



**HAL**  
open science

# Variations of salinity during reproduction and development affect ontogenetic trajectories in a coastal amphibian

Léa Lorrain-Soligon, Timothé Bizon, Frédéric Robin, Marko Jankovic,  
François Brischoux

## ► To cite this version:

Léa Lorrain-Soligon, Timothé Bizon, Frédéric Robin, Marko Jankovic, François Brischoux. Variations of salinity during reproduction and development affect ontogenetic trajectories in a coastal amphibian. *Environmental Science and Pollution Research*, 2024, 31, pp.11735-11748. 10.1007/s11356-024-31886-1. hal-04416589

**HAL Id: hal-04416589**

**<https://hal.science/hal-04416589v1>**

Submitted on 29 Apr 2024

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

1 **Variations of salinity during reproduction and development affect**  
2 **ontogenetic trajectories in a coastal amphibian**

3 Léa Lorrain-Soligon<sup>1</sup>, Timothé Bizon<sup>1</sup>, Frédéric Robin<sup>2,3</sup>, Marko Jankovic<sup>3</sup>, François  
4 Brischoux<sup>1</sup>

5

6 **Institutional affiliations**

7 1. UMR 7372 : Centre d'Etudes Biologiques de Chizé (CEBC) - CNRS - La Rochelle  
8 Université, 79360 Villiers en Bois, France

9 2. LPO France, Fonderies Royales, 17300 Rochefort, France

10 3. Réserve naturelle du marais d'Yves LPO, Ferme de la belle espérance, 17340 Yves,  
11 France

12

13 **Corresponding author:**

14 [llorrain.lea@gmail.com](mailto:llorrain.lea@gmail.com)

15 ID ORCID: 0000-0002-8723-7478

16 Full postal address : Centre d'Etudes Biologiques de Chizé, CEBC UMR 7372 CNRS -  
17 405 route de Prissé la Charrière, 79360 Villiers en Bois, France

18

19 **ID ORCIDs**

20 LLS : 0000-0002-8723-7478

21 FR: 0000-0003-0232-1142

22 FB: 0000-0002-5788-1326

23

24 **Acknowledgements**

25 The authors would like to thank all the staff of the Marais d'Yves national reserve

26 (Thomas Hérault, Karine Vennel, Camille Chave, Alexandra Kratz) for their help

27 capturing amplexant toads, as well as Mathieu Plateau for its help bringing them to

28 the laboratory.

29

30 **Abstract**

31 Although coastal ecosystems are naturally submitted to temporal variations of salinity,  
32 salinization has been increasing over time threatening coastal biodiversity. Species that  
33 exploit such habitats can thus be exposed to brackish water at different life stages.  
34 However, the impacts of variations of salinity on wildlife remain poorly understood.  
35 This is particularly true for coastal amphibians, due to the strong dependency of early  
36 life stages (embryos and larvae) on aquatic environments. In order to investigate the  
37 effect of salinity during egg laying and embryonic and larval development of coastal  
38 amphibians, we used a full-factorial design to expose reproductive adults, eggs and  
39 larvae of coastal spined toads (*Bufo spinosus*) to fresh (0 g.l<sup>-1</sup>) or brackish water (4 g.l<sup>-1</sup>).  
40 At egg laying, we evaluated parental investment in reproduction. During embryonic  
41 and larval development, we assessed effects on survival, development, and growth.  
42 We highlighted strong effects of environmental salinity on reproduction (reduced egg  
43 laying time, marginally reduced egg size, and reduced investment in reproduction).  
44 Responses to salinity were highly dependent on the developmental stages of exposure  
45 (stronger effects when individuals were exposed during embryonic development).  
46 These effects carried over when exposure occurred at egg laying or during embryonic  
47 development, highlighting the importance of the environmental conditions during  
48 early life on ontogenetic trajectories. We also highlighted partial compensation when  
49 individuals were transferred back to freshwater. Whether the magnitude of these  
50 responses can allow coastal biodiversity to overcome the observed detrimental effects  
51 of salinization remain to be assessed.

52 **Key-words:** Carry-over effects, Embryonic development, Freshwater, Recovery,  
53 Reproductive investment, Tadpoles

54        **1. INTRODUCTION**

55        Salinization of freshwater bodies is strongly increasing over time (Williams 2001).  
56        Coastal wetlands are particularly subjected to salinization because of salt water  
57        intrusions (Knighton et al. 1991; Visschers et al. 2022), reductions in freshwater flow  
58        resulting from dams and reservoirs, droughts and increased abstraction (Reid et al.  
59        2019), rising sea levels (Vermeer and Rahmstorf 2009; Church and White 2011; Bakker  
60        et al. 2017), and the predicted increase in frequency and intensity of marine surges  
61        (Nicholls et al. 1999; McLean et al. 2001; Knutson et al. 2010; Dettinger 2011; Trenberth  
62        et al. 2015; IPCC 2022). Due to their particular position between terrestrial and oceanic  
63        systems, coastal ecosystems are also naturally submitted to variations of salinity (Xue  
64        et al. 2013), and are thus known to experience temporal and spatial heterogeneity of  
65        salinity (Estévez et al. 2019; Ranjbar and Ehteshami 2019; Fu et al. 2021). Importantly,  
66        salinity can increase through time, but can also decrease when precipitations increase  
67        (Lorrain-Soligon et al. 2023c). However, the impacts of these short term variations of  
68        salinity on wildlife remain poorly understood.

69

70        Salinization is expected to strongly affect coastal biodiversity (Amores et al. 2013;  
71        Debue et al. 2022). Indeed, most organisms need to maintain their internal homeostasis  
72        and rely on physiological compensatory mechanisms to regulate water and ion fluxes  
73        (Schultz and McCormick 2012; Evans and Kültz 2020). Most species have specific  
74        ranges of tolerance, and crossing these limits of tolerance activates mechanisms that  
75        aim at regulating ionic and hydric fluxes (Evans 2009). These mechanisms include  
76        modulation of drinking and urination rates, regulation of the permeability of

77 membranes to water, remodeling of cells and tissues, and increased expression and  
78 activity of ion transporters (Evans 2009; Kültz 2015; Rivera-Ingraham and Lignot 2017).  
79 However, these mechanisms are often metabolically costly and the associated  
80 energetic expenditures can affect energetic allocation to other functions (Herbert et al.  
81 2015; Rivera-Ingraham and Lignot 2017). As such, salinity can influence critical  
82 functions such as foraging (Chuang et al. 2022), activity (Leite et al. 2022;  
83 Moniruzzaman et al. 2022), anti-predator responses (Hoover et al. 2013) and growth  
84 (Liu et al. 2022). In addition, elevated salinity can also increase the occurrence of  
85 malformations (Hieu et al. 2021), potentially leading to increased mortality (Cañedo-  
86 Argüelles et al. 2013; Moniruzzaman et al. 2022; Woodley et al. 2023). In adults,  
87 increased salinity can reduce egg production and fecundity (Pinder et al. 2005;  
88 Froneman 2023; Woodley et al. 2023), egg size (Lorrain-Soligon et al. 2023a), or the age  
89 at first reproduction (Woodley et al. 2023). In addition, increasing salinity is known to  
90 reduce sperm performance, motility and velocity (Wilder and Welch 2014; Byrne et al.  
91 2015, 2022; Green et al. 2021). Ultimately, salinization can alter community structure  
92 (Hart et al. 2003; Anufrieva and Shadrin 2018), across all trophic levels (Hintz and  
93 Relyea 2019).

94

95 This is especially true for coastal amphibians. Indeed, amphibians are particularly  
96 sensitive to salinity due to their highly permeable skin used for gas exchanges, and for  
97 ions and water transport (Shoemaker and Nagy 1984; Martin and Nagy 1997), and to  
98 their relatively low osmoregulatory abilities (Katz 1989). Early life stages (i.e. eggs and  
99 larvae) are particularly susceptible to environmental salinity (Albecker and McCoy

100 2017) because of their strong dependency on aquatic environment compared to adults  
101 (Wells 2007) and to their comparatively lower osmoregulatory abilities (Karraker and  
102 Gibbs 2011). Increasing salinity from various sources can lead to reduced thyroid  
103 hormones levels (Gomez-Mestre et al. 2004) and to changes in osmoregulatory  
104 hormones such as corticosterone and aldosterone (Tornabene et al. 2021b, 2022) in  
105 larval amphibians. Ultimately, this lead to decreased embryonic and larval survival  
106 (Christy and Dickman 2002; Chinathamby et al. 2006; Dougherty and Smith 2006;  
107 Sanzo and Hecnar 2006; Karraker et al. 2008; Bernabò et al. 2013; Jones et al. 2015), and  
108 to increased malformations (Gosner and Black 1957; Sanzo and Hecnar 2006;  
109 Haramura 2007; Karraker 2007; Hopkins et al. 2013; Brady 2013; Tornabene et al.  
110 2021a), time to hatching (Haramura 2016; Tornabene et al. 2021a), hatching success  
111 (Tornabene et al. 2021a), larval duration (Christy and Dickman 2002; Gomez-Mestre  
112 and Tejedo 2003; Lukens and Wilcoxon 2020; Tornabene et al. 2021a), and to reduced  
113 growth and thus to induce smaller body size (Wu and Kam 2009; Bernabò et al. 2013;  
114 Wood and Welch 2015; Haramura 2016; Lukens and Wilcoxon 2020; Tornabene et al.  
115 2021a, b).

116

117 Despite their sensitivity, amphibians are known to be very plastic in behavioral and  
118 morphological traits (Hoverman and Relyea 2008), and their developmental traits can  
119 vary in response to environmental cues (Chivers et al. 2001; Warkentin 2011). For  
120 instance, tadpoles can modulate their growth rates according to the quality of  
121 environmental conditions (Werner 1986; Vonesh and Warkentin 2006). Additionally,  
122 it has been suggested that the influence of a given environmental factor on

123 development and growth of tadpoles is highly dependent on the stage and condition  
124 during which they experience such factor (Denver et al. 2002). This can be highly  
125 relevant for changes in salinity. For example, *Fejervarya limnocharis* and *Litoria ewingii*  
126 tadpoles released from salinity stress at early larval stages reached a size at  
127 metamorphosis similar to that of tadpoles maintained in low salinity throughout  
128 development, indicating compensatory growth (Squires et al. 2010; Wu et al. 2012).  
129 Yet, the efficiency of such compensatory mechanisms may vary if individuals are  
130 exposed earlier or later during larval development (Hsu et al. 2018). Additionally,  
131 whether parents can influence the tolerance of their offspring according to the salinity  
132 in which they are laying eggs is unknown.

133

134 In order to investigate the effect of salinity during egg-laying and embryonic and larval  
135 development of coastal amphibians, we used a full-factorial experimental design to  
136 expose reproductive adults, eggs and larvae of coastal spined toads (*Bufo spinosus*, a  
137 species which coastal individuals are supposedly adapted to exposure to salinity) to  
138 fresh (0 g.l<sup>-1</sup>) or brackish water (4 g.l<sup>-1</sup>, Figure 1). More specifically, reproductive pairs  
139 (amplexus) were exposed to fresh or brackish water prior to egg-laying (Figure 1).  
140 Following egg laying, we exposed eggs to either fresh or brackish water until hatching  
141 (Figure 1). Following hatching, we exposed larvae to either fresh or brackish water  
142 (Figure 1). At egg laying, we evaluated fecundity and parental investment in  
143 reproduction. During both embryonic and larval development, we assessed effects of  
144 each experimental treatment on survival (hatching rate, larval survival), development  
145 (duration of embryonic and larval development until Gosner stage 30 [Gosner 1960],



146 malformation), and growth (body length). We predicted that (1) Brackish water would  
147 impact reproductive investment and egg size, and alter fecundity because salinity can  
148 impact sperm motility (Byrne et al. 2015, 2022). (2) Salt exposure would decrease  
149 embryonic survival, larval survival and growth (Albecker and McCoy 2017; Lukens  
150 and Wilcoxon 2020; Tornabene et al. 2021a) as well as malformations (Gosner and Black  
151 1957; Sanzo and Hecnar 2006; Haramura 2007; Karraker 2007; Hopkins et al. 2013;  
152 Brady 2013; Tornabene et al. 2021a), regardless of the stage of exposure. These effects  
153 should be alleviated in individuals transferred to freshwater, because of the resilience  
154 capacities of amphibians to salt exposure (Squires et al. 2010; Wu et al. 2012; Hsu et al.  
155 2018; Lorrain-Soligon et al. 2022).

156 **2. METHODS**

157 **2.1. Study species**

158 Spined toads (*Bufo spinosus*) are a common amphibian species found in western Europe  
159 (Speybroeck et al. 2018; Meek 2022). Breeding occurs in late winter, during which  
160 adults converge to reproductive ponds where they mate (amplexus) and lay their eggs  
161 constituted of 2 eggs strings which can be constituted of up to 10000 eggs (Miaud and  
162 Muratet 2018). Egg laying, embryonic and larval developments all occur in ponds.

