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From behaviour to complex communities: Resilience to anthropogenic noise in a fish-induced trophic cascade

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1 **TITLE**

2 From behaviour to complex communities: Resilience to anthropogenic noise in a fish-induced
3 trophic cascade

4

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35 **KEY WORDS:** chronic noise pollution, freshwater plankton, predation, mesocosms, *Rutilus*

36 *rutilus*, cascading effect

37

38 **SUMMARY**

39 Sound emissions from human activities represent a pervasive environmental stressor.

40 Individual responses in terms of behaviour, physiology or anatomy are well documented but

41 whether they propagate through nested ecological interactions to alter complex communities

42 needs to be better understood. This is even more relevant for freshwater ecosystems that

43 harbour a disproportionate fraction of biodiversity but receive less attention than marine and

44 terrestrial systems. We conducted a mesocosm investigation to study the effect of chronic

45 exposure to motorboat noise on the dynamics of a freshwater community including

46 phytoplankton, zooplankton, and roach as a planktivorous fish. As expected under the trophic

47 cascade hypothesis, roach predation induced structural changes in the planktonic
48 communities. Surprisingly, although roach changed their feeding behaviour in response to
49 noise, the dynamics of the roach-dominated planktonic communities did not differ between
50 noisy and noiseless mesocosms. This suggests that the top-down structuring influence of
51 roach on planktonic communities might be resilient to noise and reveals the difficulties on
52 extrapolating impacts from individual responses to complex communities.

53

54 **1. INTRODUCTION**

55

56 The trophic cascade, one of the most influential concepts in ecology, specifies the effects of
57 predators that propagate downward through food webs across multiple trophic levels [1,2].
58 Considering a series of nested consumer-resource interactions (i.e., a food chain), top
59 predators have a direct negative effect on mesopredators and indirect positive and negative
60 effects alternatively on lower trophic levels. Top-down cascade effects can result from
61 changes in predator density (density-mediated trophic cascade) or behaviour (trait-mediated
62 trophic cascade) and much attention has focused on identifying the intrinsic and extrinsic
63 determinants of their strength [3,4]. In particular, this helped to better understand the
64 structural impact of several anthropogenic stressors including warming, salinization,
65 chemical pollution or habitat degradation [5–7].

66 Noise emissions from transportation, cities, industry, military and recreational
67 activities represent another pervasive anthropogenic stressor [8,9]. They span all ecosystems
68 even in the most remote places [10] and have been shown to alter communication, social
69 interactions, use of space, activity patterns, foraging and reproduction in a wide range of taxa

70 [11–13]. First evidence of the cascading effects of noise pollution came from the long-term
71 investigations conducted in the natural gas fields of northwest New Mexico. Bird response to
72 gas-well-compressor noise was found species-specific with some key seed dispersers
73 (mountain bluebirds and Woodhouse’s scrub-jays) avoiding noisy areas where pollinators
74 like hummingbirds had on the contrary higher reproductive success [14]. Long-term
75 consequences include alterations in plant communities that persist after removal of the noise
76 source [15]. The propensity of anthropogenic noise to indirectly affect species, and typically
77 primary producers, through a series of nested direct interactions had also been suggested
78 experimentally. Barton *et al.*[16] exposed a three-level terrestrial food chain to various
79 soundscapes for 14 days in plant growth chambers and found that urban sounds and rock
80 music made lady beetles less effective predators, reducing the strength of top-down control
81 on aphids, whose density increased. More aphids ultimately resulted in reduced soybean
82 biomass. Although freshwaters harbour a disproportionate fraction of earth’s biodiversity
83 [17] and suffer a greater decline in species richness compared to terrestrial and marine
84 habitats [18,19], they often receive less attention, and research on the impacts of noise
85 pollution is no exception. For instance, we known that fish responses to noise include
86 changes in behaviour and abundances [20–23] but whether these effects spread along food
87 webs to alter planktonic communities through cascading effects remains to be investigated.
88 Similarly, the response of freshwater plankton to noise is largely overlooked. Available
89 evidence to date comes from water fleas, *Daphnia* spp., which are widespread pelagic
90 crustaceans (Cladocera) and an important source of food for upper trophic levels [24,25].
91 Surprisingly, knowing that marine invertebrates of similar size were found to adjust their
92 swimming activity in response to natural or artificial sounds [26], water fleas exposed to

93 band-pass filtered white noise either continuous or intermittent did not show any alteration in
94 swimming speed or depth [27,28]. However, long-term effects of chronic exposure on their
95 survival and reproductive success have yet to be explored, and overall, we lack knowledge on
96 the dynamics of plankton under anthropogenic noise. Here we conducted a mesocosm
97 investigation to study the temporal dynamics of a zooplankton – phytoplankton system under
98 the presence or absence of a planktivorous fish, with and without exposure to motorboat
99 noise. We used the roach *Rutilus rutilus* as top predator: a widespread Eurasian cyprinid fish
100 whose response to motorboat noise has been documented. Roach have specialized hearing
101 structures, the Weberian ossicles, that conduct sound from the swim-bladder to the inner ear
102 and provide high sensitivity to sound pressure [29–31]. They can detect sounds between 10
103 Hz and 5 kHz with a maximum sensitivity of 60 dB re. 1 μ Pa between 500 and 1000 Hz [32].
104 Roach have been found to respond to authentic motorboat sounds with fewer feeding
105 attempts, higher latency to enter the open area and longer time spent in the vegetation, and
106 these effects persisted after five days of exposure suggesting the absence of habituation [33].
107 After our mesocosm investigation, and in order to get insights into fish growth and behaviour,
108 the roach have been collected, weighted, and measured, and moved to aquaria to assess prey
109 consumption, mobility and group cohesion in the presence or absence of boat noise. Given
110 the lack of knowledge on how freshwater plankton respond to chronic noise exposure, we had
111 no clear prediction on the effect of boat noise on the dynamics of the zooplankton –
112 phytoplankton system without fish. Under the trophic cascade hypothesis, we expected roach
113 presence to reduce the top-down control of phytoplankton by zooplankton. Considering that
114 motorboat noise was found to negatively influence foraging in roach [33], we predicted a
115 decrease in the strength of top-down cascading effect. Concerning roach behaviour, we

116 expected behavioural alterations consistent with the weakening of the trophic cascade in the
117 noisy mesocosms.

118

119 **2. MATERIALS AND METHOD**

120

121 The investigation has been conducted at the PLANAQUA experimental platform of the
122 CEREEP-Ecotron Île-de-France research station (48° 16'10.92 N, 2° 43'50.879 E, Seine et
123 Marne, France) and lasted six weeks (August 31 – October 14, 2020), which corresponds to a
124 prolonged exposure to motorboat noise following Johansson et al. (2016). We assigned three
125 mesocosms to one of four treatments ($N = 3$ replicates, 12 mesocosms in total): (1) no fish -
126 no noise, (2) no fish - noise, (3) fish – no noise, and (4) fish – noise.

127

128 2.1 Preparation of the mesocosms and animal collection

129

130 Each mesocosm (3.4 m diameter, 1.1 m depth) was filled with 9,079 L of water from the
131 storage lakes of the field station that naturally host zooplankton and phytoplankton
132 communities. An underwater loudspeaker (Electrovoice UW30) was submerged five cm
133 below the surface in the center of each mesocosm. It was connected to an amplifier (Dynavox
134 CS-PA 1MK) and then to an audio player (Handy's H4n zoom), both placed inside a
135 waterproof electric box next to the mesocosm. To promote the growth of phytoplankton, we
136 added 30 mL of Algoflash® (41.4 µg of phosphorus, nitrogen, and potassium per liter) at the
137 beginning of the investigation (August 20) and 50 additional mL at the middle of the
138 investigation (September 19) after we detected a drop in the amount of chlorophyll in the

139 mesocosms using a multiparameter probe (YSI ExO-2). From March to April 2020, we used
140 fish traps to gradually collect roach from the storage lakes of the PLANAQUA platform, and
141 we stored them in a pond containing the same planktonic communities as the mesocosms.
142 These fish were the descendants of roach used in previous investigations conducted on the
143 platform. They grew in quiet conditions and had never experienced motorboat noise before.
144 At Day 0, 96 roach of similar size (8.54 ± 2.32 cm for standard length, SL) were randomly
145 collected from the storage pond using a seine net, measured, and weighted to the nearest 0.01
146 cm and 1 g, and distributed in groups of 16 between the six mesocosms (fish – no noise and
147 fish – noise treatments) so as to homogenize size distribution and total biomass between the
148 mesocosms. We placed anti-bird nets on top of the mesocosms to avoid avian predation.

