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4 Assessing the effects of temperature and salinity oscillations on a key mesopredator fish from  
5 European coastal systems

6

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19

## 20 **Abstract**

21 A population dynamics model was developed to assess the short and long-term effects of  
22 temperature and salinity variations in the common goby *Pomatoschistus microps* in a  
23 Portuguese estuary (Minho estuary, NW Portugal). The population was divided into juveniles,  
24 females and males, which constituted the model's state variables. Linear regressions between  
25 the observed and the predicted density of juveniles, females and the total population were  
26 significant. Parameter's sensitivity and uncertainty analysis were estimated. The model was able  
27 to satisfactory describe the *P. microps* population dynamics, and thus was used to simulate the  
28 effects of climatic changes on the fish population. Simulations indicated that the common goby

29 population is sensitive to both temperature and salinity changes. Overall, scenarios of + 4°C  
30 increase caused significant population decreases. Similarly, increased salinities led to a  
31 population shrinkage, whereas scenarios of salinity decrease generated an opposite variation on  
32 the population. According to the IPCC predictions for climatic tendencies, the population of the  
33 common goby will tend to decrease in the near future, experiencing marked oscillations  
34 (decrease or increase) during climatic extremes, namely droughts and floods, respectively.  
35 These results may be a useful tool for future planning and management of estuarine systems  
36 given that the common goby is an important species of estuarine food webs in many temperate  
37 ecosystems.

38

39 **Keywords:** Population modelling, *Pomatoschistus microps*, climate change, uncertainty,  
40 estuary, Portugal

41

## 42 **1. Introduction**

43 Estuaries are among the most complexes, productive and valuable ecosystems (Costanza  
44 et al. 1997; McLusky and Elliot, 2004). A considerable number of aquatic species, depend on  
45 these systems during different periods of their life cycle. Some species are residents and remain  
46 inside the estuary during their entire life cycle (Elliott et al., 2007), while, others are migratory  
47 or transitory and use the estuarine area during shorter periods of time on their way to spawning  
48 grounds, where reproduction and/or juveniles' recruitment take place (Claridge et al., 1986;  
49 Potter et al., 1997). Furthermore, several other species use estuaries as nursery grounds (Beck et  
50 al., 2001; Peterson, 2003), since they provide abundant prey resources and low predation risk  
51 for juveniles (Joseph, 1973), and sexually immature individuals can safely increase their feeding  
52 and growth rates (Houde, 1989; Cabral et al., 2007; Martinho et al., 2007).

53 Climate change is currently one of the most significant threats to biodiversity, it can  
54 affects species phenology, metabolic costs, range of suitable areas of occurrence and ecological  
55 interactions among species, and results in modifications on the structure, composition and  
56 dynamics of biological communities (Parmesan, 2006). The IPCC projections suggest that water

57 temperature and salinity regimes will shift in coastal and transitional waters (IPCC, 2014).  
58 These changes are already occurring and influencing all trophic levels, from phytoplankton to  
59 carnivorous fishes (Beaugrand, 2009). However, up to date most studies on the effects of  
60 climate change on fishes have focused on commercially exploited species (e.g. Hare et al.,  
61 2010; MacKenzie et al., 2012). In contrast, studies that focus on small-sized fishes with no  
62 commercial interest are still scant. These species have an essential role in the structure and  
63 dynamics of food webs because they provide a link between species on lower and higher trophic  
64 levels (Doornbos, 1984; Moreira et al., 1992; Cabral, 2000). Their intermediate trophic position  
65 within food webs creates a “wasp-waist” flow control, that can be amplified in systems  
66 harboring these species in very high densities (Coll and Libralato, 2012; Cury et al., 2000). In a  
67 global climate scenario it is expected that temperature and salinity will change in the near future  
68 (IPCC, 2014), and for this reason it is important to understand how changes in these two  
69 parameters will affect small-sized fish populations that occupy intermediate positions within  
70 trophic food webs.

71         The common goby (*Pomatoschistus microps*) is a very abundant and widespread small-  
72 sized fish occurring in temperate estuaries. This species is highly tolerant to environmental  
73 constraints, being able to tolerate wide ranges of temperature and salinity, and thrive in harsh  
74 environmental conditions (Fonds, 1973; Moreira et al., 1992; Rigal et al., 2008). Despite this  
75 several biological and ecological traits of *P. microps*, such as growth, reproduction, migration  
76 and mortality are highly dependent on the conditions of these two parameters (Jones and Miller,  
77 1966; Fonds, 1973; Claridge et al., 1985; Wiederholm, 1987; Moreira et al., 1992; Rigal et al.,  
78 2008). The broad tolerance towards temperature and salinity oscillations makes the common  
79 goby a good model species to assess the responses of biota to environmental changes, given that  
80 *P. microps* is theoretically less sensitive to minor changes on these parameters, and hence the  
81 shifts in its population dynamics can provide clear signs of responses to changes in  
82 environmental conditions.

83 Towards this end, a modelling approach was implemented to test the response of the  
84 small-sized fish species *P. microps* under different climatic scenarios. To preclude the possible  
85 effects of climate change in the common goby population a system where the species is highly  
86 dense and productive was chosen (Souza et al., 2014). This study aims at understanding how a  
87 small-sized fish species that occupy intermediate positions within trophic food webs will be able  
88 to cope with changes on the climatic conditions.

89

## 90 **2. Material and methods**

### 91 *2.1. Study area*

92 This study was conducted in Minho estuary (NW Iberian Peninsula – 41°53'N 8°50'W),  
93 which ranges up to 40 km (considering the upstream limit of spring tides), covering a total area  
94 of 23 km<sup>2</sup>. This estuary is a shallow system (Moreno et al., 2005), with a mean depth of 2.6 m  
95 and maximum width of 2 km (Sousa et al., 2005; Freitas et al., 2009); and is characterized as a  
96 mesotidal and partially mixed system, although it tends towards a salt wedge estuary during  
97 periods of high river flow (Sousa et al., 2005).

98 The estuarine fauna is dominated by the European green crab (*Carcinus maenas*) and the  
99 common goby on the epibenthic compartment (Dias et al., 2010; Dolbeth et al., 2010; Souza et  
100 al., 2014; Mota et al., 2014), while two non-indigenous species (NIS), the Asian clam  
101 (*Corbicula fluminea*) and the red swamp crayfish (*Procambarus clarkii*), are the dominant  
102 macroinvertebrates in the study area (Sousa et al., 2008a; 2013). In fact, Minho estuary have  
103 been invaded by several aquatic NIS in the last decades, which impacted the system in various  
104 ways (Sousa et al., 2008b; 2013; Mota et al., 2014; Novais et al., 2015; 2016, Ilarri et al., 2015a;  
105 2018).

106 Samples were collected at three sampling stations (S1, S2 and S3) located within the first  
107 8 km of the Minho estuary, considering a gradient of distance to the river mouth (Fig. 1). S1 is  
108 located closer to the river mouth (*ca.* 1.5 km), and characterized by soft bottoms, often densely  
109 covered by debris (Souza et al., 2011; 2013; 2014; 2015). S2 is located within a salt marsh area

110 (ca. 3.5 km upwards from the river mouth), with narrow channels, bordered by the small  
111 cordgrass *Spartina maritima*. The channels' soft bottoms are sparsely covered by debris and  
112 empty peppery furrow shells *Scrobicularia plana* (Souza *et al.*, 2011; 2013; 2014; 2015). S3 is  
113 ca. 5 km upstream from S2, and is characterized by high densities of *C. fluminea*, with the soft  
114 bottoms also sparsely covered by debris and underwater vegetation (Souza *et al.*, 2008a; 2008c;  
115 Souza *et al.*, 2013). Over the 12 months of the study the salinity and temperature at the three  
116 sampling stations ranged between 0.12 to 35.41 psu and 8.86 to 16.54 °C in S1, between 0.04 to  
117 33.86 psu and 9.73 to 17.34 °C in S2, and between 0.03 to 27.51 psu and 8.31 to 20.46 °C in S3.

118

### 119 **3. Data set**

#### 120 *3.1. Fish and abiotic data*

121 The model was developed and calibrated with data of *P. microps* sampled monthly, from  
122 February 2009 to January 2010, in the three nearby stations at the lower Minho estuary (Fig. 1).  
123 In each site, three replicates per month were collected using a 1 m beam trawl (5 mm mesh size)  
124 towed at constant speed (2 km.h<sup>-1</sup>) for two to three minutes, during daylight at high tide of  
125 spring tides (for further details see Souza *et al.*, 2014; 2015). This sampling procedure has been  
126 shown to be equivalent to an average area of 100 ± 4 m<sup>2</sup> (Freitas *et al.*, 2009). The density of *P.*  
127 *microps* was determined by counting all sampled individuals, and its density was then  
128 standardized to the same scale (ind. 100 m<sup>-2</sup>). Density values input into the model refers to the  
129 average of the three sampling station per month, and the standard deviation was used as the  
130 confidence interval for model fit validation. Fifty randomly selected individuals from each  
131 sample were observed under a magnifying glass for sex distinction based upon dimorphic  
132 features on their morphology and gonads (Whitehead *et al.*, 1986). Individuals smaller than 26  
133 mm of TL showed no clear morphological signs of their sex, and are considered sexually  
134 immature and classified as juveniles (see Bouchereau *et al.*, 1989). Females with advanced stage  
135 of development were considered mature and this information was posteriorly used to estimate  
136 the relative amount of mature females in the population. The total density of juveniles, males

137 and females was estimated based on the percentage of contribution of each group within the  
138 fifty randomly selected fishes from each sample.

139 The water temperature and salinity at the bottom were measured each month in the three  
140 sampling stations using a multiparameter probe YSI 6820.

141 The daylight duration data were obtained from NOAA website ([http://www.esrl.noaa.gov/  
142 gmd/grad/solcalc/sunrise.html](http://www.esrl.noaa.gov/gmd/grad/solcalc/sunrise.html)). Monthly daylight duration (minutes) was used as a proxy for  
143 the variation in day length at the study site.

144

#### 145 **4. Conceptualization and formulation of the model based on *P. microps* biological and 146 ecological traits**

147 Stage structured models have been proven to be advantageous because they account for  
148 different kinetics and parameters that regulate the dynamics and physiology of different life  
149 stages of a given species (e.g. juveniles, males and females) (Batchelder and Miller, 1989;  
150 Labat, 1991).

151 In the present model, the estuarine *P. microps* population was divided into three groups:  
152 juveniles, females and males, which are the state variables of the model. The flows between  
153 state variables are individuals per unit of time, while the units of the state variables are  
154 individuals.100m<sup>-2</sup>. The processes that regulate the number of individuals in each group over  
155 time are: growth, (the number of individuals transferred from one group to the next), death (the  
156 number of individuals subtracted to each group by mortality), migration (the number of  
157 individuals subtracted to females and males by the overwintering migration (Jones and Miller,  
158 1966)), and recruitment(the input of juveniles to the population).