163

164 **2.2. Captures and measurements**

165 Amplectant pairs were captured on one coastal pond (salinity 3.1 g.l<sup>-1</sup> during captures,  
166 conductimeter YSI Professional Plus) situated in the Réserve Naturelle Nationale du  
167 Marais d'Yves (location: 46.04013, -1.05363). This site can display seasonal variations  
168 of salinity ranging from 0.5 g.l<sup>-1</sup> to 6 g.l<sup>-1</sup>, as what is found in nearby ponds. Captures  
169 occurred at night (between 20 pm and 4 am) on 21/02/2023 and 22/02/2023. Twenty  
170 one amplectant pairs were captured by hand, placed in a transport box (14\*16\*9cm),  
171 and brought to the laboratory immediately after field sessions.

172 At the laboratory, individuals were kept in a thermally controlled room with  
173 temperature set at 17 °C and controlled photoperiod (12 h dark-12 h light),  
174 temperature and photoperiod being set for the totality of the experiment. Pairs were  
175 transitorily (for measurements only) separated and all individuals were measured  
176 (snout-vent length, SVL) using a caliper ( $\pm$  1 mm) and weighed using an electronic  
177 balance ( $\pm$  0.1g). Once measurements were completed, separated amplectant

178 individuals were shortly reunited and pairs re-formed systematically as soon as the  
179 partners were brought back into contact.

180

### 181 **2.3. Experimental procedures**

182 Amplectant pairs, embryos and larvae were exposed to either freshwater or brackish  
183 water (sea salt, NaCl), following a full factorial design (Figure 1). At the end of the  
184 experiment, larval individuals were thus exposed to one of the eight following  
185 treatments: (1) FFF: clutch obtained in freshwater, embryonic development in  
186 freshwater, larval development in freshwater; (2) FSF: clutch obtained in freshwater,  
187 embryonic development in brackish water, larval development in freshwater; (3) FFS:  
188 clutch obtained in freshwater, embryonic development in freshwater, larval  
189 development in brackish water; (4) FSS: clutch obtained in freshwater, embryonic  
190 development in brackish water, larval development in brackish water; (5) SFF: clutch  
191 obtained in brackish water, embryonic development in freshwater, larval  
192 development in freshwater; (6) SSF: clutch obtained in brackish water, embryonic  
193 development in brackish water, larval development in freshwater; (7) SFS: clutch  
194 obtained in brackish water, embryonic development in freshwater, larval  
195 development in brackish water; (8) SSS: clutch obtained in brackish water, embryonic  
196 development in brackish water, larval development in brackish water. Water of these  
197 treatments was changed every seven days.

198

199 Tadpoles were fed ad libitum with thawed frozen organic spinach. Individuals were  
200 checked twice a day for their specific developmental stage, for mortality and for  
201 abnormalities (which were checked visually).

202

### 203 2.3.1. Egg laying (n=21)

204 Once the amplexant pairs were reunited, they were placed in a plastic container  
205 (35\*55\*26 cm) containing either freshwater (~20L, salinity: 0.3 g.l<sup>-1</sup>, 10 amplexant pairs)  
206 or brackish water (~20L, salinity: 4.0 g.l<sup>-1</sup>, 11 amplexant pairs) as well as branches for  
207 laying support. The two groups did not differ in size (freshwater: females= 74.7 mm ±  
208 1.61 SE, males= 64.1 mm ± 1.00 SE; brackish water: females= 75.9 mm ± 2.08 SE, males=  
209 62.7 mm ± 1.22 SE; differences between females in the two groups: Estimate=1.209,  
210 SE=2.604, t<sub>1,19</sub>=0.464, p-value=0.648; differences between males in the two groups:  
211 Estimate=1.373, SE=1.601, t<sub>1,19</sub>=0.857, p-value=0.402). Amplexant pairs were left in  
212 these tanks until egg laying. Individuals were checked every two hours to compute  
213 time to egg laying (measured from their placement in a plastic container to the  
214 completion of egg laying). Adult individuals were then released at their site of capture.  
215 Adults were thus kept under laboratory conditions for a maximum of seven days  
216 (maximal time to egg laying 151 hours), and the water of their treatment was left  
217 unchanged during this duration. They were unfed during this period, as adults  
218 anurans usually don't feed during the reproduction. Twelve pieces of each egg strings,  
219 containing 30 eggs each (i.e. a total of 360 eggs for each egg string) were selected  
220 randomly and kept for our experiment, and the remaining eggs (i.e. 100– 4500) were  
221 released at the site of origin of their parents.

222

223 *2.3.2. Embryonic development (n=232)*

224 The two treatments were applied in 2 L individual tanks (13\*18\*18cm, n=232, see table  
225 1) containing one of the two treatment (freshwater: 0 g.l<sup>-1</sup> salinity: 0.3 ± 0.0 g.l<sup>-1</sup>;  
226 brackish water : 4 g.l<sup>-1</sup> salinity 4.0 ± 0.06 g.l<sup>-1</sup>). Water was changed once a week. Each  
227 clutch was represented by 6 segments of 30 eggs in each of the experimental  
228 treatments. To prevent osmotic shock, segments for which the clutch was obtained in  
229 another salinity than which their embryonic development occur (i.e. clutch that were  
230 obtained at 0 g.l<sup>-1</sup> but for which embryonic development will occur at 4 g.l<sup>-1</sup> and clutch  
231 that were obtained at 4 g.l<sup>-1</sup> but for which embryonic development will occur at 0 g.l<sup>-1</sup>  
232 <sup>1</sup>) were gradually exposed to the salinity of the treatment, with an increase or a  
233 decrease of 1 g.l<sup>-1</sup> a day (Hsu et al. 2018). This way, segments were exposed to their  
234 final treatment over 4 days. Each segment were kept in the laboratory until tadpoles  
235 hatched and reached a free feeding stage (Gosner stage 25, hereafter GS25) (Gomez-  
236 Mestre and Tejedo 2003).

237

238 *2.3.3. Larval development (n=232)*

239 Upon hatching (GS25), we selected 1 individual per segment (randomly, among alive  
240 and not malformed tadpoles of each segment), and these individuals were once again  
241 distributed in two treatments: freshwater (0 g.l<sup>-1</sup> salinity: 0.3 ± 0.0 g.l<sup>-1</sup>), and brackish  
242 water (4 g.l<sup>-1</sup> salinity 4.0 ± 0.06 g.l<sup>-1</sup>). For each clutch, three segments and thus three  
243 tadpoles were thus exposed to each treatment (FFF, FFS, FSF, FSS, SFF, SFS, SSF, SSS).  
244 In some segments, no individuals survived until GS25. In these cases, individuals were

245 replaced by other individuals from the same treatments but originating from different  
246 clutches in order to keep a total of 232 tadpoles that were followed during larval  
247 development (see table 1 for the count of tadpoles in each treatment, and Appendix A  
248 for the contribution of each clutch). All other tadpoles were released at the site where  
249 their parents were captured.

250 Similarly to embryos, when individuals were transferred to a different treatment (i.e.  
251 tadpoles for which embryonic development occur at 0 g.l<sup>-1</sup> but larval development will  
252 occur at 4 g.l<sup>-1</sup> and tadpoles for which embryonic development occur at 4 g.l<sup>-1</sup> but larval  
253 development will occur at 0 g.l<sup>-1</sup>), tadpoles were gradually exposed to the salinity of  
254 the treatment, with an increase or a decrease of 1 g.l<sup>-1</sup> a day to prevent osmotic shock  
255 (Hsu et al. 2018).

256 Larval development was monitored until G30 (Gosner 1960), in order to have  
257 approximatively the same time considered for embryonic development and larval  
258 development, and because GS30 is a pivotal stage when somatic growth decreases and  
259 significant morphological changes occur Cheron et al. (2021). At the end of this  
260 experimental procedure, individuals were released at the site where their parents were  
261 captured.

262

## 263 **2.4. Measurements**

### 264 *2.4.1. Reproductive effort (n=21)*

265 Once egg laying was completed, individuals were again weighed to calculate  
266 variations in body mass. Additionally, each clutch was weighed using an electronic  
267 balance ( $\pm 0.1g$ ). Moreover, in order to assess fecundity, each egg string was placed in

268 a container (35 × 20 × 25 cm) containing 2 cm of dechlorinated tap water and a scale  
269 (graph paper). A picture was taken from above in order to measure the total length of  
270 the egg string using ImageJ software (Schneider et al. 2012). For each clutch, we  
271 randomly selected six 10-cm segments and individually counted the number of eggs  
272 within each segment. The mean number of eggs per 10-cm segment was calculated and  
273 used to assess fecundity (number of eggs) for each clutch based on the length of the  
274 egg strings. Finally, on a subsample of 100 randomly selected eggs in each egg strings,  
275 we measured egg diameter.

276

#### 277 *2.4.2. Embryonic development (n=232)*

278 At GS 25, hatching success (proportion of eggs that hatched, on the segment of 30 eggs)  
279 and deformation rates (proportion of larvae that hatched but were malformed, on the  
280 total number of hatched individuals) were calculated. Additionally, for each segments,  
281 we described general activity of all hatchlings as being, on a scale of 1 to 5, the  
282 proportion of live individuals that were active; 1=0-20%, 2=20-40%, 3=40-60%, 4=60-  
283 80%, 5=80-100%) over a 1-min period.

284

#### 285 *2.4.3. Larval development (n=232)*

286 At GS25 and GS30, we measured total length of individuals. Each tadpole was put into  
287 a Petri dish with the water from its own tank, and photographed. Individuals were  
288 than measured using the software ImageJ (Schneider et al. 2012). We also measured  
289 activity following a scale ranging from 1 to 5 (from 1 if the individual is amorphous,

290 to 5 if the individual move energetically, following Lorrain-Soligon et al. [2022]). The  
291 tadpoles were not stimulated to record these observations.

292

293

## 294 **2.5. Statistical analyses**

295 We computed Linear Models (LMs) or Linear Mixed Models (LMMs) and Generalized  
296 Linear Mixed Models (GLMMs) using the lme4 (Bates et al. 2015) and lmerTest  
297 (Kunzetsova et al. 2017) packages. For all test computed, models accuracy was tested  
298 using the check\_model function from the performance package (Lüdecke et al. 2020).  
299 When models did not fit the data, the response variable was log+1 transformed.  
300 Binomials models accuracy was also tested by checking overdispersion. Significance  
301 level was set at 0.05, differences at a p-value level <0.1 were considered marginal. For  
302 all comparisons studied, mean  $\pm$  SE of each group are given in Appendix B.

303

### 304 **2.5.1. Reproductive effort**

305 We evaluated the effect of salinity (clutches laid in freshwater [0 g.l<sup>-1</sup>] or in brackish  
306 water [4 g.l<sup>-1</sup>]) on clutch length, clutch size (number of eggs), clutch mass, egg  
307 diameter, laying time, variation of body mass (for females and males). For these  
308 analyses, we set linear models (LMs), with salinity as an explanatory variable. We also  
309 tested for the relationships between egg diameter and clutch size in each salinity by  
310 setting a LM with egg diameter as a dependent variable, and clutch size, salinity and  
311 their interaction as explanatory variables. Finally, we tested for the effect of the  
312 interaction between female mass and salinity on clutch size and clutch mass, using



313 LMs. For these models, best variables were retained using a top-down selection (using  
314 p-values), and only the retained variables are presented.

315

### 316 *2.5.2. Embryonic development*

317 We evaluated the effect of salinity during spawning (clutch laid in freshwater [0 g.l<sup>-1</sup>]  
318 or in brackish water [4 g.l<sup>-1</sup>]), and during embryonic development (individuals  
319 developing in freshwater [0 g.l<sup>-1</sup>] or brackish water [4 g.l<sup>-1</sup>]).

320

321 We computed these effects on time to hatching (log+1 transformed) and individuals  
322 total size with Linear Mixed models (LMMs), and on hatching success, malformation  
323 rate, general activity and tadpole activity (both rated on a scale from 1 to 5) using  
324 binomial Generalized Linear Mixed Models (GLMMS). For all these models, we  
325 included salinity during spawning, salinity during embryonic development and their  
326 interaction as explanatory variables, and the clutch as a random effect (as multiple  
327 individuals originated from the same clutch). Best variables were retained using a top-  
328 down selection (using p-values), and only the retained variables are presented.

