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1 **Parasites suffer too: Effects of host's pollutant exposure on some life-history traits**  
2 **of acanthocephalan parasites**

3 Léa Lorrain-Soligon<sup>\*1,2</sup>, Simon Agostini<sup>2</sup>, Alexandre Bauer<sup>3</sup>, Béatriz Decencièrè<sup>2</sup>,  
4 Côme Girard<sup>1</sup>, Alexis Golven<sup>1</sup>, Alexis Millot<sup>2</sup>, Thierry Rigaud<sup>3</sup>, Eliott Salles<sup>1</sup>, Aurélie  
5 Goutte<sup>1</sup>

6

7 <sup>1</sup> Sorbonne Université, Université PSL, EPHE, CNRS, Milieux Environnementaux, Transferts et  
8 Interactions dans les hydrosystèmes et les Sols, METIS, F-75005 Paris, France

9 <sup>2</sup>Centre de recherche en écologie expérimentale et prédictive (CEREPEP-Ecotron IleDeFrance),  
10 Département de biologie, Ecole normale supérieure, CNRS-UAR 3194, PSL University, 77140 Saint-  
11 Pierre-lès-Nemours, France

12 <sup>3</sup>Biogéosciences (UMR-CNRS 6282), Université de Bourgogne, Dijon, France

13

14 **ORCIDs**

15 LLS: 0000-0002-8723-7478

16 AB: 0000-0003-3162-9285

17 BD: 0000-0002-2847-7631

18 TR: 0000-0002-0163-6639

19 AuG: 0000-0001-8322-5843

20

21

22

23 **\*Correspondence:** lorrain.lea@gmail.com

24 ID ORCID: 0000-0002-8723-7478

25 Full postal address : Sorbonne université, UMR 7619 METIS EPHE/SU/CNRS, 4 place

26 Jussieu 75252 PARIS

27

28 **Abstract**

29 Parasites are integral components of biodiversity, influencing host populations, food  
30 web dynamics, and ecosystem stability. However, they may be influenced by  
31 environmental conditions and are increasingly threatened by environmental stressors,  
32 including pollution, which can directly affect their survival, development, and  
33 reproduction. Despite growing concerns over global declines in parasite populations,  
34 little is known about how contaminants influence their fitness in freshwater  
35 ecosystems. Here, we investigated the effects of environmental variability, host traits,  
36 and pollutant exposure on the fitness and infection patterns of acanthocephalan  
37 parasites in chub (*Squalius cephalus*). Using a mesocosm approach, we examined  
38 parasite abundance, size, and reproductive traits in relation to host size, body  
39 condition, site of capture, and seasonality. Additionally, we experimentally exposed  
40 fish to environmentally relevant concentrations of common freshwater contaminants,  
41 including the pesticide imidacloprid, pharmaceutical compounds paracetamol and  
42 diclofenac, and the herbicide S-metolachlor. Our results indicate that host size was a  
43 key driver of parasite abundance, while parasite size increased over time but was  
44 independent of host condition and parasite density. Larger parasites produced more  
45 eggs, yet overall reproductive output declined in fish with better body condition and  
46 with time. Pollutant exposure had complex effects: chronic imidacloprid exposure (15  
47 ng.g<sup>-1</sup>) reduced parasite size, while acute paracetamol exposure (16 µg.g<sup>-1</sup>) led to larger  
48 parasites but completely inhibited egg production. Other pollutants showed no  
49 significant effects. These findings emphasize the context-dependent nature of

50 pollution impacts on parasite fitness and highlight the importance of integrating host-  
51 parasite interactions into ecotoxicological assessments of freshwater ecosystems.

52 **Keywords** : Abundance, Egg production, Host-parasite interactions, Pesticides,  
53 Pharmaceuticals, Size

54

55

## 56 1. Introduction

57

58 Parasites are ubiquitous in natural systems and integral components of biodiversity  
59 (Wood and Johnson, 2015), often playing significant roles in regulating host  
60 populations, influencing food web dynamics, and maintaining ecosystem stability  
61 (Anderson, 1978; Collinge and Ray, 2006; Peacock et al., 2015). Parasites exert a potent  
62 selective force on their hosts, thus contributing to shaping the evolution of species  
63 (Duffy and Forde, 2009; Heil, 2016; Papkou et al., 2016). Many parasites species are  
64 threatened by environmental stressors, including pollution and climate change,  
65 directly or indirectly via effects on their host (Altizer et al., 2013; Caminade et al., 2019;  
66 Lafferty and Kuris, 1999), despite their plasticity (Aleuy and Kutz, 2020). Indeed,  
67 environmental stressors may influence parasites' development, survival, and  
68 reproductive outputs (Gleichsner et al., 2016). Recent studies have highlighted a  
69 decade-long decline in parasite populations, attributed to climate-associated stressors  
70 (Welicky et al., 2021; Wood et al., 2023). This decline poses major problems for  
71 ecosystems whose stability and resilience depend on these organisms.

72 Anthropogenic pollution is a significant threat to freshwater ecosystems and  
73 their inhabitants (Schäfer et al., 2016; Schmutz and Sendzimir, 2018). While the impacts  
74 of pollutants on hosts have been well-documented (Amoatey and Baawain, 2019;  
75 Relyea, 2009), it is crucial to evaluate the effects of pollutant exposure on parasites, in  
76 particular direct toxicity (Šebelová et al., 2002). These effects are difficult to assess to  
77 date, as numerous studies focus on the free-living stages of parasites (Pietroock and  
78 Marcogliese, 2003). Additionally, disentangling the direct effects of pollutants on

79 parasites from indirect effects mediated through their hosts is a challenging task. For  
80 example, environmental pollutants can increase susceptibility and infection rates (Buss  
81 and Hua, 2023; Koprivnikar et al., 2007), through immunotoxicity and lower resistance  
82 of the host (Morley et al., 2006; Regala et al., 2001; Sures and Knopf, 2004), and because  
83 some parasites exhibit very high pollutant burdens (Sures et al., 2017). In contrast,  
84 pollutants can affect susceptibility to parasites by impeding transmission and  
85 decreasing infection levels (Koprivnikar et al., 2007; Pietrock and Goater, 2005), and by  
86 inducing parasites mortality (Rohr et al., 2008). Potential impacts of pollution on  
87 parasite populations are difficult to evaluate and predict and may be context-  
88 dependent, varying with factors such as stage of development of the parasite (Dhakal  
89 et al., 2020), timing of infection (Dhakal et al., 2020) but also timing and dose of  
90 pollutant exposure (Koprivnikar et al., 2006; Rohr et al., 2008).

91 An additional layer of complexity is that, contrary to the traditional view of  
92 parasites as harmful entities, they can provide unexpected benefits for their host. For  
93 instance, some parasite species are capable of accumulating pollutants from their hosts  
94 (Rosa Leite et al., 2021; Sures et al., 1994), potentially reducing the toxic burden on host  
95 organisms. The enormous accumulation of pollutants in certain parasites (e.g.,  
96 Trematoda, Cestoda, Acanthocephala) can affect persistent pollutant bioavailability  
97 for their hosts (Goutte and Molbert, 2022; Morley et al., 2006; Sures et al., 2017; Sures  
98 and Siddall, 1999; Turcekova and Hanzelova, 1999). For example, cadmium and lead  
99 concentrations can be up to 2,700 times higher in the acanthocephalan parasite  
100 *Pomphorhynchus laevis* than in its hosts' muscle tissues (Sures et al., 1994; Sures and  
101 Taraschewski, 1995). While such bioaccumulation may benefit hosts by reducing their

102 toxic burden, it also exposes parasites to high pollutant loads, with largely unknown  
103 consequences for their survival, growth, and reproduction.

104

105 Parasites' responses to pollutants are also influenced by various ecological and  
106 biological factors beyond mere pollutant exposure. Environmental factors and host-  
107 related traits can profoundly influence parasite dynamics (Fleury et al., 2009; Patz et  
108 al., 2000). Temperature, for instance, plays a critical role in determining the growth  
109 and transmission rates of many parasites, as well as their ability to complete life cycles  
110 (Schoebel et al., 2011; Studer et al., 2010). Seasonal changes and water quality  
111 parameters also impact parasite survival and infectivity (Altizer et al., 2006; Erkanon,  
112 2021), as well as host diet, which might be related to their size, affecting the availability  
113 of nutrients critical for parasite development (Pulkkinen and Ebert, 2004). These  
114 intricate interactions underscore the complexity of parasitic relationships, which are  
115 shaped by an interplay of environmental conditions and host-specific characteristics,  
116 often resulting in context-dependent outcomes for parasite populations and their  
117 ecosystems (Marcogliese and Pietrock, 2011). Understanding how pollutants, habitat  
118 and parameters of the host itself impact parasites, and how these impacts might  
119 feedback into broader ecological systems, is crucial for comprehensively assessing the  
120 consequences of pollution on freshwater ecosystems.

121

122 In this study, we tested whether the experimental exposure to pesticides and  
123 pharmaceutical residues, as well as environmental and host related factors may

124 influence parasites infection and fitness, using acanthocephalan parasites of chub  
125 (*Squalius cephalus*), as a freshwater model system. These intestinal thorny-headed  
126 worms are known to bioaccumulate many organic pollutants (Molbert et al., 2020), and  
127 to be particularly resistant to pollutants (Fanton et al., 2022), so that they provide an  
128 ideal framework for studying both direct and indirect effects of contamination (Perrot-  
129 Minnot et al., 2023). First of all, given the impact on parasites of the environment in  
130 which the fish develop (Altizer et al., 2006; Erkano, 2021; Pulkkinen and Ebert, 2004),  
131 we investigated how host traits (size, body condition) and environmental factor (site  
132 of capture, seasonality) influence parasites number, size, and reproductive outputs.  
133 We also expected that parasites number negatively influenced parasites size due to  
134 intra individual competition (Dianne et al., 2012; Lagrue and Poulin, 2008), and that  
135 parameters relative to parasites themselves (parasites number and size) will influence  
136 parasites reproductive output (Poulin et al., 2003). Then, using experimental exposure  
137 to various pollutants at environmentally relevant doses –including the pesticide  
138 imidacloprid, the pharmaceutical compounds acetaminophen, diclofenac, and the  
139 herbicide S-metolachlor, all found in high concentrations in Seine river tributaries  
140 (Marchand et al., 2024)— we evaluated their differential impacts on parasite  
141 abundance, size, and reproductive traits. Given the heightened sensitivity of  
142 invertebrates, including parasites, to certain toxicants (Blanar et al., 2009), we  
143 hypothesize that exposure to these pollutants will negatively impact some major  
144 components of the parasite’s fitness.

## 145 2. Methods

### 146 2.1. Ethical Note

147 All experiments complied with Europe and France laws on animal experimentation.  
148 All fish were reared in reasonable population density and fed regularly (see below for  
149 rearing methods). Animal care protocols were approved by national ethics committee  
150 for animal experimentation under file number APAFIS #42968-2023032907492372.  
151 Wild fish were captured, manipulated and transported under authorization n°2023-  
152 DDT-SE-147.