159 The model forcing functions are daylight duration, salinity and water temperature, which  
160 affect recruitment, growth, mortality and migration. The model was written in STELLA  
161 (Structural Thinking, Experimental Learning Laboratory with Animation) 5.0 software, an  
162 object-oriented graphical programming language designed specifically for modeling dynamic  
163 systems (Jørgensen and Bendoricchio, 2001), which translates the graphical representation of  
164 the model into ordinary differential equations (ODE). The model used a time step (i.e. temporal

165 resolution) of one month to 12 months, chosen to allow a direct comparison with the data  
166 obtained on the field (Souza et al., 2014). A simplified conceptual diagram of the model is  
167 shown in Fig. 2. The parameters and equations that regulate the number of individuals in each  
168 population group are presented in Tables 1 and 2, respectively, and together with Fig. 2 outline  
169 the graphical and the mathematical description of the model. The justification of the values used  
170 in the model are explained in the following sub-sections.

171 Calibration refers to the systematic adjustment of model parameter estimates so that the  
172 model outputs reflect more accurately the observed dynamic behavior of the system. This  
173 procedure is applied when the available information for the parameters is likely to deviate from  
174 the normal behavior of the dynamic model. Calibration is a modeling tool often applied when  
175 the data for the parameter is adapted from a different system, the population displays  
176 heterogeneity and/or is subject to change through time (Beaudouin et al., 2008).

177

#### 178 *4.1. Sensitivity and uncertainty analysis*

179

180 The sensitivity analysis of the model was estimated for variations of  $\pm 10\%$  on each  
181 parameter at a time (i.e. all the other parameters were kept unchanged according to the one-step-  
182 at-a-time (OAT) approach). This method explores the parameter space and provides a robust  
183 sensitivity measure in the presence of nonlinearity and interactions among the parameters  
184 (Wainwright et al., 2014), being widely used in ordinary differential equations models (ODE)  
185 due to its simplicity and efficiency.

186 To estimate the sensitivity of parameters, the following expression (Jørgensen, 1994) was  
187 used:

188

$$189 \quad (1) \quad Y'_{xi} = \frac{\partial Y}{\partial X_i}$$

190

191 Where  $Y'$  is the sensitivity of the model outputs to variations on parameters ( $X_i$ ).

192

193         The output of any model can be affect by different sources of uncertainty, including input  
194 data, choice of parameters, or calibration method, and thus it is important to have an explicit  
195 measure quantification of how much the uncertainty affects models outputs (Confalonieri et al.,  
196 2016; Roux et al., 2014). To understand how much the model outputs could have been affected  
197 by the uncertainty in the measurements of the state variables we performed an uncertainty  
198 analysis (UA), on the four model parameters scoring highest in the sensitivity analysis (Table 3).  
199 These parameters are those most likely to affect the results of the model, and thus we assessed  
200 accuracy of the model by estimating the relative root square mean error (RRMSE) (Confalonieri  
201 et al., 2016). The lower the value of RRMSE, the lower the influence of uncertainty on the  
202 outputs of the model and higher is its accuracy. The UA allows to quantify the propagation of  
203 uncertainty in the model output that could be caused by natural variation and potential errors  
204 associated with the measurement of the state variables (i.e. the density of individuals in each  
205 group of the *P. microps* population) used in the model calibration. To this end, we used a Latin  
206 hypercube sampling (LHS) strategy (McKay et al., 1979) to generate a series of virtual  
207 observations for each state variable, and assuming a Poisson distribution. The LHS expands the  
208 concept of a Latin square for any number of dimensions. The distribution of each variable is  
209 divided in equally probable “n” number of intervals (strata) . For each variable a sample is  
210 randomly drawn at each interval (McKay et al., 1979), and the values of each variable are then  
211 randomly paired to each other. This is a type of stratified random sampling procedure that can  
212 be understood as a compromise between a random and stratified sampling techniques that  
213 provides a stable analysis outcomes (Helton and Davis, 2003), and is not computationally  
214 demanding. The efficient stratification obtained with the LHS allows the use of a relatively low  
215 small sample ( $10n$ , with  $n$  being the number of observations in the empirical dataset) of the  
216 distribution space of the variables (Helton and Davis, 2003). Thus, we generated a virtual series  
217 of 90 observations for each state variable, which represents the data that could have been  
218 collected due to the uncertainty in the sampling procedure (Confalonieri et al., 2016). With each  
219 data series we recalibrated the most sensitive parameters in the model while accounting for the



220 uncertainty in the measured state variables. The outputs obtained with the virtual data series  
221 were then used to estimate the objective function of the RRMSE between the observed data and  
222 the model output for each of the virtual series. The RRMSE function was minimized using a  
223 multi-start point downhill simplex optimization algorithm (Nelder and Mead, 1965). The  
224 distribution of the RRMSE values of the model outputs obtained by calibration with the virtual  
225 data series was compared against that of the model outputs obtained by calibration with the  
226 empirical data (Confalonieri et al., 2016).

227 The virtual data series was generated with function *randomLHS* from the package *lhs* (Carnell,  
228 2018), the RRMSE calculated with function *rrmse* from the package *Fgmutils* (Fraga-Filho et  
229 al., 2016), and the RRMSE minimization with function *optim* from the package *stats*, for R  
230 software.

231

## 232 4.2. Studied species

233 The common goby *Pomatoschistus microps* is a widely distributed estuarine species  
234 spanning *ca.* 44° in latitudinal range, occurring from Norway to Mauritania, including the  
235 Canary Islands, western Mediterranean and Baltic Sea (Froese and Pauly, 2016). This species is  
236 often reported as one of the most abundant fish in northern Atlantic estuaries (Martinho et al.,  
237 2007; Dolbeth et al., 2010). This species is frequently found in areas where the sympatric goby  
238 *P. minutus* co-occurs and both species tend to present similar densities (Arruda et al., 1993;  
239 Leitão et al., 2006; Martinho et al., 2007; Dolbeth et al., 2010). However, in Minho estuary the  
240 common goby seems to be much more abundant than the sand goby, presenting a remarkably  
241 dense and productive population, which is attributed to site-specific favorable conditions (Souza  
242 et al., 2014, 2015).

243

### 244 4.2.1. Reproduction and recruitment

245 The reproductive behavior of *P. microps* is relatively well known, with spawning usually  
246 when water temperature ranges between 15 and 20°C (Wiederholm, 1987). During the  
247 reproduction season, mature females lay eggs on nests built by males using empty bivalve shells

248 (Nyman, 1953; Jones and Reynolds, 1999; Pampoulie, 2001). Males fertilize the eggs, fan and  
249 guard them until hatching (Svensson et al., 1998; Jones and Reynolds, 1999; Pampoulie, 2001).  
250 During nest guarding behavior, males often prey on their own brood (Magnhagen, 1992)  
251 removing *ca.* 30% of the egg mass of a clutch (Forsgren et al., 1996).  
252 Common gobies are known to have a high individual fecundity (Bouchereau and Guelorget,  
253 1998), with each mature female being able to generate from 460 to 3400 eggs (Miller, 1986;  
254 Bouchereau et al., 1989; Bouchereau and Guelorget, 1998), but the mortality rate during the  
255 early stages of fish development is also very high (Leis, 2007). In fact, the survival rate of  
256 marine and diadromous fish larvae varies between  $6.7 \times 10^{-5}$  and 0.1% (Dahlberg, 1979). No  
257 information was found in the literature regarding the mortality rate of *P. microps* larvae, and due  
258 to this, the value of larvae mortality used in the model was obtained through calibration and  
259 based on values of other marine and estuarine fishes.

260 The percentage of mature females on the population during spawning season was  
261 estimated as the ratio between the number of females in advanced stages of gonadal  
262 development and the total number of females.

263 The lag between spawning and recruitment was established in one-time-step, given that  
264 the species has a very short larval phase (2 to 10 days), and the recruitment likely occurs shortly  
265 after (Riley, 2003).

266

#### 267 4.2.2. Mortality

268 One of the most important shortcomings in the knowledge of estuarine fishes is the lack  
269 of estimates on the source of mortality for any life history stage (Houde, 2008). Even where  
270 mortality estimates have been made for estuarine species, the influence of confounding factors  
271 (i.e. gear avoidance, inaccessible habitats, etc.) makes it difficult to determine mortality rates  
272 (Able and Fahay, 2010). As far as we know, there is no published paper addressing the mortality  
273 rate of the common goby in nature, therefore mortality rates used in the model were obtained  
274 through calibration. Given that juveniles, females and males of this species can behave

275 differently, we assume that their mortality rate is also different (Magnhagen, 1992; Svensson et  
276 al., 1998).

277 Notwithstanding, mortality rate may vary throughout the year in temperate estuarine  
278 fishes (Able and Fahay, 2010). In fact, during winter, small and relatively immobile fish  
279 experience an increase in their mortality rates, due to net energy deficits caused by low  
280 temperatures and food scarcity (Sogard, 1997; Hurst et al., 2000; Hales and Able, 2001; Hurst,  
281 2007). This may lead to an increase in the mortality of estuarine fish of about 33% during winter  
282 (Able and Fahay, 2010). The seasonal variation of *P. microps* mortality was taken into account  
283 in the model by assuming an increment of 30% in the mortality rate of all population groups  
284 when water temperature was decreases below 10°C.

285 The number of *P. microps* individuals subtracted to each population group was defined  
286 by:

287

$$288 \quad (2) \quad Mortality_i = MortRate_i \times D_i$$

289

290 Where  $Mortality_i$  = mortality of the population group  $i$ ;  $MortRate_i$  = mortality rate of the  
291 population group  $i$ ;  $D_i$  = density of the population group  $i$ .

292 The parameters values and the equations of each population groups are presented in Tables 1  
293 and 2, respectively.

294

#### 295 4.2.3. Migration

296 The typical life cycle of the common goby lasts for one year, with adults migrating to  
297 warmer waters during winter (Jones and Miller, 1966; Muus, 1967). Given that the common  
298 goby presents a dynamic and plastic behavior in several life traits (Reynolds and Jones, 1999;  
299 Pampoulie et al., 2000; Heubel et al., 2008), it is expected that the temperature level which  
300 triggers seasonal migration in estuarine populations should also be different across the  
301 geographical range of the species (Jones and Miller, 1966). For instance, Jones and Miller  
302 (1966) reported that migration is triggered when temperature is lower than 7°C, while Claridge

303 et al. (1985) mentioned that at 5°C migration is triggered. For other estuarine overwintering  
304 migrating species in nearby systems, it is argued that 10°C is responsible for triggering seasonal  
305 migration (Gomes, 1991). Given the scarcity of information regarding the temperature level that  
306 triggers overwintering migration of common gobies in Southern European estuaries, we have  
307 considered reasonable to assume that temperatures lower than 10°C induce *P. microps* migration  
308 in Minho estuary.