329

### 330 *2.5.3. Larval development*

331 We evaluated the effect of salinity at different stages of exposure. We computed the  
332 effect of salinity during spawning (clutches laid in freshwater [0 g.l<sup>-1</sup>] or in brackish  
333 water [4 g.l<sup>-1</sup>]), salinity during embryonic development (eggs developing in freshwater  
334 [0 g.l<sup>-1</sup>] or brackish water [4 g.l<sup>-1</sup>]), and salinity during larval development (individuals

335 developing in freshwater [0 g.l<sup>-1</sup>] or brackish water [4 g.l<sup>-1</sup>]). We computed these effects  
336 on development duration between S25 and S30, growth rate between GS25 and GS30,  
337 and total size (log+1 transformed) at GS30 with LMMs, and on mortality and activity  
338 (rated on a scale from 1 to 5) using binomial GLMMs. For all these models, we  
339 included salinity during spawning, salinity during embryonic development, salinity  
340 during larval development and their interaction as explanatory variables, and the  
341 clutch as a random effect (as multiple individuals originated from the same clutch).  
342 Best variables were retained using a top-down selection (using p-values), and only the  
343 retained variables are presented. At GS30, only 2 individuals were malformed (in FFS  
344 and FSF) and thus statistics were not computed. All data analysis were performed  
345 using R 3.6.3 (R Core Team 2020) and Rstudio v1.1.419.

346 **3. RESULTS**

347 **3.1. Reproductive effort**

348 Clutches produced in freshwater or in brackish water were similar for length  
349 (Estimate=70.05, SE= 263.58,  $t_{1,19}=0.27$ , p-value=0.793) and number of eggs  
350 (Estimate=182.60, SE= 405.40,  $t_{1,19}=0.45$ , p-value=0.658). However, clutches produced  
351 in freshwater were heavier (Estimate=28.21, SE= 13.07,  $t_{1,19}=2.16$ , p-value=0.044), and  
352 their eggs were marginally larger (Estimate=0.11, SE= 0.06,  $t_{1,19}=1.80$ , p-value=0.088,  
353 Figure 2A). Laying time was shorter for individuals that laid eggs in brackish water  
354 compared to those that laid eggs in freshwater (Estimate=-31.77, SE= 14.84,  $t_{1,19}=-2.14$ ,  
355 p-value=0.046, Figure 2B).

356

357 Egg diameter was related to the interaction between clutch size and salinity  
358 (Estimate<0.001, SE<0.001,  $t_{3,17}=2.65$ , p-value=0.017, Figure 2C). Egg diameter was not  
359 influenced by clutch size in clutches laid in freshwater (Estimate<0.001, SE<0.001,  
360  $t_{1,8}=1.21$ , p-value=0.260, Figure 2C), but increased with increasing clutch size in  
361 clutches laid in brackish water (Estimate<0.001, SE<0.001,  $t_{1,9}=2.40$ , p-value=0.040,  
362 Figure 2C).

363

364 Interestingly, females spawning at 0 g.l<sup>-1</sup> (-13.56 % ± 2.23 SE) and 4 g.l<sup>-1</sup> (-12.21 % ± 1.36  
365 SE) lost similar mass during egg laying (Estimate=1.35, SE=2.56,  $t_{1,19}=0.53$ , p-  
366 value=0.604). Males reproducing at 0 g.l<sup>-1</sup> lost mass (-1.63 % ± 2.19 SE) while males  
367 reproducing at 4 g.l<sup>-1</sup> gained mass (3.79% ± 1.27 SE) during egg laying (Estimate=5.41,  
368 SE=2.47,  $t_{1,19}=2.19$ , p-value=0.041).

369

370 Clutch size increased with female mass (Estimate=40.876, SE=10.303,  $t_{1.19}=3.967$ , p-  
371 value<0.001). When testing for the interaction between females body mass and  
372 salinity, clutch mass increased with female body mass (Estimate=1.211, SE=0.362,  
373  $t_{1.19}=3.347$ , p-value=0.004) and was higher in the freshwater treatment compared to the  
374 brackish one (Estimate=25.192, SE=10.579,  $t_{1.19}=2.831$ , p-value=0.029).

375

### 376 *3.2. Embryonic development*

377 Hatching success was higher for clutches produced in freshwater (Estimate=0.480,  
378 SE=0.194,  $z=2.649$ , p-value=0.014), and higher in embryos that developed in  
379 freshwater (Estimate=0.972, SE=0.064,  $z=15.103$ , p-value<0.001). There was an  
380 interaction between the salinity during spawning and the salinity during embryonic  
381 development (Estimate=-1.493, SE=0.141,  $z=-10.580$ , p-value<0.001, Figure 3A,  
382 Appendix C), hatching success being higher for individuals originating from a clutch  
383 laid in freshwater, and that developed in freshwater.

384 Malformation rate was higher in embryos which developed in brackish water  
385 (Estimate=0.893, SE=0.114,  $z=7.840$ , p-value<0.001), but not related to salinity during  
386 spawning (Estimate=0.086, SE=0.242,  $z=0.357$ , p-value=0.721). There was an  
387 interaction between the salinity during spawning and the salinity during embryonic  
388 development (Estimate=-1.059, SE=0.301,  $z=-3.524$ , p-value<0.001, Figure 3B,  
389 Appendix C), malformation rate being higher for individuals originating from a clutch  
390 laid in freshwater, and that developed in brackish water.

391 Time to hatching was higher in embryos which developed in brackish water  
392 (Estimate=0.107, SE=0.013,  $t_{1.221}=8.387$ , p-value<0.001), but not related to spawning in

393 brackish water (Estimate=0.004, SE=0.025,  $t_{1.27}=0.168$ , p-value=0.868). There was an  
394 interaction between the salinity during spawning and the salinity during embryonic  
395 development (longer time to hatching for individuals that were laid in freshwater but  
396 developed in brackish water, Estimate=-0.065, SE=0.021,  $t_{1.218}=-3.104$ , p-value=0.002,  
397 Appendix C).

398 General activity (Estimate=1.164, SE=0.173,  $z=6.735$ , p-value<0.001), tadpole activity  
399 (Estimate=1.141, SE=0.117,  $z=9.706$ , p-value<0.001) and total length (Estimate=-2.157,  
400 SE=0.0.139,  $t_{1.228}=-15.540$ , p-value<0.001, Figure 3C) were all influenced by salinity  
401 experienced during embryonic development solely, and were higher for embryos that  
402 developed in freshwater.

403

404

### 405 ***3.3. Larval development***

406 Mortality at GS30 was influenced by salinity to which individuals were exposed  
407 during embryonic development (higher for individuals which embryonic  
408 development occurred in brackish water [FSF, FSS, SSF and SSS], Estimate=3.405,  
409 SE=0.005,  $z=676.3$ , p-value<0.001, Figure 4A) and during larval development (higher  
410 for larvae developing in brackish water [FFS, FSS, SFS and SSS], Estimate=1.421,  
411 SE=0.005,  $z=282.5$ , p-value<0.001, Figure 4A), but not their interaction.

412 Development duration between S25 and S30 varied with salinity during embryonic  
413 development (longer for individuals which embryonic development occurred in  
414 brackish water [particularly FSS, SSF and SSS], Estimate=1.409, SE=0.635,  $t_{1.101}=2.218$ ,

415 p-value=0.029, Figure 4B), and there was an interaction between salinity during  
416 embryonic development and salinity during larval development (Estimate=3.307,  
417 SE=1.095,  $t_{1,91}=3.020$ , p-value=0.003, Figure 4B, Appendix D), as well as between  
418 salinity during spawning and salinity during larval development (Estimate=-2.914,  
419 SE=0.768,  $t_{1,94}=-3.793$ , p-value<0.001, Figure 4B, Appendix D).

420 Growth rate between GS25 and GS30 was only influenced by salinity during  
421 embryonic development, and was higher for individuals which embryonic  
422 development occurred in brackish water (particularly FSF for individuals laid in  
423 freshwater, and SSF and SSS for individuals laid in brackishwater, Estimate=0.081,  
424 SE=0.036,  $t_{1,110}=2.240$ , p-value=0.027, Figure 4C).

425 Total length was influenced by salinity experienced during embryonic development  
426 solely, decreasing for individuals which embryonic development occurred in brackish  
427 water (Estimate=-0.033, SE=0.012,  $t_{1,110}=-2.653$ , p-value=0.009, Figure 4D). Conversely,  
428 activity (Estimate=-0.350, SE=0.147,  $z=-2.387$ , p-value=0.017) was influenced by  
429 salinity during larval development solely, decreasing for larvae that developed in  
430 brackish water (particularly FFS, FFS and SFS).

## 431 4. DISCUSSION

432 Our study demonstrated that environmental salinity can negatively affect  
433 reproduction, as well as embryonic and larval development in a coastal anuran.  
434 Importantly, our full-factorial design allowed us to highlight that early exposure to  
435 brackish water did not induce increased tolerance during later exposure (i.e., tadpoles  
436 spawned in brackish water did not perform better in brackish water). However,  
437 individuals returned to freshwater after being exposed to brackish water expressed  
438 partial recovery, indicating resilience to salinity stress.

439

### 440 *4.1. Reproduction*

441 Clutch size did not differ between freshwater and brackish water treatment, and clutch  
442 size increased with female size and female mass loss for both treatments, with no  
443 difference between the two treatments. Such results further suggest that clutch size  
444 might depend on energetic investment that occurred prior to egg laying (Sinervo and  
445 DeNardo 1996; Nilsson and Svensson 1997; Lorrain-Soligon et al. 2023a). Interestingly,  
446 we found that salinity influenced some reproductive parameters in adults, suggesting  
447 a rapid modulation of reproductive effort based on the salinity to which reproductive  
448 adults were exposed. Indeed, reproductive adults exposed to brackish water laid their  
449 eggs more rapidly than those kept in fresh water. Two opposing hypotheses can  
450 explain such result. First, females may lay their eggs more rapidly in brackish water  
451 in order to evade an osmotically constraining environment. Conversely, because adult  
452 individuals originated from salt-exposed coastal environment, they may consider  
453 brackish water as a favourable environment if they are locally adapted to such

454 conditions and if there are less competitors in this environment (Hopkins and Brodie  
455 2015; Lorrain-Soligon et al. 2023b); but delay laying in freshwater because they  
456 consider this environment as suboptimal. This later hypothesis seems relatively  
457 unlikely as our first hypothesis is further supported by the fact that, in brackish water,  
458 eggs were smaller but not fewer. This result suggests that females produced eggs of  
459 comparatively lower quality in brackish water, as eggs produced in the freshwater  
460 treatment are marginally larger, and larger eggs often have higher hatching success  
461 and offspring fitness (Xu et al. 2019; Renoirt et al. 2022). The number of undeveloped  
462 eggs (presumably unfertilized given the negative effect of salinity on sperm, (Wilder  
463 and Welch 2014; Green et al. 2021)) was also higher in brackish water.

464

465 Interestingly, despite the marginal effect of salinity on egg size, females from both  
466 treatments lost a similar amount of mass. In combination with smaller eggs, this result  
467 could be linked to a relatively larger investment in egg jellies (which are critical to egg  
468 development and protection, Bonnell & Chandler, 1996; Yurewicz et al., 1975) in  
469 females exposed to brackish water, a hypothesis that is not supported by clutch mass  
470 which was higher for females exposed to freshwater. However, investigations focusing  
471 on investment in egg protection (egg jellies) in response to environmental salinity  
472 remain too scarce. More likely, the fact that females exposed to brackish water have  
473 lost a similar amount of mass than their counterpart exposed to freshwater but laid  
474 smaller eggs might be linked to direct costs of osmoregulation in adult amphibians  
475 exposed to brackish water (Lorrain-Soligon et al. 2022). These variations should be



476 investigated through the evaluation of metabolic rates in reproducing adults exposed  
477 to different salinities.

478

479 The fact that clutch mass was higher in the freshwater treatment is likely linked to  
480 water absorption due to osmotic exchanges with the environment (Venturino et al.  
481 2003; Karraker and Gibbs 2011; López-Alcaide and Macip-Ríos 2011), or due to higher  
482 investment in glycoproteins surrounding the eggs (i.e. egg jellies, see above). More  
483 importantly, we found a positive correlation between egg size and clutch size for  
484 clutches laid in brackish water but not for clutches laid in freshwater, while fecundity  
485 was expected to negatively trade off with egg size (Lasne et al., 2018; Smith & Fretwell,  
486 1974). Based on the fractional egg hypothesis (Ricklefs 1968; Nussbaum 1981; Ford and  
487 Seigel 2010), the negative relation between fecundity and egg size is expected because  
488 species with large clutch sizes and small eggs (typical of Bufonid toads, Wells, 2007)  
489 should add additional offspring should extra energy become available (Ricklefs 1968;  
490 Nussbaum 1981). In our study, we found that increased clutch size is concomitant  
491 with increased egg size in clutches laid in brackish water suggesting that complex  
492 interactions between prior energetic investment in reproduction and current spawning  
493 conditions govern reproductive effort.

494

495 Lastly, reproducing males have lost mass in freshwater, but gained mass in brackish  
496 water. Such result could be linked to reduced ejaculate volume, with males in  
497 freshwater producing more sperm than their counterparts exposed to brackish water.