149

150 2.2 Plankton dynamics

151

152 To assess plankton dynamics, we sampled the mesocosms 13 times from Day 0 to Day 42
153 and every two or four days. The temporal variation of phytoplankton was assessed through
154 the quantification of green algae, cyanobacteria, and diatom densities. We sampled eight
155 liters of water per mesocosm using a 2-L sampling bottle (Uwitec) at four different positions.
156 Analyses were made in the laboratory using a BBE FluoroProbeTM spectrofluorometer (BBE
157 Moldaenke GmbH, Schwentimental) on a 125-mL subsample previously kept in the dark for
158 one hour. For detecting potential top-down effects on zooplankton, we choose to focus on
159 mesoplankton organisms (Cladocera, copepodits and adults of Copepods, and *Chaoborus*
160 larvae), which appeared as the most responsive organisms in previous mesocosm experiments
161 realized in comparable conditions [34]. To assess their temporal variation in zooplankton, we

162 sampled 24 liters of water using a 2-L sampling bottle at twelve different positions and
163 depths in each mesocosm. Water was filtered with a 50- μ m nylon filter and zooplankton
164 fixed in 15-mL of 90% ethanol. Taxa identification and counting was made on a 3-mL
165 subsample following [35] for cladocerans and copepods (nauplii not counted), and [36] for
166 aquatic insects.

167

168 2.3 Fish growth and behaviour

169

170 The behavioural tests took place in an experimental room of the PLANAQUA platform
171 thermo-regulated at 17°C. We equipped four 110-L aquaria (80 cm length x 35 cm width x 40
172 cm height) with an underwater loudspeaker (Electrovoice UW30) in the middle of the left end
173 surrounded by acoustic foam (1.5-cm thick) to attenuate vibrations, a neon light, and a
174 camera (HD-TVI ABUS TVVR33418) above, and black plastic boards outside to avoid
175 visual contacts with the experimenters that may provide stress. The speaker was connected to
176 an amplifier (Dynavox CS-PA 1MK) and to an audio player (Handy's H4n zoom). The
177 aquaria were filled with water from the control mesocosms (no fish – no noise treatment)
178 filtered through a 50- μ m nylon mesh filter to remove zooplankton. This experimental design
179 allowed us to run four tests simultaneously with one treatment *per* aquarium depending on
180 the noise condition in the mesocosm and later in the aquarium (“mesocosm – aquarium”
181 noise conditions): (1) no noise – no noise, (2) no noise – noise, (3) noise – no noise and (4).
182 Between two consecutive runs of tests, each aquarium was assigned another treatment to
183 avoid an effect of the aquarium, while water was changed to remove chemical cues.

184 At the end of the mesocosm investigation (Day 44), roach were removed from the
185 mesocosms using a seine net and measured and weighted to the nearest 0.01 cm and 1 g. We
186 matched these values with the weights and lengths measured at the beginning of the
187 mesocosm investigation to recognize fish and calculate individual growth. Roach were then
188 randomly assigned to groups of three individuals and moved into one of the four
189 experimental aquaria. In total, we formed 28 groups ($N = 7$ replicates per treatment) with two
190 or three groups per mesocosm. Once in the aquarium, they first experienced ambient noise
191 during an acclimatization period of one hour, and then 40 minutes of either ambient noise or
192 ambient noise supplemented with motorboat sounds, depending on the treatment (see section
193 2.4 for further detail on the playback tracks). At the middle of the exposure period (i.e. after
194 20 min), we introduced 50 *Chaoborus* larvae (Diptera) and 50 *Daphnia* sp. (Crustacea:
195 Cladocera), previously collected from the control mesocosms using a 2-L sampling bottle and
196 50- μ m nylon mesh filter. Both invertebrates are common prey of roach, differ in terms of size
197 and mobility, and were found in the mesocosms. Although *Chaoborus* larvae are natural
198 predators of *Daphnia* [37], we expected no predation events considering the short duration of
199 the experiment. At the end of the experiment, roach and invertebrates were removed from the
200 aquarium, counted, and returned to the storage pond. The videos were analyzed using
201 Kinovea v. 0.9.4 to get the xy coordinates of each fish each second and during each boat
202 sound (for a total of 691s and corresponding to ambient noise for the other treatment), and
203 then the following parameters were calculated: (1) the cumulative swimming distance (total
204 distance covered by the three individuals) as a proxy of mobility, (2) the distance between the
205 barycenter of each group and the center of the speaker as a proxy of aversion to noise, and (3)
206 the area occupied by the group as a proxy of group cohesion.

207 Group's barycenter was calculated using individual coordinates as follows:

$$208 \quad X_{\text{barycenter}} = (X_{\text{fish1}} + X_{\text{fish2}} + X_{\text{fish3}}) / 3$$

$$209 \quad Y_{\text{barycenter}} = (Y_{\text{fish1}} + Y_{\text{fish2}} + Y_{\text{fish3}}) / 3$$

210 The distance between the barycenter and the loudspeaker (D in cm) was calculated as
211 follows:

$$212 \quad D = \sqrt{((X_{\text{barycenter}} - X_{\text{loudspeaker}})^2 + (Y_{\text{barycenter}} - Y_{\text{loudspeaker}})^2)}$$

213 Group's area (A in cm^2) was calculated as follows:

$$214 \quad A = \sqrt{((P * (P - d_{\text{fish1-fish2}}) * (P - d_{\text{fish1-fish3}}) * (P - d_{\text{fish2-fish3}})))}$$

215 Where d corresponds to the distance between two fish in cm and P to the perimeter of the
216 group in cm with:

$$217 \quad P = \frac{1}{2} (d_{\text{fish1-fish2}} + d_{\text{fish1-fish3}} + d_{\text{fish2-fish3}})$$

218 Group barycenter and area were calculated every second during the boat sounds and then
219 averaged.

220 The behavioural tests took place from 8 am to 6 pm and needed two consecutive days with
221 four mesocosms (two from the fish – no noise treatment and two from the fish – noise
222 treatment) processed on Day 43 and the two others (one *per* treatment) on Day 44. We also
223 conducted four additional tests (two *per* noise condition) without roach to control for
224 *Chaoborus* predation on *Daphnia* and overall invertebrate mortality in the absence of
225 predation.

226

227 2.4 Noise treatments

228

229 We used Audacity 2.2.1 to generate the audio tracks and an Aquarian Audio H2A-HLR
230 hydrophone (frequency response from 10 to 100 kHz) connected to a ZOOM H4next Handy
231 recorder for all the recordings. The level of background noise did not differ between the
232 mesocosms and ranged from 90 to 95 dB re. μPa . In the mesocosms without boat noise, a 1-
233 hr audio track of silence was looped continuously. In the mesocosms with boat noise, we
234 used the audio tracks described in [38] where 150 sounds of small recreational boats have
235 been distributed over the nine consecutive 1-hr audio tracks of silence going from 9 a.m. to 6
236 p.m. so as to mimic the daily activity of a small leisure base (Fig. 1A and Supp. Mat. 1, see
237 Rojas et al. 2021 for more details on the audio tracks and the original recordings). We
238 broadcasted silence the rest of the time. We applied a linear fading on both ends of the boat
239 sounds to make them emerge from background noise and adjusted their levels with Audacity
240 to obtain naturally occurring signal-to-noise ratios (SNR) ranging from 4.81 to 27 dB. We
241 used the SNR function of the *seewave* R package [39]:

$$242 \quad \text{SNR} = 20\log_{10}(\text{RMS}_{\text{boat sound}}/\text{RMS}_{\text{background noise}})$$

243 where RMS is the root-mean-square sound pressure of either the re-recordings of the boat
244 sounds in the mesocosm or the recording of background noise.