309 Moreover, migration can also be triggered by other environmental cues, such as  
310 precipitation, drought, water discharge and photoperiod (Bauer et al., 2011). In a recent study,  
311 McNamara et al. (2011) suggested that photoperiod is probably the most prominent and  
312 universal variable, indicating that the time of the year can also be relevant to several organisms.  
313 Photoperiod is a reliable indicator of the time of the year, and thus, can be a useful predictor of  
314 the phenology of resources (Bauer et al., 2011). In this context, the photoperiod was also taken  
315 into account in the migration equation. The number of migrating *P. microps* individuals in each  
316 population group was defined by:

317

$$318 \quad (3) \quad Migra_i = MigraRate_i \times D_i$$

319

320 Where  $Migra_i$  = migration of the population group  $i$ ;  $MigraRate_i$  = migration rate of the  
321 population group  $i$ ;  $D_i$  = density of the population group  $i$ .

322

#### 323 4.2.4. Effect of temperature and salinity on growth

324 Since *P. microps* is not able to control its body temperature to a significant degree, the  
325 typical response is that its metabolic rate varies directly with ambient temperature (von Oertzen,  
326 1983). The common goby presents a relatively wide tolerance range for temperature variation,  
327 and is able to cope with temperatures ranging from -1°C to 24°C (Fonds, 1973; Moreira et al.,  
328 1992). Freitas et al. (2010) assumed that the optimal temperature for *P. microps* growth is 20°C,  
329 but since this value could not be experimentally validated, the value used in the model was

330 obtained by calibration, using the optimal temperature reported by Freitas et al. (2010) as a  
331 proxy.

332 Salinity is one of the most important environmental factors affecting the growth and  
333 survival of aquatic organisms, influencing both physiological and ecological processes (Poizat  
334 et al., 2004; Nordlie, 2006), and many studies have demonstrated the influence of external  
335 salinity on growth capacities of fishes (Bœuf and Payan, 2001). The metabolic rate of *P.*  
336 *microps* varies directly with salinity (Rigal et al., 2008), and the species has a relatively wide  
337 tolerance range for salinity variation, withstanding salinities ranging from 0 to 51 psu (Rigal et  
338 al., 2008), though better physiological performances occur at low salinities (Pampoulie et al.,  
339 2000; Rigal et al., 2008). To cope with this, the model uses an optimum curve to describe the  
340 effect of salinity on *P. microps* growth. The optimum salinity value for the species (SOpt) was  
341 obtained in the literature and then by calibrated (see Table 1)

342 The effect of temperature and salinity on *P. microps* growth was described as an optimum-type  
343 curve (Martins et al., 2008), where:

344

$$345 \quad (4) \quad f(i) = e^{-2.3 \left( \frac{(i - i_{opt})}{(i_{min} - i_{opt})} \right)^2} \text{ for } i \leq i_{opt}$$

346

347 and

348

$$349 \quad (5) \quad f(i) = e^{-2.3 \left( \frac{(i - i_{opt})}{(i_{max} - i_{opt})} \right)^2} \text{ for } i > i_{opt}$$

350

351 Where  $i$  = temperature/salinity;  $i_{opt}$  = optimum temperature/salinity for growth;  $i_{min}$  = minimum  
352 temperature/salinity at which growth ceases;  $i_{max}$  = maximum temperature/salinity at which  
353 growth ceases.

354

355 Long run simulations (240 months) were performed to test the stability of the model.

#### 356 *4.6. IPCC predictions*

357 The IPCC (Intergovernmental Panel on Climate Change) Fifth Assessment Report (AR5)  
358 predicted that, surface air warming in the 21<sup>st</sup> century will range from 1.1 to 6.4°C (IPCC,  
359 2014). Also, the annual temperature over Europe will warm at a rate of 0.1 and 0.4 C° per  
360 decade, and warming will be greater in southern Europe and northeast Europe (IPCC, 2014).

361 The IPCC projections show that the annual precipitation will decrease across southern  
362 Europe (maximum 1% per decade), resulting in drier summers and wetter winters (IPCC, 2014).  
363 This is likely to cause changes on the salinity levels of estuarine systems, since droughts and  
364 floods events will be more frequently triggered in these systems, as recently reported (Cardoso  
365 et al., 2008; Dolbeth et al., 2010; Santos et al., 2010; Ilarri et al., 2011).

366 In this context, several scenarios of temperature and salinity variations in Minho estuary  
367 were simulated. Four levels of water temperature increasing (+1, +2, +3 and +4°C) and four  
368 different levels of salinity change (-5 psu, +5 psu, +10 psu, and oscillatory (-5 psu from  
369 November to April and +5 psu from May to October)) were simulated. Additionally, the  
370 combined effects of temperature and salinity variations were also simulated.

371 Finally, we performed projection simulations (for 20 years) to assess the extended effects  
372 of expected temperature and salinity variations in Southwestern Europe under climatic change  
373 scenarios on the common goby population in Minho estuary. Two different rates of temperature  
374 increase were simulated: slow (+0.01°C per year) and rapid (+0.04°C per year) combined with  
375 different scenarios of salinity (normal, -5 psu, +5 psu, and oscillatory). The initial conditions of  
376 the simulations followed the conditions measured in the field accompanied by the modification  
377 related to the scenarios of temperature and salinity tested in each simulation.

378

379

## 380 **5. Results**

### 381 *5.1. Model results*

382 The density of *P. microps* juveniles predicted by the model followed the same pattern as  
383 the observed variation, with a marked peak of abundance in December (Fig. 3). The density  
384 predicted for females, males and total population also followed similar patterns than those of the  
385 observed data, with density continuously increasing after spring and reaching a peak in  
386 December or January (Fig. 3).

387

### 388 5.2. Model stability, sensitivity and uncertainty analysis

389 The model showed long-term stability, which supports the internal logic of the model  
390 (Jørgensen, 1994). The sensitivity analysis identified the parameters related to reproduction (egg  
391 loss, fecundity, larval dispersal and mortality, mature females) to be the most sensitive (Table 3).  
392 The uncertainty analysis carried out through the recalibration of the most sensitive parameters  
393 with the data series generated by the LHS delivered a very narrow frequency distribution of the  
394 RRMSE values, ranging from 17.10% and 18.20%. Most of these were lower than that obtained  
395 with the empirical data (17.82%, Fig. 4). However, the RRMSE value of the empirical model  
396 was still low thus well within the range obtained with the virtual data series (Fig. 4), indicating  
397 that uncertainty had low influence on the empirical model outputs.

398

### 399 5.3. Climatic change simulations

400 Once the correlation between the model outputs and real data was shown to be  
401 satisfactory (Table 4), the model was considered suitable to simulate the effects of the  
402 forthcoming climatic changes on the common goby population during a year cycle (12 months).

403

### 404 5.4. Temperature variations

405 Simulations suggest that *P. microps* population will be greatly affected by water  
406 temperature warming. For low increases of temperature scenarios, the overall density of *P.*  
407 *microps* would increase by 3%, 33% and 58% for (+1°C, +2°C and +3°C, respectively) in the  
408 one year simulation, while in the +4°C scenario the common goby population would decline on  
409 a year basis by 21% (Fig. 5). Also, the timing of the density peaks changed for the increasing

410 water temperature scenarios, with the juveniles recruiting earlier in the year in all scenarios  
411 except in +1°C. In +4°C scenario, the density peak of juveniles will change from December to  
412 June, while females and males peaking in July instead of January (Fig. 5).

413

#### 414 5.5. Salinity variations

415 Simulations accounting for salinity variations suggest that *P. microps* population would  
416 be benefited by a decrease in salinity (19% increase of the total density in one year), while an  
417 increase (+5 and +10 psu) or an oscillatory pattern in salinity would lead to a decrease in *P.*  
418 *microps* population (25, 44% and 24%, respectively) (Fig. 6).

419

#### 420 5.6. Combined effects of temperature and salinity variations

421 Overall, the combined effects of temperature and salinity increase would lead to a  
422 decrease in *P. microps* population in all scenarios, except the +3°C combined with a decrease of  
423 5 psu in salinity (19% increase). When oscillatory pattern in salinity is combined with  
424 temperature increase fish population would decline only in +1°C and +4°C (21% and 33%,  
425 respectively), while an increase of 8% and 19% would be observed for +2°C and +3°C  
426 scenarios, respectively. On the other hand, a temperature increase combined with a salinity  
427 decrease would cause a noticeable increase in population levels of *P. microps* for all scenarios  
428 (ranging from 23% to 61%), but it is in +4°C that the population would decline by nearly 30%  
429 in a year cycle. (Fig. 7).

430

#### 431 5.7. Projection simulations

432 According to results, temperature increase for longer periods of time would have  
433 significant consequences for *P. microps* population in Minho estuary, with a continuous  
434 decrease in population density throughout time in all scenarios (Fig. 8). Similarly an oscillatory  
435 pattern of salinity or a salinity increase would lead to a marked decrease in *P. microps*  
436 population, while a salinity decrease would have the opposite effect (Fig. 9).



437 The combined effects of temperature increase and salinity variation will cause an even  
438 faster decrease of *P. microps* density levels in all scenarios accounting for an oscillatory salinity  
439 pattern or salinity increases. On contrary, with salinity decreases, the common goby population  
440 will initially decrease, recovering after 20 years on the slow IPCC scenario. Conversely, on the  
441 rapid IPCC scenario, the population would immediately increase, reaching density values 5  
442 times higher than when compared to the present situation (Fig. 10).

443

## 444 **6. Discussion**

445 The model was capable to satisfactory simulate the variation of *P. microps* density and  
446 dynamics at the Minho estuary. Projection simulations indicated that *P. microps* population will  
447 be highly sensitive to changes in both temperature and salinity. According to predictions, rises  
448 in water temperature will cause long-term detrimental effects on *P. microps* population, with  
449 harsher scenarios affecting *P. microps* more severely.

450 Furthermore, predictions also suggest that the spawning season might change due to  
451 increasing water temperature. In milder scenarios, changes in spawning season might be  
452 associated to an extension of the recruitment season, with common gobies spawning earlier in  
453 the year. However, in harsher scenarios, the spawning season will be greatly altered, with  
454 juveniles starting to recruit in winter but with a marked shortage in the duration of the  
455 recruitment season. According to experimental evidence, the duration of spawning seasons has a  
456 major effect on *P. microps* populations (Bouchereau and Guelorget, 1998), and it may be one of  
457 the reasons behind the high density of the species in Minho estuary, once in this system, the  
458 reproduction season appears to be longer than in other estuaries (Souza et al., 2014).

459 Freitas et al. (2010) assumed that the optimal temperature for *P. microps* growth is 20°C.  
460 Nevertheless, previous empirical observations (Dolbeth et al., 2010) and the results from the  
461 present model indicated that the species is more abundant and productive at lower temperatures.  
462 However, unless specific experimental studies are conducted to determine the optimal  
463 temperature for the growth of *P. microps*, all other values are assumed and may need to be  
464 reviewed in future studies. .