153

### 154 2.2. Species, capture and housing conditions

155 The chub, *Squalius cephalus*, is a ubiquitous fish species occurring in Europe, and is  
156 naturally infested by acanthocephalan parasites. In our study populations (see below),  
157 chubs are parasitized by two closely-related species of acanthocephalan  
158 (*Pomphorhynchus tereticollis* and *Pomphorhynchus laevis*, identified using molecular  
159 diagnostic markers as in (Bauer et al., 2024)). Briefly, DNA extractions were performed  
160 using an extraction kit (EZ-10 96 Well Plate Genomic DNA Isolation kit, BioBasic Inc.)  
161 following the manufacturer instructions. The gene encoding the first subunit of  
162 cytochrome oxidase (CO1) was amplified using the universal primers LCO1490 and  
163 HCO2198 (Flomer, 1994), in conditions described in (Bauer et al., 2024). Sequences  
164 were obtained by Sanger sequencing at Genewiz company (Leipzig, Germany). The  
165 sequences were aligned using Mega software (V10; www.megasoftware.net) and  
166 compared to reference sequences (AY423351.1 for *P. tereticollis*; EF051071.1 for *P.*  
167 *laevis*). In total, 21 parasites were randomly selected for typing, revealing a ratio of  
168 approximately two-thirds *P. laevis* to one-third *P. tereticollis*.

169 A total of 214 European chub, *S. cephalus*, were captured by electrofishing on 5  
170 tributary of the Seine River (Ecole, Essone, Loing, Orvanne, Ru de Cerny) and on the  
171 Seine on different occasions (see Table 1). All individuals were brought back to the  
172 CEREEP-Ecotron facilities (situated at a distance of less than 65 km from all field  
173 capture sites). Chubs were then anesthetized in diluted eugenol (dilution 1/2000<sup>e</sup>).  
174 Anesthetized chubs were carefully tagged with a passive integrated transponder  
175 device (PIT-tag dimensions: 1.2×7 mm biolog-nano, Biolog-id, France, [ISO 11784 /  
176 11785], 0.024 g, diameter of the injector: 1.6 mm) inserted into the left flank  
177 intramuscularly. They were then weighted ( $\pm 0.5$  g, Ohaus, Valor 2000W) and measured  
178 (from beginning of the head to the end of the tail  $\pm 0.1$  cm). They were left for recovery in  
179 100 L tanks filled with well-aerated pond water, until complete awakening of  
180 individuals. They were then transferred into five 12 000 L outdoor mesocosms (350 cm  
181 diameter, 120 cm height, see description in (Lorrain-Soligon et al., 2025)). During the  
182 whole duration of the acclimation and experimental phase, fish were fed once every  
183 day with commercial fish pellets (Tetra).

184 Fish from different dates and different sites of capture were assigned to three  
185 independent experiments (Table 1): 1) Exposure to imidacloprid at three doses (0, 15  
186 or 150 ng imidacloprid per gram of fish, once a week during 6 weeks), 2) Exposure to  
187 paracetamol at two levels (Acute [0 or 16  $\mu$ g paracetamol per gram of fish, once a day  
188 during 2 days], or chronic [0 or 1.6  $\mu$ g paracetamol per gram of fish, once a week during  
189 3 weeks]) and 3) Cocktail exposure to diclofenac and S-metolachlor (2  $\mu$ g diclofenac or  
190 S-metolachlor or a mixture of both per gram of fish, twice week during 2 weeks, for all  
191 see Table 1). The mean length and weight of chubs did not differ among groups within

192 each experiment (table 1). For all experiments, individuals from different origin were  
193 assigned equitably between different treatments. It was not possible to separate the  
194 two parasite species in our experimental analyses, as we did not have prior knowledge  
195 of infection levels and whether the infections were mono- or pluri-specific, making it  
196 impossible to balance sample sizes accordingly. Additionally, *P. laevis* and *P. tereticollis*  
197 share similar ecological traits, including the same intermediate hosts (various  
198 gammarid species) and potentially the same definitive hosts, such as the chub, despite  
199 exhibiting some host infection preferences (Perrot-Minnot et al., 2019), and individuals  
200 from different origin were assigned equitably between treatments which should thus  
201 not led to bias in our results.

202         To ensure ecological relevance, we scaled the doses of pollutant to approximate  
203 oral exposure by expected intake based on the body mass of our experimental fish (see  
204 (Lorrain-Soligon et al., 2025)), according to environmentally relevant doses. This oral  
205 administration approximates the internal exposure due to feeding on contaminated  
206 sources, such as prey bioaccumulating the pollutant, and this exposure route was  
207 chosen to ensure that acanthocephalans were also exposed to the pollutant. Solutions  
208 were injected orally using a syringe in anesthetized chub. Control solution consisted  
209 only of milliQ water. Concentrations given to fish for each experiment and pollutant  
210 are given in table 1.

211

### 212 **2.3. Measurements on acanthocephalan parasites**

213 After exposure, fish from all experiments were euthanized with an Eugenol overdose  
214 (dilution 1/200<sup>e</sup>, see experiment duration and date of dissection in Table 1). They were  
215 dissected and parasites were removed from the intestine and counted. Total biomass  
216 of acanthocephalan was then computed using a precision balance ( $\pm 0.01$  g, Ohaus).  
217 Individual were then individually placed upon a scale (graph paper). A picture was  
218 taken from above in order to measure total length using the software ImageJ  
219 (Schneider et al., 2012). Individually, all acanthocephalan was then dissected, and the  
220 eggs (if any), were collected in a tube containing 1 mL of milliQ water. Two samples  
221 of 1  $\mu$ L of each solution was then inspected using a X20 ocular microscope (Microscope  
222 Primo Star 8, total magnification X200). Total number of eggs and number of mature  
223 eggs [following (Bauer, 2022)] were computed for each sample of 1  $\mu$ L.

224

#### 225 **2.4. Statistical analyses**

226

227 All statistical analyses were performed using R 3.6.3 (R Core Team, 2020) and Rstudio  
228 v1.1.419. We computed Linear Mixed Models (LMMs), or Gamma, quasipoisson and  
229 binomial Generalized Linear Mixed Models (GLMMs) from the *lme4* (Bates et al., 2015)  
230 and the *MASS* package (Ripley et al., 2013)(Table 2). For LMMs, normality was  
231 checked (shapiro test) and data were log<sub>10</sub> transformed when residuals did not follow  
232 the normality assumption. For all computed tests, models accuracy was also tested  
233 using the *check\_model* function from the *performance* package (Lüdecke et al., 2020).  
234 Significance level was set at 0.05, effects were considered marginally significant at  
235  $\alpha < 0.10$ . Best variables were retained using a top-down selection.

236           Since fish are coming from different sites of capture and were captured at  
237 different dates, so that site, date and type of pollutant were sometimes coincident  
238 factors (table 1), it was not possible to run a single statistical model. We therefore  
239 analyzed separately data for the effects of environment on one side, on non-exposed  
240 fish, and the effects of pollutant exposure on the other side (in which dates and sites  
241 of capture are homogeneous).

242

#### 243 2.4.1. Environmental variability

244 Using only fish exposed to control treatments in all experiments, using LMMs or  
245 GLMMs (see table 2), we tested for the effect of different variables linked to the  
246 environment on acanthocephalan number, on acanthocephalan size, on the proportion  
247 of acanthocephalan producing eggs (thereafter called egg production), on the number  
248 of eggs produced by females (for each female producing eggs), and on the proportion  
249 of mature eggs. Site of capture, fish size, fish body condition [as the residuals of the  
250 relation between  $\log_{10}(\text{mass})$  and  $\log_{10} \text{size}$ ], time spent in mesocosm (as a categorical  
251 variable because we had only three time-points), and period of dissection (month  
252 during which the dissection occurs) were used as explicative variables for all  
253 parameters. The mesocosm ID and unique ID of fish were treated as random effects  
254 for all parameters. Additionally, acanthocephalan number per fish was set as an  
255 explicative variable for the analysis of acanthocephalan size. Lastly, acanthocephalan  
256 number and size were set as additional explicative variables for egg production,  
257 number of eggs produced by females, and proportion of mature eggs. Unique ID of

258 acanthocephalan was added as an additional random effect for the analyses on the  
259 number of eggs produced by females, and the proportion of mature eggs.

260

#### 261 2.4.2. Pollutants effects

262 To test for the effect of treatment on the four different experiments (namely [1]  
263 imidacloprid exposure, [2] acute paracetamol exposure, [3] chronic paracetamol  
264 exposure, [4] diclofenac and S-metolachlor cocktail exposure), we computed separated  
265 models for each experiment. Using LMMs or GLMMs or otherwise stated (see table 2),  
266 we investigated separately the effect of treatment on acanthocephalan number  
267 (mesocosm and unique ID of fish as random effects), acanthocephalan size (mesocosm  
268 and unique ID of fish as random effects), egg production (mesocosm and unique ID of  
269 fish as random effects), number of eggs produced by females and proportion of mature  
270 eggs (where mesocosm ID, unique ID of fish and unique ID of acanthocephalan as  
271 random effects). Effect on egg production for the acute paracetamol exposition was  
272 tested using a Gamma GLMM instead of a binomial GLMM due to the  
273 overrepresentation of 0, which represent a perfect separation, not taken into account  
274 in a binomial GLMM. When there was an effect of contaminants on acanthocephalan  
275 size, we also tested whether exposure led to selective elimination of smaller or larger  
276 individuals, or if there was a problem in parasite growth. To this purpose, the dataset  
277 was split in two size categories at the median size for each treatment, using the  
278 mutate() function from the dplyr package (Wickham et al., 2023), and the treatment  
279 effect was analyzed separately, using linear mixed models, for smaller category (SC)  
280 and larger category (LC). If pollutants induce selective mortality in small parasites,

281 size should be larger in the SC exposed parasites than in SC control parasites, but there  
282 should be no difference between exposed and control LC parasites (the same  
283 reasoning, but reversing SC and LC, can apply for a selective mortality in larger  
284 individuals). Accordingly, the number of parasites should be different between  
285 exposed and control parasites. If pollutants induced a general problem in parasite  
286 growth, the effect of pollutant should be the same in both SC and LC parasites.  
287 Concomitantly, the number of parasites should be similar between exposed and  
288 control parasites.

289

290

### 291 3. Results

#### 292 3.1. Effect of environmental variability on parasite traits

293 The number of acanthocephalans was positively correlated with host fish size (Figure  
294 1A, Table 2), but not influenced by site of capture, fish mass, duration since capture or  
295 period of dissection. Acanthocephalan size was higher in individuals that spent 7  
296 months in mesocosms (as compared to 2, Figure 1B, Table 2), and was influenced by  
297 site of capture (Appendices AB, Table 2). Acanthocephalan size was neither influenced  
298 by acanthocephalan number, fish size or body condition index. Acanthocephalan egg  
299 production was not influenced by any of the measured parameters (Table 2). The  
300 number of eggs produced by female acanthocephalans was negatively correlated with  
301 fish size (Figure 1C, Table 2), fish body condition index (Figure 1D, Table 2),  
302 acanthocephalan number (Figure 1E, Table 2), but positively correlated to  
303 acanthocephalan size (Figure 1F, Table 2). Number of eggs produced was also lower  
304 in individuals that spent 7 months in mesocosms (as compared to 1 and 2, Figure 1G,  
305 Table 2), and was influenced by site of capture (Appendices AB, Table 2). The  
306 proportion of mature eggs relative to the total number of eggs was marginally  
307 positively correlated to acanthocephalan size (Figure 1H, Table 2), and was not  
308 influenced by site, acanthocephalan number, fish size or body condition index.

