

# *Additive multiple predator effects can reduce mosquito populations*

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1 *Original Article*

2 **Additive multiple predator effects can reduce mosquito populations**

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20

21 **Abstract**

22 1. Multiple predator interactions may profoundly alter ecological community dynamics and  
23 can complicate predictions of simpler pairwise predator/prey interaction strengths. In  
24 particular, multiple predator effects may lessen or enhance prey risk, with implications for  
25 community-level stability. Such emergent effects may modulate natural enemy efficacy  
26 towards target organisms.

27 2. In the present study, we use a functional response approach to quantify emergent multiple  
28 predator effects among natural enemies towards the disease vector mosquito complex, *Culex*  
29 *pipiens*. We quantify conspecific multiple predator-predator interactions of the cyclopoid  
30 copepod *Macrocyclus albidus* (intermediate predator) by comparing multiple predator  
31 consumption simulations, based on individual consumption rates, with multiple predator  
32 consumption rates experimentally observed. Further, we examine the influence of the  
33 presence of a predator at a higher trophic level, *Chaoborus flavicans*, on copepod group  
34 predation.

35 3. Both predators displayed Type II functional responses, with *C. flavicans* consuming  
36 significantly more prey than *M. albidus* individually. Overall consumption levels of  
37 mosquitoes increased with greater predator density and richness. We did not detect  
38 antagonistic or synergistic emergent multiple predator effects between conspecifics of *M.*  
39 *albidus*, and the higher level predator did not reduce effects of the intermediate predator.  
40 Accordingly, evidence for additive multiple predator interactions was found.

41 4. The lack of predator-predator interference between cyclopoid copepods and larval  
42 chaoborid midges provides strong support for their combined application in mosquito  
43 biocontrol. We propose increased examination of multiple predator effects in assessments of

44 natural enemy efficacies to better understand overall predatory effects within communities  
45 and utilities in vector control.

## 46 **Keywords**

47 biological control; mosquito-borne disease; functional response; multiple predator effects;  
48 cyclopoid; chaoborid

49

## 50 **Introduction**

51 Ecological communities typically comprise multiple consumers (e.g., predators) sharing  
52 common resources (Sih et al., 1998; Barrios O'Neill et al., 2014; Wasserman et al., 2016).

53 Whilst community dynamics are often inferred on the basis of simple pairwise interaction  
54 strengths (e.g., the effects of a predator on a prey population) (Schmitz, 2007, Tang et al.,

55 2014; Vázquez et al., 2015; Cuthbert et al., 2018d), biotic factors such as ontogenic shifts

56 (Bofill and Yee, 2019) and multiple predator-predator interactions (Sih et al., 1998; Bolker et  
57 al., 2003; Wasserman et al., 2016) can also have profound implications for the outcomes of

58 predator-prey interactions. Utilisation of shared resources may often lead to competition

59 among predator species, and it is well established that these interactions may not combine

60 additively in the context of prey risk (Soluk, 1993; Sih et al., 1998; Barrios-O'Neill et al.,

61 2014). This can lead to erroneous inferences based on pairwise interaction strengths at the

62 community-level. Additionally, the presence of predators at a higher trophic level may alter

63 the efficacy of intermediate consumers through both density-mediation (i.e., direct predation)

64 and trait-mediation (i.e., non-consumptive effects) (Peacor and Werner, 2001; Werner and

65 Peacor, 2003). There is increasing evidence for the primary importance of trait-mediation as a

66 driver of trophic cascades within ecosystems (Gabowski, 2004; Schmitz et al., 2004; Trussell

67 et al., 2004). In particular, the impacts of aquatic predator cues in ecosystems may be

68 profound due to their immediacy and influence at the population-level, and simultaneously  
69 across multiple life history stages (Peacor and Werner, 2001; Trussell et al., 2004, 2008;  
70 Alexander et al., 2013).

71 Multiple predator effects can manifest in three ways: (1) additively, (2) synergistically or (3)  
72 antagonistically. Whilst synergistic multiple predator effects result in enhancement of prey  
73 risk to predation (Soluk and Collins, 1998; Losey and Denno, 1998; Sih et al., 1998),  
74 antagonistic effects result in prey risk reductions (Sih et al., 1998; Vance-Chalcraft and  
75 Soluk, 2005), both of which have implications that differ from additive multiple predator  
76 effects inferred from pairwise predator-prey interaction strengths.