465 The common goby population also responds negatively to salinity increases, indicating  
466 that droughts may cause a shrinkage in *P. microps* populations, which are in line with the results  
467 reported by Dolbeth et al. (2010), who observed a decrease in *P. microps* secondary production  
468 after drought events in the same studied site. On the other hand, model outputs suggested that *P.*  
469 *microps* population would be largely benefited by flood events, due to the decrease in salinity  
470 within the estuary. This agrees with Pampoulie et al. (2000), who described an increased  
471 reproductive investment by *P. microps* after a high freshwater inflow in a coastal lagoon in  
472 France. Also, the common goby seemed to be further benefited by the reduction of competitors  
473 such as, the sand goby *P. minutus*, within the lagoon (Pampoulie et al., 2000). Similarly, in a  
474 long-term study of *P. microps* population dynamics Nyitrai et al. (2013) showed that the species  
475 peaks in years with higher precipitation, which further suggests that the species is benefited in  
476 scenarios of salinity decrease. Notwithstanding, the model showed that the effect of a reduced  
477 salinity in winter is voided when accompanied by an increased salinity during summer,  
478 suggesting that *P. microps* populations would decrease in the next years, if the IPCC predictions  
479 of wetter winters and drier summers are accurate.

480 However, it is important to consider that the subsequent effects of climatic extremes may  
481 have opposite trends and negative feedback processes (IPCC, 2014). For instance, a massive  
482 die-off of bivalves after droughts (Ilarri et al., 2011) and floods (Sousa et al., 2012), may lead to  
483 a significant increase on the quantity of empty shells in the river bottom that might be used for  
484 *P. microps* reproduction in the next breeding season, which may led to an increase in the  
485 population density after one or more generations due to the persistence of these shells in the  
486 system for years (Ilarri et al., 2015b). Actually, the reproduction of common gobies seems to be  
487 limited by the presence of nest substrates (Nyman, 1953; Magnhagen, 1998) and their  
488 abundance and availability can directly influence the number of breeding males (Breitburg,  
489 1987; Lindström, 1988).

490 The model was able to predict more accurately the dynamics of juveniles and females,  
491 whilst the predicted male dynamics differed more from real data, which may be related to the  
492 nest guarding behavior of males, that makes them difficult to be caught within estuaries (Miller,

493 1984) and, is considered as one of the reasons behind the apparent dominance of females in  
494 estuarine populations of *Pomatoschistus* spp. (Bouchereau et al., 1993; Fouda et al., 1993;  
495 Koutrakis and Tskliras, 2009). In fact, most of the dissimilarities between the observed and the  
496 predicted variation of male density occurred during the breeding season, which supports the  
497 idea that male guarding behavior may have influenced the results and lead to such  
498 dissimilarities, that are partially because this behavior is not accounted by the present model.

499 The model was most sensitive to variations in the reproduction parameters. This was  
500 somehow expected given that the common gobies present high plasticity on their reproductive  
501 traits (Reynolds and Jones, 1999; Pampoulie et al., 2000; Heubel et al., 2008), and suggests that  
502 the species can rapidly respond to environmental constrains and rapidly adapt to new  
503 environmental conditions. The uncertainty analysis showed that the model output is somewhat  
504 sensitive to uncertainty in the measurements of the data used to perform the model calibration  
505 (RRMSE = 17.82%). However the range of RRMSE obtained by recalibrating the model with  
506 the virtual data series was very narrow, with the RRMSE of the empirical model was well  
507 within that range, and thus can be considered to be accurate (Confalonieri et al., 2016).

508 Despite of the IPCC predictions referring to temperature increase in the air, it should be  
509 expected that the water temperature will also increase due to global changes in climate (Bates et  
510 al., 2008). Nevertheless, it is unlikely that water temperature will increase at the same rate of the  
511 atmospheric temperature, given the differences in the thermal properties between the two fluids;  
512 and hence, temperature increase in water probably would be smaller than in air. There are  
513 uncertainties in projected changes in hydrological systems since it often depends on a number of  
514 variables such as precipitation, evapotranspiration, soil moisture and runoff (Bates et al., 2008).  
515 In this context, we opted to use the IPCC projections for air temperature increase despite of  
516 knowing that the temperature increase in water would be smaller. Nonetheless, it is unlikely that  
517 the water temperature would increase as much as the most extreme IPCC scenarios, therefore,  
518 the projections on the *P. microps* population dynamics at +3°C and +4°C should be seen with  
519 caution and understood as predictions for extreme climatic scenarios.

520 The model predicted that for every tested scenario of temperature increase, the *P. microps*  
521 population would experience a gradual decrease in projection simulations. Also, the most likely  
522 scenario of salinity change (oscillatory pattern) in extreme climatic events would lead to a sharp  
523 decrease in *P. microps* density. In this context, it is probable that during the next decades at  
524 Minho estuary, common gobies may experience population shrinkage. Given the trophic  
525 position and abundance of the species, this could cascade through the estuarine biological  
526 community, especially in a system where the species is remarkably abundant such as in Minho  
527 estuary (Souza et al., 2014). As a mesopredator, the common goby connects low and high levels  
528 of the food-web of fishes (Doornbos, 1984; Moreira et al., 1992; Cabral, 2000); therefore,  
529 changes in *P. microps* population would affect both higher and lower trophic levels, with its  
530 trophic role being even more relevant in systems where it achieves higher densities (Pockberger  
531 et al., 2014). Nevertheless, the real ecological impact of the *P. microps* population reduction is  
532 hard to predict, since the sympatric species *P. minutus* may play a similar ecological role  
533 (Salgado et al., 2004) to provide functional redundancy (Ives, 1995) and creating an “insurance  
534 effect” in the system (Yachi and Loreau, 1999; Loreau et al., 2003). Actually, both species are  
535 morphologically and ecologically similar, differing mostly on salinity preferences, with *P.*  
536 *minutus* preferring to inhabit saltier waters compared to *P. microps* (Leitão et al., 2006; Dolbeth  
537 et al., 2007). Also, both species can often compete for food and space (Złoch and Sapota, 2010)  
538 and hence, it is reasonable to assume that *P. minutus* may perhaps be benefited by a decrease in  
539 *P. microps* population, and potentially fulfill the ecological gaps left by the common goby.  
540 Notwithstanding, given the uncertainty about the ecological effects that a decrease in *P. microps*  
541 density might trigger, it would be interesting to perform further studies on the interactions  
542 between *P. microps* and *P. minutus* particularly at different conditions of temperature, salinity  
543 and density.

544 Given that the *P. microps* geographical range of occurrence is wide, and our study was  
545 conducted in a system located nearer to the southern edge of the species distribution (Froese and  
546 Pauly, 2016), the populations inhabiting systems at higher latitudes and thus subjected to colder  
547 temperatures could experience milder effects of climate change, while populations located

548 further south may suffer more serious consequences. Still, given the plasticity of *P. microps*,  
549 each population may respond differently to environmental changes, and hence, each system  
550 should be treated as a unique case of study, despite the trend presented in this study, which  
551 predicts a decrease in *P. microps* density caused by warming waters.

552         The use of ecological models has been increasing in the last decades, with significant  
553 developments in the software tools available and also in their accuracy. Nonetheless, modeling  
554 approach still have limitations, which also include the IPCC projections themselves (Hollowed  
555 et al., 2013; Cheung et al., 2016). Population dynamics models are widely used but they require  
556 a good data set containing homogeneously distributed data. Additionally, the calibration of  
557 parameters in population dynamics models are especially difficult (Chatzinikolaou, 2012). The  
558 model we developed was tested against a dataset of 12 data entries, which is not a long time-  
559 series for this type of model, but is reasonable enough considering the life cycle of the species,  
560 logistic constrains related to the sampling and the time-frame of the project. In addition, the  
561 model showed not to be affected by the uncertainty of the state variables and therefore was  
562 accurate in its outputs (i.e. low values of RRMSE = relatively high accuracy = model with  
563 relatively low susceptibility to uncertainty). Furthermore, it is also important to state that several  
564 parameters inputted into the model were obtained from different species and/or localities due to  
565 the lack of information in the literature about the common goby and the Minho estuary. These  
566 probably influenced the outputs of model, and for this reason, the outcome of our model needs  
567 to be seen with caution. Despite of these issues, the robustness of model and its design allowed  
568 us to drawn good and cautious interpretations regarding the direction and the magnitude of the  
569 shifts in the population dynamics of *P. microps*.

570         Our study did not account for limiting factors in the environmental carrying capacity to  
571 sustain a population increase of *P. microps*, therefore the model outputs ought to be seen with  
572 caution in this respect, and the magnitude of the population increase might not be realistic  
573 enough. For that reason it is important to take into consideration mostly the direction of the  
574 changes and the differences in strength among scenarios. Nevertheless, our results point out to  
575 possible fate of *P. microps* population, and stakeholders can use this information to anticipate

576 the consequences for the ecosystem. For instance, a decrease on the common goby population  
577 might have detrimental consequences for the fishery yield, given that the high abundance of *P.*  
578 *microps* certainly provides resources for carnivorous fishes targeted by fishermen, but further  
579 studies are needed in order to better comprehend the inter-specific responses towards the decline  
580 of *P. microps* population and its consequences for fishery.

581

## 582 **7. Conclusion**

583 The model for *P. microps* population dynamics seems to be effective in simulating the  
584 performance of the common goby in the Minho estuary when submitted to changes in  
585 temperature and salinity conditions. The obtained simulations are relevant in the context of the  
586 global climate (IPCC, 2014) since they demonstrated that the populations of *P. microps* in  
587 scenarios of temperature and salinity increase responded with a population decrease. While in  
588 scenarios of a decrease in salinity, the population will experience a substantial increase in terms  
589 of density.

590 The obtained results presents a projection approach on how a core species will cope with  
591 climatic change in the near future. This type of approach represents a useful tool for future  
592 planning and management of estuarine systems, once the results predict how *P. microps*, an  
593 important component of estuarine biological communities, will vary with global effects of  
594 climate change.

595

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907

908 **Figure captions**

909

910 **Fig. 1** Map of the study site showing the three sampling stations (S1, S2 and S3) at the Minho  
911 estuary, NW Iberian Peninsula.

912 **Fig. 2** Simplified conceptual diagram of the population dynamics model of the common goby  
913 *Pomatoschistus microps*. State variables are represented by shaded boxes, while the arrows  
914 represents the fluxes and interactions between parameters and state variables. All state variables  
915 and fluxes indicate the number of individuals in 100.m<sup>-2</sup> per month.

916 **Fig. 3** Observed ± SD (shaded ribbon) and predicted variation of juveniles, females, males and  
917 the total density (ind.100m<sup>-2</sup>) of the common goby *Pomatoschistus microps* in the Minho  
918 estuary, NW Iberian Peninsula.