309

#### 310 3.2. Effects of pollutants on parasite traits

311 For the imidacloprid experiment, treatment dose (0, 15 or 150 ng.g<sup>-1</sup> imidacloprid)  
312 influenced only parasite size, with larger parasites found in fish exposed to the control

313 and the highest concentration, and smaller parasites in the 15 ng.g<sup>-1</sup> imidacloprid  
314 exposure group (Figure 2A, Tables 2,3). Interestingly, this pattern was also found  
315 when comparing individually both small and large individuals (as compared to the  
316 median for each treatment, Tables 2,3, Appendix C). Treatment did not influence egg  
317 production (Figure 3A, Table 2), acanthocephalan number, the number of eggs  
318 produced by females, or proportion of mature eggs (Table 2, Appendix B).

319 For the acute paracetamol experiment, treatment (0 or 16 µg.g<sup>-1</sup> paracetamol,  
320 once a day during 2 days) influenced parasite size, with larger parasites found in fish  
321 exposed to paracetamol (Figure 2B, Tables 2,3). This pattern was also found when  
322 analyzing separately large or small individuals, but was not significant when  
323 analyzing small individuals only (as compared to the median for each treatment,  
324 Tables 2,3, Appendix C). Treatment did not influenced acanthocephalan number  
325 (Table 2, Appendix B). Importantly, during this experiment, parasites from fish  
326 exposed to paracetamol did not produced eggs (Figure 3B, Table 2).

327 For the chronic paracetamol experiment (0 or 1.6 µg.g<sup>-1</sup> paracetamol, once a week  
328 during 3 weeks) and the diclofenac and S-metolachlor cocktail experiment (0 µg.g<sup>-1</sup>, 2  
329 µg.g<sup>-1</sup> diclofenac, 2 µg.g<sup>-1</sup> S-metolachlor, 2 µg.g<sup>-1</sup> cocktail of diclofenac and S-  
330 metolachlor), treatment did not influenced either acanthocephalan number,  
331 acanthocephalan size, egg production, the number of eggs produced by females, or  
332 proportion of mature eggs (Figure 2C,D, Figure 3C,D, Table 2, Appendix B).

## 333 **4. Discussion**

334 Our study highlights for the first time key fitness-related traits in parasites, in an  
335 ecotoxicological context. We aimed to assess how environmental parameters and  
336 various pollutants influence parasite life-history traits, particularly their development  
337 and reproduction. We found that parasite traits were influenced by both host  
338 characteristics and environmental conditions, with parasite size and reproduction  
339 varying according to host size, time spent in mesocosms, and site of origin. Regarding  
340 pollutant exposure, chronic imidacloprid exposure at intermediate concentration (15  
341  $\text{ng.g}^{-1}$ ) was associated with smaller parasites, while acute exposure to paracetamol (16  
342  $\mu\text{g.g}^{-1}$ ) was associated with larger individuals but no egg production. Neither chronic  
343 exposure to paracetamol nor the chronic exposure to diclofenac/S-metolachlor  
344 cocktail or their individual components showed significant effects on parasites  
345 number, size, or reproductive output.

346

### 347 **4.1. Environmental variability**

348 Our results underscore the influence of environmental and host-related variability on  
349 acanthocephalan biology. Host size emerged as an important factor driving parasite  
350 abundance (Sackett, 2018), likely reflecting larger hosts' increased capacity to support  
351 higher parasite loads. Larger fish are older fish, that probably spent more time feeding  
352 on gammarids, the intermediate hosts of these parasites (Bauer et al., 2024; Médoc et  
353 al., 2006) or on small fish that could be paratenic hosts (Médoc et al., 2011).  
354 Importantly, duration in mesocosms did not influence acanthocephalan number,

355 indicating that parasites stay hooked for at least 7 months, the longest duration a fish  
356 has stayed in our mesocosms, an important parameter given the durable nature of this  
357 host-parasite interaction (Kennedy, 2006). Longer-term studies would be informative  
358 to estimate how long an acanthocephalan parasite can remain associated with its host,  
359 at least in captive conditions.

360         While the parasite intensity was variable among sites, we found very few  
361 parasites and very few egg production as compared to what can be found in other sites  
362 (Bauer, 2022; Kennedy, 2006). This may reflect site-specific differences in infection  
363 pressure or environmental constraints affecting parasite development and  
364 reproduction (Rohde and Heap, 1998; Thorburn et al., 2022), emphasized by the fact  
365 that parasites size and number of eggs produced were influenced by the site of capture.

366         However, the observation that parasite size was positively correlated with time  
367 in mesocosms, and because fish cannot be infested in our mesocosms because they  
368 were not feed with gammarids, suggests that parasites continue growing over  
369 extended periods in the host (Crompton and Nickol, 1985). On the contrary, the lack  
370 of influence of parasites number on parasite size did not support the hypotheses of  
371 intra individual competition (Dianne et al., 2012; Lagrue and Poulin, 2008), and  
372 resource dependent host-parasite associations (Hassell, 2000; Penczykowski et al.,  
373 2016). A possible explanation is that infectious levels were relatively low in our study,  
374 as highlighted above, thus limiting the depletion of resources with increasing number  
375 of parasites.

376           Unsurprisingly, larger parasites produced more eggs (Poulin et al., 2003), with  
377 a higher proportion of mature eggs, representative of the parasite volume necessary  
378 for egg stock, and the developmental stage necessary for such production. However,  
379 overall egg production was lower in fish with better body condition and larger body  
380 size. This suggests potential host-mediated constraints on parasite reproduction, such  
381 as larger fish in better condition are able to invest more in immune responses or are  
382 able to limit the parasite effects (Barber, 2005; Truyens and Carlier, 2010), so that less  
383 energy is available to parasites for reproduction. This is emphasized by the negative  
384 relationship between egg number and duration in mesocosms, which might indicate  
385 progressive depletion of resources necessary for reproduction over time. Importantly  
386 for our experiments, reproductive output was not influenced by the period of  
387 manipulation, which might exemplify no influence of environmental conditions such  
388 as temperature and photoperiod, which has previously been emphasize to modulate  
389 parasite metabolism and reproductive cycles (Martinez-Bakker and Helm, 2015).  
390 Together with the fact that egg production remained largely stable, this suggests a  
391 consistent allocation of resources to egg production despite variations in  
392 environmental conditions or host traits.

393           Our pollutant exposure experiments, discussed below, were made at different  
394 period of time with different sites of capture, which differ in their environmental  
395 characteristics and exposure to pollutants. Therefore, even if each of the different  
396 experiments were made within homogeneous time-frame and origin of fish, we will  
397 have to keep in mind all these environmental sources of variation when interpreting  
398 the following results.

## 400 4.2. Pollutant effects

401 Experimental exposure of fish host revealed complex and context-dependent effects of  
402 pollutants on acanthocephalan parasites. Chronic imidacloprid exposure (only at the  
403 intermediate concentration of 15 ng.g<sup>-1</sup>, staying in the range of environmental  
404 pollution) was associated with smaller parasites, possibly due to a growth depletion  
405 as suggested by the fact that this pattern was found in both large and small individuals.  
406 This corroborates the fact that this neonicotinoid insecticide induces toxic effects in  
407 non-target invertebrates (Pisa et al., 2015). The fact that only the intermediate  
408 concentration of imidacloprid (15 ng.g<sup>-1</sup>) affected parasite size, while the highest  
409 concentration (150 ng.g<sup>-1</sup>) did not, could be explained by hormetic (non-monotonic)  
410 responses, intermediate doses in some toxic having a stronger biological impact than  
411 low or high doses (Calabrese, 2008), emphasizing that pollutant does not always have  
412 a dose-dependent effect on parasites (Hua et al., 2016). Additionally, if imidacloprid  
413 influences the host's physiology, as shown in many studies (e.g., metabolism, immune  
414 response) (Abdel Rahman et al., 2023; Gajula et al., 2024), the effects on parasites might  
415 not be linear. At intermediate exposure, parasites might also accumulate pollutants  
416 reducing pollutants effects on their host, hosts thus still being able to express immune  
417 defenses, while at higher exposure pollutants may directly affect the host, overriding  
418 the accumulation properties of parasites (Goutte and Molbert, 2022), and limiting their  
419 immune defenses thus favoring parasites as compared to intermediate doses.

421 Acute exposure to paracetamol was associated with an absence of egg  
422 production in parasites. Since in all other series we found around 25% animals  
423 producing eggs, it is highly improbable that this only series include only male  
424 parasites by chance. This result rather suggests a negative effect of pharmaceuticals  
425 products on egg production (Morley, 2009). Simultaneously, parasites size was larger  
426 in exposed animals. This pattern was found in both small and larger parasites, but the  
427 effect only significant in larger individuals. In small parasites, the lack of significance  
428 was possibly due to a small statistical power due to small sample size instead of no  
429 effect at all. Since there was no difference in parasite number between exposed and  
430 control animals, the difference in parasite size between exposed and control animals  
431 was probably due to a higher parasite growth under paracetamol exposure. These  
432 simultaneous absence of reproduction and higher growth suggest a possible  
433 compensatory growth response. Pollutant may modify the parasites' phenology  
434 (Heath, 2021), or, according to the theory of evolution of life-history traits, parasites  
435 may strategically reallocate their energetic investment toward growth after  
436 reproduction disruption (Goussen et al., 2015; Stearns, 1998). Chronic exposure to the  
437 same pollutant did not induce effects on parasites size or eggs production. Other  
438 studies have shown few effects of sublethal doses of pollutants, not affecting the  
439 degree of infestation, while higher doses might cause mortality of parasites (Rohr et  
440 al., 2008). It is therefore possible that higher doses will induce higher effects.

441

442 Importantly, neither the combination of diclofenac and S-metolachlor nor their  
443 individual exposures had discernible effects on any measured parasite parameters,

444 indicating that these compounds may exert minimal influence on acanthocephalans in  
445 the tested conditions. This might also suggest once again a dose dependent (Rohr et  
446 al., 2008) or pollutant dependent effect (Grabner et al., 2023), as well as site specific  
447 effects because different exposure to pollutant may have induce pollutant tolerance  
448 (Sun et al., 2014). The lack of effect of chronic pollutant exposure on parasite abundance  
449 also suggests that acanthocephalans are robust against certain environmental stressors  
450 (Fanton et al., 2022), though this resilience may vary depending on the pollutant type  
451 and exposure regime. Importantly, the effects of pollutants on parasites varied among  
452 species (Koprivnikar et al., 2006), even within the same clade. As we found that two  
453 species of acanthocephalan are present in our study sites (*Pomphorhynchus tereticollis*  
454 and *Pomphorhynchus laevis*), but as we did not identify species for all individual  
455 parasites in this study, it is also possible that the two species respond differently to  
456 contaminants, which needs to be further investigated. Lastly, beyond the effects on  
457 adult parasites, acanthocephalan have a complex life cycle where cystacanths larvae  
458 first develop in amphipod crustaceans (Crompton and Nickol, 1985), where they also  
459 are now recognize to accumulate pollutants (Soose et al., 2025), thus being subjected  
460 to pollutant effects even at early stages. Future studies should explore the effect of  
461 pollutants on the full life cycle of these parasites. This would provide a more  
462 comprehensive understanding of the potential ecological consequences of pollution on  
463 parasite transmission and population dynamics.

464

465 The interpretation of these results in terms of parasite effects is limited due to the  
466 low number of parasites found in individuals (as compared to individuals originating

467 from sites in eastern France, A. Bauer pers. Obs.), and because of the environmental  
468 origin of infections. The pattern observed could also arise from confounding factors  
469 that were not controlled for, such as initial parasite load or developmental stages of  
470 the parasites differing among groups, which might react differently to pollutants (Yen  
471 Le et al., 2014). As pollutants effects might also depend on whether the parasites are  
472 installed before and after infestation (Dhakal et al., 2020), future studies should control  
473 the infection of fish (Médoc et al., 2011; Nachev et al., 2024), in order to precisely  
474 control for pollution exposure but also number and life stage of parasites, which will  
475 allow to precisely compute the effect of pollutants on parasites. Our findings highlight  
476 the importance of considering both the dose-dependent nature of pollutant effects and  
477 the temporal variability in exposure when evaluating the ecological consequences of  
478 environmental pollution.