498 This hypothesis seems corroborated by the reduced proportion of fertilized eggs in the  
499 brackish treatment. However, we did not evaluate sperm volume in each treatment,  
500 which might need to be investigated. However, this gain of mass in males can also be  
501 linked to the fact that they can be osmotically imbalanced (Hall et al. 2020; Tornabene  
502 et al. 2021b).

503

504 Overall, the effects of salinity we found on reproductive adults and clutches clearly  
505 affect the investment in reproduction, which suggest that reproductive pond selection  
506 in heterogeneous environment may allow to circumvent such environmental  
507 constraint (Albecker and McCoy 2017). However, if coastal salinization continues to  
508 increase (Herbert et al. 2015; Singh 2021; Cunillera-Montcusí et al. 2022) and  
509 individuals are constrained to reproduce in brackish water, this could affect the quality  
510 of subsequent offspring development, and thereby negatively influence coastal  
511 population persistence.

512

#### 513 *4.2. Embryonic development*

514 We show that embryonic development duration increased for individuals that were  
515 exposed to 4 g.l<sup>-1</sup> salinity during embryonic development, but only when they were  
516 spawned in freshwater. Increased development time in response to salinity has been  
517 described in amphibians (see Christy and Dickman 2002; Sanzo and Hecnar 2006; Wu  
518 and Kam 2009; Wijethunga et al. 2016; Lukens and Wilcoxon 2020), an effect which can  
519 be due to increasing energy expenditure in osmotically stressful environments. At

520 hatching, individuals in the 4 g.l<sup>-1</sup> treatment were smaller (irrespective of the salinity  
521 in which they were spawned) (Wu and Kam 2009; Wood and Welch 2015; Haramura  
522 2016; Lukens and Wilcoxon 2020; Tornabene et al. 2021a), which is probably linked to  
523 higher costs of osmoregulation (Gomez-Mestre et al. 2004). Individuals in the 4 g.l<sup>-1</sup>  
524 treatment also presented lower activity. Interestingly, hatching success was always  
525 lower for individuals originating from a clutch that was spawned in brackish water  
526 irrespective of the salinity in which the remaining embryonic development occurred.  
527 Additionally, individuals that were laid in freshwater but developed in brackish water  
528 had a higher malformation rate compared to individuals in any other treatments. As  
529 individuals developing in the SF and SS groups (that were laid in brackish water)  
530 presented a higher mortality rate, this could indicate selective mortality affecting  
531 individuals susceptible to salinity, while more tolerant - surviving - individuals  
532 displayed lower malformation rates. This hypothesis is further supported by the fact  
533 that higher malformation rates were found in individuals spawned in freshwater that  
534 developed in brackish water (Gosner and Black 1957; Hopkins et al. 2013). Taken  
535 together, these results indicate long lasting effects of the salinity in which the clutch  
536 was produced (and thus long-lasting effect of very early exposure to salinity during  
537 embryonic development). Our results thus emphasize that embryos are sensitive to  
538 change in salinity during their development, which can occur through changes of  
539 temperatures and precipitations in coastal environments (Lorrain-Soligon et al. 2023c),  
540 which may carry-over during later larval development and potentially during post-  
541 metamorphic stages (Traversari 2021; Dahrouge and Rittenhouse 2022), affecting  
542 overall amphibian populations.

543

### 544 *4.3. Larval development*

545 Overall, development duration was longer for individuals that were spawned in  
546 brackish water, indicating long lasting, carry-over effects of the salinity in which adults  
547 lay eggs, and accumulating effects during larval development (see Tornabene et al.  
548 2021a). Individuals that experienced salinity during either embryonic or larval  
549 development (FSF, FFS, SSF and SFS) or during both stages (FSS and SSS) expressed  
550 higher mortality (see also Squires et al. 2010; Wu et al. 2012; Albecker and McCoy 2017;  
551 Hsu et al. 2018). Additionally, individuals that developed in brackish water during  
552 embryonic development were smaller (see also Squires et al. 2010), while there was no  
553 effects of salinity experienced during larval development on total length. These  
554 responses remain consistent regardless of the salinity in which clutches were spawned.  
555 This further suggest that salinity experienced during embryonic development is more  
556 detrimental than salinity experienced during larval development, which is in line with  
557 the idea that early developmental stages (embryos) are more sensitive to salinity than  
558 later developmental stages (larvae) (Albecker and McCoy 2017). This is likely due to  
559 the development of internal gills (the main organs responsible for ion and water  
560 balance in tadpoles, Uchiyama and Yoshizawa 1992) which improve the  
561 osmoregulation ability at this developmental stage. However, in the context of  
562 accumulating effects, larvae can be found to be more sensitive than embryos  
563 (Tornabene et al. 2021a), which highlight that this effect might be context dependent.

564

565 The detrimental effects of salinity on growth could be linked to changes in activity we  
566 found. Indeed, larvae exposed to higher salinity have been shown to express reduced  
567 activity and foraging behaviors (Hall et al. 2017; Tornabene et al. 2021a), lower  
568 responses to stimuli (Sanzo and Hecnar 2006; Karraker 2007), lower swimming  
569 performance (Haramura 2016), erratic movements (Tornabene et al. 2021a), and  
570 reduced speed and distance (Denoël et al. 2010).

571

572

573 Importantly, if individuals exposed to freshwater during larval development after  
574 being exposed to brackish water during their embryonic development (FSF and SSF),  
575 were smaller compared to those that were exposed to freshwater during most of their  
576 development (FFF and SFF), they expressed a higher growth rate. This result suggest  
577 partial compensatory responses, rather than full compensation or over-compensation  
578 (Ali et al. 2003). Compensatory growth may act as an adaptive mechanism because it  
579 increases the chance of an organism attaining a critical size at a given developmental  
580 stage and (i.e., metamorphosis, Wilbur and Collins 1973), which can ultimately  
581 influence fitness (Dmitriew 2011). It is a likely mechanisms in response to osmotic  
582 stress in coastal organisms (Hsu et al. 2018), allowing to overcome the negative effects  
583 of salinity by expressing catch-up growth when the salt stress ceases. Interestingly,  
584 some individuals were able to express compensatory growth, but not all, which may  
585 indicate differences in genotype or bacterium composition between individuals that  
586 may lead to local adaptation (Albecker et al. 2019, 2021; Gabriel et al. 2021).

587 Importantly, recent research suggests that, although compensatory growth can  
588 produce rapid benefits, it is also associated with delayed costs during later stages of  
589 development and/or adult life (Metcalfe and Monaghan 2001). Such costs include  
590 increased risk of predation, decreased resistance to starvation, decreased protein  
591 maintenance and increased muscle lesions, reduction in locomotor performance,  
592 reduced age at sexual maturation and higher telomere attrition rate (Metcalfe and  
593 Monaghan 2001). Indeed, accelerated growth is known to induce accumulated cellular  
594 damages which ultimately may impair fitness later in life (Mangel and Munch 2005),  
595 which could thus affect adults amphibians living in coastal environments

596

## 597 **5. CONCLUSION**

598 Reproduction, embryonic and larval development in amphibians are all affected by  
599 environmental salinity. Salinity in which individuals were spawned or salinity  
600 experienced during embryonic development can also carry-over during subsequent  
601 developmental stages, highlighting the importance of the environmental conditions  
602 during early development on ontogenetic trajectories. Our study focused on a salt-  
603 exposed – presumably salt tolerant -coastal anuran, highlighting that temporal and  
604 spatial variations of salinity might outperform local adaptation, potentially  
605 threatening coastal populations if salinity happens to increase. Importantly, we also  
606 highlighted partial compensation when individuals were transferred to freshwater,  
607 which can be a useful response in coastal environments. This partial compensation  
608 (which will still depend on the response of each life stage to these fluctuating levels of  
609 salinity) might be helpful for individuals in order to express resilience when

610 freshwater become available, and might help to set-up conservation measures. Indeed,  
611 our results might indicate that, following a massive salinization, individuals may be  
612 transferred to less impacted adjacent ponds, which might induce survival of the  
613 populations given individuals' resilience. This might be applicable by practitioners  
614 following a brutal marine submersion, focusing preferentially on embryos, that are  
615 shown to be more sensitive. Whether such approach reveals cost-effective in response  
616 to ongoing global changes remain to be considered.

617

618

619 **References**

- 620 Albecker MA, Belden LK, McCoy MW (2019) Comparative analysis of anuran  
621 amphibian skin microbiomes across inland and coastal wetlands. *Microb Ecol*  
622 78:348–360. <https://doi.org/10.1007/s00248-018-1295-9>
- 623 Albecker MA, McCoy MW (2017) Adaptive responses to salinity stress across  
624 multiple life stages in anuran amphibians. *Front Zool* 14:1–16.  
625 <https://doi.org/10.1186/s12983-017-0222-0>
- 626 Albecker MA, Stuckert AMM, Balakrishnan CN, McCoy MW (2021) Molecular  
627 mechanisms of local adaptation for salt-tolerance in a treefrog. *Molecular*  
628 *Ecology* 30:2065–2086. <https://doi.org/10.1111/mec.15867>
- 629 Ali M, Nicieza A, Wootton RJ (2003) Compensatory growth in fishes: a response to  
630 growth depression. *Fish and fisheries* 4:147–190.  
631 <https://doi.org/10.1046/j.1467-2979.2003.00120.x>
- 632 Amores MJ, Verones F, Raptis C, et al (2013) Biodiversity impacts from salinity  
633 increase in a coastal wetland. *Environmental science & technology* 47:6384–  
634 6392. <https://doi.org/10.1021/es3045423>
- 635 Anufriieva E, Shadrin N (2018) Diversity of fauna in Crimean hypersaline water  
636 bodies. *Journal of Siberian Federal University Biology* 11:294–305.  
637 <https://doi.org/10.17516/1997-1389-0073>
- 638 Bakker AM, Wong TE, Ruckert KL, Keller K (2017) Sea-level projections representing  
639 the deeply uncertain contribution of the West Antarctic ice sheet. *Scientific*  
640 *Reports* 7:1–7. <https://doi.org/10.1038/s41598-017-04134-5>
- 641 Bates D, Mächler M, Bolker B, Walker S (2015) Fitting linear mixed-effects models  
642 using lme4. *Journal of Statistical Software* 67:1–48.  
643 <https://doi.org/10.18637/jss.v067.i01>
- 644 Bernabò I, Bonacci A, Coscarelli F, et al (2013) Effects of salinity stress on *Bufo*  
645 *balearicus* and *Bufo bufo* tadpoles: Tolerance, morphological gill alterations and  
646 Na<sup>+</sup>/K<sup>+</sup>-ATPase localization. *Aquatic toxicology* (Amsterdam, Netherlands)  
647 132-133C:119–133. <https://doi.org/10.1016/j.aquatox.2013.01.019>
- 648 Bonnell BS, Chandler DE (1996) Egg jelly layers of *Xenopus laevis* are unique in  
649 ultrastructure and sugar distribution. *Molecular Reproduction and*  
650 *Development: Incorporating Gamete Research* 44:212–220.  
651 [https://doi.org/10.1002/\(SICI\)1098-2795\(199606\)44:2<212::AID-](https://doi.org/10.1002/(SICI)1098-2795(199606)44:2<212::AID-MRD10>3.0.CO;2-4)  
652 [MRD10>3.0.CO;2-4](https://doi.org/10.1002/(SICI)1098-2795(199606)44:2<212::AID-MRD10>3.0.CO;2-4)
- 653 Brady SP (2013) Microgeographic maladaptive performance and deme depression in  
654 response to roads and runoff. *PeerJ* 1:e163. <https://doi.org/10.7717/peerj.163>