919

920 **Fig. 4** Frequency distribution (%) of the relative root mean square error (RRMSE, %), obtained  
921 by recalibration of the most sensitive parameters in the model and using the virtual data series  
922 generated with the Latin hypercube sampling technique. Dashed vertical line refers to the  
923 RRMSE by calibration of the model with the empirical data.

924 **Fig. 5** One year simulations of juveniles, females, males and total density (ind.100m<sup>-2</sup>) of the  
925 common goby *Pomatoschistus microps* in different scenarios of temperature increase according  
926 to the IPCC projections (IPCC, 2014) for the future.

927 **Fig. 6** One year simulations of juveniles, females, males and total density of the common goby  
928 *Pomatoschistus microps* in different scenarios of salinity decreasing (-5 psu) and increasing (+5  
929 psu, +10 psu) and oscillatory pattern (-5 psu from November to April, and +5 psu from May to  
930 October).

931

932 **Fig. 7** One year simulations of juveniles, females, males and the total density of the common  
933 goby *Pomatoschistus microps* in different climatic change scenarios of temperature and salinity  
934 changes. Oscillatory = -5 psu from November to April, and +5 psu from May to October.

935 **Fig. 8** Projection simulations temperature increasing on *Pomatoschistus microps* population in  
936 Minho estuary, NW Iberian Peninsula. IPCC Slow scenario =  $+0.01^{\circ}\text{C}\cdot\text{y}^{-1}$  and IPCC Rapid  
937 scenario =  $+0.04^{\circ}\text{C}\cdot\text{y}^{-1}$ .

938 **Fig. 9** Projection simulations of salinity variation on *Pomatoschistus microps* population in  
939 Minho estuary, NW Iberian Peninsula. Oscillatory = -5 psu from November to April, and +5 psu  
940 from May to October..

941 **Fig. 10** Projection simulations of temperature increase combined with salinity variation on  
942 *Pomatoschistus microps* population in Minho estuary, NW Iberian Peninsula. Oscillatory = -5  
943 psu from November to April, and +5 psu from May to October. Slow scenario =  $+0.01^{\circ}\text{C}\cdot\text{y}^{-1}$  and  
944 Rapid scenario =  $+0.04^{\circ}\text{C}\cdot\text{y}^{-1}$ .

945

#### 946 **Table captions**

947

948 **Table 1** Elements of the model and their respective values, symbols, description, units and  
949 estimation method, and initial values used on the model, when applied.

950

951 **Table 2** Equations used in the model of the population dynamics of the common goby  
952 *Pomatoschistus microps* in Minho estuary, NW Iberian Peninsula. See table 1 for abbreviations.

953

954 **Table 3** Sensitivity (*sensu* Jørgensen 1994) of the population density to  $\pm 10\%$  variations of the  
955 parameters used on the population dynamics model of the common goby *Pomatoschistus*  
956 *microps* in Minho estuary, NW Iberian Peninsula.

957

958 **Table 4** Linear regressions between the observed and the predicted values for the common goby  
959 *Pomatoschistus microps* density inside Minho estuary, NW Iberian Peninsula. SS = Sum of  
960 squares, MS = Mean square, F = F-statistic, SD = Standard deviation (slope).

961

962

963 **Tables**

964

965 **Table 1** Elements of the model and their respective values, symbols, description, units and  
 966 estimation method, and initial values used on the model, when applied.

Type	Symbol	Description	Units	Used value
Equation	$F_{sal}$	Equation for the variation on salinity	Non-dimensional	Variable
Equation	$F_{temp}$	Equation for the variation on temperature	°C	Variable
Equation	$Migra_{fem}$	Number of migrating females	Per month	Variable
Equation	$Migra_{mal}$	Number of migrating males	Per month	Variable
Equation	$Mort_{fem}$	Mortality rate of females	Per month	Variable
Equation	$Mort_{juv}$	Mortality rate of juveniles	Per month	Variable
Equation	$Mort_{mal}$	Mortality rate of males	Per month	Variable
Equation	Recruitment	Number of juveniles entering in the system	Individuals.100m <sup>-2</sup>	Variable
Equation	Total abundance	Sum of the number of juveniles, females and males	Individuals.100m <sup>-2</sup>	Variable
Equation	$Transfer_{fem}$	Transfer rate from juveniles to females	Per month	Variable
Equation	$Transfer_{mal}$	Transfer rate from juveniles to males	Per month	Variable
Forcing function	Daylight	Monthly variation of the daylight duration	Minutes	Variable/experimental
Forcing function	Sal	Monthly variation of the salinity inside the estuary	Non-dimensional	Variable/experimental
Forcing function	Temp	Monthly variation of the water temperature inside the estuary	°C	Variable/experimental
Parameter	Egg loss	Rate of eggs not hatched in nests	Per month	0.30/literature
Parameter	Fecundity	Mean number of eggs	Per month	2000/literature;

Parameter	Larval dispersal and mortality	generated per mature female Rate of larvae that fail to recruit	Per month	calibration 0.020338/literature; calibration
Parameter	Mature females	Rate of reproductive females	Per month	0.13/experimental
Parameter	MigraRate <sub>fem</sub>	Rate of migrating females	Per month	0.65/calibration
Parameter	MigraRate <sub>mal</sub>	Rate of migrating females	Per month	0.65/calibration
Parameter	MortRate <sub>fem</sub>	Mortality rate of females	Per month	0.15/calibration
Parameter	MortRate <sub>juv</sub>	Mortality rate of males	Per month	0.175/calibration
Parameter	MortRate <sub>mal</sub>	Mortality rate of juveniles	Per month	0.20/calibration
Parameter	S <sub>max</sub>	Maximum salinity for <i>P. microps</i> growth	Non-dimensional	51/literature
Parameter	S <sub>min</sub>	Minimum salinity for <i>P. microps</i> growth	Non-dimensional	0.3/literature
Parameter	S <sub>opt</sub>	Optimum salinity for <i>P. microps</i> growth	Non-dimensional	10/literature; calibration
Parameter	T <sub>max</sub>	Maximum temperature for <i>P. microps</i> growth	°C	24/literature
Parameter	T <sub>min</sub>	Minimum temperature for <i>P. microps</i> growth	°C	-1/literature
Parameter	T <sub>opt</sub>	Optimum temperature for <i>P. microps</i> growth	°C	16/calibration
Parameter	TransfRate <sub>fem</sub>	Rate of juveniles maturing into females	Individuals.100m <sup>-2</sup>	0.60/experimental
Parameter	TransfRate <sub>mal</sub>	Rate of juveniles maturing into males	Individuals.100m <sup>-2</sup>	0.20/experimental
State variable	Female	Initial density of females	Individuals.100m <sup>-2</sup>	23/experimental
State variable	Juvenile	Initial density of juveniles	Individuals.100m <sup>-2</sup>	10/experimental
State variable	Male	Initial density of males	Individuals.100m <sup>-2</sup>	13/experimental

967

968 **Table 2** Equations used in the model of the population dynamics of the common goby

969 *Pomatoschistus microps* in Minho estuary, NW Iberian Peninsula. See table 1 for abbreviations.

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**Juvenile density**

Variation in (1)

$$\text{Juvenile}(t) = \text{Juvenile}(t-\Delta t) + (\text{Recruitment} - \text{Transfer}_{\text{mal}} - \text{Transfer}_{\text{fem}} - \text{Mort}_{\text{juv}}) * \Delta t$$

juvenile density per unit of time

**- Inflows:**

- Recruitment = IF(Temp>15)AND(Temp<20)THEN(Female \* Mature females \* Fecundity \* Egg loss \* Larval dispersal and mortality \*  $F_{\text{temp}} * F_{\text{sal}}$ )ELSE(0)

**- Outflows:**

- $\text{Transfer}_{\text{mal}} = \text{Juvenile} * \text{TransfRate}_{\text{mal}} * F_{\text{temp}} * F_{\text{sal}}$
- $\text{Transfer}_{\text{fem}} = \text{Juvenile} * \text{TransfRate}_{\text{fem}} * F_{\text{temp}} * F_{\text{sal}}$
- $\text{Mort}_{\text{juv}} = \text{Juvenile} * \text{MortRate}_{\text{juv}} * F_{\text{temp}} * F_{\text{sal}}$

**Male density**

Variation in male (2)

$$\text{Male}(t) = \text{Male}(t-\Delta t) + (\text{Transfer}_{\text{mal}} - \text{Mort}_{\text{mal}} - \text{Migra}_{\text{mal}}) * \Delta t$$

density per unit of time

**- Inflows:**

- $\text{Transfer}_{\text{mal}} = \text{Juvenile} * \text{TransfRate}_{\text{mal}} * F_{\text{temp}} * F_{\text{sal}}$

**- Outflows:**

- $\text{Mort}_{\text{mal}} = \text{IF}(\text{Temp} < 10) \text{ THEN } (\text{Male} * \text{MortRate}_{\text{mal}} * 1.3) \text{ ELSE } (\text{Male} * \text{MortRate}_{\text{mal}})$
- MigraMal = IF(Temp<10)OR(Daylight<575)THEN(Male\*MigraRate\_Mal)ELSE(0)
- $\text{Migra}_{\text{mal}} = \text{IF}(\text{Temp} < 10) \text{ OR } (\text{Daylight} < 575) \text{ THEN } (\text{Male} * \text{MigraRate}_{\text{mal}}) \text{ ELSE } (0)$

**Female density**

Variation in female (3)

$$\text{Female}(t) = \text{Female}(t-\Delta t) + (\text{Transfer}_{\text{fem}} - \text{Mort}_{\text{fem}} - \text{Migra}_{\text{fem}}) * \Delta t$$

density per unit of time

**- Inflows:**

- $\text{Transfer}_{\text{fem}} = \text{Juvenile} * \text{TransfRate}_{\text{fem}} * F_{\text{temp}} * F_{\text{sal}}$

**- Outflows:**

- $\text{Mort}_{\text{fem}} = \text{IF}(\text{Temp} < 10) \text{ THEN } (\text{Female} * \text{MortRate}_{\text{fem}} * 1.3) \text{ ELSE } (\text{Female} * \text{MortRate}_{\text{fem}})$

○  $Migra_{fem} = IF (Temp < 10) OR (Daylight < 575) THEN (Female * MigraRate_{fem}) ELSE (0)$

**Temperature** Equation for the (4)

$F_{temp} = IF (Temperature \leq T_{opt}) THEN (EXP(-2.3 * ((Temperature - T_{opt}) / (T_{min} - T_{opt}))^2))$  limit factor of

$ELSE (EXP(-2.3 * ((Temperature - T_{opt}) / (T_{max} - T_{opt}))^2))$  temperature

**Salinity** Equation for the (5)

$F_{sal} = IF (Salinity \leq S_{opt}) THEN (EXP(-2.3 * ((Salinity - S_{opt}) / (S_{min} - S_{opt}))^2))$  limit factor of

$(EXP(-2.3 * ((Salinity - S_{opt}) / (S_{max} - S_{opt}))^2))$  temperature

970

971 **Table 3** Sensitivity (*sensu* Jørgensen 1994) of the population density to  $\pm 10\%$  variations of the

972 parameters used on the population dynamics model of the common goby *Pomatoschistus*

973 *microps* in Minho estuary, NW Iberian Peninsula.

