. (2009), major developments  
571 and improvements have been undertaken. Those recent improvements are in bold italics in  
572 Figure 3.

### 573 **Integration of specific available life traits data**

574 The parameterization of Bald et al.'s (2009) model relied mainly on different  
575 bibliographic sources related to population dynamics of the Manila clam (Beninger and  
576 Lucas, 1984; Melià et al., 2004; Rodríguez-Moscoso et al., 1992; Solidoro et al., 2000, 2003)  
577 together with data related to Arcachon Bay (Caill-Milly et al., 2003 and G. Trut, unpublished  
578 data). Recent ecological data available at the bay scale led to the revision of the previous  
579 model's assumptions.

580 First, environmental drivers on key processes of the population dynamics have been  
581 reinforced thanks to integration of real data or to new formulations. This evolution mainly  
582 regarded the reproduction phase. Until now this phase, which is one of the key processes of  
583 population dynamics (Flye-Saint-Marie, 2007) was only controlled by seawater temperature.  
584 A preliminary modulation relying on food availability expressed by chlorophyll a levels and  
585 on total suspended matter concentrations was undertaken. Measurement of photosynthetic  
586 pigment water concentration remains relatively easy to acquire and appears to be the most  
587 common indicator used for food availability (*e.g.* Shibata et al., 1999). Unlike the older stages

588 (Flye-Sainte-Marie et al., 2003), we have not identified any work questioning the validity of  
589 this descriptor as an adequate substitute for food availability in young Manila clams.  
590 Nevertheless, it is always interesting to consider other trophic resource proxies when  
591 available. In the case of Arcachon, the evolution of the monthly average of phytoplankton  
592 abundance also showed a change consistent with the hypothesis adopted for this work  
593 [Phytoplankton and Phycotoxin Monitoring Network (REPHY, Ifremer), unpublished data].  
594 In those conditions, the retained formulation corresponded to a more realistic hypothesis since  
595 those modelled environmental parameters (temperature, food supply and total suspended  
596 matter) are well known for influencing the reproductive phase (Delgado and Pérez-Camacho,  
597 2007; Devauchelle, 1990; Holland and Chew, 1974; Le Pennec and Benninger, 2000; Mann,  
598 1979; Ohba, 1959; Soudant et al., 2004; Toba and Miyama, 1995) or described as driving  
599 factors for Arcachon Bay (Caill-Milly, 2012). However, the applied modulation does not take  
600 into account the observation of a phenomenal number of juveniles in 2014 (Sanchez et al.,  
601 2014). Moreover, the sensitivity analysis highlighted that the target variable – the biomass –  
602 was very sensitive to the uncertainty of the parameter recruitment. Such results advocate for  
603 deeper analysis of the processes related to the younger stages including data collection efforts  
604 as recommended by Sterman (2000). This encourages the implementation of a monitoring of  
605 the number of clam larvae just as it is already practiced for the intra-basin oysters but for the  
606 moment not carried out on Manila clam for lack of means. In the meanwhile, as long as such  
607 an episode remains exceptional and the current conditions on chlorophyll a and TSM do not  
608 exhibit major changes, the applied rules should be maintained.

609 A second important process for population dynamics, *i.e.* growth, could also have been  
610 determined by this integration of specific environmental drivers. The reason is that numerous  
611 authors agree with the main role played by the temperature on *Venerupis species* (Beiras et  
612 al., 1994; Fan et al., 2007; Laing et al., 1987; Toba, 1987 in Nakamura et al., 2002), but also

613 food supply (Maître-Allain, 1982; Yamamoto et al., 1956) and even duration of immersion  
614 (Gouilletquer et al., 1987). Nevertheless, two reasons led to the application of minor changes  
615 in the formulation of the growth process. First, the highlighted interrelations between the  
616 studied stock status and temperature did not consider growth but mainly the reproductive  
617 phase (Caill-Milly et al., 2012). Secondly, the possible effects involved (directly and  
618 indirectly via the link between temperature and trophic resources) were highly complex and  
619 the current constitution of the model did not allow their consideration. Numerous references  
620 have already addressed the problem of model complexity (Costanza and Sklar, 1985;  
621 Håkanson, 1999; Jørgensen, 1988) since the right balance must be struck between simplicity  
622 and complexity. On one hand, a simplistic model may not account for important ecological  
623 processes and may reduce descriptive and realistic model properties (Cetin, 2007). On the  
624 other hand, a highly complex model may reduce predictive accuracy, be difficult to run, and  
625 produce a high number of errors (Håkanson, 1999; Tsang, 1991). High dependence on  
626 assumptions, parameter values, and environmental forcing functions was also mentioned by  
627 Murray and Parslow (1999). It was assumed that ecological processes involved in the growth  
628 phase were insufficiently controlled.