77 Functional responses quantify the relationship between resource (e.g., prey) density and  
78 consumption rate (Holling, 1959), and have been applied extensively by ecologists as a  
79 means of quantifying the density-dependence of *per capita* interaction strengths across  
80 multiple fields (Abrams, 1982, Dick et al., 2014; Cuthbert et al., 2018d). Both functional  
81 response form or Type (i.e., Types I, II, III), and their magnitude (e.g., curve asymptote), are  
82 powerful indicators of the strength of interactions between trophic groups and, at least  
83 theoretically, can aid inferences of population-level stability under different environmental  
84 contexts (Murdoch and Oaten, 1975; Dick et al., 2014). Centrally, the attack rate (i.e., initial  
85 curve slope) and handling time (i.e., curve asymptote, inversely maximum feeding rate) of  
86 consumers can be used to quantitatively compare ecological impacts under different resource  
87 densities and context-dependencies (e.g., Cuthbert et al., 2018b). However, the application of  
88 functional responses to derivations of multiple predator effects has remained scarce and  
89 produced equivocal results across different experimental systems (Soluk, 1993; Losey and  
90 Denno, 1998; Barrios-O'Neill et al., 2014; Wasserman et al., 2016).

91 Functional responses have been a staple in quantifications of natural enemy efficacies  
92 towards target organisms (Solomon, 1949; O'Neill, 1990; Van Drieche and Bellows, 2011;  
93 Cuthbert et al., 2018c), but have again neglected multiple predator effects. Mosquitoes are  
94 exposed to a broad range of predators across their life history (e.g., copepods, dragonflies,  
95 spiders), and many important natural enemies have been identified across multiple habitat  
96 types (Medlock and Snow, 2008; Shaalan and Canyon, 2009). In a biological control context,  
97 synergism among predators is targetted as this may enhance effects upon target species  
98 groups. On the other hand, antagonistic predator-predator interactions could reduce predatory  
99 effects and alleviate target prey risk. In turn, this may heighten mosquito proliferations and  
100 worsen disease risk. Additive effects are also desirable as this indicates a lack of interference  
101 between predators. Copepods copepods (freshwater crustaceans) have been identified as  
102 particularly efficacious agents for the population-level suppression of mosquitoes (Marten  
103 and Reid, 2007; Cuthbert et al., 2018b). Their application has successfully eradicated  
104 pathogens vectored by medically important mosquitoes at community-level scales (Kay and  
105 Nam, 2005; Nam et al., 2012), and their predatory effects have been proven to be context-  
106 independent to variables such as water clarity and habitat complexity (Cuthbert et al., 2018b,  
107 c). Cyclopoids are a particularly diverse group with a worldwide distribution (Dussart and  
108 Defaye, 2001), and often dominate lentic freshwater habitats where medically important  
109 mosquitoes can breed. Furthermore, their ecological versatility facilitates application to  
110 minute or ephemeral container-style habitats where many other predators cannot persist  
111 (Marten and Reid, 2007).

112 Despite their importance for the natural regulation of mosquitoes, there has hitherto been a  
113 lack of consideration for the implications of con/heterospecific multiple predator interactions  
114 for the efficacy of copepods in mosquito biocontrol. Such multiple predator interactions have  
115 been shown to substantially affect predatory effects by other mosquito antagonists (e.g.,

116 Barry and Roberts, 2014; Brahma et al., 2015). Further, chaoborid larvae (flies with an  
117 aquatic larval stage) are important predators in many fishless aquatic ecosystems and have  
118 the capacity to influence zooplankton assemblages *via* predation (Yan et al., 1991; Arnott and  
119 Vanni, 1993; Nyberg, 1998). Although comparatively less studied than copepods in a vector  
120 control context, larval chaoborids have also been identified as effective predators of larval  
121 mosquitoes (Borkent, 1980; Cuthbert et al., 2019b), and have the capacity to colonise  
122 artificial container-style habitats where mosquitoes breed *via* aerial dispersal in their adult  
123 stage (Sunahara et al., 2002). Owing to their strong predatory capacity towards zooplankton  
124 such as cyclopoid copepods (Smyly, 1979), chaoborid-copepod interactions may result in  
125 prey risk reductions for mosquitoes, given that the two predator groups are known to co-  
126 occur and interact in freshwater habitats (e.g., Moore et al., 1994). Alternatively, synergistic  
127 or additive effects would indicate utility in their joint use. Therefore, the present study uses a  
128 functional response approach to quantify con- and heterospecific multiple predator effects  
129 within and between the cyclopoid copepod *Macrocyclops albidus* (Jurine, 1820) (Cyclopoida:  
130 Cyclopidae) and a predator at a higher trophic level, larvae of the chaoborid *Chaoborus*  
131 *flavicans* (Meigen, 1830) (Diptera: Chaoboridae), using larvae of the *Culex pipiens* (Diptera:  
132 Culicidae) mosquito complex as basal prey. Firstly, we quantify individual functional  
133 responses of the two predators, before secondly quantifying and comparing predicted  
134 multiple predator effects among conspecific copepod groups in the presence or absence of the  
135 predator at a higher trophic level. Based on previous findings, we hypothesise that: (1) *C.*  
136 *flavicans* will exhibit a higher consumption rate than *M. albidus*; (2) overall consumption  
137 rates will generally increase with greater predator density and richness; (3) the consumption  
138 rates by multiple conspecific copepods will combine independently in the absence of the  
139 higher predator, whilst negative interactions between chaoborids and copepods will reduce  
140 consumption rates for the prey.