Parameter	-10%	Base	+10%	Sensitivity
Egg loss	0.27	0.30	0.33	1.33
Fecundity	1800	2000	2200	1.33
Larval dispersal and mortality	0.0183042	0.020338	0.0223718	1.33
Mature females	0.117	0.13	0.143	1.33
$MigraRate_{fem}$	0.585	0.65	0.715	0.00
$MigraRate_{mal}$	0.585	0.65	0.715	0.00
$MortRate_{fem}$	0.135	0.15	0.165	-0.76
$MortRate_{juv}$	0.18	0.20	0.22	-0.27
$MortRate_{mal}$	0.135	0.15	0.165	-0.07
$S_{max}$	45.9	51	56.1	1.03
$S_{min}$	0.27	0.30	0.33	0.00
$S_{opt}$	9	10	11	0.34
$T_{max}$	21.6	24	26.4	0.15
$T_{min}$	-0.9	-1	-1.1	0.00
$T_{opt}$	14.4	16	17.6	0.48
$TransfRate_{fem}$	0.54	0.60	0.66	0.48
$TransfRate_{mal}$	0.18	0.20	0.22	-0.08



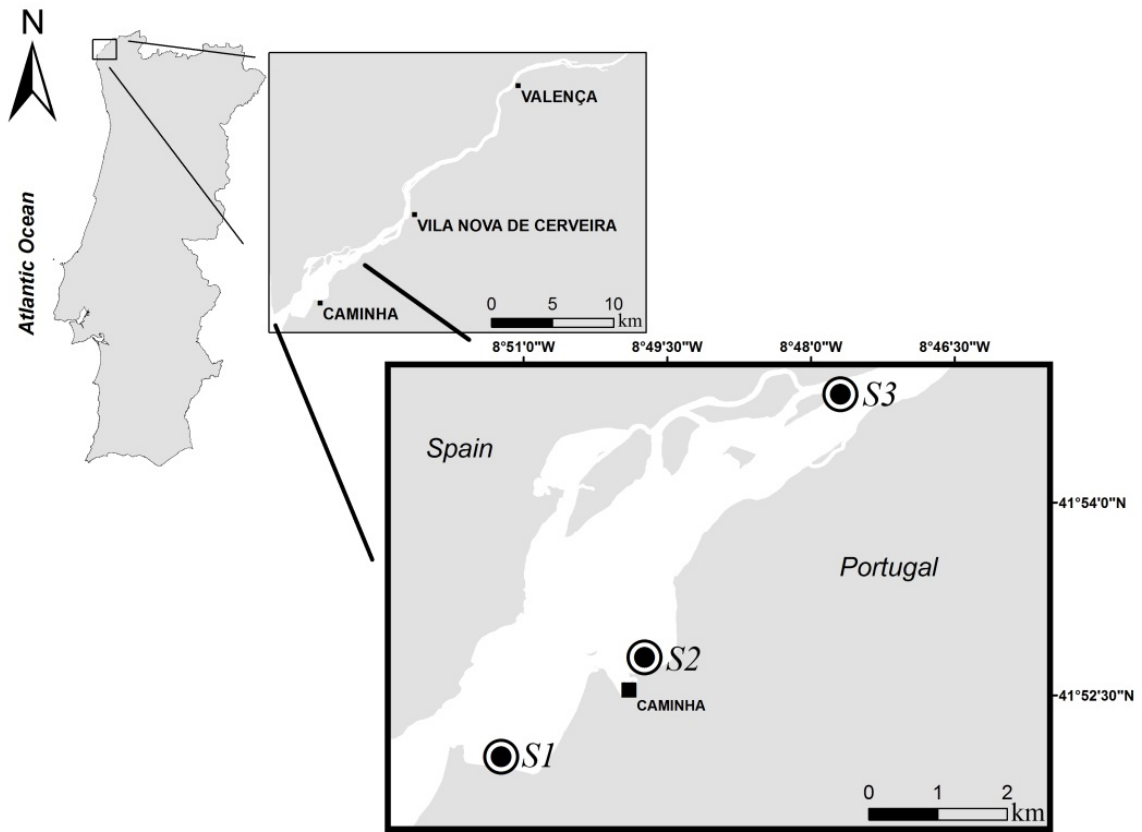
974

975 **Table 4** Linear regressions between the observed and the predicted values for the common goby  
976 *Pomatoschistus microps* density inside Minho estuary, NW Iberian Peninsula. SS = Sum of  
977 squares, MS = Mean square, F = F-statistic, SD = Standard deviation (slope).

Group	SS	MS	F	Slop	SD	R <sup>2</sup>	P
Juvenile	11559	11559	5.50	1.04	0.4	0.3	<0.05*
Female	32750	32750	26.12	1.56	0.3	0.7	<0.001***
Male	349.4	349.4	2.95	0.53	0.3	0.2	0.12 <sup>ns</sup>
Total	135941	135941	46.52	1.73	0.2	0.8	<0.001***

978

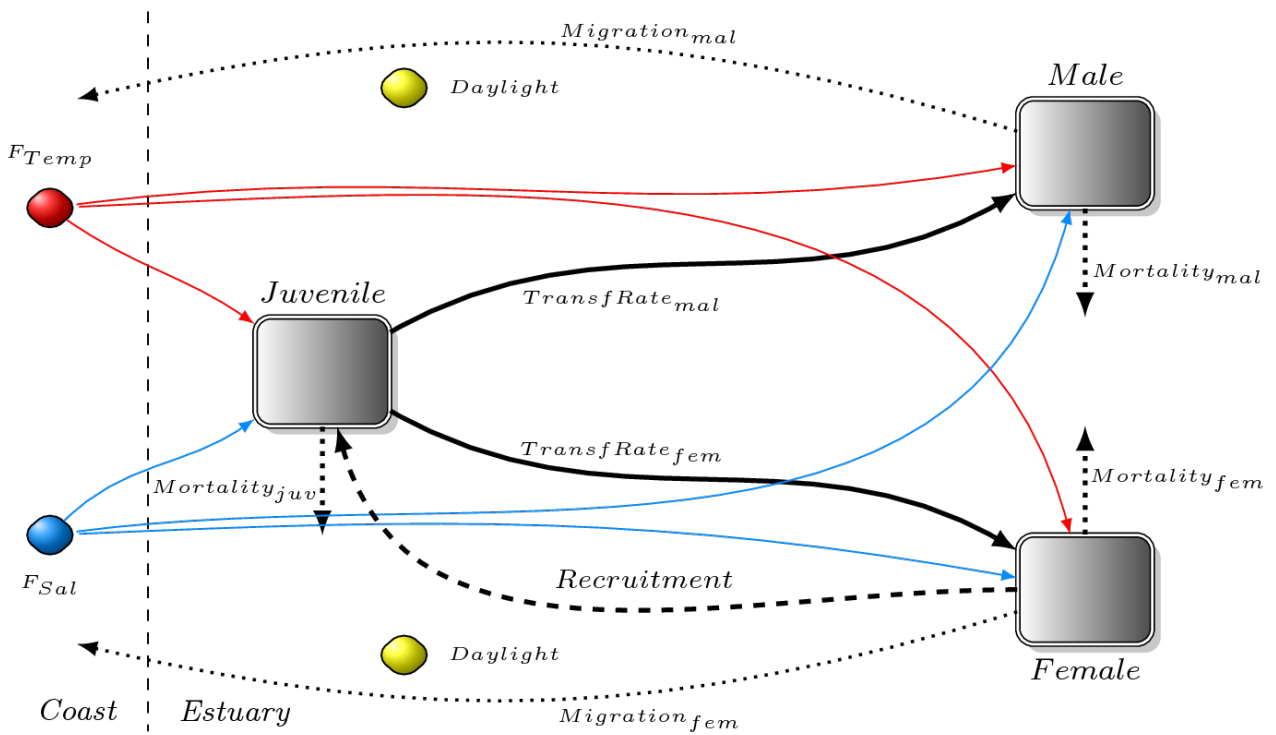
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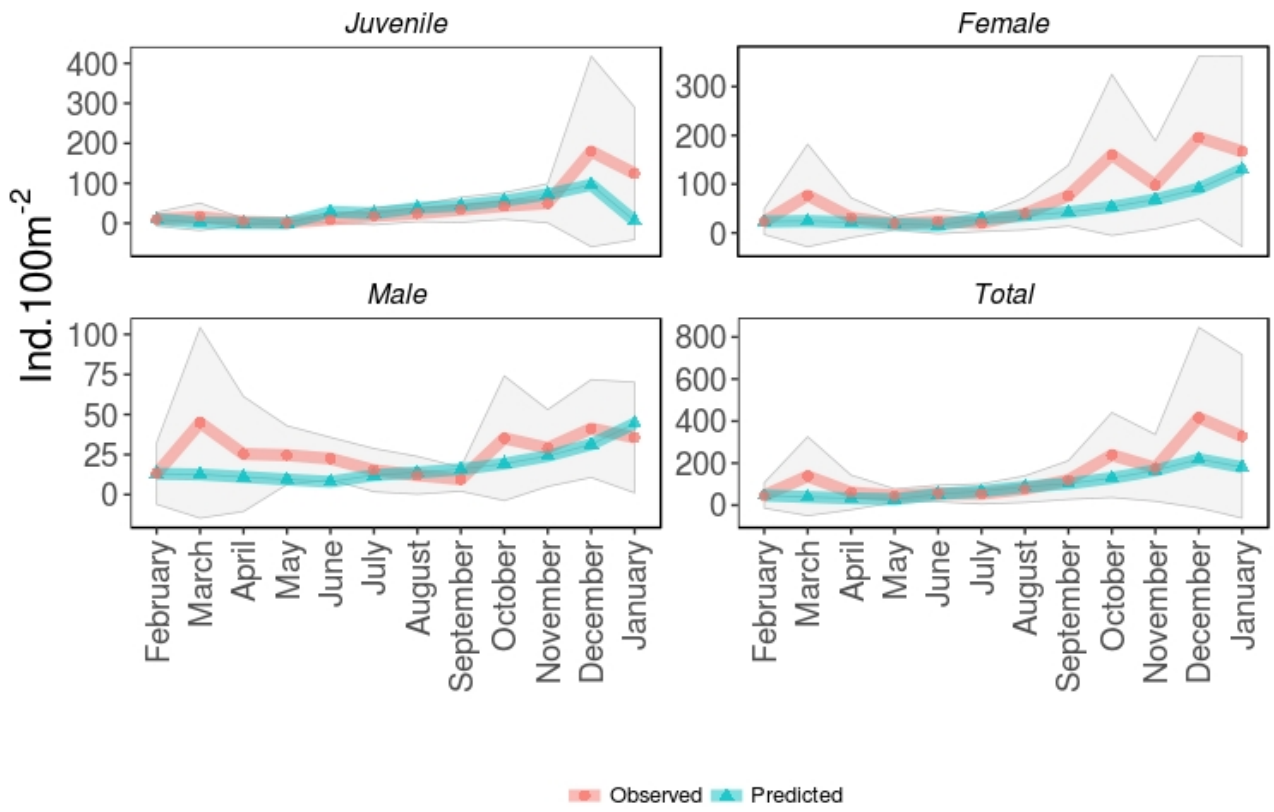
981 **Fig. 1**