- 655 Byrne PG, Anastas ZM, Silla AJ (2022) A test for plasticity in sperm motility  
656 activation in response to osmotic environment in an anuran amphibian.  
657 Ecology and Evolution 12:e9387. <https://doi.org/10.1002/ece3.9387>
- 658 Byrne PG, Dunne C, Munn AJ, Silla AJ (2015) Environmental osmolality influences  
659 sperm motility activation in an anuran amphibian. Journal of Evolutionary  
660 Biology 28:521–534. <https://doi.org/10.1111/jeb.12584>
- 661 Cañedo-Argüelles M, Kefford BJ, Piscart C, et al (2013) Salinisation of rivers: An  
662 urgent ecological issue. Environmental Pollution 173:157–167.  
663 <https://doi.org/10.1016/j.envpol.2012.10.011>
- 664 Cheron M, Raelison L, Kato A, et al (2021) Ontogenetic changes in activity,  
665 locomotion and behavioural complexity in tadpoles. Biological Journal of the  
666 Linnean Society 134:165–176. <https://doi.org/10.1093/biolinnean/blab077>
- 667 Chinathamby K, Reina RD, Bailey PCE, Lees BK (2006) Effects of salinity on the  
668 survival, growth and development of tadpoles of the brown tree frog, *Litoria*  
669 *ewingii*. Aust J Zool 54:97–105. <https://doi.org/10.1071/ZO06006>
- 670 Chivers DP, Kiesecker JM, Marco A, et al (2001) Predator-induced life history  
671 changes in amphibians: egg predation induces hatching. Oikos 92:135–142.  
672 <https://doi.org/10.1034/j.1600-0706.2001.920116.x>
- 673 Christy M, Dickman C (2002) Effects of salinity on tadpoles of the Green and Golden  
674 Bell Frog (*Litoria aurea*). Amphibia-Reptilia 23:1–11.  
675 <https://doi.org/10.1163/156853802320877582>
- 676 Chuang M, Cheng Y-J, Andersen D, et al (2022) Increasing salinity stress decreases  
677 the thermal tolerance of amphibian tadpoles in coastal areas of Taiwan.  
678 Scientific Reports 12:9014. <https://doi.org/10.1038/s41598-022-12837-7>
- 679 Church JA, White NJ (2011) Sea-level rise from the late 19th to the early 21st century.  
680 Surv Geophys 32:585–602. <https://doi.org/10.1007/s10712-011-9119-1>
- 681 Cunillera-Montcusí D, Beklioğlu M, Cañedo-Argüelles M, et al (2022) Freshwater  
682 salinisation: a research agenda for a saltier world. Trends in Ecology &  
683 Evolution 37:440–453. <https://doi.org/10.1016/j.tree.2021.12.005>
- 684 Dahrouge NC, Rittenhouse TAG (2022) Variable temperature regimes and wetland  
685 salinity reduce performance of juvenile wood frogs. Oecologia 199:1021–1033.  
686 <https://doi.org/10.1007/s00442-022-05243-3>
- 687 Debue M, Ouédraogo D-Y, Sordello R, Reyjol Y (2022) Impacts of coastal realignment  
688 on biodiversity. A systematic review and meta-analysis. Basic and Applied  
689 Ecology 60:48–62. <https://doi.org/10.1016/j.baae.2022.01.009>

- 690 Denoël M, Bichot M, Ficetola GF, et al (2010) Cumulative effects of road de-icing salt  
691 on amphibian behavior. *Aquatic Toxicology* 99:275–280.  
692 <https://doi.org/10.1016/j.aquatox.2010.05.007>
- 693 Denver RJ, Glennemeier KA, Boorse GC (2002) Endocrinology of complex life cycles:  
694 amphibians. In: *Hormones, brain and behavior*. Elsevier, pp 469–XI
- 695 Dettinger M (2011) Climate change, atmospheric rivers, and floods in California - A  
696 multimodel analysis of storm frequency and magnitude changes. *JAWRA*  
697 *Journal of the American Water Resources Association* 47:514–523.  
698 <https://doi.org/10.1111/j.1752-1688.2011.00546.x>
- 699 Dmitriew CM (2011) The evolution of growth trajectories: what limits growth rate?  
700 *Biological Reviews* 86:97–116. [https://doi.org/10.1111/j.1469-](https://doi.org/10.1111/j.1469-185X.2010.00136.x)  
701 [185X.2010.00136.x](https://doi.org/10.1111/j.1469-185X.2010.00136.x)
- 702 Dougherty C, Smith G (2006) Acute effects of road de-icers on the tadpoles of three  
703 anurans. *Appl Herpetol* 3:87–93.  
704 <https://doi.org/10.1163/157075406776984266>
- 705 Estévez E, Rodríguez-Castillo T, González-Ferreras AM, et al (2019) Drivers of spatio-  
706 temporal patterns of salinity in Spanish rivers: a nationwide assessment.  
707 *Philosophical Transactions of the Royal Society B* 374:20180022.  
708 <https://doi.org/10.1098/rstb.2018.0022?rss=1>
- 709 Evans DH (2009) *Osmotic and ionic regulation: cells and animals*. CRC Press.
- 710 Evans TG, Kültz D (2020) The cellular stress response in fish exposed to salinity  
711 fluctuations. *Journal of Experimental Zoology Part A: Ecological and*  
712 *Integrative Physiology* 333:421–435. <https://doi.org/10.1002/jez.2350>
- 713 Ford NB, Seigel RA (2010) An experimental test of the fractional egg size hypothesis.  
714 *Herpetologica* 66:451–455. <https://doi.org/10.1655/09-057.1>
- 715 Froneman PW (2023) The effect of salinity on the egg production rate of the sac-  
716 spawning calanoid copepod, *Pseudodiaptomus hessei*, in a temporarily  
717 open/closed Southern African estuary. *Diversity* 15:263.  
718 <https://doi.org/10.3390/d15020263>
- 719 Fu Z, Wu F, Zhang Z, et al (2021) Sea surface salinity estimation and spatial-temporal  
720 heterogeneity analysis in the gulf of Mexico. *Remote Sensing* 13:881.  
721 <https://doi.org/10.3390/rs13050881>
- 722 Gabriel A, Costa S, Henriques I, Lopes I (2021) Effects of long-term exposure to  
723 increased salinity on the amphibian skin bacterium *Erwinia toletana*. *Arch*  
724 *Environ Contam Toxicol* 80:779–788. [https://doi.org/10.1007/s00244-021-](https://doi.org/10.1007/s00244-021-00845-z)  
725 [00845-z](https://doi.org/10.1007/s00244-021-00845-z)

- 726 Gomez-Mestre I, Tejedo M (2003) Local adaptation of an anuran amphibian to  
727 osmotically stressful environments. *Evolution* 57:1889–1899.  
728 <https://doi.org/10.1111/j.0014-3820.2003.tb00596.x>
- 729 Gomez-Mestre I, Tejedo M, Ramayo E, Estepa J (2004) Developmental alterations and  
730 osmoregulatory physiology of a larval anuran under osmotic stress.  
731 *Physiological and Biochemical Zoology* 77:267–274.  
732 <https://doi.org/10.1086/378143>
- 733 Gosner KL (1960) A simplified table for staging anuran embryos and larvae with  
734 notes on identification. *Herpetologica* 16:183–190
- 735 Gosner KL, Black IH (1957) The effects of acidity on the development and hatching of  
736 New Jersey frogs. *Ecology* 38:256–262. <https://doi.org/10.2307/1931684>
- 737 Green L, Niemax J, Herrmann J-P, et al (2021) Sperm performance limits the  
738 reproduction of an invasive fish in novel salinities. *Diversity and Distributions*  
739 27:1091–1105. <https://doi.org/10.1111/ddi.13258>
- 740 Hall EM, Brady SP, Mattheus NM, et al (2017) Physiological consequences of  
741 exposure to salinized roadside ponds on wood frog larvae and adults.  
742 *Biological Conservation* 209:98–106.  
743 <https://doi.org/10.1016/j.biocon.2017.02.013>
- 744 Hall EM, Brunner JL, Hutzenbiler B, Crespi EJ (2020) Salinity stress increases the  
745 severity of ranavirus epidemics in amphibian populations. *Proc R Soc B*  
746 287:20200062. <https://doi.org/10.1098/rspb.2020.0062>
- 747 Haramura T (2016) Hatching plasticity in response to salinity levels in a rhacophorid  
748 frog inhabiting a coastal area. *J Zool* 299:125–131.  
749 <https://doi.org/10.1111/jzo.12323>
- 750 Haramura T (2007) Salinity tolerance of eggs of *Buergeria japonica* (Amphibia, Anura)  
751 inhabiting coastal areas. *Zoological Science* 24:820–823.  
752 <https://doi.org/10.2108/zsj.24.820>
- 753 Hart BT, Lake PS, Webb JA, Grace MR (2003) Ecological risk to aquatic systems from  
754 salinity increases. *Aust J Bot* 51:689–702. <https://doi.org/10.1071/bt02111>
- 755 Herbert ER, Boon P, Burgin AJ, et al (2015) A global perspective on wetland  
756 salinization: ecological consequences of a growing threat to freshwater  
757 wetlands. *Ecosphere* 6:1–43. <https://doi.org/10.1890/ES14-00534.1>
- 758 Hieu DQ, Hang BTB, Huong DTT, et al (2021) Salinity affects growth performance,  
759 physiology, immune responses and temperature resistance in striped catfish  
760 (*Pangasianodon hypophthalmus*) during its early life stages. *Fish Physiol*  
761 *Biochem* 47:1995–2013. <https://doi.org/10.1007/s10695-021-01021-9>

- 762 Hintz WD, Relyea RA (2019) A review of the species, community, and ecosystem  
763 impacts of road salt salinisation in fresh waters. *Freshwater biology* 64:1081–  
764 1097. <https://doi.org/10.1111/fwb.13286>
- 765 Hoover Z, Ferrari MC, Chivers DP (2013) The effects of sub-lethal salinity  
766 concentrations on the anti-predator responses of fathead minnows.  
767 *Chemosphere* 90:1047–1052.  
768 <https://doi.org/10.1016/j.chemosphere.2012.08.051>
- 769 Hopkins G, French S, Brodie III E (2013) Increased frequency and severity of  
770 developmental deformities in rough-skinned newt (*Taricha granulosa*) embryos  
771 exposed to road deicing salts (NaCl & MgCl<sub>2</sub>). *Environmental pollution*  
772 (Barking, Essex : 1987) 173C:264–269.  
773 <https://doi.org/10.1016/j.envpol.2012.10.002>
- 774 Hopkins GR, Brodie ED (2015) Occurrence of amphibians in saline habitats: A review  
775 and evolutionary perspective. *Herpetological Monographs* 29:1–27.  
776 <https://doi.org/10.1655/HERPMONOGRAPHS-D-14-00006>
- 777 Hoverman JT, Relyea RA (2008) Temporal environmental variation and phenotypic  
778 plasticity: a mechanism underlying priority effects. *Oikos* 117:23–32.  
779 <https://doi.org/10.1111/j.2007.0030-1299.15969.x>
- 780 Hsu W-T, Wu C-S, Hatch KA, et al (2018) Full compensation of growth in salt-  
781 tolerant tadpoles after release from salinity stress. *Journal of Zoology* 304:141–  
782 149. <https://doi.org/10.1111/jzo.12508>
- 783 IPCC (2022) *Climate change 2022: Impacts, adaptation, and vulnerability.*  
784 *Contribution of Working Group II to the Sixth Assessment Report of the*  
785 *Intergovernmental Panel on Climate Change.* [H.-O. Pörtner, D.C. Roberts, M.  
786 Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S.  
787 Löschke, V. Möller, A. Okem, B. Rama (Eds.)], Cambridge Univ. Press.  
788 Cambridge Univ. Press.
- 789 Jones B, Snodgrass JW, Ownby DR (2015) Relative toxicity of NaCl and road deicing  
790 salt to developing amphibians. *Copeia* 103:72–77.  
791 <https://doi.org/10.1643/CP-13-082>
- 792 Karraker NE (2007) Are embryonic and larval green frogs (*Rana clamitans*) insensitive  
793 to road deicing salt? *Herpetol Conserv Biol* 2:35–41
- 794 Karraker NE, Gibbs JP (2011) Road deicing salt irreversibly disrupts osmoregulation  
795 of salamander egg clutches. *Environmental Pollution* 159:833–835.  
796 <https://doi.org/10.1016/j.envpol.2010.11.019>
- 797 Karraker NE, Gibbs JP, Vonesh JR (2008) Impacts of road deicing salt on the  
798 demography of vernal pool-breeding amphibians. *Ecological Applications*  
799 18:724–734. <https://doi.org/10.1890/07-1644.1>