141

142 **Materials and methods**

143 *Animal collection and maintenance*

144 The intermediate predator, *M. albidus*, was collected from Glastry Clay Pit ponds, Northern  
145 Ireland (54° 29' 18.5" N 5° 28' 19.9" W) using a polypropylene dipper. Copepods were  
146 transported in source water to a laboratory at Queen's Marine Laboratory (QML), and  
147 maintained in controlled laboratory conditions (25 ± 2 °C; 50 – 60 % relative humidity; 16:8  
148 light:dark regime) to stimulate proliferation. Gravid females were isolated from samples and  
149 used to initiate pure cultures in accordance with the available literature (Suarez et al., 1992;  
150 Marten and Reid, 2007). After nauplii emerged (larval stage), originating females were  
151 dissected and identified to confirm the species. *Macrocyclus albidus* cultures were then  
152 initiated in 10 litre tanks and fed *ad libitum* with *Paramecium caudatum* and *Chilomonas*  
153 *paramecium* (Sciento, Manchester, England). These protozoan cultures were prepared in 2  
154 litre flasks using autoclaved wheat seeds in the same laboratory conditions. The predator at a  
155 higher trophic level, fourth instar *C. flavicans*, were purchased from a commercial supplier  
156 (Northampton Reptile Centre, Northampton, England) and fed *ad libitum* with *Daphnia* sp.,  
157 obtained from the same supplier. This predator was acclimatised to the insectary conditions  
158 for five days prior to experimentation. The prey, newly hatched *C. pipiens* complex  
159 mosquitoes, were obtained from the same insectary where a colony had been maintained.  
160 Adult mosquitoes were kept in 32.5 × 32.5 × 32.5 cm cages (Bugdorm, Watkins and  
161 Doncaster, Leominster, England) and blood fed using defibrinated horse blood (TCS  
162 Biosciences, Buckingham, England) through a membrane feeding system (Hemotek Ltd,  
163 Accrington, England). Cotton pads soaked in a 10 % sucrose solution were provided for other  
164 sustenance. Egg rafts were extracted regularly from cages and placed into 3 litre larval bowls,



165 and hatched larvae were fed *ad libitum* using ground guinea pig pellets until pupation (Pets at  
166 Home, Newtownabbey, Northern Ireland), upon which they were transferred into the above  
167 cages.

### 168 *Experimental design*

169 We starved non-ovigerous adult female *M. albidus* and fourth instar *C. flavicans* individually  
170 for 24 hours before the experiment to standardise hunger levels. The experiment was  
171 undertaken in plastic arenas of 42 mm diameter containing 20 mL of dechlorinated tap water  
172 from an aerated source under insectary conditions (see above). To quantify functional  
173 responses, we supplied prey densities of 2, 4, 8, 15, 30 or 60 first instar *C. pipiens*. (1.1 – 1.3  
174 mm) per arena to four different predator treatments comprising adult female *M. albidus* (1.6 –  
175 1.8 mm) and fourth instar larval *C. flavicans* (10.0 – 12.0 mm) over a six hour experimental  
176 feeding period ( $n = 3$  per experimental treatment group). The four predator treatments were:  
177 one *M. albidus*; one *C. flavicans*; three *M. albidus*; or three *M. albidus* alongside one *C.*  
178 *flavicans*. Quantifications of single predator functional responses enabled modelling of the  
179 expected multiple predator consumption rates, which could then be compared to those  
180 actually observed (see below). In the multiple predator species trials, where a copepod was  
181 killed by a chaoborid, it was immediately replaced from a surplus supply (observed once).  
182 We did not observe conspecific killing between copepods. Prey were allowed to settle for two  
183 hours before the experiment was initiated through the addition of predators. After six hours,  
184 the predators were removed and remaining live prey counted to derive those killed. Controls  
185 consisted of three replicates at each prey density in the absence of any predator.