982



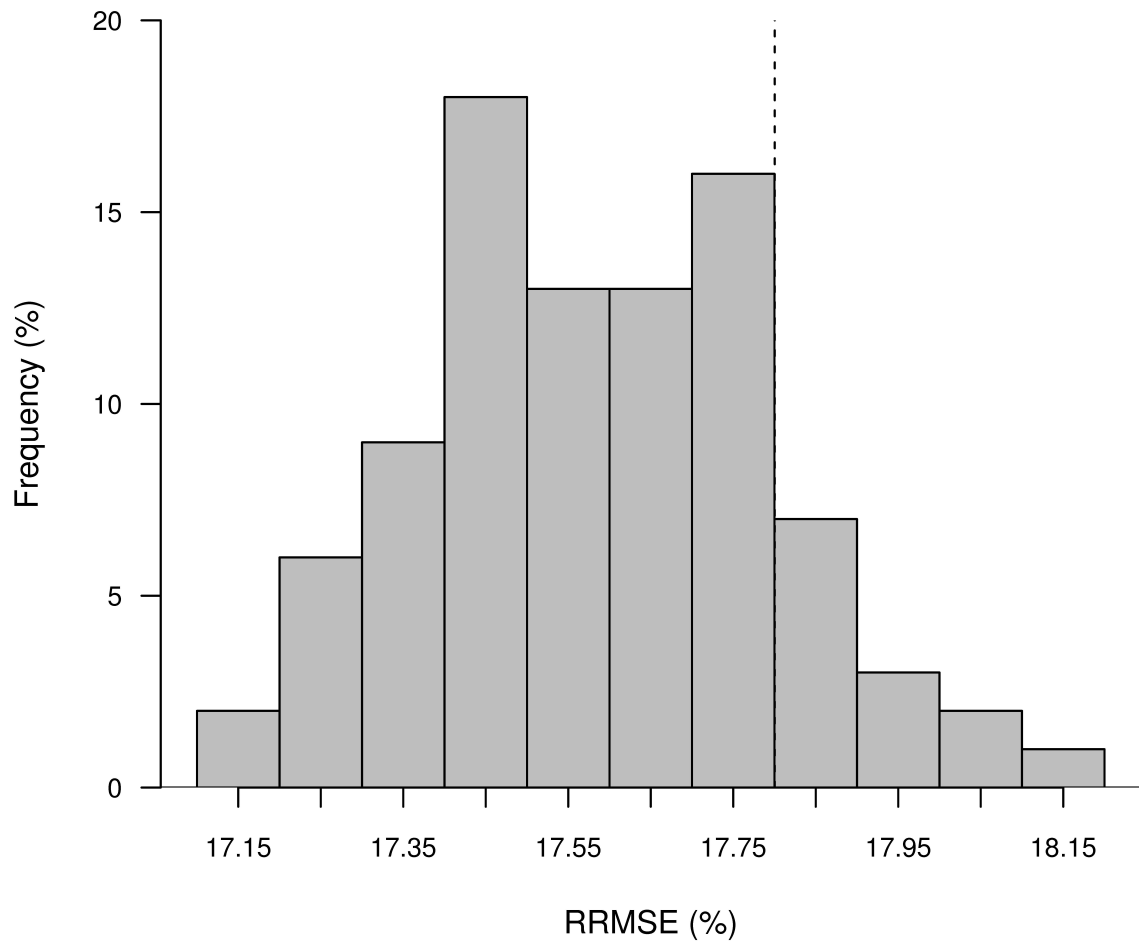
984 **Fig. 2**

985



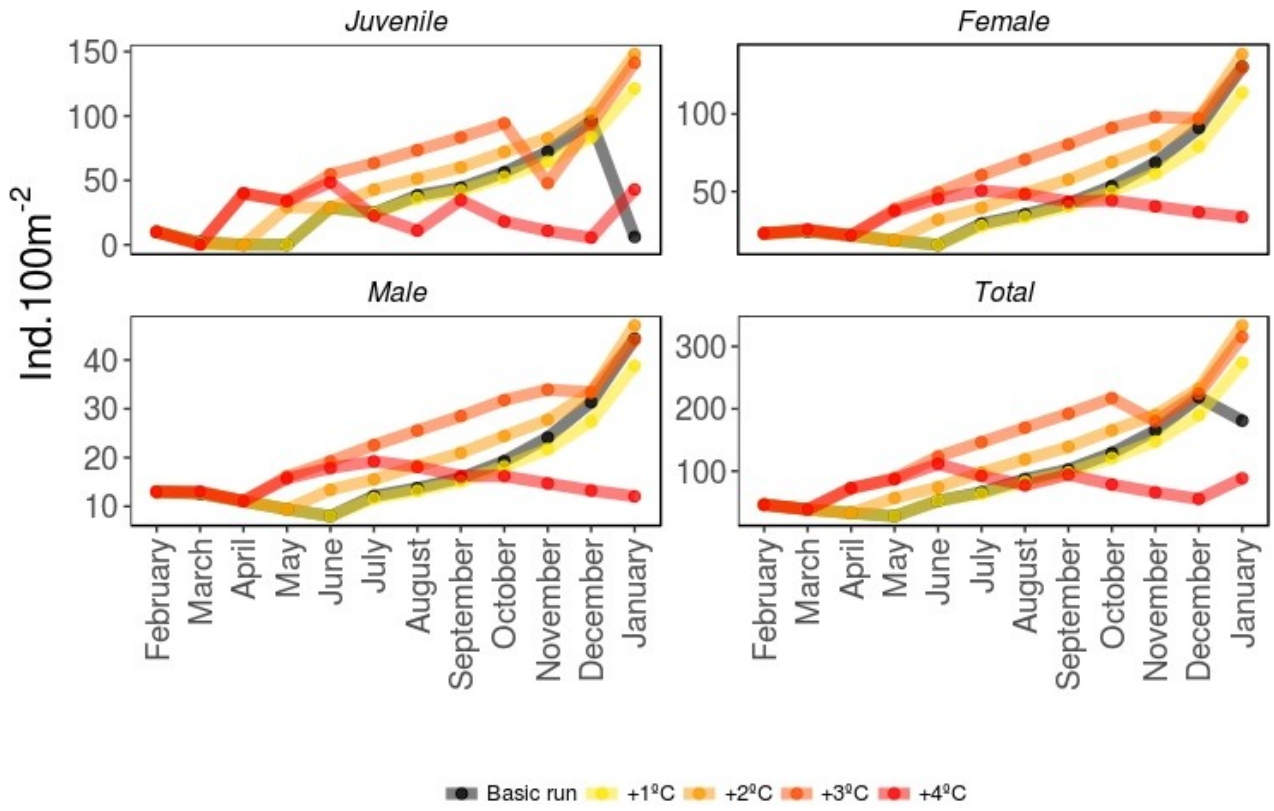
987 **Fig. 3.**

988



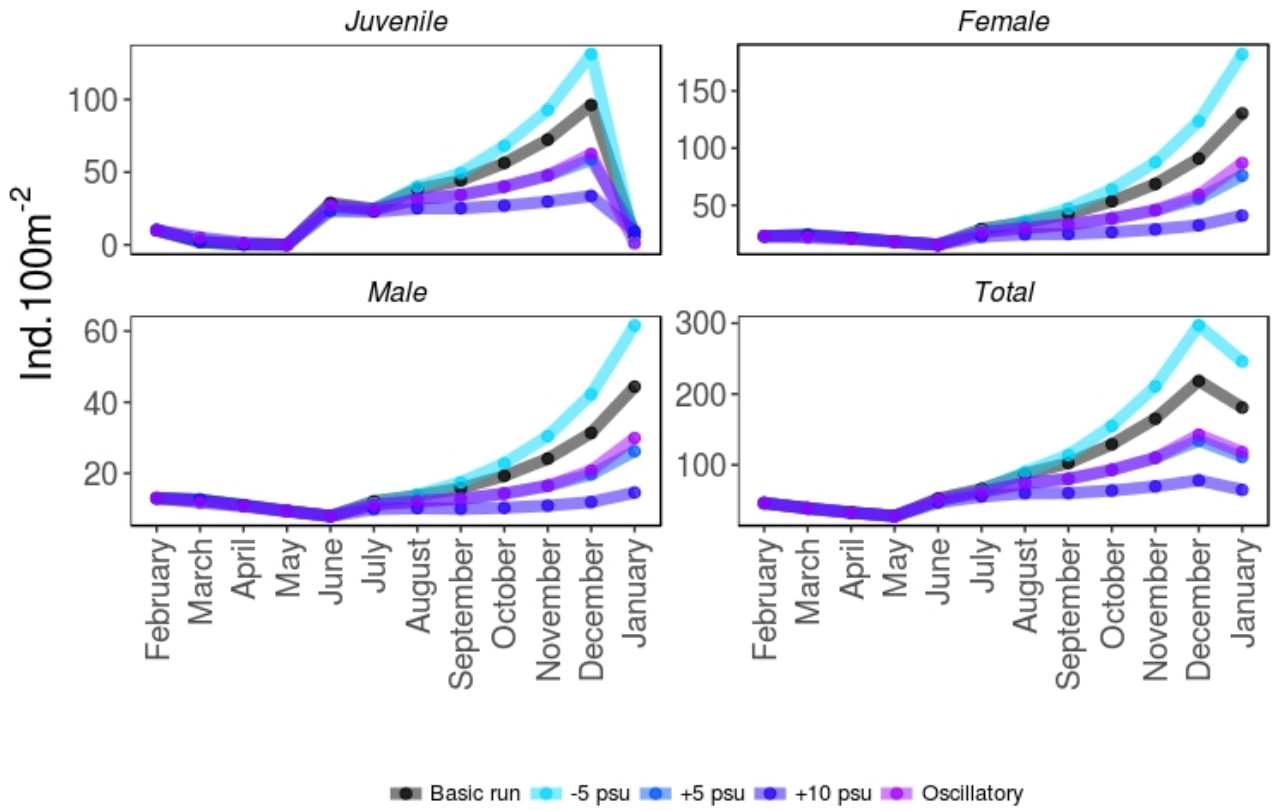
990 **Fig. 4**

991



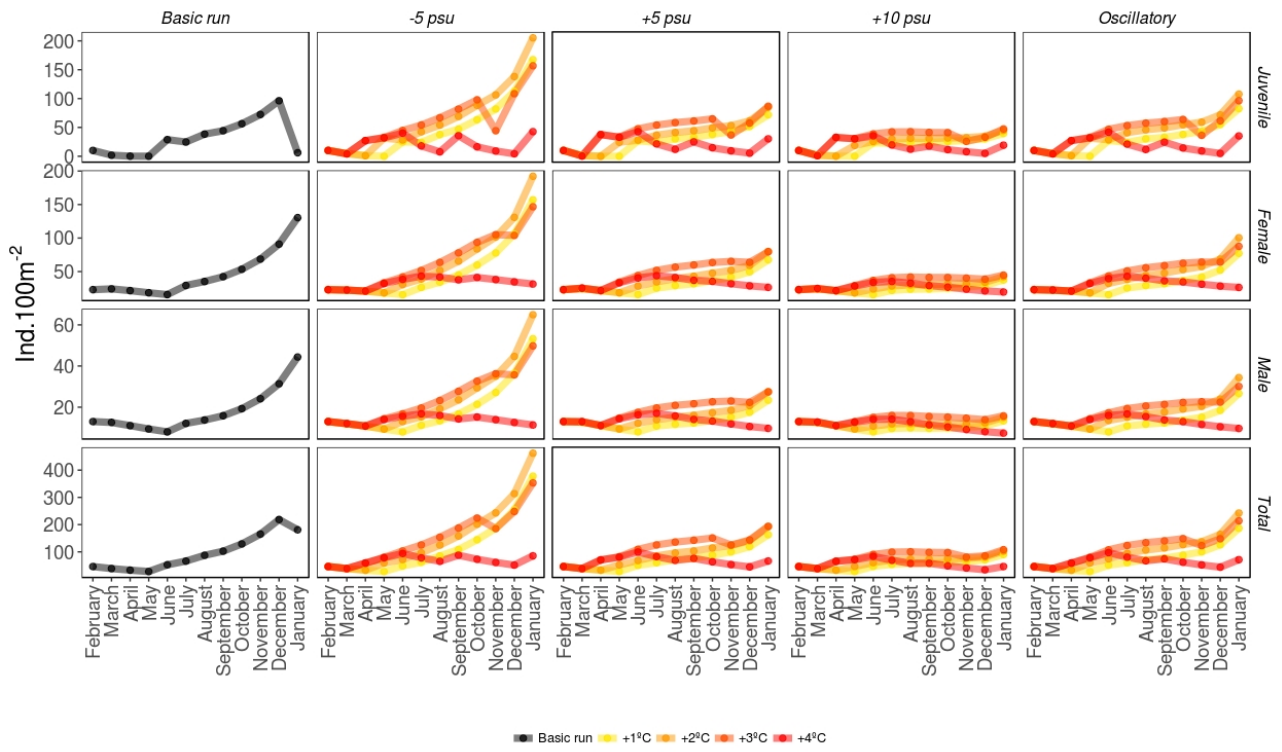
993 Fig 5.

994



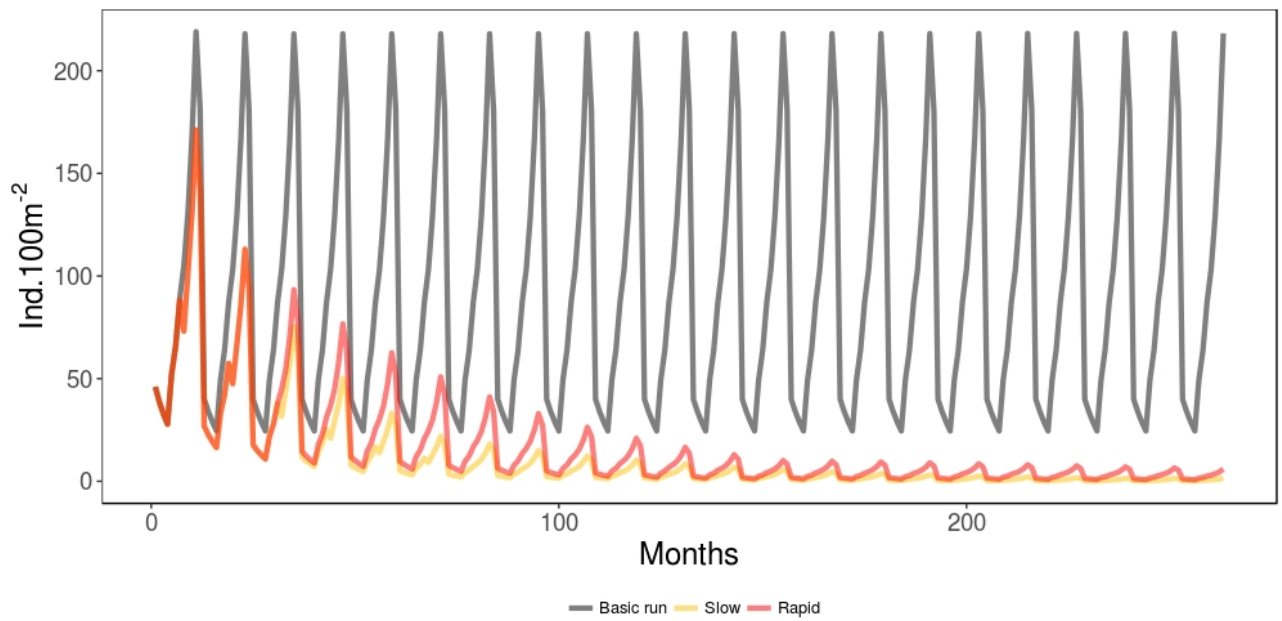
996 **Fig 6.**