479

## 480 **5. Conclusion**

481 Our study emphasize complex, context-dependent, effects of some pollutant stressors  
482 on life-history traits of acanthocephalan parasites, alongside ecological factors such as  
483 host characteristics and environmental conditions. By demonstrating that both biotic  
484 and abiotic factors shape parasite development and reproductive output, our findings  
485 underscore the importance of adopting a holistic approach in ecotoxicological  
486 research, pollutants effects on parasites potentially cascading on host health and  
487 population dynamics. These results reinforce the necessity of integrating host-parasite  
488 interactions into ecotoxicological assessments of freshwater ecosystems.

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502

503 **Conflict of interest statement**

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

505

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510

511 **Data archiving statement**

512 The data that supports the findings of this study will be made available by the  
513 corresponding author upon request.

514

515 **CRedit**

516

517 LLS and AuG conceptualized the study. LLS, SA, BD, AIG, AM, ES, and AuG  
518 participated to fish sampling and fish tagging. LLS, SA, CG, AIG and ES participated  
519 to pollutant exposure. LLS, CG, AIG, AB, TR, and ES participated to parasites  
520 differentiation. LLS analyzed data, and LLS and AuG wrote the initial draft. All  
521 authors have reviewed and edited the manuscript and approved the final version.

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525 **References**

- 526 Abdel Rahman, A.N., AbdelMageed, M.A., Assayed, M.E.M., Gharib, H.S.A.-R., Nasr, M.A.,  
 527 Elshopakey, G.E., Moniem, H.A., Shahin, S.E., ELHusseiny, E., Ahmed, S.A.A., 2023.  
 528 Imidacloprid induced growth, hematological, neuro-behavior, anti-oxidant, economic,  
 529 genetic, and histopathological alterations in *Clarias gariepinus*: Alleviative role of  
 530 dietary *Hyphaene thebaica*. *Aquaculture* 564, 739058.  
 531 <https://doi.org/10.1016/j.aquaculture.2022.739058>
- 532 Aleuy, O.A., Kutz, S., 2020. Adaptations, life-history traits and ecological mechanisms of  
 533 parasites to survive extremes and environmental unpredictability in the face of climate  
 534 change. *International Journal for Parasitology: Parasites and Wildlife, Including*  
 535 *Articles from the Special Issue 'Parasites in Extreme Environments'*, pp. 250 - 325 12,  
 536 308-317. <https://doi.org/10.1016/j.ijppaw.2020.07.006>
- 537 Altizer, S., Dobson, A., Hosseini, P., Hudson, P., Pascual, M., Rohani, P., 2006. Seasonality and  
 538 the dynamics of infectious diseases. *Ecology Letters* 9, 467-484.  
 539 <https://doi.org/10.1111/j.1461-0248.2005.00879.x>
- 540 Altizer, S., Ostfeld, R.S., Johnson, P.T.J., Kutz, S., Harvell, C.D., 2013. Climate change and  
 541 infectious diseases: From evidence to a predictive framework. *Science* 341, 514-519.  
 542 <https://doi.org/10.1126/science.1239401>
- 543 Amoatey, P., Baawain, M.S., 2019. Effects of pollution on freshwater aquatic organisms. *Water*  
 544 *Environment Research* 91, 1272-1287. <https://doi.org/10.1002/wer.1221>
- 545 Anderson, R.M., 1978. The regulation of host population growth by parasitic species.  
 546 *Parasitology* 76, 119-157. <https://doi.org/10.1017/S0031182000047739>
- 547 Barber, I., 2005. Parasites grow larger in faster growing fish hosts. *International Journal for*  
 548 *Parasitology* 35, 137-143. <https://doi.org/10.1016/j.ijpara.2004.11.010>
- 549 Bates, D., Mächler, M., Bolker, B., Walker, S., 2015. Fitting linear mixed-effects models using  
 550 lme4. *Journal of Statistical Software* 67, 1-48. <https://doi.org/10.18637/jss.v067.i01>
- 551 Bauer, A., 2022. Gammares et acanthocéphales, un système multi-hôtes (cryptiques) et multi-  
 552 parasites ?
- 553 Bauer, A., Develay Nguyen, L., Motreuil, S., Teixeira, M., Debrosse, N., Rigaud, T., 2024.  
 554 Differences in specificity, development time and virulence between two  
 555 acanthocephalan parasites, infecting two cryptic species of *Gammarus fossarum*. *Peer*  
 556 *Community Journal* 4, e61. <https://doi.org/10.24072/pcjournal.434>
- 557 Blanar, C.A., Munkittrick, K.R., Houlahan, J., MacLatchy, D.L., Marcogliese, D.J., 2009.  
 558 Pollution and parasitism in aquatic animals: A meta-analysis of effect size. *Aquatic*  
 559 *Toxicology* 93, 18-28. <https://doi.org/10.1016/j.aquatox.2009.03.002>
- 560 Buss, N., Hua, J., 2023. Host exposure to a common pollutant can influence diversity-disease  
 561 relationships. *Journal of Animal Ecology* 92, 2151-2162.  
 562 <https://doi.org/10.1111/1365-2656.13988>
- 563 Calabrese, E.J., 2008. Hormesis: Why it is important to toxicology and toxicologists.  
 564 *Environmental Toxicology and Chemistry* 27, 1451-1474. <https://doi.org/10.1897/07-541.1>
- 565
- 566 Caminade, C., McIntyre, K.M., Jones, A.E., 2019. Impact of recent and future climate change  
 567 on vector-borne diseases. *Annals of the New York Academy of Sciences* 1436, 157-173.  
 568 <https://doi.org/10.1111/nyas.13950>
- 569 Collinge, S.K., Ray, C., 2006. *Disease ecology: Community structure and pathogen dynamics*.  
 570 OUP Oxford.
- 571 Crompton, D.W.T., Nickol, B.B., 1985. *Biology of the acanthocephala*. Cambridge University  
 572 Press.
- 573 Dhakal, S., Meyling, N.V., Pedersen, K.E., Cedergreen, N., Fredensborg, B.L., 2020. Timing of  
 574 sub-lethal insecticide exposure determines parasite establishment success in an insect-

575 helminth model. Parasitology 147, 120–125.  
576 <https://doi.org/10.1017/S0031182019001331>

577 Dianne, L., Bollache, L., Lagrue, C., Franceschi, N., Rigaud, T., 2012. Larval size in  
578 acanthocephalan parasites: Influence of intraspecific competition and effects on  
579 intermediate host behavioural changes. Parasites Vectors 5, 166.  
580 <https://doi.org/10.1186/1756-3305-5-166>

581 Duffy, M.A., Forde, S.E., 2009. Ecological feedbacks and the evolution of resistance. Journal of  
582 Animal Ecology 78, 1106–1112. <https://doi.org/10.1111/j.1365-2656.2009.01568.x>

583 Erkan, W.K., 2021. Impacts of environmental parameters on the infectivity of freshwater  
584 snail, in: Update on Malacology. IntechOpen.  
585 <https://doi.org/10.5772/intechopen.99829>

586 Fanton, H., Franquet, E., Logez, M., Cavalli, L., Kaldonski, N., 2022. Acanthocephalan parasites  
587 reflect ecological status of freshwater ecosystem. Science of The Total Environment 838,  
588 156091. <https://doi.org/10.1016/j.scitotenv.2022.156091>

589 Fleury, F., Gibert, P., Ris, N., Allemand, R., 2009. Chapter 1 Ecology and life history evolution  
590 of frugivorous *Drosophila* parasitoids, in: Advances in Parasitology, Advances in  
591 Parasitology. Academic Press, pp. 3–44. [https://doi.org/10.1016/S0065-308X\(09\)70001-6](https://doi.org/10.1016/S0065-308X(09)70001-6)

592

593 Flomer, O., 1994. DNA primers for amplification of mitochondrial cytochrome c oxidase  
594 subunit I from diverse metazoan invertebrates. Mol Mar Biol Biotech 3, 294–299.

595 Gajula, S.K., Konkala, A., Narra, M.R., 2024. Physiological and biochemical responses of *Labeo*  
596 *rohita* to neonicotinoids imidacloprid, clothianidin, and their mixture. Fish Physiol  
597 Biochem 51, 13. <https://doi.org/10.1007/s10695-024-01412-8>

598 Gleichsner, A.M., Cleveland, J.A., Minchella, D.J., 2016. One stimulus – Two responses: Host  
599 and parasite life-history variation in response to environmental stress. Evolution 70,  
600 2640–2646. <https://doi.org/10.1111/evo.13061>

601 Goussen, B., Péry, A.R.R., Bonzom, J.-M., Beaudouin, R., 2015. Transgenerational adaptation  
602 to pollution changes energy allocation in populations of nematodes. Environ. Sci.  
603 Technol. 49, 12500–12508. <https://doi.org/10.1021/acs.est.5b03405>

604 Goutte, A., Molbert, N., 2022. Benefits of parasitism in polluted environments: A review and  
605 perspectives. Frontiers in Ecology and Evolution 10, 361.  
606 <https://doi.org/10.3389/fevo.2022.847869>

607 Grabner, D., Rothe, L.E., Sures, B., 2023. Parasites and pollutants: Effects of multiple stressors  
608 on aquatic organisms. Environmental Toxicology and Chemistry 42, 1946–1959.  
609 <https://doi.org/10.1002/etc.5689>

610 Hassell, M., 2000. The spatial and temporal dynamics of host-parasitoid interactions. OUP  
611 Oxford.

612 Heath, A., 2021. Climate change and its potential for altering the phenology and ecology of  
613 some common and widespread arthropod parasites in New Zealand. New Zealand  
614 Veterinary Journal 69, 5–19. <https://doi.org/10.1080/00480169.2020.1787276>

615 Heil, M., 2016. Host manipulation by parasites: Cases, patterns, and remaining doubts.  
616 Frontiers in Ecology and Evolution 4. <https://doi.org/10.3389/fevo.2016.00080/full>

617 Hua, J., Buss, N., Kim, J., Orlofske, S.A., Hoverman, J.T., 2016. Population-specific toxicity of  
618 six insecticides to the trematode *Echinoparyphium* sp. Parasitology 143, 542–550.  
619 <https://doi.org/10.1017/S0031182015001894>

620 Kennedy, C.R., 2006. Ecology of the acanthocephala. Cambridge University Press.

621 Koprivnikar, J., Forbes, M.R., Baker, R.L., 2007. Contaminant effects on host-parasite  
622 interactions: atrazine, frogs, and trematodes. Environmental Toxicology and  
623 Chemistry 26, 2166–2170. <https://doi.org/10.1897/07-220.1>

624 Koprivnikar, J., Forbes, M.R., Baker, R.L., 2006. Effects of atrazine on cercarial longevity,  
625 activity, and infectivity. *Journal of Parasitology* 92, 306–311.  
626 <https://doi.org/10.1645/GE-624R.1>

627 Lafferty, K.D., Kuris, A.M., 1999. How environmental stress affects the impacts of parasites.  
628 *Limnology and Oceanography* 44, 925–931.  
629 [https://doi.org/10.4319/lo.1999.44.3\\_part\\_2.0925](https://doi.org/10.4319/lo.1999.44.3_part_2.0925)