629         With respect to growth and natural mortality, the previous formulations relied on  
630 growth model developed for the Sacca di Goro Lagoon (Italy) (Bald et al., 2009) or on an  
631 empirical equation proposed by Solidoro et al. (2000, 2003) for Northern Adriatic lagoons.  
632 Direct assessments of growth and of this source of mortality were drawn from enclosure field  
633 experiments undertaken by Dang et al. (2010) within Arcachon Bay between December 2005  
634 and November 2007. In addition to being reliable data for the considered stock, their  
635 variations with age (related to mean size) were coherent with the models proposed by Caddy  
636 (1991) and Appeldoorn (1988) notably to reproduce mortality at age. Moreover, those values  
637 were used to account for the natural predation of Manila clams, which was considered to be

638 important in Arcachon Bay (Robert and Deltreil, unpublished results). They also included the  
639 effect of diseases.

640         Regarding ecological processes not treated until now, future improvements could  
641 mainly concern the question of linkage between the stock and the recruitment. The current  
642 biomass surveys led every two years indicated high variability of the recruitment levels at the  
643 bay scale (Sanchez et al., 2018) that was in accordance with the work undertaken by Tezuka  
644 et al. (2012). Nevertheless, they did not allow the validation of any intraspecific  
645 stock/recruitment relationship for the investigated population. To identify this relationship for  
646 coastal species, Freire and García-Allut (2000) reported the importance of scale  
647 considerations or the occurrence of low stock levels to be detected. Moreover, processes  
648 involved are complicated because a stronger effect of interspecific stock-recruitment  
649 relationship can also occur as demonstrated for *Donax hanleyanus* by Defeo (1998). In the  
650 absence of evidence, recruitment fluctuations in response to environmental parameters were  
651 deemed much stronger than those linked to density-dependent mechanisms (intra and  
652 interspecific). If this hypothesis were to be revised, the model structure would allow, for  
653 example in considering fertility rates according to size classes, since reproductive effort and  
654 fecundity are age-related (Gosling, 2003). For the lagoon of Venice, Solidoro et al. (2003)  
655 considered that each parental class (minimum length required 18 mm) enabled the successful  
656 implantation of one hundred juveniles. For Arcachon Bay, a first approach could be  
657 undertaken by using the age-related gonadal production established by Urrutia et al. (1999)  
658 for *Venerupis decussatus*.

#### 659         **Adjustment of the realized fishing activity and its control parameters**

660         Reformulations of the monthly catches volume per fishing license using data from two  
661 databases (“Système d’Informations Halieutiques” and “Base Pêche Aquitaine”) was  
662 integrated, and is considered as the most reliable parameter for professional fishing activities.

663 In addition, the fishing effort according to the different length classes was reallocated based  
664 on more realistic field information. Those improvements permitted a reformulation of the  
665 temporal fishing catches evolution expressed in effective per surface unit for each length class  
666 (units in  $\text{m}^{-2} \text{month}^{-1}$ ). The fishery block was also amended by a first option to simulate a  
667 price effect on the fishing strategies. Socio-economic objectives are generally poorly defined  
668 so a price-effect has been recently integrated into the model to enrich it and to take into  
669 account human behavior. Such relationships could be more precisely established as well as  
670 the relationship between biomass availability, effort and profitability of the fishery. For  
671 instance, it would be interesting to introduce modification of *CVL* level in response to strong  
672 decrease of total biomass. As well, a reflection on the desired breakdown of the licenses  
673 between full time and part time activities could be set.

674 In addition, the current fishing activity modelled within the model remained the  
675 commercial one. Manila clams are also caught by recreational fishermen, but their impact is  
676 considered negligible in comparison to commercial fishing (FMPAA, unpublished results).  
677 Under those conditions, it did not seem useful to include this factor in the modeled  
678 parameters.

### 679 **Performance of the model, sensitivity and used framework**

680 The adequacy of the model with regards to reality was considered by using the  
681 acceptable limit of deviation percentage between observed and predicted data sets (Bald et al.,  
682 2006, 2009). The obtained average of the absolute values of the deviation percentage  
683 (considering years 2003, 2006, 2008, 2010, 2012, 2014 and 2018) is equal to 5.3%. This level  
684 reflects a slightly better performance than that described by Bald et al (2009) and over a larger  
685 number of years. In the future, it would be worth considering the model performance with  
686 new indices of performance, such as those implemented by Anastácio et al. (2009) for  
687 *Scrobicularia plana*. The implementation of the Loague and Green's modeling efficiency

688 (EF) would also provide an overall indication of the goodness of fit (Mayer and Butler, 1993).  
689 EF is a dimensionless statistic based on the coefficient of determination and directly compares  
690 predictions with real-world observations.

691 This paper proposed a first sensibility analysis of biological and environmental control  
692 parameters. The temperature conditions related to spawning periods and recruitment appear to  
693 give the highest sensitivity for determining the total biomass. This highlights the importance  
694 of selecting the right parameters that control the number of recruits on the modelled  
695 dynamics. A first modulation according to Chlorophyll a and TSM concentrations was  
696 undertaken for this work. It is clearly an area for future work to improve the model.