- 800 Katz U (1989) Strategies of adaptation to osmotic stress in anuran Amphibia under  
801 salt and burrowing conditions. *Comparative Biochemistry and Physiology*  
802 *Part A: Physiology* 93:499–503. [https://doi.org/10.1016/0300-9629\(89\)90001-7](https://doi.org/10.1016/0300-9629(89)90001-7)
- 803 Knighton AD, Mills K, Woodroffe CD (1991) Tidal-creek extension and saltwater  
804 intrusion in northern Australia. *Geology* 19:831–834.  
805 [https://doi.org/10.1130/0091-7613\(1991\)019<0831:TCEASI>2.3.CO;2](https://doi.org/10.1130/0091-7613(1991)019<0831:TCEASI>2.3.CO;2)
- 806 Knutson TR, McBride JL, Chan J, et al (2010) Tropical cyclones and climate change.  
807 *Nature geoscience* 3:157–163. <https://doi.org/10.1002/wcc.371>
- 808 Kültz D (2015) Physiological mechanisms used by fish to cope with salinity stress.  
809 *The Journal of Experimental Biology* 218:1907–1914.  
810 <https://doi.org/10.1242/jeb.118695>
- 811 Kunzetsova A, Brockhoff P, Christensen R (2017) lmerTest package: Tests in linear  
812 mixed effect models. *Journal of Statistical Software* 82:1–26.  
813 <https://doi.org/10.18637/jss.v082.i13>
- 814 Lasne E, Leblanc CA-L, Gillet C (2018) Egg size versus number of offspring trade-off:  
815 Female age rather than size matters in a domesticated Arctic charr population.  
816 *Evolutionary Biology* 45:105–112. <https://doi.org/10.1007/s11692-017-9433-8>
- 817 Leite T, Branco P, Ferreira MT, Santos JM (2022) Activity, boldness and schooling in  
818 freshwater fish are affected by river salinization. *Science of The Total*  
819 *Environment* 819:153046. <https://doi.org/10.1016/j.scitotenv.2022.153046>
- 820 Liu P, Zhao B, Zhang J, et al (2022) Responses of survival, growth, and feeding of the  
821 invasive Golden Apple Snail (*Pomacea canaliculata*) to salinity stress.  
822 *Freshwater Science* 41:000–000. <https://doi.org/10.1086/721026>
- 823 López-Alcaide S, Macip-Ríos R (2011) Effects of climate change in amphibians and  
824 reptiles. In: *Biodiversity loss in a changing planet*, Grillo, O., Y. G., Venora,  
825 Eds.; InTech: Rijeka,. InTech Rijeka, pp 163–184
- 826 Lorrain-Soligon L, Bichet C, Robin F, Brischoux F (2022) From the field to the lab:  
827 Physiological and behavioural consequences of environmental salinity in a  
828 coastal frog. *Frontiers in Physiology* 13:919165.  
829 <https://doi.org/10.3389/fphys.2022.919165>
- 830 Lorrain-Soligon L, Périsset L, Robin F, et al (2023a) The costs of living on the coast:  
831 Reduction in body size and size-specific reproductive output in coastal  
832 populations of a widespread amphibian. *Functional Ecology* 37:2703–2717.  
833 <https://doi.org/10.1111/1365-2435.14413>
- 834 Lorrain-Soligon L, Robin F, Barbraud C, Brischoux F (2023b) Some like it salty:  
835 Spatio-temporal dynamics of salinity differentially affect anurans and  
836 caudates in coastal wetlands. *Freshwater Biology* 68:1279–1292.  
837 <https://doi.org/10.1111/fwb.14103>

- 838 Lorrain-Soligon L, Robin F, Bertin X, et al (2023c) Long-term trends of salinity in  
839 coastal wetlands: Effects of climate, extreme weather events, and sea water  
840 level. *Environmental Research* 237:116937.  
841 <https://doi.org/10.1016/j.envres.2023.116937>
- 842 Lüdecke D, Makowski D, Waggoner P, Patil I (2020) Performance: assessment of  
843 regression models performance. *Journal of Open Source Software* 6:3139.  
844 <https://doi.org/10.21105/joss.03139>
- 845 Lukens E, Wilcoxon TE (2020) Effects of elevated salinity on Cuban treefrog  
846 *Osteopilus septentrionalis* aldosterone levels, growth, and development. *Marine*  
847 *and Freshwater Behaviour and Physiology* 53:99–111.  
848 <https://doi.org/10.1080/10236244.2020.1772062>
- 849 Mangel M, Munch SB (2005) A life-history perspective on short-and long-term  
850 consequences of compensatory growth. *The American Naturalist* 166:E155–  
851 E176. <https://doi.org/10.1086/444439>
- 852 Martin KL, Nagy KA (1997) Water balance and the physiology of the amphibian to  
853 amniote transition. In: *Amniote Origins*. Elsevier, pp 399–423
- 854 McLean RF, Tsyban A, Burkett V, et al (2001) Coastal zones and marine ecosystems.  
855 *Climate change* 343–379
- 856 Meek R (2022) Long-term changes in four populations of the spiny toad, *Bufo*  
857 *spinosus*, in Western France; Data from road mortalities. *Conservation* 2:248–  
858 261. <https://doi.org/10.3390/conservation2020017>
- 859 Metcalfe NB, Monaghan P (2001) Compensation for a bad start: grow now, pay later?  
860 *Trends in ecology & evolution* 16:254–260. [https://doi.org/10.1016/S0169-5347\(01\)02124-3](https://doi.org/10.1016/S0169-5347(01)02124-3)
- 862 Miaud C, Muratet J (2018) Identifier les oeufs et les larves des amphibiens de France.  
863 Editions Quae
- 864 Moniruzzaman M, Mukherjee M, Kumar S, Chakraborty SB (2022) Effects of salinity  
865 stress on antioxidant status and inflammatory responses in females of a “Near  
866 Threatened” economically important fish species *Notopterus chitala*: a  
867 mechanistic approach. *Environ Sci Pollut Res* 29:75031–75042.  
868 <https://doi.org/10.1007/s11356-022-21142-9>
- 869 Nicholls R, Hoozemans F, Marchand M (1999) Increasing flood risk and wetland  
870 losses due to global sea-level rise: regional and global analyses. *Global*  
871 *Environmental Change* 9:S69–S87. [https://doi.org/10.1016/S0959-3780\(99\)00019-9](https://doi.org/10.1016/S0959-3780(99)00019-9)
- 873 Nilsson J-Åke, Svensson E (1997) The cost of reproduction: a new link between  
874 current reproductive effort and future reproductive success. *Proceedings of*

- 875 the Royal Society of London Series B: Biological Sciences 263:711–714.  
876 <https://doi.org/10.1098/rspb.1996.0106>
- 877 Nussbaum RA (1981) Seasonal shifts in clutch size and egg size in the side blotched  
878 lizard *Uta stansburiana* Baird and Girard. *Oecologia* 49:8–13.  
879 <https://doi.org/10.1007/BF00376891>
- 880 Pechenik JA (2006) Larval experience and latent effects – metamorphosis is not a new  
881 beginning. *Integrative and Comparative Biology* 46:323–333.  
882 <https://doi.org/10.1093/icb/icj028>
- 883 Pinder AM, Halse SA, McRae JM, Shiel RJ (2005) Occurrence of aquatic invertebrates  
884 of the wheatbelt region of Western Australia in relation to salinity.  
885 *Hydrobiologia* 543:1–24. <https://doi.org/10.1007/s10750-004-5712-3>
- 886 R Core Team (2020) R: A language and environment for statistical computing. R  
887 Foundation for Statistical Computing. Austria: Vienna. [https://www.R-](https://www.R-project.org/)  
888 [project.org/](https://www.R-project.org/)
- 889 Ranjbar A, Ehteshami M (2019) Spatio-temporal mapping of salinity in the  
890 heterogeneous coastal aquifer. *Appl Water Sci* 9:1–14.  
891 <https://doi.org/10.1007/s13201-019-0908-x>
- 892 Reid AJ, Carlson AK, Creed IF, et al (2019) Emerging threats and persistent  
893 conservation challenges for freshwater biodiversity. *Biological Reviews*  
894 94:849–873. <https://doi.org/10.1111/brv.12480>
- 895 Renoirt M, Angelier F, Cheron M, Brischoux F (2022) What are the contributions of  
896 maternal and paternal traits to fecundity and offspring development? A case  
897 study in an amphibian species, the spined toad *Bufo spinosus*. *Current Zoology*  
898 zoac072. <https://doi.org/10.1093/cz/zoac072/6694174>
- 899 Ricklefs RE (1968) On the limitation of brood size in passerine birds by the ability of  
900 adults to nourish their young. *Proceedings of the National Academy of*  
901 *Sciences* 61:847–851. <https://doi.org/10.1073/pnas.61.3.847>
- 902 Rivera-Ingraham GA, Lignot J-H (2017) Osmoregulation, bioenergetics and oxidative  
903 stress in coastal marine invertebrates: raising the questions for future research.  
904 *J Exp Biol* 220:1749–1760. <https://doi.org/10.1242/jeb.135624>
- 905 Sanzo D, Hecnar SJ (2006) Effects of road de-icing salt (NaCl) on larval wood frogs  
906 (*Rana sylvatica*). *Environmental Pollution* 140:247–256.  
907 <https://doi.org/10.1016/j.envpol.2005.07.013>
- 908 Schneider CA, Rasband WS, Eliceiri KW (2012) NIH Image to ImageJ: 25 years of  
909 image analysis. *Nature methods* 9:671–675.  
910 <https://doi.org/10.1038/nmeth.2089>

- 911 Schultz ET, McCormick SD (2012) Euryhalinity in an evolutionary context. *Fish*  
912 *physiology* 32:477–533. <https://doi.org/10.1016/B978-0-12-396951-4.00010-4>
- 913 Shoemaker VH, Nagy KA (1984) Osmoregulation in the Galápagos marine iguana,  
914 *Amblyrhynchus cristatus*. *Physiological zoology* 57:291–300.  
915 <https://doi.org/10.1086/physzool.57.3.30163717>
- 916 Sinervo B, DeNardo DF (1996) Costs of reproduction in the wild: path analysis of  
917 natural selection and experimental tests of causation. *Evolution* 50:1299–1313.  
918 <https://doi.org/10.1111/j.1558-5646.1996.tb02370.x>
- 919 Singh A (2021) Soil salinization management for sustainable development: A review.  
920 *Journal of Environmental Management* 277:111383.  
921 <https://doi.org/10.1016/j.jenvman.2020.111383>
- 922 Smith CC, Fretwell SD (1974) The optimal balance between size and number of  
923 offspring. *The American Naturalist* 108:499–506.  
924 <https://doi.org/10.1086/282929>
- 925 Speybroeck J, Beukema W, Bok B, Van Der Voort J (2018) Guide Delachaux des  
926 amphibiens & reptiles de France et d'Europe. Delachaux et Nieslé
- 927 Squires ZE, Bailey PCE, Reina RD, Wong BBBM (2010) Compensatory growth in  
928 tadpoles after transient salinity stress. *Mar Freshwater Res* 61:219–222.  
929 <https://doi.org/10.1071/MF09123>
- 930 Tornabene BJ, Breuner CW, Hossack BR (2021a) Comparative effects of energy-  
931 related saline wastewaters and sodium chloride on hatching, survival, and  
932 fitness-associated traits of two amphibian species. *Environmental Toxicology*  
933 *and Chemistry* 40:3137–3147. <https://doi.org/10.1002/etc.5193>
- 934 Tornabene BJ, Crespi EJ, Breuner CW, Hossack BR (2022) Testing whether adrenal  
935 steroids mediate phenotypic and physiologic effects of elevated salinity on  
936 larval tiger salamanders. *Integrative Zoology* 18:27–44.  
937 <https://doi.org/10.1111/1749-4877.12669>
- 938 Tornabene BJ, Hossack BR, Crespi EJ, Breuner CW (2021b) Corticosterone mediates a  
939 growth-survival tradeoff for an amphibian exposed to increased salinity.  
940 *Journal of Experimental Zoology Part A: Ecological and Integrative*  
941 *Physiology* 335:703–715. <https://doi.org/10.1002/jez.2535>
- 942 Traversari BA (2021) Carry-over effects of elevated salinity and temperature on wood  
943 frog (*Rana sylvatica*) survival, growth, and behavior. PhD Thesis, Washington  
944 State University
- 945 Trenberth KE, Fasullo JT, Shepherd TG (2015) Attribution of climate extreme events.  
946 *Nature Clim Change* 5:725–730. <https://doi.org/10.1038/nclimate2657>



- 947 Uchiyama M, Yoshizawa H (1992) Salinity tolerance and structure of external and  
948 internal gills in tadpoles of the crab-eating frog, *Rana cancrivora*. Cell Tissue  
949 Res 267:35–44. <https://doi.org/10.1007/BF00318689>
- 950 Venturino A, Rosenbaum E, Caballero A, et al (2003) Biomarkers of effect in toads  
951 and frogs. Biomarkers : biochemical indicators of exposure, response, and  
952 susceptibility to chemicals 8:167–86.  
953 <https://doi.org/10.1080/1354700031000120116>
- 954 Vermeer M, Rahmstorf S (2009) Global sea level linked to global temperature.  
955 Proceedings of the National Academy of Sciences 106:21527–21532.  
956 <https://doi.org/10.1073/pnas.0907765106>
- 957 Visschers LLB, Santos CD, Franco AMA (2022) Accelerated migration of mangroves  
958 indicate large-scale saltwater intrusion in Amazon coastal wetlands. Science of  
959 The Total Environment 836:155679.  
960 <https://doi.org/10.1016/j.scitotenv.2022.155679>
- 961 Vonesh JR, Warkentin KM (2006) Opposite shifts in size at metamorphosis in  
962 response to larval and metamorph predators. Ecology 87:556–562.  
963 <https://doi.org/10.1890/05-0930>
- 964 Warkentin KM (2011) Plasticity of hatching in amphibians: evolution, trade-offs, cues  
965 and mechanisms. Integrative and comparative biology 51:111–127.  
966 <https://doi.org/10.1093/icb/icr046>
- 967 Wells KD (2007) The Ecology and Behavior of Amphibians, University of Chicago  
968 Press. University of Chicago Press
- 969 Werner EE (1986) Amphibian metamorphosis: growth rate, predation risk, and the  
970 optimal size at transformation. The American Naturalist 128:319–341.  
971 <https://doi.org/10.1086/284565>
- 972 Wijethunga U, Greenlees M, Shine R (2016) Living up to its name? The effect of  
973 salinity on development, growth, and phenotype of the “marine” toad  
974 (*Rhinella marina*). J Comp Physiol B 186:205–213.  
975 <https://doi.org/10.1007/s00360-015-0944-2>
- 976 Wilbur HM, Collins JP (1973) Ecological aspects of amphibian metamorphosis:  
977 nonnormal distributions of competitive ability reflect selection for facultative  
978 metamorphosis. Science 182:1305–1314
- 979 Wilder AE, Welch AM (2014) Effects of salinity and pesticide on sperm activity and  
980 oviposition site selection in green Treefrogs, *Hyla cinerea*. Copeia 2014:659–667.  
981 <https://doi.org/10.1643/CE-14-053>
- 982 Williams WD (2001) Anthropogenic salinisation of inland waters. In: Melack JM,  
983 Jellison R, Herbst DB (eds) Saline Lakes. Springer Netherlands, Dordrecht, pp  
984 329–337