630 Lagrue, C., Poulin, R., 2008. Intra- and interspecific competition among helminth parasites:  
631 Effects on *Coitocaecum parvum* life history strategy, size and fecundity. *International*  
632 *Journal for Parasitology* 38, 1435–1444. <https://doi.org/10.1016/j.ijpara.2008.04.006>

633 Lorrain-Soligon, L., Golven, A., Agostini, S., Millot, A., Bauer, A., Rigaud, T., Decencière, B.,  
634 Puppo, C., Goutte, A., 2025. Acclimation and recovery dynamics of behavioral and  
635 coloration responses of a common fish (*Squalius cephalus*) to paracetamol exposure.  
636 *Chemosphere* 374, 144225. <https://doi.org/10.1016/j.chemosphere.2025.144225>

637 Lüdecke, D., Makowski, D., Waggoner, P., Patil, I., 2020. Performance: assessment of  
638 regression models performance. *Journal of Open Source Software* 6, 3139.  
639 <https://doi.org/10.21105/joss.03139>

640 Marchand, E., Petit, F., Alliot, F., Blanchoud, H., Costantini, D., Guigon, E., Martin, N., Traore,  
641 S., Goutte, A., 2024. Contrasted antibiotics and pesticides occurrence in fish exposed in  
642 situ to urban effluents: a 20-day caging experiment. *Environmental Toxicology and*  
643 *Chemistry* 43, 701–711. <https://doi.org/10.1002/etc.5810>

644 Marcogliese, D.J., Pietrock, M., 2011. Combined effects of parasites and contaminants on  
645 animal health: parasites do matter. *Trends in Parasitology* 27, 123–130.  
646 <https://doi.org/10.1016/j.pt.2010.11.002>

647 Martinez-Bakker, M., Helm, B., 2015. The influence of biological rhythms on host–parasite  
648 interactions. *Trends in Ecology & Evolution* 30, 314–326.  
649 <https://doi.org/10.1016/j.tree.2015.03.012>

650 Médoc, V., Bollache, L., Beisel, J.-N., 2006. Host manipulation of a freshwater crustacean  
651 (*Gammarus roeseli*) by an acanthocephalan parasite (*Polymorphus minutus*) in a biological  
652 invasion context. *International Journal for Parasitology* 36, 1351–1358.  
653 <https://doi.org/10.1016/j.ijpara.2006.07.001>

654 Médoc, V., Rigaud, T., Motreuil, S., Perrot-Minnot, M.-J., Bollache, L., 2011. Paratenic hosts as  
655 regular transmission route in the acanthocephalan *Pomphorhynchus laevis*: potential  
656 implications for food webs. *Naturwissenschaften* 98, 825.  
657 <https://doi.org/10.1007/s00114-011-0831-y>

658 Molbert, N., Alliot, F., Leroux-Coyau, M., Médoc, V., Biard, C., Meylan, S., Jacquin, L., Santos,  
659 R., Goutte, A., 2020. Potential benefits of acanthocephalan parasites for chub hosts in  
660 polluted environments. *Environ. Sci. Technol.* 54, 5540–5549.  
661 <https://doi.org/10.1021/acs.est.0c00177>

662 Morley, N.J., 2009. Environmental risk and toxicology of human and veterinary waste  
663 pharmaceutical exposure to wild aquatic host–parasite relationships. *Environmental*  
664 *Toxicology and Pharmacology* 27, 161–175. <https://doi.org/10.1016/j.etap.2008.11.004>

665 Morley, N.J., Lewis, J.W., Hoole, D., 2006. Pollutant-induced effects on immunological and  
666 physiological interactions in aquatic host–trematode systems: implications for parasite  
667 transmission. *Journal of Helminthology* 80, 137–149.  
668 <https://doi.org/10.1079/JOH2006345>

669 Nachev, M., Hohenadler, M., Bröckers, N., Grabner, D., Sures, B., 2024. Suitability of invasive  
670 gobies as paratenic hosts for acanthocephalans of the genus *Pomphorhynchus sp.*  
671 *Parasitology* 1–8. <https://doi.org/10.1017/S0031182024001197>

672 Papkou, A., Gokhale, C.S., Traulsen, A., Schulenburg, H., 2016. Host–parasite coevolution:  
673 why changing population size matters. *Zoology, SI: Host-Parasite Coevolution* 119,  
674 330–338. <https://doi.org/10.1016/j.zool.2016.02.001>

675 Patz, J.A., Graczyk, T.K., Geller, N., Vittor, A.Y., 2000. Effects of environmental change on  
676 emerging parasitic diseases. *International journal for parasitology* 30, 1395–1405.

677 Peacock, S.J., Krkošek, M., Bateman, A.W., Lewis, M.A., 2015. Parasitism and food web  
678 dynamics of juvenile Pacific salmon. *Ecosphere* 6, 1–16.  
679 <https://doi.org/10.1890/ES15-00337.1>

680 Penczykowski, R.M., Laine, A.-L., Koskella, B., 2016. Understanding the ecology and evolution  
681 of host-parasite interactions across scales. *Evolutionary Applications* 9, 37–52.  
682 <https://doi.org/10.1111/eva.12294>

683 Perrot-Minnot, M.-J., Cozzarolo, C.-S., Amin, O., Barčák, D., Bauer, A., Filipović Marijić, V.,  
684 García-Varela, M., Servando Hernández-Orts, J., Yen Le, T.T., Nachev, M., Orosová,  
685 M., Rigaud, T., Šariri, S., Wattier, R., Reyda, F., Sures, B., 2023. Hooking the scientific  
686 community on thorny-headed worms: interesting and exciting facts, knowledge gaps  
687 and perspectives for research directions on Acanthocephala. *Parasite* 30, 23.  
688 <https://doi.org/10.1051/parasite/2023026>

689 Perrot-Minnot, M.-J., Guyonnet, E., Bollache, L., Lagrue, C., 2019. Differential patterns of  
690 definitive host use by two fish acanthocephalans occurring in sympatry:  
691 *Pomphorhynchus laevis* and *Pomphorhynchus tereticollis*. *International Journal for*  
692 *Parasitology: Parasites and Wildlife* 8, 135–144.  
693 <https://doi.org/10.1016/j.ijppaw.2019.01.007>

694 Pietroock, M., Goater, C.P., 2005. Infectivity of *Ornithodiplostomum ptychocheilus* and  
695 *Posthodiplostomum minimum* (trematoda: diplostomidae) cercariae following exposure  
696 to cadmium. *Journal of Parasitology* 91, 854–856. <https://doi.org/10.1645/GE-473R.1>

697 Pietroock, M., Marcogliese, D.J., 2003. Free-living endohelminth stages: at the mercy of  
698 environmental conditions. *Trends in Parasitology* 19, 293–299.  
699 [https://doi.org/10.1016/S1471-4922\(03\)00117-X](https://doi.org/10.1016/S1471-4922(03)00117-X)

700 Pisa, L.W., Amaral-Rogers, V., Belzunces, L.P., Bonmatin, J.M., Downs, C.A., Goulson, D.,  
701 Kreuzweiser, D.P., Krupke, C., Liess, M., McField, M., Morrissey, C.A., Noome, D.A.,  
702 Settele, J., Simon-Delso, N., Stark, J.D., Van der Sluijs, J.P., Van Dyck, H., Wiemers, M.,  
703 2015. Effects of neonicotinoids and fipronil on non-target invertebrates. *Environ Sci*  
704 *Pollut Res* 22, 68–102. <https://doi.org/10.1007/s11356-014-3471-x>

705 Poulin, R., Wise, M., Moore, J., 2003. A comparative analysis of adult body size and its  
706 correlates in acanthocephalan parasites. *International Journal for Parasitology* 33, 799–  
707 805. [https://doi.org/10.1016/S0020-7519\(03\)00108-5](https://doi.org/10.1016/S0020-7519(03)00108-5)

708 Pulkkinen, K., Ebert, D., 2004. Host starvation decreases parasite load and mean host size in  
709 experimental populations. *Ecology* 85, 823–833. <https://doi.org/10.1890/03-0185>

710 R Core Team, 2020. R: A language and environment for statistical computing. R Foundation  
711 for Statistical Computing. Austria: Vienna. <https://www.R-project.org/>.

712 Regala, R.P., Rice, C.D., Schwedler, T.E., Dorociak, I.R., 2001. The effects of tributyltin (TBT)  
713 and 3,3',4,4',5-Pentachlorobiphenyl (PCB-126) mixtures on antibody responses and  
714 phagocyte oxidative burst activity in channel catfish, *Ictalurus punctatus*. *Arch. Environ.*  
715 *Contam. Toxicol.* 40, 386–391. <https://doi.org/10.1007/s002440010187>

716 Relyea, R.A., 2009. A cocktail of contaminants: how mixtures of pesticides at low  
717 concentrations affect aquatic communities. *Oecologia* 159, 363–376.  
718 <https://doi.org/10.1007/s00442-008-1213-9>

719 Ripley, B., Venables, B., Bates, D.M., Hornik, K., Gebhardt, A., Firth, D., Ripley, M.B., 2013.  
720 Package ‘mass’. *Cran r* 538, 113–120.

721 Rohde, K., Heap, M., 1998. Latitudinal differences in species and community richness and in  
722 community structure of metazoan endo- and ectoparasites of marine teleost fish.  
723 *International Journal for Parasitology* 28, 461–474. [https://doi.org/10.1016/S0020-7519\(97\)00209-9](https://doi.org/10.1016/S0020-7519(97)00209-9)