245 In the aquaria without boat noise and to encompass the 1-h acclimatization period and
246 the 40-min exposure period, we used a 100-min audio track of background noise previously
247 recorded in the center of one mesocosm from the no noise – no fish treatment. We adjusted
248 sound level to match that of the mesocosms. In the aquaria with boat noise, we used the 100-
249 min audio track of background noise to which we added twelve boat sounds randomly
250 selected from those broadcasted in the mesocosms. We randomly distributed the sounds over
251 the 40-min exposure period and adjusted their level to match the range of SNR values we had

252 in the mesocosms (approx. 4.81 to 27 dB). In terms of boat traffic, this acoustic regime was
253 representative of the highest activity that roach experienced within a day in the mesocosms
254 (Fig. 1B and Supp. Mat. 1).

255

256 2.5 Data analysis

257

258 All the statistics were performed using R [40] with a significance level of 0.05. We used the
259 Principal Response Curve (PRC, *prc* function of the *vegan* R package [41]) to study how the
260 planktonic communities exposed to roach, boat noise, or both, have diverged over time
261 compared to control communities (i.e. from the no fish – no noise treatment). PRC is a
262 special case of redundancy analysis including time-series data particularly suited to the study
263 of community dynamics in mesocosms [42]. It typically results in a diagram with one curve
264 for each treatment, the time on the x-axis, the first major component of the community effects
265 on the left y-axis and the weights of the taxa on the right y-axis. The more the weight
266 deviates from zero the more the corresponding taxon contributes to the deviation from the
267 control. We used Hellinger-transformed taxa (square root of the relative abundance) to reduce
268 the influence of both rare (low abundances and/or many zeros) and abundant taxa [43].
269 Significance in the PRC was tested using a permutation test (*anova.cca* function of the *vegan*
270 R package) accounting for the non-independence of data due to repeated measurements on
271 the same mesocosm. Significance in the difference between each treatment and the control
272 was assessed with a multiple comparison test (*multiconstrained* function of the *BiodiversityR*
273 R package).

274 Roach' growth rate (G) was computed using the formulae:

$$275 \quad G = (L_{\text{final}} - L_{\text{initial}}) / L_{\text{initial}} * 100$$

276 where L_{final} and L_{initial} are the final and initial SL of roach, respectively.

277 Because growth data met the normality and homoscedasticity assumptions (Shapiro-Wilk and
278 Bartlett tests, all p values > 0.05), we used a linear mixed-effect model (*lme4* R package [44])
279 with the noise condition as fixed factor and the mesocosm as random factor to test for
280 significance of the difference in growth rate between the treatments.

281 The effects of noise and pre-exposure to noise on roach predation were assessed in
282 two ways. First, we used a generalized linear mixed-effect model assuming a Poisson
283 distribution to explain the total number of prey eaten as a function of the noise condition in
284 the mesocosm, the noise condition in the aquarium and their interaction as fixed factors, and
285 the mesocosm ID as random factor. Second, we estimated the preference of roach for
286 *Daphnia* over *Chaoborus* larvae using the Manly's alpha (α) preference index [45,46]:

$$287 \quad \alpha_{daphnia} = \ln(50 - N_{daphnia}) / (\ln(50 - N_{daphnia}) + \ln(50 - N_{chaoborus}))$$

288 where 50 is the initial number of each prey, and $N_{daphnia}$ and $N_{chaoborus}$ the numbers of daphnia
289 and *Chaoborus* larvae eaten. The Manly's alpha accounts for prey depletion during the
290 predation test and ranges from zero when only the alternative prey (here *Chaoborus* larvae) is
291 eaten to one when only the focal prey (here *Daphnia*) is eaten. The value of 0.5 indicates a
292 lack of preference. As recommended by [47], we compared obtained values to the theoretical
293 value of 0.5 using t tests except for the "no fish – noise" treatment where we used a Wilcoxon
294 test to deal with the non-normality of data.

295 Roach behaviour was analyzed with model averaging and an information-theory
296 approach. We used linear mixed-effect models to model each of the three response variables
297 (cumulative swimming distance, distance to the speaker and area of the group) as a function
298 of the noise condition in the mesocosm, the noise condition in the aquarium, the time, and
299 taking the mesocosm ID as random factor as several groups came from the same mesocosm.
300 Because the noise condition that roach have experienced in the mesocosm might have
301 changed their response to boat noise in the aquarium and because the effect of time may vary

302 with the noise condition, we also included the interactions between the two noise treatments
303 and between each noise treatment and time in the predictors. All predictors were centered and
304 scaled using the *standardization* function of the *arm* R package. We ranked all the submodels
305 based on small sampled-corrected AIC values (AIC_c , *dredge* and *get.models* functions of the
306 *MuMIn* Rpackage [48]) and performed model averaging on a confidence set of models using
307 a cut-off of 10 AIC_c (*model.avg* function of the *AICcmodavg* R package). The predictors
308 whose parameter estimate had a 95% confidence interval (CI) that included the value of zero
309 were considered as having no significant effect.

310

311 **3. RESULTS**

312

313 The pelagic zooplankton communities of the mesocosms included four cladoceran families
314 (Bosminidae, Daphniidae, Sididae and Chydoridae), cyclopoid and calanoid copepods,
315 dipteran larvae of the genus *Chaoborus*, and some ostracods captured in the pelagic zone
316 although being mainly benthic organisms. The diagram of the PRC analysis illustrates how
317 adding roach, boat noise or both make the planktonic communities gradually deviate over
318 time from those of the no fish – no noise treatment (i.e., control) considered as the baseline
319 (Fig. 2). Adding boat noise made the communities deviate from the control and adding roach
320 induced a larger deviation without variation between the two noise conditions (i.e., similar
321 trajectories, Fig. 2). Table 1A shows that 30% of total variance was attributed to time and
322 34% to the treatment regime, including its interaction with time. On the basis of the
323 permutation tests, the treatment regime as well as time and their interaction had a significant
324 influence on the community dynamics (Table 1B). The pairwise comparisons revealed that
325 the difference between the two treatments with roach (with or without noise) was the only to

326 be not significant (Table 1C). Bosminidae and in a lesser extent Chydoridae, both copepod
327 taxa and green algae are indicated with a positive taxon weight in the PRC, suggesting they
328 were expected to increase in abundance with the treatments relative to the control and in
329 proportion to their weight. On the other hand, Daphniidae and, to a lesser extent ostracod,
330 Sididae and *Chaoborus* larvae exhibited negative species weights and were expected to
331 decrease in abundance with the treatments. The taxa weights of diatoms and cyanobacteria
332 were the smallest and close to zero (Fig. 2).

333 Individual fish growth did not significantly differ between the noise conditions ($\chi_1^2 =$
334 1.4813 and $p = 0.2236$, Fig. 3). In the absence of roach, prey survival in the aquaria was
335 100% for both prey in the absence of boat noise, and 100% for *Chaoborus* larvae and 98%
336 for *Daphnia* in the presence of boat noise. We therefore considered prey mortality during the
337 predation tests to be the result of fish predation only. The effect of noise on the total number
338 of consumed prey depended on the noise condition in the mesocosms, with significantly less
339 prey consumed only for roach coming from the noiseless mesocosms ($\chi_1^2 = 18.36$ and $p <$
340 0.001 for the interaction between the two noise conditions, Fig. 4A). Whatever the noise
341 condition in the mesocosm, the Manly's alpha index did not differ from the theoretical value
342 of 0.5 in noiseless aquaria ($t = 1.36$ and $p = 0.22$ for ambient noise, $t = -0.32$ and $p = 0.76$ for
343 boat noise) but was significantly higher with boat noise ($V = 27$ and $p = 0.03$ for ambient
344 noise, $t = 3.10$ and $p = 0.02$ for boat noise, Fig. 4B). Concerning the cumulative swimming
345 distance and the distance to the speaker, the 95% CI of the parameter estimate included the
346 value of zero for all the predictors. Concerning the area occupied by the group, boat noise in
347 the aquarium and time were the only predictors whose parameter estimate 95% CI did not
348 include the value of zero, with significantly positive values (Fig. 5).