- 985 Wood L, Welch AM (2015) Assessment of interactive effects of elevated salinity and  
986 three pesticides on life history and behavior of southern toad (*Anaxyrus*  
987 *terrestris*) tadpoles. *Environmental Toxicology and Chemistry* 34:667–676.  
988 <https://doi.org/10.1002/etc.2861>
- 989 Woodley A, Hintz LL, Wilmoth B, Hintz WD (2023) Impacts of water hardness and  
990 road deicing salt on zooplankton survival and reproduction. *Sci Rep* 13:2975.  
991 <https://doi.org/10.1038/s41598-023-30116-x>
- 992 Wu C-S, Gomez-Mestre I, Kam Y-C (2012) Irreversibility of a bad start: early  
993 exposure to osmotic stress limits growth and adaptive developmental  
994 plasticity. *Oecologia* 169:15–22. <https://doi.org/10.1007/s00442-011-2170-2>
- 995 Wu C-S, Kam Y-C (2009) Effects of salinity on the survival, growth, development,  
996 and metamorphosis of *Fejervarya limnocharis* tadpoles living in brackish water.  
997 *Zoological science* 26:476–82. <https://doi.org/10.2108/zsj.26.476>
- 998 Xu F, Yang W, Li Y (2019) Enlarged egg size increases offspring fitness of a frog  
999 species on the zhoushan archipelago of china. *Sci Rep* 9:11653.  
1000 <https://doi.org/10.1038/s41598-019-48147-8>
- 1001 Xue Z, He R, Fennel K, et al (2013) Modeling ocean circulation and biogeochemical  
1002 variability in the Gulf of Mexico. *Biogeosciences* 10:7219–7234.  
1003 <https://doi.org/10.5194/bg-10-7219-2013>
- 1004 Yurewicz EC, Oliphant G, Hedrick JL (1975) Macromolecular composition of *Xenopus*  
1005 *laevis* egg jelly coat. *Biochemistry* 14:3101–3107.  
1006 <https://doi.org/10.1021/bi00685a010>
- 1007

1008 **Statements & Declarations**

1009 **Ethical approval**

1010 This work was approved by the French authorities under permits

1011 DREAL/2020D/8041 (animals capture) and APAFIS #33592-2021102610033982

1012 (animals husbandry).

1013

1014 **Consent to participate**

1015 Not applicable.

1016

1017 **Consent to publish**

1018 Not applicable.

1019

1020 **Authors contribution**

1021 LLS and FB have conceptualized the study. LLS, FR and MJ participated to field

1022 prospection. LLS and TB participated to data collection. LLS analyzed the data. LLS

1023 and FB wrote the initial draft. All authors have reviewed and edited the manuscript

1024 and approved the final version.

1025

1026 **Funding statement**

1027 Funding was provided by the CNRS, La Rochelle Université, the LPO, the Agence de

1028 l'Eau Adour-Garonne, the Conseil Départemental de la Charente-Maritime, the ANR

1029 PAMPAS (ANR-18-CE32-0006), the Beauval Nature association and the Contrat de

1030 plan Etat-région Econat.

1031

1032 **Competing interest**

1033 The authors declare that they have no conflict of interest.

1034

1035 **Data archiving statement**

1036 Data supporting the findings of this study are made available as a supplementary  
1037 material.

1038

1039

1040 Caption to figures

1041 Figure 1 – Experimental design used to assess the effects of salinity during different  
1042 stages of development in *Bufo spinosus*. Colours represent salinity treatments (light  
1043 blue = fresh water [0 g.l<sup>-1</sup>], dark blue = brackish water [4 g.l<sup>-1</sup>]).

1044

1045 Figure 2 – Effects of salinity during spawning on reproductive parameters. (A) Egg  
1046 diameter, (B) clutch size (number of eggs), (C) relationships between clutch size and  
1047 egg diameter, for clutches produced in freshwater (0 g.l<sup>-1</sup>) or brackish water (4 g.l<sup>-1</sup>).  
1048 Data are presented as mean ± SE. See Figure 1 for sample size.

1049

1050 Figure 3 – Effects of salinity during spawning and embryonic development on  
1051 different aspects of embryonic development assessed upon hatching (Gosner stage 25).  
1052 (A) Hatching success, (B) malformation rate, and (C) total length (mm). FF: spawning  
1053 in freshwater [0 g.l<sup>-1</sup>], embryonic development in freshwater; FS: spawning in  
1054 freshwater, embryo in brackish water [4 g.l<sup>-1</sup>]; SF: spawning in brackish water, embryo  
1055 in freshwater; SS: spawning in brackish water, embryo in brackish water. Data are  
1056 presented as mean ± SE. See Figure 1 for sample size.

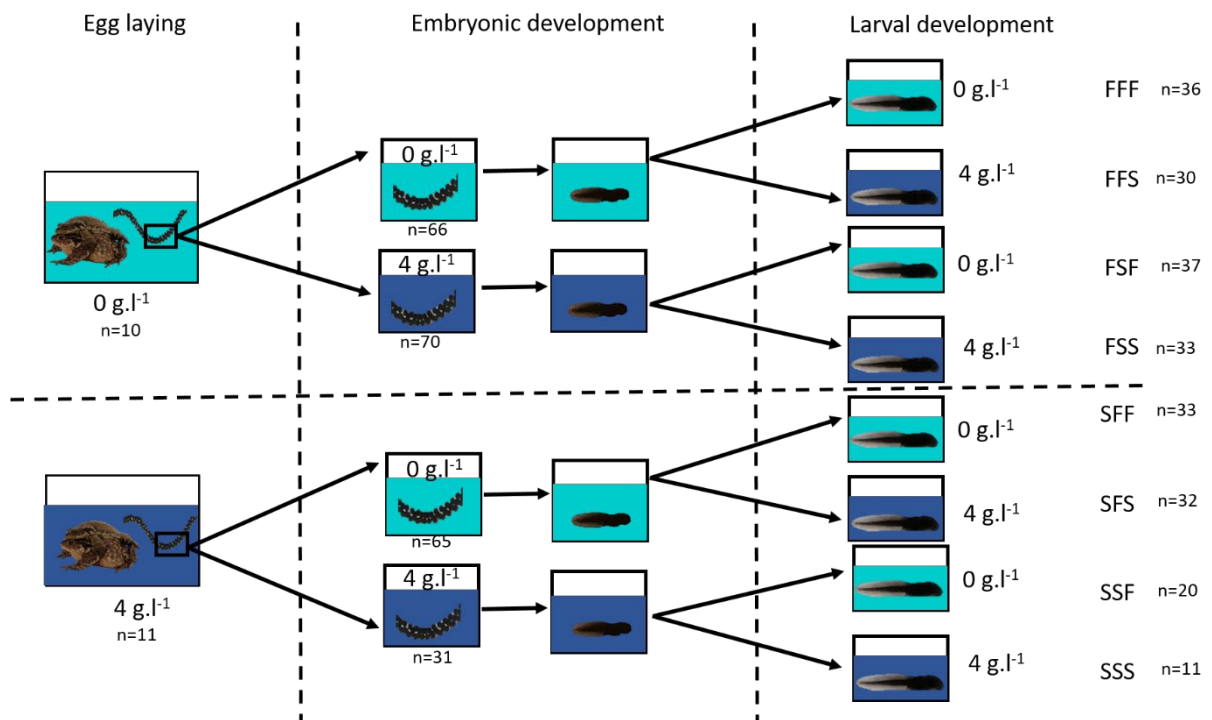
1057

1058 Figure 4 – Effects of salinity during spawning, embryonic development and larval  
1059 development on different parameters of larval development measured at Gosner stage  
1060 30. (A) Mortality rate, (B) duration between GS25 and GS30, (C) growth between GS25  
1061 and GS30, and (D) total length (mm). FFF: spawning in freshwater [0 g.l<sup>-1</sup>], embryonic  
1062 development in freshwater, larval development in freshwater; FSF: spawning in  
1063 freshwater, embryo in brackish water [4 g.l<sup>-1</sup>], larvae in freshwater; FFS: spawning in  
1064 freshwater, embryo in freshwater, larvae in brackish water; FSS: spawning in  
1065 freshwater, embryo in brackish water, larvae in brackish water; SFF: spawning in  
1066 brackish water, embryo in freshwater, larvae in freshwater; SSF: spawning in brackish  
1067 water, embryo in brackish water, larvae in freshwater; SFS: spawning in brackish  
1068 water, embryo in freshwater, larvae in brackish water; SSS: spawning in brackish  
1069 water, embryo in brackish water, larvae in brackish water. Data are presented as mean  
1070 ± SE. Treatments and sample size are illustrated in Figure 1.