- 725 Rohr, J.R., Raffel, T.R., Sessions, S.K., Hudson, P.J., 2008. Understanding the net effects of  
726 pesticides on amphibian trematode infections. *Ecological Applications* 18, 1743–1753.  
727 <https://doi.org/10.1890/07-1429.1>
- 728 Rosa Leite, L.A., dos Reis Pedreira Filho, W., Kozłowski de Azevedo, R., Doro Abdallah, V.,  
729 2021. Patterns of distribution and accumulation of trace metals in *Hysterothylacium* sp.  
730 (Nematoda), *Phyllostomum* sp. (Digenea) and in its fish host *Hoplias malabaricus*, from  
731 two neotropical rivers in southeastern Brazil. *Environmental Pollution* 277, 116052.  
732 <https://doi.org/10.1016/j.envpol.2020.116052>
- 733 Sackett, L.C., 2018. Does the host matter? Variable influence of host traits on parasitism rates.  
734 *International journal for parasitology* 48, 27–39.
- 735 Schäfer, R.B., Kühn, B., Malaj, E., König, A., Gergs, R., 2016. Contribution of organic toxicants  
736 to multiple stress in river ecosystems. *Freshwater Biology* 61, 2116–2128.  
737 <https://doi.org/10.1111/fwb.12811>
- 738 Schmutz, S., Sendzimir, J., 2018. Riverine ecosystem management. Springer International  
739 Publishing Switzerland.
- 740 Schneider, C.A., Rasband, W.S., Eliceiri, K.W., 2012. NIH Image to ImageJ: 25 years of image  
741 analysis. *Nature methods* 9, 671–675. <https://doi.org/10.1038/nmeth.2089>
- 742 Schoebel, C.N., Tellenbach, C., Spaak, P., Wolinska, J., 2011. Temperature effects on parasite  
743 prevalence in a natural hybrid complex. *Biol Lett* 7, 108–111.  
744 <https://doi.org/10.1098/rsbl.2010.0616>
- 745 Šebelová, Š., Kuperman, B., Gelnar, M., 2002. Abnormalities of the attachment clamps of  
746 representatives of the family Diplozoidae. *Journal of Helminthology* 76, 249–259.  
747 <https://doi.org/10.1079/JOH2002133>
- 748 Soose, L.J., Krauss, M., Landripet, M., Laier, M., Brack, W., Hollert, H., Klimpel, S., Oehlmann,  
749 J., Jourdan, J., 2025. Acanthocephalans as pollutant sinks? Higher pollutant  
750 accumulation in parasites may relieve their crustacean host. *Science of The Total*  
751 *Environment* 958, 177998. <https://doi.org/10.1016/j.scitotenv.2024.177998>
- 752 Stearns, S.C., 1998. The evolution of life histories. Oxford university press.
- 753 Studer, A., Thielges, D.W., Poulin, R., 2010. Parasites and global warming: net effects of  
754 temperature on an intertidal host–parasite system. *Marine Ecology Progress Series* 415,  
755 11–22. <https://doi.org/10.3354/meps08742>
- 756 Sun, P.Y., Foley, H.B., Handschumacher, L., Suzuki, A., Karamanukyan, T., Edmands, S., 2014.  
757 Acclimation and adaptation to common marine pollutants in the copepod *Tigriopus*  
758 *californicus*. *Chemosphere* 112, 465–471.  
759 <https://doi.org/10.1016/j.chemosphere.2014.05.023>
- 760 Sures, B., Knopf, K., 2004. Parasites as a threat to freshwater eels? *Science* 304, 209–211.  
761 <https://doi.org/10.1126/science.304.5668.209>
- 762 Sures, B., Nachev, M., Selbach, C., Marcogliese, D.J., 2017. Parasite responses to pollution: what  
763 we know and where we go in ‘Environmental Parasitology.’ *Parasites Vectors* 10, 1–19.  
764 <https://doi.org/10.1186/s13071-017-2001-3>
- 765 Sures, B., Siddall, R., 1999. *Pomphorhynchus laevis*: The intestinal acanthocephalan as a lead sink  
766 for its fish host, chub (*Leuciscus cephalus*). *Experimental Parasitology* 93, 66–72.  
767 <https://doi.org/10.1006/expr.1999.4437>
- 768 Sures, B., Taraschewski, H., 1995. Cadmium concentrations in two adult acanthocephalans,  
769 *Pomphorhynchus laevis* and *Acanthocephalus lucii*, as compared with their fish hosts and  
770 cadmium and lead levels in larvae of *A. lucii* as compared with their crustacean host.  
771 *Parasitol Res* 81, 494–497. <https://doi.org/10.1007/BF00931792>
- 772 Sures, B., Taraschewski, H., Jackwerth, E., 1994. Lead accumulation in *Pomphorhynchus laevis*  
773 and its host. *The Journal of Parasitology* 80, 355–357. <https://doi.org/10.2307/3283403>
- 774 Thorburn, D.-M.J., Bal, T.M.P., Deflem, I.S., Volckaert, F.A.M., Eizaguirre, C., Raeymaekers,  
775 J.A.M., 2022. Context-dependent parasite infection affects trophic niche in populations

776 of sympatric stickleback species. *Parasitology* 149, 1164–1172.  
777 <https://doi.org/10.1017/S0031182022000531>  
778 Truyens, C., Carlier, Y., 2010. Protective host response to parasite and its limitations, in:  
779 Telleria, J., Tibayrenc, M. (Eds.), *American Trypanosomiasis*. Elsevier, London, pp.  
780 601–668. <https://doi.org/10.1016/B978-0-12-384876-5.00024-1>  
781 Turcekova, L., Hanzelova, V., 1999. Concentrations of Cd, As and Pb in non-infected and  
782 infected *Perca fluviatilis* with *Proteocephalus percae*. *Helminthologia* 36, 31.  
783 Welicky, R.L., Preisser, W.C., Leslie, K.L., Mastick, N., Fiorenza, E., Maslenikov, K.P.,  
784 Tornabene, L., Kinsella, J.M., Wood, C.L., 2021. Parasites of the past: 90 years of change  
785 in parasitism for English sole. *Frontiers in Ecology and the Environment* 19, 470–477.  
786 <https://doi.org/10.1002/fee.2379>  
787 Wickham, H., François, R., Henry, L., Müller, K., Vaughan, D., 2023. dplyr: a grammar of data  
788 manipulation. R package version 1.1. 2. Computer software.  
789 Wood, C.L., Johnson, P.T., 2015. A world without parasites: exploring the hidden ecology of  
790 infection. *Frontiers in Ecology and the Environment* 13, 425–434.  
791 <https://doi.org/10.1890/140368>  
792 Wood, C.L., Welicky, R.L., Preisser, W.C., Leslie, K.L., Mastick, N., Greene, C., Maslenikov,  
793 K.P., Tornabene, L., Kinsella, J.M., Essington, T.E., 2023. A reconstruction of parasite  
794 burden reveals one century of climate-associated parasite decline. *Proceedings of the*  
795 *National Academy of Sciences* 120, e2211903120.  
796 <https://doi.org/10.1073/pnas.2211903120>  
797 Yen Le, T.T., Rijdsdijk, L., Sures, B., Jan Hendriks, A., 2014. Accumulation of persistent organic  
798 pollutants in parasites. *Chemosphere* 108, 145–151.  
799 <https://doi.org/10.1016/j.chemosphere.2014.01.036>  
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801

802 **Caption to figures**

803 **Figure 1** - Effect of (A) fish size on acanthocephalan number, (B) time spent in  
804 mesocosm on acanthocephalans size (mean  $\pm$  SE), (C) fish size on number of eggs  
805 produced, (D) body condition index of the fish on number of eggs produced, (E)  
806 acanthocephalan number on number of eggs produced, (F) acanthocephalan size on  
807 number of eggs produced, (G) time spent in mesocosms on number of eggs produced  
808 (mean  $\pm$  SE), and (H) acanthocephalan size on mature eggs proportion. Solid lines and  
809 different letters represent significant relationship at  $\alpha=0.05$ , dashed lines represent  
810 significant relationship at  $\alpha=0.10$ .

811 **Figure 2** - Effect of treatment during (A) imidacloprid experiment, (B) acute  
812 paracetamol experiment, (C) chronic paracetamol experiment, (D) diclofenac and S-  
813 metolachlor cocktail experiment, on acanthocephalan size. Mean  $\pm$  SE, small points are  
814 the observed values, different letters represent a significant difference at  $\alpha=0.05$ .

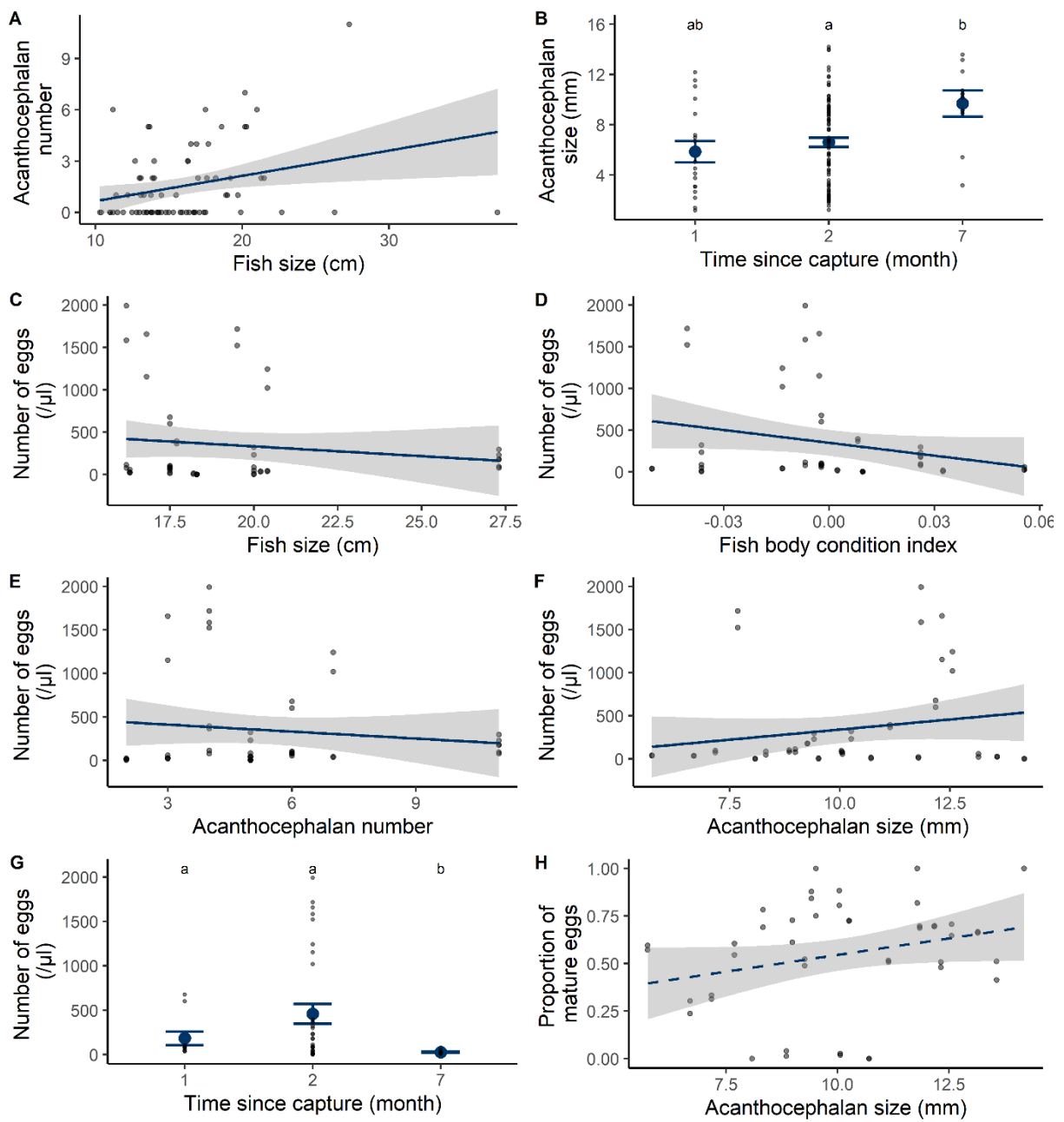
815 **Figure 3** - Effect of treatment during (A) imidacloprid experiment, (B) acute  
816 paracetamol experiment, (C) chronic paracetamol experiment, (D) diclofenac and S-  
817 metolachlor cocktail experiment, on egg production. Mean  $\pm$  SE, different letters  
818 represent a significant difference at  $\alpha=0.05$ . Note that, in this figure, observed values  
819 were not included as they constituted only of 0 or 1 values.