697 The sensitivity analysis was mainly local and to a lesser extent global. It remains an  
698 elementary sensitivity analysis realized with the available module in Vensim (Faivre et al.,  
699 2013). Another avenue for improvement in this work would be to fully implement the method  
700 proposed by Pianosi et al. (2016) by implementing the packages for GSUA<sup>3</sup>. Another possible  
701 avenue would be to extend the sensitivity analysis to resource exploitation parameters. The  
702 improvement of the model was conducted step by step and the formulations both reinforced  
703 environmental and socio-economic considerations within the model. Cumulative effects of  
704 those drivers could therefore be considered (Scenarios 9 to 10). Although limitations on the  
705 modeling of biological processes were identified by the sensitivity analysis. Bearing these  
706 limitations in mind, we are convinced that this model remains reliable to investigate different  
707 management strategies under current environmental conditions but is not well suited to  
708 consider strong environmental shifts such as those considered in the worst climate change  
709 case scenarios.

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<sup>3</sup> <https://www.safetoolbox.info/info-and-documentation/>

710           **For the accompaniment of a co-management approach for this local exploited**  
711 **stock**

712           From the start, the model specifically intended to strengthen the management of the  
713 stock by enabling a robust and well-informed decision-making process based on science. This  
714 tool was used for the first time in 2008-2009. The simulations were presented and discussed  
715 in the framework of working groups (associating scientists, fishermen and administration  
716 representatives) (Caill-Milly et al., 2021). When the results of the last stock assessment  
717 campaign will be presented to professionals, the model can again be used to support  
718 management decision-making. The different management scenarios tested with this last  
719 version of the model should help in this context in the coming months. The results argue for  
720 the choice of a management strategy involving several management measures as opposed to  
721 one strong measure modification. Such combinations are part of the arsenal of measures that  
722 are implemented on Manila clam resource in other European coastal systems (Coelho et al.,  
723 2021). Different combinations are possible and additional ones may stem from discussion.  
724 The acceptability dimension will have to be considered in this context.

725           Most of the existing management models dealing with clams necessitate the  
726 assessment of a large number of parameters (Cossarini et al., 2009; Pastres et al., 2001;  
727 Solidoro et al., 2000). Conversely, our present model necessitates fewer parameters and relies  
728 on a “system dynamic” approach implemented to understand and conceptualize the complex  
729 system regarding both the surrounding environment and human activity (Costanza and Ruth,  
730 1998).

731           Similar approaches based on models were conducted *inter alia* on the gooseneck  
732 barnacle (Bald et al., 2006) and the Peruvian scallop (Ortiz et al., 2002). In our situation, its  
733 implementation complemented the existing collaborations between scientists and fishermen,  
734 who have both conducted field surveys since 2003. This type of functioning is in line with the



735 directions of Oregon's Development Fisheries Program (see Harte et al., 2008) because it  
736 aims at incorporating design of science and management plans for small-scale fisheries.  
737 Integration of different kinds of operational management measures and institutional structures  
738 for governance was highlighted by Defeo (2011) as a key issue in successful management of  
739 sandy beach fisheries. This approach is considered by the coastal Galician fisheries (Freire  
740 and García-Allut, 2000; Freire et al., 2002) and has been applied in Southeast Asia coastal  
741 fisheries since the 1960s (Pomeroy, 1995). Management of numerous other local French  
742 resources such as bivalves (Manila clam, scallop, mussel ...), crustaceans (spiny lobster) or  
743 algae, mainly in Brittany and in Normandy (Picault et al., 2014; D'Hardivillé and Bouché,  
744 2018; ICES, 2018) rely on close collaborations between scientists and commercial industries;  
745 however, none of them has used such a dynamic model before. In our case this approach has  
746 proven its effectiveness in selecting management measures for the sustainability of the  
747 neonatural resource, however the environment and design of the software should be enhanced  
748 in order to be used more systematically. Indeed, it is very difficult to change tack midway  
749 through a period and currently lacks an interface, which can also easily be used by managers  
750 (Caill-Milly et al., 2021). Moreover, the license restricts the use of the software in an easily  
751 accessible web-type form (Elsawah et al., 2017). Recent publications (Garcia, 2021a and  
752 Garcia, 2021b) should make it possible to solve some of the aforementioned points in the near  
753 future.

754         Such developments are in accordance with the four main uses of a model as reported  
755 by del Granado (2007): increasing the human understanding of the considered system;  
756 communicating visually, making predictions and supporting decision-making. This last use  
757 was also described by other authors (Felleman, 1999; Hannon and Ruth, 1994; Shenk and  
758 Franklin, 2001). Opening science to society becomes a significant subject at a national level  
759 since a dedicated charter was revised and signed at the end of 2020 by eight French institutes

760 (public establishments for research, expertise and /or risk assessment in the fields of health  
761 and the environment) (Caill-Milly et al., 2021). Regarding the improvements of the model  
762 identified, this recent context militates for a rapid interface development to be more easily  
763 shared with and used by managers.

764



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772

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