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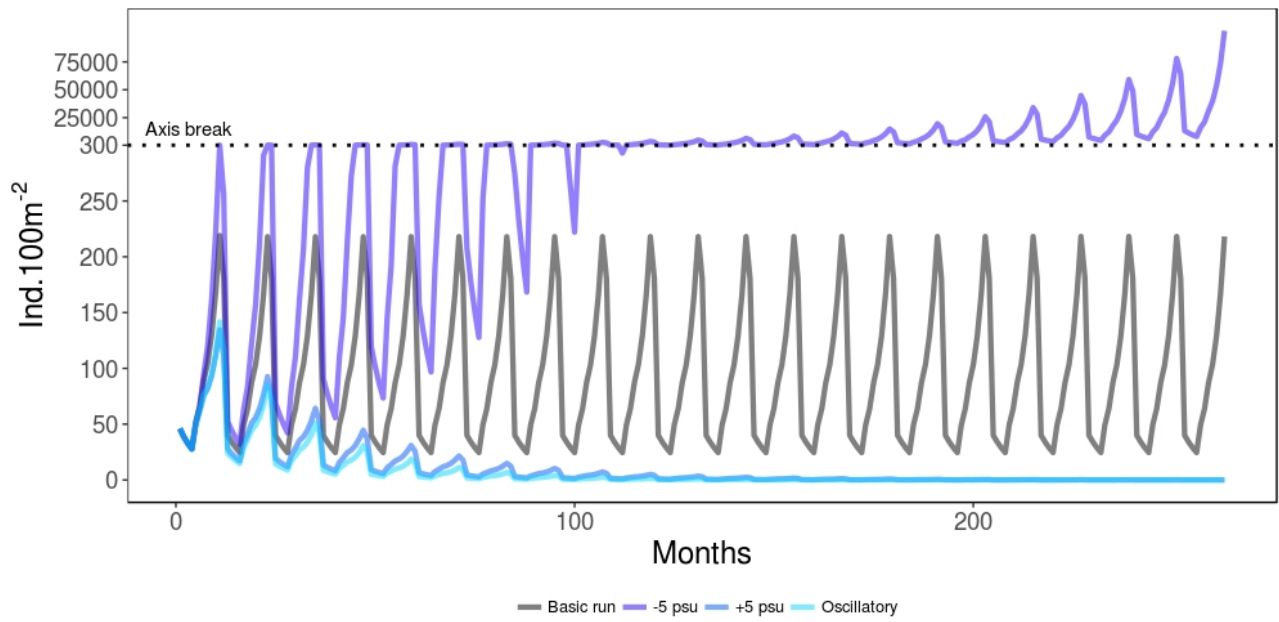
999 **Fig. 7**

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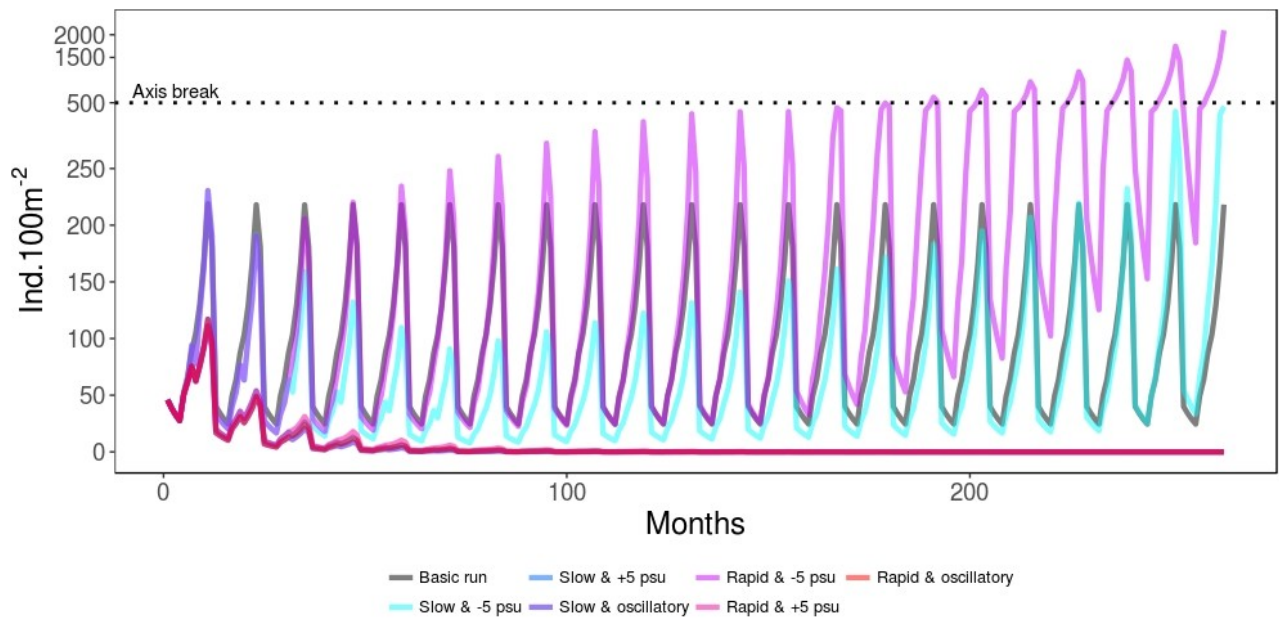
1002 **Fig. 8**

1003



1005 **Fig. 9**

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1008 **Fig. 10**

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