349

350 **4. DISCUSSION**

351

352 Exposure to anthropogenic noise is known to elicit physiological or behavioural responses in
353 individual organisms [8,11–13,22]. But to what extent these alterations spread across
354 ecological interactions to alter community dynamics and ecosystem functions is not clear. We
355 conducted a mesocosm investigation to study the impact of chronic exposure to motorboat
356 noise on the dynamics of a zooplankton – phytoplankton system either alone or dominated by
357 a planktivorous fish. Although we detected alterations in fish feeding and behaviour, the
358 strength of top-down control and its consequences on the structure of the planktonic
359 communities were resilient to motorboat noise. This suggests that individual responses to
360 noise do not necessarily result in ecological effects at the level of communities.

361 The pelagic mesoplankton communities of our mesocosms were dominated by
362 cladocerans and copepods, two major groups of herbivorous microcrustaceans widespread in
363 freshwater bodies. In smaller proportions, they also included ostracods (coming from the
364 benthic areas of the mesocosms), and predatory larvae of the *Chaoborus* genus, known to
365 feed on small zooplankton [49]. In fishless mesocosms, daphnid cladocerans gradually
366 became the most abundant taxa. Compared to copepods, cladocerans have higher
367 reproduction rates. Moreover, because daphnids are the largest cladocerans, they suffer
368 smaller predation risk by *Chaoborus* larvae than the other cladocerans [50]. The presence of
369 roach made the planktonic communities gradually deviate from those of the fishless
370 communities with a shift in the dominant taxon of zooplankton from daphnids to bosminids
371 whose abundance greatly increased. Visual-feeding fish like roach tend to prefer large

372 zooplankton [51] and it might be that selective predation on the two largest taxa: *Chaoborus*
373 larvae and daphnids, has released bosminids from predation and competition. Alteration in
374 the daphnids – bosminids balance is symptomatic of fish presence [52]. To a lesser extent,
375 copepods and Chydoridae have also benefited from the roach-induced decrease in daphnids.
376 This might be explained by the greater availability of food resources like green algae, which
377 slightly increased in the presence of roach, but also rotifers that represent another important
378 taxon of freshwater zooplankton. Due to their small size, we did not count the number of
379 rotifers but they are known to increase in the presence of fish because of the removal of large
380 cladocerans [53]. The slight increase in green algae in the presence of roach is consistent with
381 the trophic cascade hypothesis: fish have a negative direct effect on zooplankton (here
382 daphnids) and indirectly benefit phytoplankton that is released from grazing [34]. Another
383 way roach can influence the planktonic communities is through the modulation of diel
384 migration patterns. Indeed, some taxa migrate to the bottom under chemical cues by predators
385 and become less frequent in the pelagic realm [54].

386 Motorboat noise did not alter the top-down structuring effect of roach on the
387 planktonic communities and particularly the shift from daphnids to bosminids. This suggests
388 that chronic exposure to noise had no effect on the feeding behaviour of roach, which is
389 consistent with the absence of difference in growth rate between the two noise conditions.
390 This is also consistent with the total number of prey eaten recorded during the predation tests,
391 which was significantly reduced by motorboat noise for the roach that never experienced boat
392 noise before but not for those pre-exposed to boat noise in the mesocosms. Weakening of the
393 response to noise after repeated exposure has been reported in other fish species [38,55,56],
394 and might reflect habituation through associative learning: naïve animals first allocate

395 attention to noise at the expense of other activities like feeding, and then resume normal
396 behaviour as they learn that it is not associated with any threat. However, when looking
397 closer to what has been eaten, we found motorboat noise to elicit selective preference for
398 daphnids over *Chaoborus* larvae even for roach pre-exposed to boat noise in the mesocosm.
399 This persistent response could find its origin in behaviour. Concerning invertebrates,
400 although we did not record their behaviour, we know from past investigations that motorboat
401 noise did not alter the mobility of daphnids [27] but triggers body rotations in *Chaoborus*
402 larvae [38], interpreted as an anti-predatory response [57,58] that could have driven the
403 choice of roach towards daphnids. Concerning roach behaviour, we found no alteration in
404 mobility and no evidence for any avoidance of the sound source, but the area occupied by the
405 three individuals was larger under motorboat noise. This effect seems to be persistent as it
406 was also observed with the roach pre-exposed to boat noise in the mesocosms. Similarly,
407 playback of pile driving was found to make juveniles of seabass less cohesive [59]. Noise
408 could mask the perception of nearest neighbours' movements through the lateral line or
409 impair the ability to process sensory information as a consequence of stress and/or distraction
410 [59]. Compared to stress or distraction, masking does not weaken with repeated exposure.
411 This could explain why the reduced group cohesion was also observed in the roach that
412 experienced motorboat noise in the mesocosms. Disruption of group cohesion could
413 ultimately compromise the benefits of grouping associated with the dilution and confusion
414 effects [60]. Regarding feeding, we can expect the strength of intra-specific competition to
415 decrease with the distance between individuals. Together with the lesser catchability of
416 moving *Chaoborus* larvae, this could explain why the roach showed selective preference for
417 daphnids under motorboat noise. At the level of communities, a selective preference for

418 daphnids, which were the main grazers, should have strengthened the trophic cascade, what
419 we did not observe. The change in feeding we found in the aquaria may not have been strong
420 enough to be detected in the mesocosms or maybe does not occur in a larger and more
421 complex environment where other prey items are available.

422 In the fishless mesocosms, adding motorboat noise induced a small but detectable
423 deviation from the control communities. This is interesting but also tricky to interpret since
424 very little is known on the response of freshwater plankton to chronic anthropogenic noise.
425 *Chaoborus* larvae occupied the highest trophic level of the fishless communities and we
426 know that they are sensitive to motorboat sounds with more body rotations [38], interpreted
427 as an anti-predatory response [58]. If noise also interferes with prey processing and reduces
428 the capture efficiency of *Chaoborus* larvae, then it could be beneficial to small zooplankton.
429 Noise could also trigger vertical migration to the bottom, as chemical cues from predators do
430 [54], making some taxa like ostracods less detectable in the pelagic realm. Additional long-
431 term investigations in mesocosms but also *in situ* are needed to better understand the response
432 of planktonic communities to chronic anthropogenic noise.

433 Our investigation illustrates how extrapolating the impact of anthropogenic noise
434 from individual responses to complex communities is far from obvious. Although we
435 observed persistent alterations in roach behaviour with less group cohesion and altered
436 feeding preference, these effects did not propagate downward along the food chain through
437 trait-mediated cascading effects. A valuable perspective would be to study the dynamics of
438 roach under chronic anthropogenic noise to test whether the behavioural responses we
439 observed ultimately decrease survival and/or reproductive success [61], and result in density-
440 mediated cascading effects.

441

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447

448 **ETHIC STATEMENTS**

449 All the procedures were conducted in accordance with appropriate European (*Directive*
450 2010/63/EU) and French national guidelines, permits, and regulations regarding animal care
451 and experimental use (Approval no. C42-218-0901).

452

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457 (Transnational Access).

458

459 **CONFLICT OF INTEREST**

460 The authors declare that they have no conflicts of interest.

461

462 **DATA AVAILABILITY**

463 The data that support the findings of this study are open available in Zenodo at

464 <https://doi.org/10.5281/zenodo.6760791>.

465

466

467 **FIGURE LEGENDS**

468

469 **Figure 1:** Sound spectra of the two noise conditions (control: dashed lines, boat noise: one
470 solid lines for each hour from 9 am to 6 pm) broadcasted in A) the mesocosms and B) the
471 aquaria. Spectra were made from 1-hour recordings in the mesocosms and 20-min recordings
472 in the aquaria.