1071

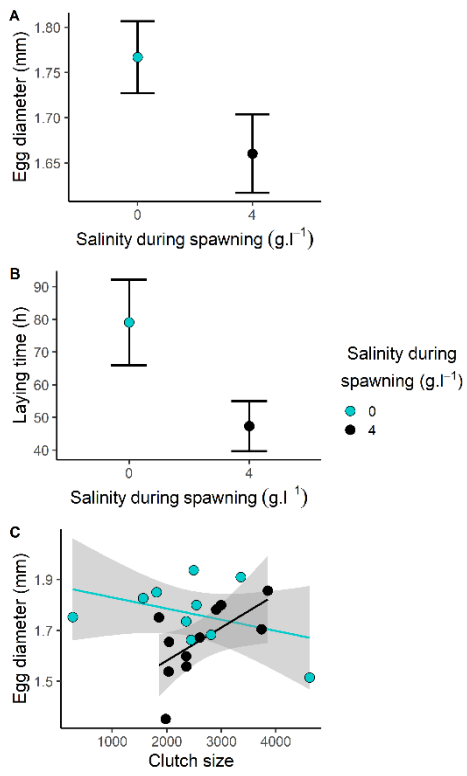
1072

1073 Figure 1



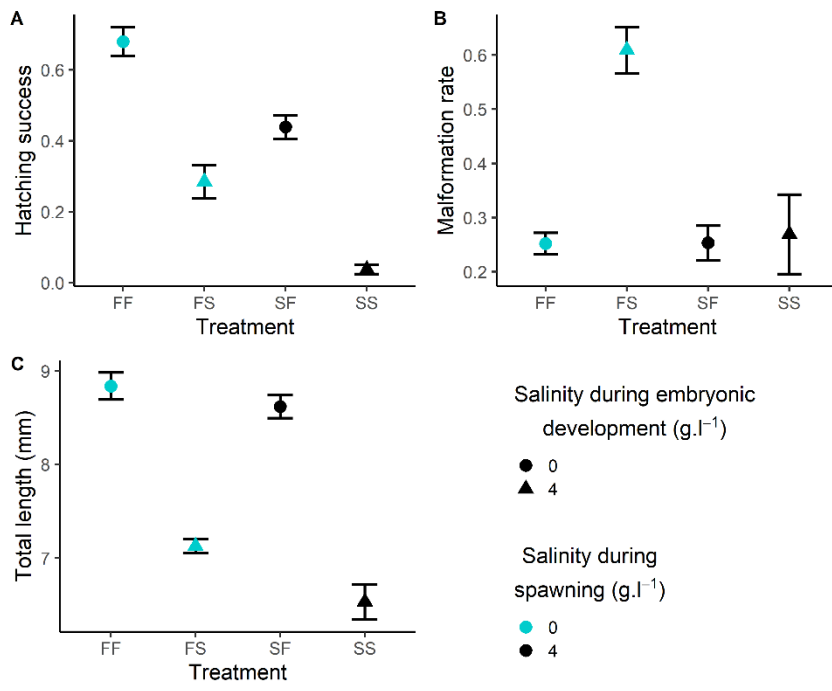
1074

1075 Figure 2



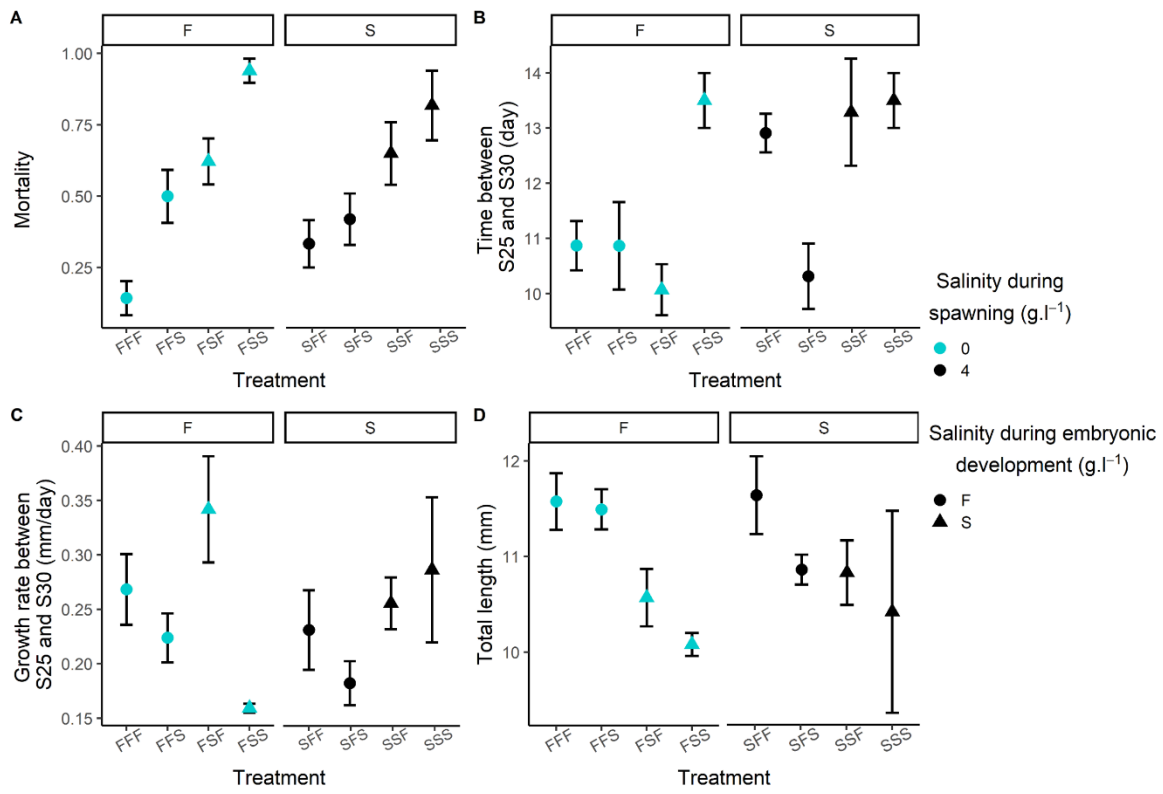
1076

1077 Figure 3



1078





1081 Caption to tables

1082 Table 1 – Number of surviving individuals in each treatment at each life stage

Embryonic treatment	Number of individuals in the treatment	Surviving individuals at GS25	Larval treatment	Number of individuals in the treatment	Surviving individuals at GS25	Surviving individuals at GS30
FF	66	66	FFF	36	36	30
			FFS	30	30	15
FS	102	70	FSF	53	37	14
			FSS	49	33	2
SF	66	65	SFF	33	33	22
			SFS	33	32	18
SS	83	31	SSF	46	20	7
			SSS	37	11	2

1083

1084 **Caption to Appendices**

1085 Appendix A - Contributions of clutches to each treatment (number of tadpoles  
1086 originating from each clutch in each treatment)

1087 Appendix B - Mean  $\pm$  SE values for all studied variables and treatments during egg  
1088 laying, embryonic development and larval development.

1089 Appendix C - Post-hoc analyses for the differences found at Gosner stage 25 (GS25)  
1090 with the interaction between salinity during spawning (clutches laid in freshwater [0  
1091 g.l<sup>-1</sup>] or brackish water [4 g.l<sup>-1</sup>]) and salinity during embryonic development  
1092 (freshwater [0 g.l<sup>-1</sup>] or brackish water [4 g.l<sup>-1</sup>]), for hatching success, malformation rate,  
1093 and time to hatching.

1094

1095 Appendix D - Post-hoc analyses for the differences found for duration between Gosner  
1096 stage 25 (GS25) and Gosner stage 30 (GS30) with the interaction between salinity  
1097 during embryonic development (freshwater [0 g.l<sup>-1</sup>] or brackish water [4 g.l<sup>-1</sup>]) and  
1098 salinity during larval development (freshwater [0 g.l<sup>-1</sup>] or brackish water [4 g.l<sup>-1</sup>]), and  
1099 the interaction between salinity during spawning (clutches laid in freshwater [0 g.l<sup>-1</sup>]  
1100 or brackish water [4 g.l<sup>-1</sup>]) and salinity during larval development (freshwater [0 g.l<sup>-1</sup>]  
1101 or brackish water [4 g.l<sup>-1</sup>]).

1102

Treatment	Clutch	Number of tadpoles
FFF	F01	3
	F02	9
	F03	3
	F04	3
	F05	3
	F06	3
	F07	3
	F08	3
	F09	3
	F10	3
FFS	F01	3
	F02	3
	F03	3
	F04	3
	F05	3
	F06	3
	F07	3
	F08	3
	F09	3
	F10	3
FSF	F01	3
	F02	1
	F05	3
	F07	21
	F08	5
	F09	4
FSS	F01	5
	F02	1
	F03	3
	F06	1
	F07	16
	F08	5
	F09	2
SFF	S01	3
	S02	3
	S03	3
	S04	3
	S05	3
	S06	3
	S07	3
	S08	3
	S09	3
	S10	3

	S11	3
	S01	3
	S02	3
	S03	3
	S04	3
	S05	3
SFS	S06	3
	S07	2
	S08	3
	S09	3
	S10	3
	S11	3
	S05	1
SSF	S10	8
	S11	11
	S02	2
	S06	3
SSS	S07	1
	S10	4
	S11	1

1104

1105

Period	Parameter	Group	Mean	SE
Egg laying	Length (cm)	F	1608.2097	185.0155628
		S	1678.259455	186.6813434
	Number of eggs	F	2427.04	358.3985591
		S	2609.6	208.7763819
	Mass (g)	F	92.82	10.71980307
		S	64.60909091	7.777607187
	Eggs diameter (mm)	F	1.76688	0.039757389
		S	1.660572727	0.043287962
	Laying time (h)	F	79.1	13.10847902
		S	47.33272727	7.662623464
	Females loss in mass (%)	F	-13.55765323	2.230276924
		S	-12.20855975	1.364961958
	Males loss in mass (%)	F	-1.627788792	2.18901737
		S	3.788011248	1.265685304
Embryonic development	Hatching success	FF	0.68	0.039014277
		FS	0.2844444444	0.043299898
		SF	0.439393939	0.032995599
		SS	0.037373737	0.018445671
	Malformation rate	FF	0.252273761	0.018871836
		FS	0.609116088	0.026959964
		SF	0.253329084	0.031584961
		SS	0.269217687	0.04932672
	Time to hatching (days)	FF	17.73333333	0.150101261
		FS	18.81428571	0.223183124
		SF	17.81538462	0.191014885
		SS	19.06451613	0.270147247
	Total length (mm)	FF	8.839393939	0.144306052
		FS	7.127058824	0.075127201
		SF	8.619230769	0.122971289
		SS	6.529354839	0.188660779
General activity (scale on 1 to 5)	FF	3.766666667	0.140376386	
	FS	1.071428571	0.031346695	
	SF	3.415384615	0.163924683	
	SS	1.214285714	0.076478688	
Larval development	Mortality	FFF	0.142857143	0.059172634
		FFS	0.5	0.092847669
		FSF	0.735849057	0.073173841
		FSS	0.959183673	0.034800726
		SFF	0.333333333	0.083333333
		SFS	0.4375	0.089098306
		SSF	0.847826087	0.081204698
		SSS	0.945945946	0.069119496
		FFF	10.87096774	1.811827957
		FFS	10.86666667	1.983972819

Duration between S25 and S30 (days)	FSF	10.07142857	1.655732658
	FSS	13.5	2.350048355
	SFF	12.90909091	2.247184286
	SFS	10.31578947	1.823591173
	SSF	13.28571429	2.970776027
	SSS	13.5	4.070403152
	Growth rate between S25 and S30	FFF	0.268393183
FFS		0.22382476	0.015880458
FSF		0.341870161	0.029992171
FSS		0.159178572	0.001028693
SFF		0.231039881	0.029893008
SFS		0.182156128	0.015580051
SSF		0.2555141	0.014131725
SSS		0.286321429	0.028431838
Total length (mm)	FFF	11.57616129	0.275041152
	FFS	11.493	0.148745132
	FSF	10.57214286	0.18434435
	FSS	10.0815	0.029665049
	SFF	11.64254545	0.331575428
	SFS	10.86410526	0.119641317
	SSF	10.83157143	0.198921964
	SSS	10.4225	0.450066712
Activity (scale of 1 to 5)	FFF	3.774193548	0.170563757
	FFS	2.533333333	0.23771398
	FSF	3.642857143	0.189178582
	FSS	1.5	0.123091491
	SFF	3.681818182	0.164587583
	SFS	2.842105263	0.251820854
	SSF	4.285714286	0.109108945
	SSS	3	0

1107

1108

1109 Appendix C

Gosner stage	Variable	Contrast	Estimate	SE	z/t	p-value
S25	Hatching success	Embryonic 0 Spawning0-Spawning4	0.48	0.194	2.469	0.014
		Embryonic 4 Spawning0-Spawning4	1.97	0.227	8.697	<0.001
		Spawning 0 Embryonic0-Embryonic4	0.972	0.064	15.103	<0.001
		Spawning 4 Embryonic0-Embryonic4	2.466	0.126	19.625	<0.001
	Malformation rate	Embryonic 0 Spawning0-Spawning4	0.087	0.242	0.357	0.721
		Embryonic 4 Spawning0-Spawning4	1.146	0.361	3.169	0.002
		Spawning 0 Embryonic0-Embryonic4	-0.893	0.114	-7.84	<0.001
		Spawning 4 Embryonic0-Embryonic4	0.166	0.278	0.598	0.55
	Time to hatching	Embryonic 0 Spawning0-Spawning4	-0.004	0.025	-0.168	0.868
		Embryonic 4 Spawning0-Spawning4	0.061	0.029	2.118	0.042
		Spawning 0 Embryonic0-Embryonic4	-0.107	0.013	-8.438	<0.001
		Spawning 4 Embryonic0-Embryonic4	-0.042	0.017	-2.544	0.012

1110

1111



			Estimate	SE	t value	p-value
		Embryonic0 - Embryonic4	-1.40912	0.63540	-2.2177	0.028809
		Spawning0 - Spawning4	-0.87456	0.81189	-1.0772	0.294830
		Larval0 - Larval4	-0.53475	0.55331	-0.9665	0.336348
		Embryonic0:Larval0      Embryonic4:Larval0	0.24447	0.58293	0.4194	0.675807
		Embryonic0:Larval0      Embryonic0:Larval4	1.11884	0.42624	2.6249	0.010097
		Embryonic0:Larval0      Embryonic4:Larval4	-1.94387	1.03537	-1.8775	0.063455
Duation		Embryonic4:Larval0      Embryonic0:Larval4	0.87437	0.58972	1.4827	0.141317
between		Embryonic4:Larval0      Embryonic4:Larval4	-2.18834	1.01502	-2.1560	0.033720
S25 and S30		Embryonic0:Larval4      Embryonic4:Larval4	-3.06271	1.03309	-2.9646	0.003827
		Spawning0:Larval0 -      Spawning4:Larval0	-2.33170	0.84095	-2.7727	0.011038
		Spawning0:Larval0 -      Spawning0:Larval4	-1.99189	0.66563	-2.9925	0.003549
		Spawning0:Larval0 -      Spawning4:Larval4	-1.40932	0.96120	-1.4662	0.151424
		Spawning4:Larval0 -      Spawning0:Larval4	0.33981	1.00336	0.3387	0.736590
		Spawning4:Larval0 -      Spawning4:Larval4	0.92238	0.68144	1.3536	0.179157
		Spawning0:Larval4 -      Spawning4:Larval4	0.58257	0.95197	0.6120	0.544697