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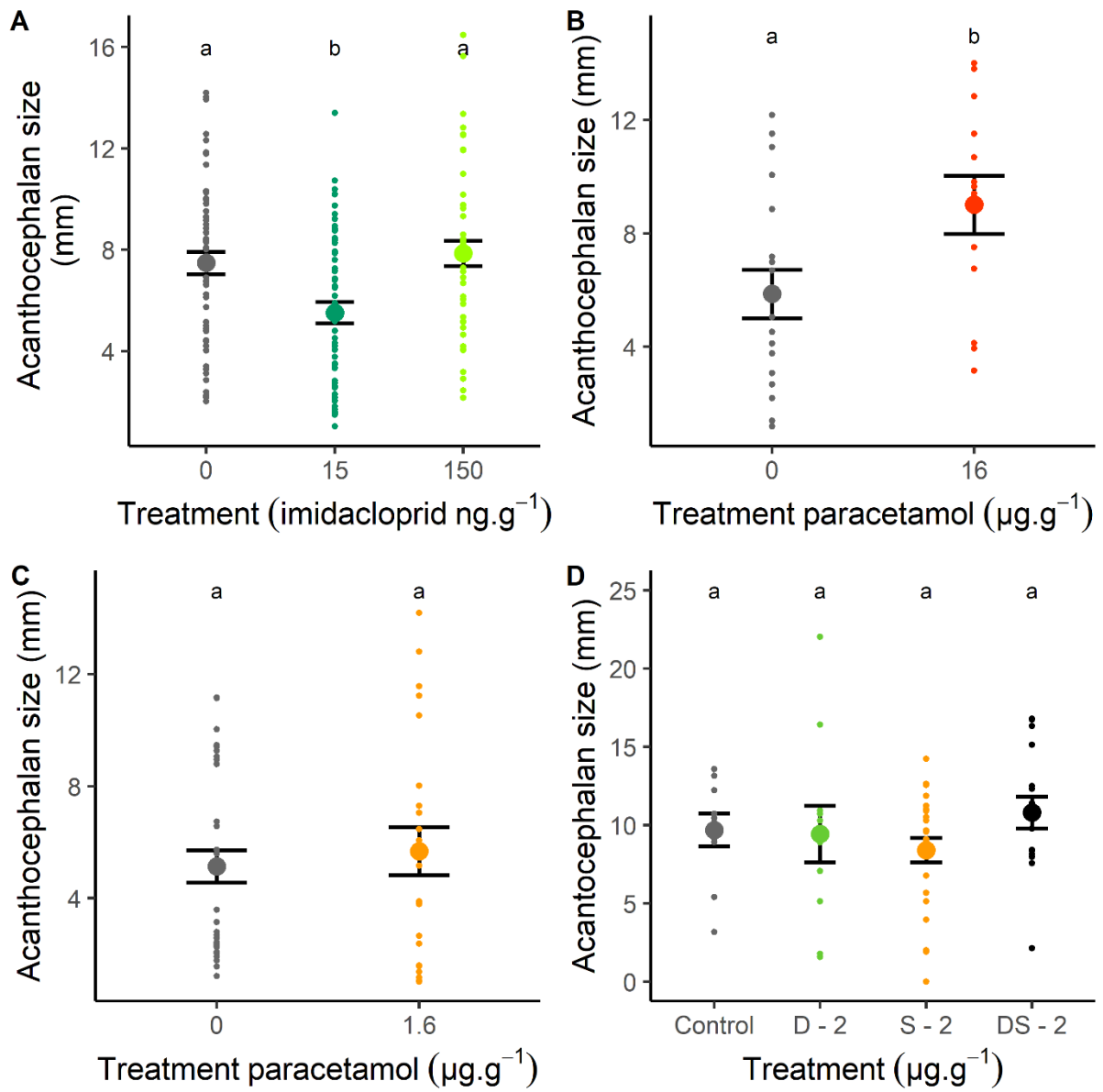
823 Figure 1



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826 Figure 2

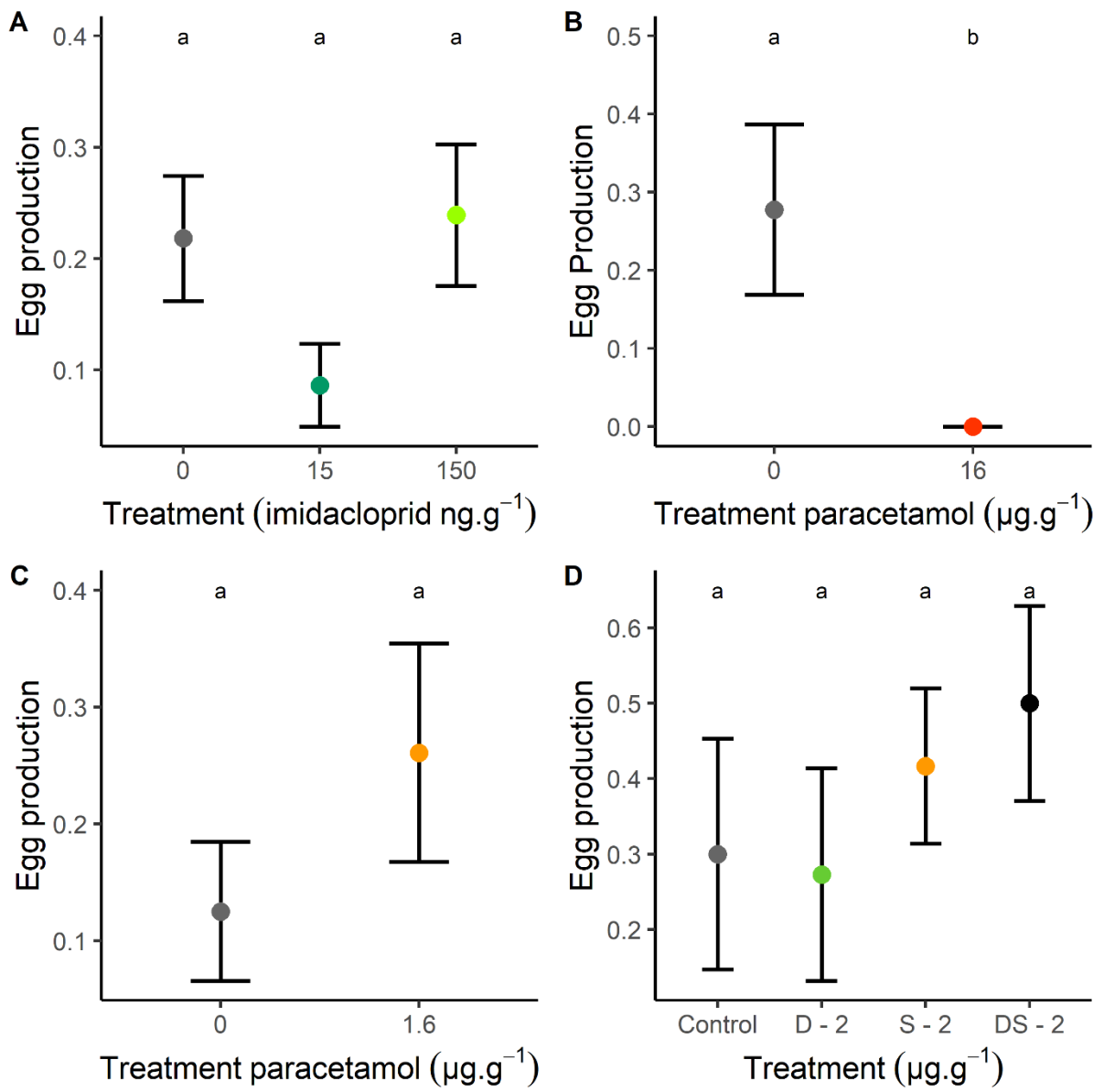


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830 **Figure 3**



831

832 **Caption to tables**

833 **Table 1** - Summary of experimental protocols and variables across different  
834 exposure scenarios (exposure to imidacloprid, acute exposure to paracetamol,  
835 chronic exposure to paracetamol, exposure to diclofenac and S-metolachlor),  
836 including capture dates, groups, doses, exposure protocols, and measured fish  
837 metrics.

838 **Table 2** - Statistical results for the effect of environmental variables for all  
839 individuals exposed to a control from all experiments on acanthocephalan number,  
840 size, egg production, number of egg produced, and proportion of mature eggs.

841 **Table 3** - Statistical results for the effect of treatment on acanthocephalan number, size,  
842 egg production, number of egg produced, and proportion of mature eggs separated  
843 for the imidacloprid experiment, acute paracetamol experiment, chronic paracetamol  
844 experiment, diclofenac and S-metolachlor cocktail experiment. Post-hoc analyses were  
845 performed when the effect was significant.

Table 1

Experiment	Sites	Date capture	Group	N	Dose	Exposure	Date dissection	Fish size ( $\pm$ SE)	Fish mass ( $\pm$ SE)
Exposure to imidacloprid	Dannemois, Montaquoy	02/10/2023 and 19/10/2023	Control	30	0 ng.g <sup>-1</sup>	once a week during six weeks, from 31/10/2023 to 04/12/2023	14/12/2023 to 22/12/2023	16.61 $\pm$ 0.69	51.58 $\pm$ 8.27
			IMI15	31	15 ng.g <sup>-1</sup>			16.54 $\pm$ 0.59	49.07 $\pm$ 5.62
			IMI150	30	150 ng.g <sup>-1</sup>			16.66 $\pm$ 0.60	49.77 $\pm$ 5.70
Acute exposure to paracetamol	Cerny, Dannemois, Gironville, Montaquoy, pont de la Planche, Saint Germain	23/01/2024, 24/01/2024, 25/01/2024, 30/01/2024 and 31/01/2024	C	15	0 $\mu$ g.g <sup>-1</sup>	once a day during two consecutive days, from 10/02/2024 to 13/02/2024	13/02/2024 and 15/02/2024	16.34 $\pm$ 1.14	48.37 $\pm$ 12.03
			P	17	16 $\mu$ g.g <sup>-1</sup>			16.14 $\pm$ 0.96	44.74 $\pm$ 8.64
Chronic exposure to paracetamol	Cerny, Dannemois, Gironville, Montaquoy, pont de la Planche, Saint Germain	23/01/2024, 24/01/2024, 25/01/2024, 30/01/2024 and 31/01/2024	C	16	0 $\mu$ g.g <sup>-1</sup>	once a week during three consecutive weeks from 22/02/2024 to 11/03/2024	15/03/2024 to 22/03/2024	16.17 $\pm$ 1.79	72.69 $\pm$ 36.27
			P	17	1.6 $\mu$ g.g <sup>-1</sup>			16.02 $\pm$ 1.51	58.65 $\pm$ 22.67
Exposure to diclofenac and S-metolachlor	Gironville, Montaquoy, Moret	13/09/2023, 02/10/2023, 03/10/2023, 04/10/2023, 05/10/2023, 08/10/2023, 19/10/2023	C	15	0 $\mu$ g.g <sup>-1</sup>	twice a week during two consecutive weeks, from 29/04/2024 to 10/05/2024	14/05/2024 to 31/05/2024	15.03 $\pm$ 0.49	33.72 $\pm$ 3.91
			D	13	2 $\mu$ g.g <sup>-1</sup>			15.0 $\pm$ 0.49	33.70 $\pm$ 3.75
			S	17	2 $\mu$ g.g <sup>-1</sup>			15.16 $\pm$ 0.99	41.59 $\pm$ 12.31
			DS	13	2 $\mu$ g.g <sup>-1</sup>			15.00 $\pm$ 1.26	44.39 $\pm$ 20.41