473

474 **Figure 2:** Principal Response Curve (PRC) showing the effects of adding fish (squares),
475 motorboat noise (dots) or both (triangles) on freshwater plankton communities compared to
476 control communities (no fish – no noise, horizontal line, see text for further detail). Species
477 weights are on the left axis (bos: Bosminidae, cyclo: cyclopoid copepods, cala: calanoid
478 copepods, chydo: Chydoridae, green: green algae, diat: diatoms, cyano: cyanobacteria, sidi:
479 Sididae, chao: *Chaoborus* larvae, ostra: ostracods, daph: Daphniidae). See Table 1 for the
480 percentages of variance accounted for and the significance levels.

481

482 **Figure 3:** Fish growth rates (medians and interquartile ranges) in the mesocosms depending
483 on the noise condition (white box: ambient, grey box: boat noise, $n = 48$ per condition).

484

485 **Figure 4:** Results of the predation tests in aquaria with A) the total number of prey eaten *per*
486 group of three fish (n=7 groups per acoustic mesocosm-aquarium treatment) presented to 50
487 *Daphnia* and 50 *Chaoborus* larvae and B) the Manly's alpha preference index for *Daphnia*
488 over *Chaoborus* larvae (medians and interquartile ranges) as a function of the noise condition
489 previously experienced in the mesocosms and the noise condition in the aquaria (white box:
490 ambient, grey box: boat noise).

491

492 **Figure 5:** Model-averaged coefficient estimates and 95% confidence intervals for the
493 predictors included in the confidence set of models explaining the behaviour of roach *Rutilus*
494 *rutilus* in groups of three individuals when feeding on *Daphnia* and *Chaoborus* larvae during
495 the predation tests in aquaria. We used as response variables A) the area of the group, B) the
496 cumulative swimming distance and C) the distance to the speaker. Predictors correspond to
497 the noise condition in the mesocosms (boat noise or ambient noise as control), the noise
498 condition in the aquaria of the predation tests (boat noise or ambient noise as control), the
499 time, and the two-way interactions between time and the noise condition in the two
500 experimental units and between the noise conditions of the two experimental units.

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515 **TABLE**

516

517 **Table 1:** Results of the Principal Response Curve (PRC) for the effect of motorboat noise

518 (absence / presence) and fish (absence / presence, for a total of four treatments) on freshwater

519 planktonic communities. A) Proportion of the total variance explained by the constraints:

520 time, treatment, and their interaction, captured by the canonical 1st axis of the PRC. B)

521 Significance of the PRC diagram on the basis on the permutation test for Constrained

522 Correspondence Analysis (CCA, 999 permutations). C) Pairwise comparisons for all the

523 possible treatment combinations following a CCA analysis.

524

525 A)

	Inertia	Proportion	Rank
Total	0.236	1	
Conditional (% of the total variance explained by time)	0.071	0.30	12
Constrained (% of the total variance explained by time*treatment)	0.085	0.36	11
Unconstrained	0.080	0.34	11

(% of the total variance not explained by predictors)			
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526

527 B)

	Df	Variance	F	Pr(>F)
Treatment	3	0.04	19.28	0.001 ***
Time	1	0.06	77.32	0.001 ***
Treatment*Time	3	0.02	8.98	0.001 ***

528

529 C)

Pairwise comparison	Df	Sum of Sqs	F	Pr(>F)
no fish - no noise fish - no noise	1	0.054	23.856	0.001 ***
no fish - no noise no fish - noise	1	0.011	4.801	0.003 **
no fish - no noise fish - noise	1	0.059	22.593	0.001 ***
fish - no noise no fish - noise	1	0.022	8.902	0.001 ***
fish - no noise fish - noise	1	0.005	1.624	0.177
no fish - noise fish - noise	1	0.027	9.523	0.001 ***

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539 **REFERENCES**

540

- 541 1. Fretwell SD. 1987 Food Chain Dynamics: The Central Theory of Ecology? *Oikos* **50**,
542 291–301. (doi:10.2307/3565489)
- 543 2. Ripple WJ *et al.* 2016 What is a Trophic Cascade? *Trends in Ecology & Evolution* **31**,
544 842–849. (doi:10.1016/j.tree.2016.08.010)
- 545 3. Schmitz OJ, Krivan V, Ovadia O. 2004 Trophic cascades: the primacy of trait-
546 mediated indirect interactions. *Ecology Letters* **7**, 153–163. (doi:10.1111/j.1461-
547 0248.2003.00560.x)
- 548 4. Su H, Feng Y, Chen J, Chen J, Ma S, Fang J, Xie P. 2021 Determinants of trophic
549 cascade strength in freshwater ecosystems: a global analysis. *Ecology* **102**, e03370.
550 (doi:10.1002/ecy.3370)
- 551 5. Hebblewhite M. 2005 Predation by Wolves Interacts with the North Pacific
552 Oscillation (NPO) on a Western North American Elk Population. *Journal of Animal Ecology*
553 **74**, 226–233.
- 554 6. Cheng BS, Grosholz ED. 2016 Environmental stress mediates trophic cascade
555 strength and resistance to invasion. *Ecosphere* **7**, e01247. (doi:10.1002/ecs2.1247)
- 556 7. Duchet C *et al.* 2018 Pesticide-mediated trophic cascade and an ecological trap for
557 mosquitoes. *Ecosphere* **9**, e02179. (doi:10.1002/ecs2.2179)
- 558 8. Sordello R, Ratel O, Flamerie De Lachapelle F, Leger C, Dambry A, Vanpeene S.
559 2020 Evidence of the impact of noise pollution on biodiversity: a systematic map.
560 *Environmental Evidence* **9**, 20. (doi:10.1186/s13750-020-00202-y)
- 561 9. Duarte CM *et al.* 2021 The soundscape of the Anthropocene ocean. *Science* **371**,
562 eaba4658. (doi:10.1126/science.aba4658)

- 563 10. Buxton RT, McKenna MF, Mennitt D, Fristrup K, Crooks K, Angeloni L, Wittemyer
564 G. 2017 Noise pollution is pervasive in U.S. protected areas. *Science* **356**, 531–533.
565 (doi:10.1126/science.aah4783)
- 566 11. Kight CR, Swaddle JP. 2011 How and why environmental noise impacts animals: an
567 integrative, mechanistic review. *Ecology Letters* **14**, 1052–1061. (doi:10.1111/j.1461-
568 0248.2011.01664.x)
- 569 12. Francis CD, Barber JR. 2013 A framework for understanding noise impacts on
570 wildlife: an urgent conservation priority. *Frontiers in Ecology and the Environment* **11**, 305–
571 313. (doi:10.1890/120183)
- 572 13. Shannon G *et al.* 2016 A synthesis of two decades of research documenting the
573 effects of noise on wildlife. *Biological Reviews* **91**, 982–1005. (doi:10.1111/brv.12207)
- 574 14. Francis CD, Kleist NJ, Ortega CP, Cruz A. 2012 Noise pollution alters ecological
575 services: enhanced pollination and disrupted seed dispersal. *Proceedings of the Royal Society*
576 *B: Biological Sciences* **279**, 2727–2735. (doi:10.1098/rspb.2012.0230)
- 577 15. Phillips JN, Termond SE, Francis CD. 2021 Long-term noise pollution affects
578 seedling recruitment and community composition, with negative effects persisting after
579 removal. *Proceedings of the Royal Society B: Biological Sciences* **288**, 20202906.
580 (doi:10.1098/rspb.2020.2906)
- 581 16. Barton BT, Hodge ME, Speights CJ, Autrey AM, Lashley MA, Klink VP. 2018
582 Testing the AC/DC hypothesis: Rock and roll is noise pollution and weakens a trophic
583 cascade. *Ecology and Evolution* **8**, 7649–7656. (doi:10.1002/ece3.4273)
- 584 17. Dudgeon D *et al.* 2006 Freshwater biodiversity: importance, threats, status and
585 conservation challenges. *Biological Reviews* **81**, 163–182.
586 (doi:10.1017/S1464793105006950)
- 587 18. Dudgeon D. 2019 Multiple threats imperil freshwater biodiversity in the
588 Anthropocene. *Current Biology* **29**, R960–R967. (doi:10.1016/j.cub.2019.08.002)
- 589 19. Maasri A *et al.* 2022 A global agenda for advancing freshwater biodiversity research.
590 *Ecology Letters* **25**, 255–263. (doi:10.1111/ele.13931)
- 591 20. Slabbekoorn H, Bouton N, van Opzeeland I, Coers A, ten Cate C, Popper AN. 2010 A
592 noisy spring: the impact of globally rising underwater sound levels on fish. *Trends in Ecology*
593 *& Evolution* **25**, 419–427. (doi:10.1016/j.tree.2010.04.005)
- 594 21. Kunc HP, McLaughlin KE, Schmidt R. 2016 Aquatic noise pollution: implications for
595 individuals, populations, and ecosystems. *Proceedings of the Royal Society B: Biological*
596 *Sciences* **283**, 20160839. (doi:10.1098/rspb.2016.0839)

- 597 22. Cox K, Brennan LP, Gerwing TG, Dudas SE, Juanes F. 2018 Sound the alarm: A
598 meta-analysis on the effect of aquatic noise on fish behavior and physiology. *Global Change*
599 *Biology* **24**, 3105–3116. (doi:10.1111/gcb.14106)
- 600 23. Mickle MF, Higgs DM. 2018 Integrating techniques: a review of the effects of
601 anthropogenic noise on freshwater fish. *Canadian Journal of Fisheries and Aquatic Sciences*
602 **75**, 1534–1541. (doi:10.1139/cjfas-2017-0245)
- 603 24. Lampert W. 2006 Daphnia: model herbivore, predator and prey. *Polish Journal of*
604 *Ecology* **54**, 607–620.
- 605 25. Reynolds CS. 2011 Daphnia: Development of Model Organism in Ecology and
606 Evolution - 2011. *Freshwater Reviews* **4**, 85–87. (doi:10.1608/FRJ-4.1.425)
- 607 26. Tidau S, Briffa M. 2016 Review on behavioral impacts of aquatic noise on
608 crustaceans. *Proceedings of Meetings on Acoustics* **27**, 010028. (doi:10.1121/2.0000302)
- 609 27. Sabet SS, Neo YY, Slabbekoorn H. 2015 The effect of temporal variation in sound
610 exposure on swimming and foraging behaviour of captive zebrafish. *Animal Behaviour* **107**,
611 49–60. (doi:10.1016/j.anbehav.2015.05.022)
- 612 28. Sabet SS, Karnagh SA, Azbari FZ. 2019 Experimental test of sound and light
613 exposure on water flea swimming behaviour. *Proceedings of Meetings on Acoustics* **37**,
614 010015. (doi:10.1121/2.0001270)
- 615 29. Hawkins A, Myrberg A. 1983 Hearing and sound communication underwater.
616 *Bioacoustics, a comparative approach, Academic Press, London* , 347–405.
- 617 30. Popper AN, Fay RR. 2011 Rethinking sound detection by fishes. *Hearing Research*
618 **273**, 25–36. (doi:10.1016/j.heares.2009.12.023)
- 619 31. Andersson MH, Dock-Akerman E, Ubral-Hedenberg R, Ohman MC, Sigray P. 2007
620 Swimming behavior of roach (*Rutilus rutilus*) and three-spined stickleback (*Gasterosteus*
621 *aculeatus*) in response to wind power noise and single-tone frequencies. *Ambio* **36**, 636–638.
622 (doi:10.1579/0044-7447(2007)36[636:sborrr]2.0.co;2)
- 623 32. Amoser S, Wysocki LE, Ladich F. 2004 Noise emission during the first powerboat
624 race in an Alpine lake and potential impact on fish communities. *The Journal of the*
625 *Acoustical Society of America* **116**, 3789–3797. (doi:10.1121/1.1808219)
- 626 33. Magnhagen C, Johansson K, Sigray P. 2017 Effects of motorboat noise on foraging
627 behaviour in Eurasian perch and roach: a field experiment. *Marine Ecology Progress Series*
628 **564**, 115–125. (doi:10.3354/meps11997)
- 629 34. Bertolo A, Lacroix G, Lescher-Moutouš F, Sala S. 1999 Effects of physical refuges
630 on fish–plankton interactions. *Freshwater Biology* **41**, 795–808. (doi:10.1046/j.1365-

- 631 2427.1999.00424.x)
- 632 35. Haney JF, et al. 2013 *'An-Image-based Key to the Zooplankton of North America'*
633 *version 5.0 released in 2013*. University of New Hampshire Center for Freshwater Biology.
634 See <http://cfb.unh.edu/cfbkey/html/index.html>.
- 635 36. Winterbourn MJ, Winterbourn G, Katharine L, Katharine D, Heath C. 1989 *Guide to*
636 *the aquatic insects of New Zealand*. Entomological Society of New Zealand Auckland.
- 637 37. Spitze K. 1991 Chaoborus predation and life-history evolution in *Daphnia pulex*:
638 temporal pattern of population diversity, fitness, and mean life history. *Evolution* **45**, 82–92.
639 (doi:10.1111/j.1558-5646.1991.tb05268.x)
- 640 38. Rojas E, Thévenin S, Montes G, Boyer N, Médoc V. 2021 From distraction to
641 habituation: Ecological and behavioural responses of invasive fish to anthropogenic noise.
642 *Freshwater Biology* **66**, 1606–1618. (doi:10.1111/fwb.13778)
- 643 39. Sueur J, Aubin T, Simonis C. 2008 Seewave, a free modular tool for sound analysis
644 and synthesis. *Bioacoustics* **18**, 213–226. (doi:10.1080/09524622.2008.9753600)
- 645 40. R Core Team. 2021 *R: A Language and Environment for Statistical Computing*.
646 Vienna, Austria: R Foundation for Statistical Computing. See <https://www.R-project.org/>.
- 647 41. Oksanen J *et al.* 2013 vegan: Community Ecology Package. *Community ecology*
648 *package, version 2*, 1–295.
- 649 42. Van den Brink PJ, Braak CJFT. 1999 Principal response curves: Analysis of time-
650 dependent multivariate responses of biological community to stress. *Environmental*
651 *Toxicology and Chemistry* **18**, 138–148. (doi:10.1002/etc.5620180207)
- 652 43. Legendre P, Gallagher ED. 2001 Ecologically meaningful transformations for
653 ordination of species data. *Oecologia* **129**, 271–280. (doi:10.1007/s004420100716)
- 654 44. Bates D, Maechler M, Bolker B, Walker S. 2015 Fitting Linear Mixed-Effects Models
655 Using lme4. *Journal of Statistical Software* **67**, 1–48. (doi:10.18637/jss.v067.i01)
- 656 45. Manly BFJ. 1974 A Model for Certain Types of Selection Experiments. *Biometrics*
657 **30**, 281–294. (doi:10.2307/2529649)
- 658 46. Chesson J. 1983 The Estimation and Analysis of Preference and Its Relationship to
659 Foraging Models. *Ecology* **64**, 1297–1304. (doi:10.2307/1937838)
- 660 47. Manly BFJ. 1995 A Note on the Analysis of Species Co-Occurrences. *Ecology* **76**,
661 1109–1115. (doi:10.2307/1940919)
- 662 48. Barton K. 2009 *MuMIn: Multi-Model Inference*. See [http://r-forge.r-project.](http://r-forge.r-project.org/projects/mumin/)
663 [org/projects/mumin/](http://r-forge.r-project.org/projects/mumin/).
- 664 49. Elser MM, Ende CN von, Sorzano P, Carpenter SR. 1987 Chaoborus populations:

- 665 response to food web manipulation and potential effects on zooplankton communities.
666 *Canadian Journal of Zoology* **65**, 2846–2852. (doi:10.1139/z87-433)
- 667 50. Jäger IS, Hölker F, Flöder S, Walz N. 2011 Impact of *Chaoborus flavicans* -Predation
668 on the Zooplankton in a Mesotrophic Lake – a Three Year Study. *International Review of*
669 *Hydrobiology* **96**, 191–208. (doi:10.1002/iroh.201011253)
- 670 51. Jarolím O, Kubečka J, Čech M, Vašek M, Peterka J, Matěna J. 2010 Sinusoidal
671 swimming in fishes: the role of season, density of large zooplankton, fish length, time of the
672 day, weather condition and solar radiation. *Hydrobiologia* **654**, 253–265.
673 (doi:10.1007/s10750-010-0398-1)
- 674 52. Post JR, McQueen DJ. 1987 The impact of planktivorous fish on the structure of a
675 plankton community. *Freshwater Biology* **17**, 79–89. (doi:10.1111/j.1365-
676 2427.1987.tb01030.x)
- 677 53. Gilbert JJ. 1988 Suppression of rotifer populations by *Daphnia*: A review of the
678 evidence, the mechanisms, and the effects on zooplankton community structure1. *Limnology*
679 *and Oceanography* **33**, 1286–1303. (doi:10.4319/lo.1988.33.6.1286)
- 680 54. Cohen JH, Forward RB. 2016 Zooplankton diel vertical migration - A review of
681 proximate control. *Oceanography and marine biology* **47**, 89–122.
- 682 55. Nedelec SL, Mills SC, Lecchini D, Nedelec B, Simpson SD, Radford AN. 2016
683 Repeated exposure to noise increases tolerance in a coral reef fish. *Environmental Pollution*
684 **216**, 428–436. (doi:10.1016/j.envpol.2016.05.058)
- 685 56. Neo YY, Hubert J, Bolle LJ, Winter HV, Slabbekoorn H. 2018 European seabass
686 respond more strongly to noise exposure at night and habituate over repeated trials of sound
687 exposure. *Environmental Pollution* **239**, 367–374. (doi:10.1016/j.envpol.2018.04.018)
- 688 57. Berendonk TU, O'Brien WJ. 1996 Movement response of *Chaoborus* to chemicals
689 from a predator and prey. *Limnology and Oceanography* **41**, 1829–1832.
690 (doi:10.4319/lo.1996.41.8.1829)
- 691 58. Burrows M, Dorosenko M. 2014 Rapid swimming and escape movements in the
692 aquatic larvae and pupae of the phantom midge *Chaoborus crystallinus*. *Journal of*
693 *Experimental Biology* **217**, 2468–2479. (doi:10.1242/jeb.102483)
- 694 59. Herbert-Read JE, Kremer L, Bruintjes R, Radford AN, Ioannou CC. 2017
695 Anthropogenic noise pollution from pile-driving disrupts the structure and dynamics of fish
696 shoals. *Proceedings of the Royal Society B: Biological Sciences* **284**, 20171627.
697 (doi:10.1098/rspb.2017.1627)
- 698 60. Krause J, Ruxton GD, Ruxton G, Ruxton IG. 2002 *Living in groups*. Oxford

699 University Press.

700 61. Amorim MCP *et al.* 2022 Boat noise impacts Lusitanian toadfish breeding males and
701 reproductive outcome. *Science of The Total Environment* **830**, 154735.

702 (doi:10.1016/j.scitotenv.2022.154735)

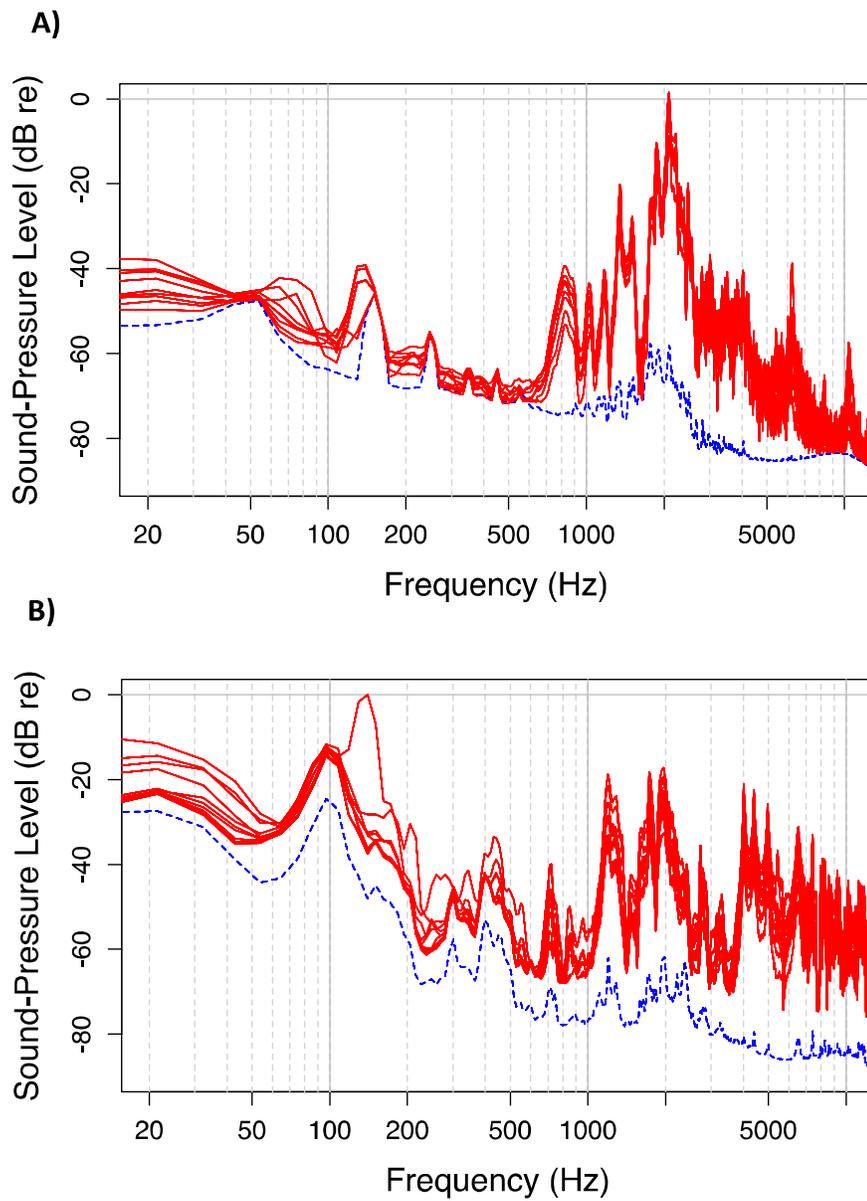
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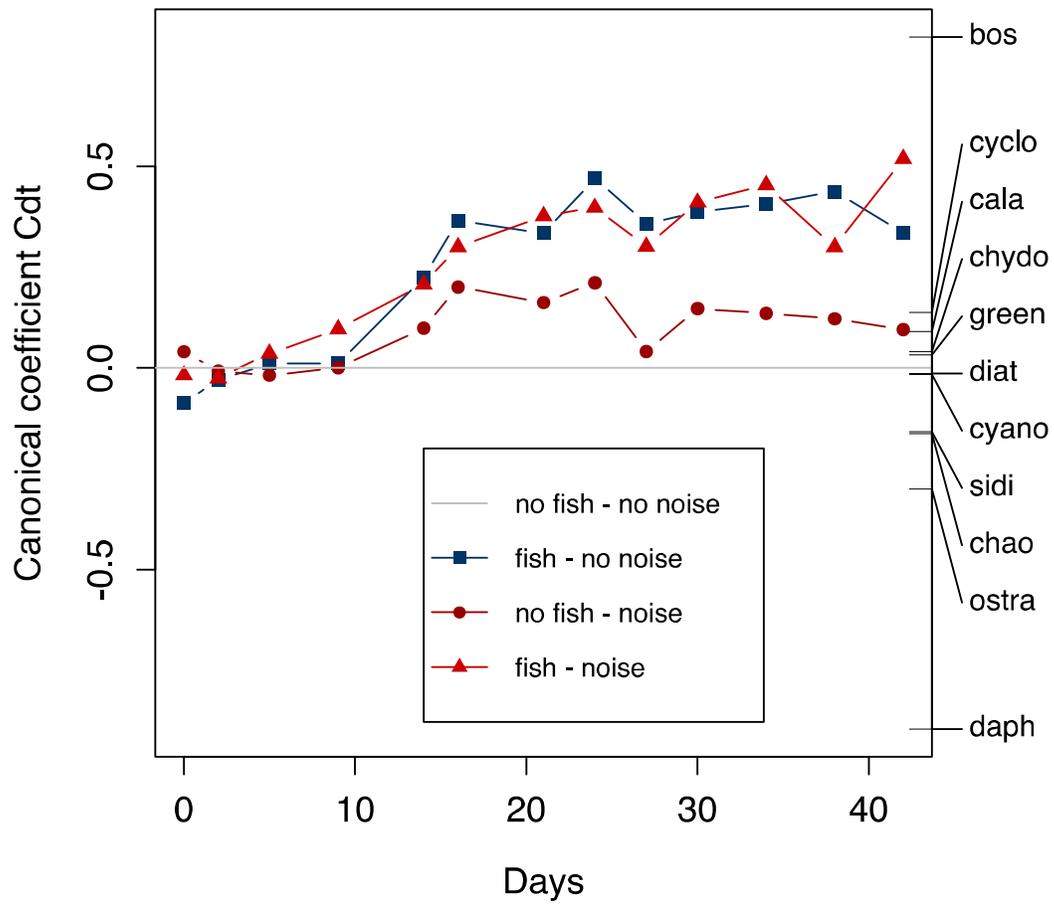