Table 2

Dependant variable	Statistical analyses of environmental variables					Post-hoc analyses				
	Model	Explicative variable	Chisq	df	p-value	Comparison	Estimate	SE	z-value	p-value
Acanthocephalan number	quasipoisson GLMM	Fish size	7.047	1	<b>0.008</b>					
Acanthocephalan size	Gamma GLMM	Time in mesocosm	4.519	1	<b>0.034</b>	2 month - 1 month	0.013	0.017	0.789	0.704
						7 month - 1 month	-0.026	0.021	-1.203	0.444
		Site of capture	27.035	6	<b>&lt;0.001</b>	7 month - 2 month	-0.039	0.016	-2.472	<b>0.035</b>
Egg production	binomial GLMM	Site of capture	3.711	6	0.716					
		Fish size	0.002	1	0.962					
		Fish body condition index	1.484	1	0.223					
		Time in mesocosm	2.225	1	0.136					
		Acanthocephalan number	0.829	1	0.362					
		Period of dissection	5.061	2	0.080					
Total number of eggs	quasipoisson GLMM	Site of capture	31.756	3	<b>&lt;0.001</b>					
		Fish size	28.479	1	<b>&lt;0.001</b>					
		Fish body condition index	38.673	1	<b>&lt;0.001</b>					
		Acanthocephalan number	5.413	1	<b>0.020</b>					
		Acanthocephalan size	9.328	1	<b>0.002</b>					
		Time in mesocosm	15.197	1	<b>&lt;0.001</b>	2 month - 1 month	0.68	1.721	0.395	0.914
						7 month - 1 month	6.047	2.12	2.852	<b>0.011</b>
				7 month - 2 month	5.367	1.283	4.182	<b>&lt;0.001</b>		
Proportion of mature eggs	Gamma GLMM	Acanthocephalan size	3.11	1	<b>0.078</b>					

Table 3

Group	Dependant variable	Statistical test of treatment effect				Post-hoc analyses				
		Model	Chisq	df	p-value	Comparison	Estimate	SE	z-value	p-value
Imidacloprid experiment	Acanthocephalan number	Gamma GLMM	0.453	2	0.798					
	Acanthocephalan size (all individuals)	LMM (log10 transformed)	18.331	2	<b>&lt;0.001</b>	15-0	-0.133	0.038	-3.487	<b>0.001</b>
						150-0	0.021	0.04	0.541	0.851
						150-15	0.154	0.04	3.867	<b>&lt;0.001</b>
	Acantocephalan size (small individuals)	LMM (log10 transformed)	0.072	2	0.965	15-0	-0.189	0.037	-5.046	<b>&lt;0.001</b>
						150-0	0.03	0.038	0.803	0.701
						150-15	0.22	0.04	5.532	<b>&lt;0.001</b>
	Acantocephalan size (large individuals)	LMM (log10 transformed)	39.303	2	<b>&lt;0.001</b>	15-0	-0.115	0.021	-5.393	<b>&lt;0.001</b>
						150-0	0.008	0.021	0.358	0.932
						150-15	0.123	0.022	5.534	<b>&lt;0.001</b>
Egg production	binomial GLMM	3.168	2	0.205						
Total number of eggs	LMM (log10 transformed)	0.227	2	0.893						
Proportion of mature eggs	Gamma GLMM	0.270	2	0.874						
Acute paracetamol experiment	Acanthocephalan number	Gamma GLMM	0.743	1	0.389					
	Acanthocephalan size (all individuals)	LMM (log10 transformed)	4.265	1	<b>0.039</b>	0-16	-0.186	0.089	-2.065	<b>0.039</b>

	Acanthocephalan size (small individuals)	LMM (log10 transformed)	0.855	1	0.355					
	Acanthocephalan size (large individuals)	LMM (log10 transformed)	6.911	1	<b>0.009</b>	0-16	-0.130	0.049	-2.629	<b>0.009</b>
	Egg production	Gamma GLMM	4.291	1	<b>0.038</b>					
Chronic paracetamol experiment	Acanthocephalan number	Gamma GLMM	0.399	1	0.528					
	Acanthocephalan size	LMM (log10 transformed)	0.048	1	0.826					
	Egg production	binomial GLMM	1.275	1	0.259					
	Total number of eggs	LMM (log10 transformed)	2.417	1	0.12					
	Proportion of mature eggs	Gamma GLMM	4.416	1	0.225					
Diclofenac and S-metolachlor cocktail experiment	Acanthocephalan number	Gamma GLMM	3.388	3	0.336					
	Acanthocephalan size	LMM (log10 transformed)	3.13	3	0.372					
	Egg production	binomial GLMM	1.816	3	0.612					
	Total number of eggs	LMM (log10 transformed)	0.134	3	0.988					
	Proportion of mature eggs	Gamma GLMM	0.529	3	0.912					

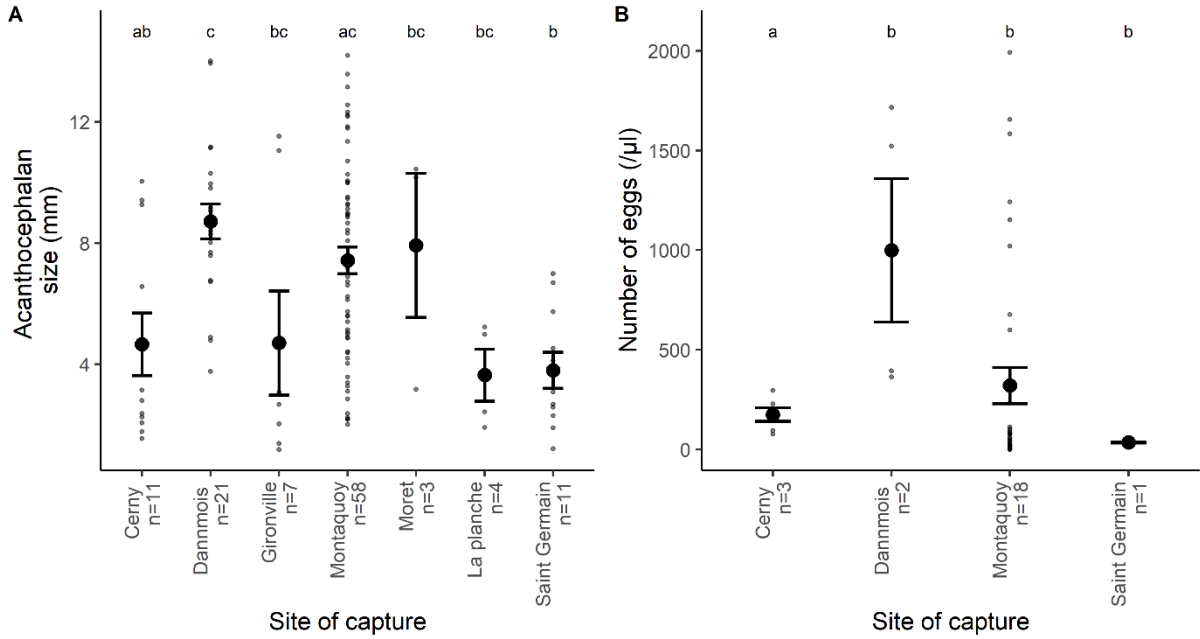
## **Caption to appendices**

**Appendix A** - Influence of site of capture on (A) acanthocephalan size and (B) number of eggs produced. Mean  $\pm$  SE, different letters represent a significant difference at  $\alpha=0.05$ . Note that not all sites from the panel A are represented in panel B, as acanthocephalan originating from some sites did not produce eggs at all, and they are thus not represented in panel B. N represent number of individuals in which it can be assessed, note that for (B), each individual have 2 values since eggs were counted for two samples of 1  $\mu$ L.

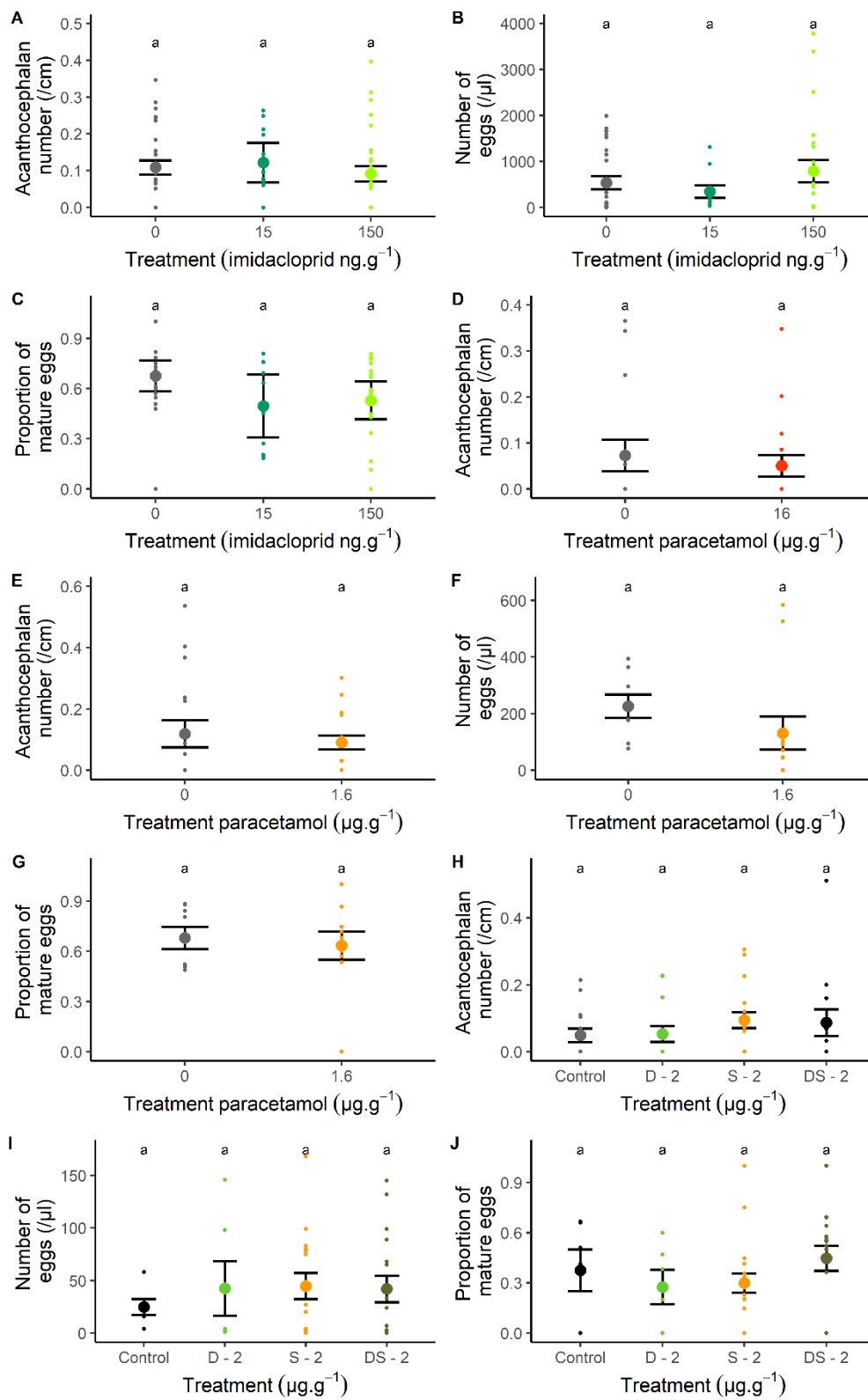
**Appendix B** - For the (ABC) imidacloprid experiment, (D) acute paracetamol experiment, (EFG) chronic paracetamol experiment, and (HIJ) diclofenac and S-metolachlor cocktail experiment, effects of treatment on number of eggs produced (AEH), proportion of mature eggs (BFI), and number of acanthocephalan (CGJ). Mean  $\pm$  SE, small points are the observed values, similar letters represent the lack of significant difference at  $\alpha=0.05$ .

**Appendix C** - Effect of treatment during (A, B) imidacloprid experiment, and (C, D) acute paracetamol experiment, for small (A, C) or large (B, D) individuals only (compared to the median size for each treatment). Mean  $\pm$  SE, small points are the observed values, different letters represent a significant difference at  $\alpha=0.05$ .

Appendix A



## Appendix B



## Appendix C