Fig. 2

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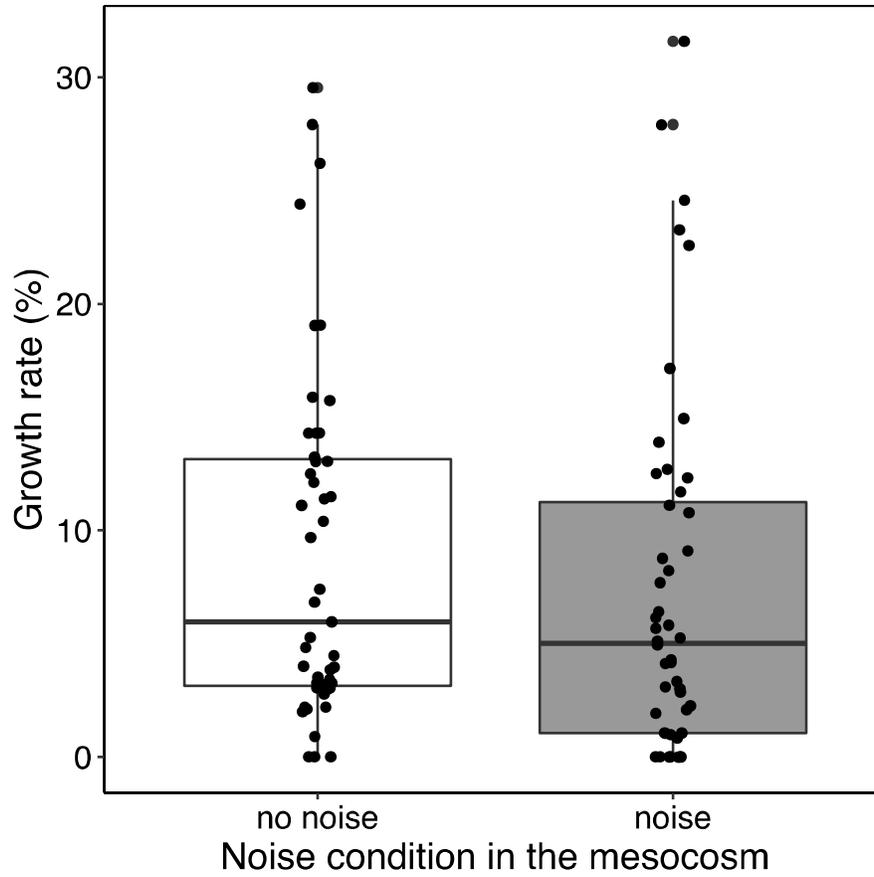


Fig. 3

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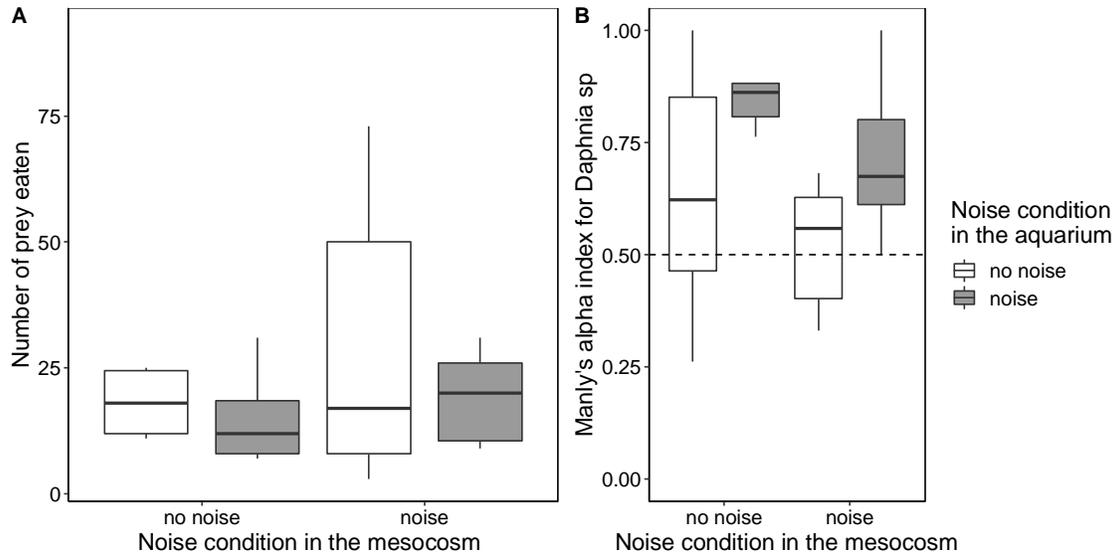
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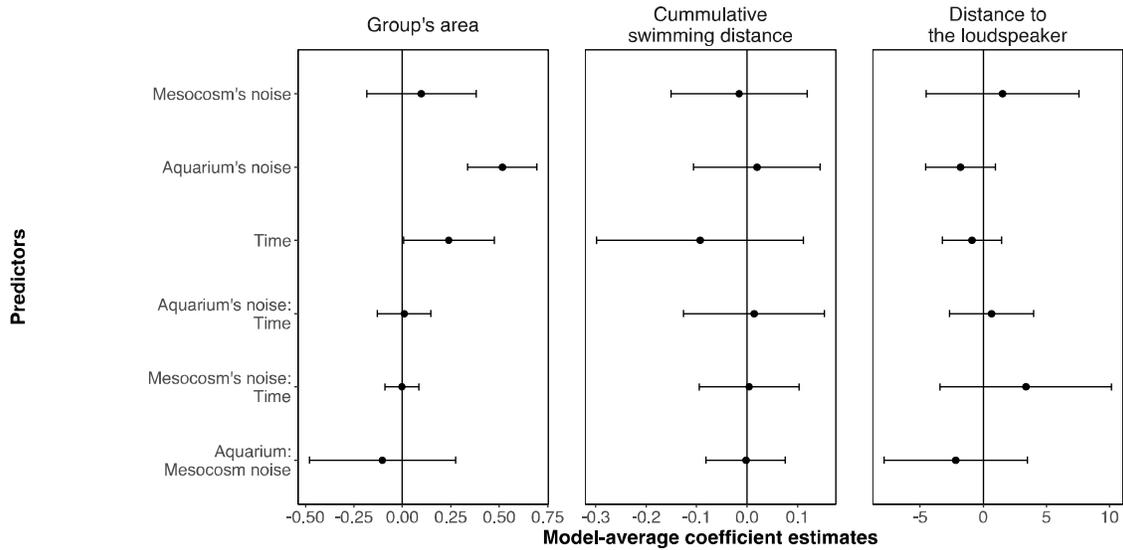
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Fig. 4



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Fig. 5