### 186 *Statistical analyses*

187 All statistical analyses were undertaken in R v3.5.1 (R Development Core Team, 2018). We  
188 compared overall consumption with respect to the ‘predator’ (4 levels) and ‘prey supply’ (6

189 levels) factors using a generalised linear model (GLM) assuming a Poisson distribution and  
190 log link as residuals were not overdispersed relative to degrees of freedom. An information  
191 theoretic approach was followed *via* model averaging to select the model which minimised  
192 information loss (Burnham and Anderson, 2002; Bartoń, 2015). The relative importance of  
193 each model term was discerned, based on the sum of AICc weights. Models with  $\Delta\text{AICc} < 2$   
194 were considered interchangeable (Burnham and Anderson, 2002). The significance of factors  
195 in the top model was discerned using likelihood ratio tests, with Tukey tests used for *post-hoc*  
196 comparisons of significant effects.

197 Functional response analyses were undertaken using the ‘frair’ package (Pritchard et al.  
198 2017). For observed consumption under each predator treatment, we determined functional  
199 response types using logistic regression of prey killed as a function of prey density  
200 (continuous predictor). A significantly negative first order term is indicative of a Type II  
201 response, whereas a significantly positive first order term followed by a significantly negative  
202 second order term indicates a Type III response (Juliano, 2001). To account for prey  
203 depletion during the experiment, we fitted Rogers’ random predator equation for conditions  
204 without prey replacement (Rogers, 1972; Trexler et al., 1988; Juliano, 2001):

$$205 \quad N_e = N_0(1 - \exp(a(N_e h - T)))$$

206 (1)

207 where  $N_e$  is the number of prey eaten,  $N_0$  is the initial density of prey,  $a$  is the attack rate,  $h$  is  
208 the handling time and  $T$  is the total experimental period. The *Lambert W* function was  
209 implemented due to the recursive nature of the Random predator equation (Bolker, 2008). We  
210 non-parametrically bootstrapped ( $n = 2000$ ) the  $a$  and  $h$  parameter estimates to produce 95 %  
211 confidence intervals around observed functional response curves. This process enabled  
212 results to be considered at the population-level, as oppose to the sample-level, negating the

213 additional use of more formal statistical tests (e.g., Barrios O’Neill et al., 2014). Moreover,  
214 using the initial  $a$  and  $h$  parameter estimates, we calculated the functional response ratio ( $a/h$ )  
215 for each predator treatment (see Cuthbert et al. 2019a). This approach balances information  
216 from both parameters, with both high values of  $a$  and low values of  $h$  conducive to ecological  
217 impact.

218 Following McCoy et al. (2012) and Sentis and Boukal (2018), we used a population-dynamic  
219 approach to generate predictions of multiple predator functional responses using  $a$  and  $h$   
220 parameter estimates from single *M. albidus* and *C. flavicans* treatments:

$$\frac{dN}{dt} = - \sum_{i=1}^n f_i(N)P_i$$

222 (2)

223 where  $N$  is the prey population density,  $P_i$  ( $i = 1, 2, \dots, n$ ) are the population densities of  
224 predators  $i$  and  $f_i(N)$  is the functional response of predator  $i$  (i.e., Eqn. 1). This generated a  
225 ‘null’ model of emergent multiple predator effects, which was then compared directly to  
226 observed multiple predator functional responses (i.e.,  $3 \times M. albidus$ ;  $3 \times M. albidus + 1 \times C.$   
227 *flavicans*). Whilst multiple modelling approaches have been developed for predictions of  
228 multiple predator effects, the population dynamic approach has been identified as more robust  
229 and precise than other methods (Sentis and Boukal, 2018). Predictions of prey consumption  
230 were generated for all experimental initial prey densities, with Eqn. 2 integrated over the total  
231 experimental time (see Sentis and Boukal, 2018). We generated 95 % confidence intervals  
232 around predictions using global sensitivity analysis which integrated the 95 % confidence  
233 intervals of the  $a$  and  $h$  parameter estimates from single predator treatments, alongside their  
234 covariance-variance matrix. This generated a number of parameter sets using a Latin  
235 hypercube sampling algorithm (Soetaert and Petzoldt, 2010). Equation 2 was integrated for

236 each set over time to generate multiple predator consumption predictions with 95 %  
237 confidence intervals derived from the 2.5 % and 97.5 % quantiles of the simulated survival  
238 values. Actual and predicted functional responses were then compared on the basis of  
239 confidence interval overlaps across prey densities.

240

## 241 **Results**

242 Prey survival in controls exceeded 99.5 % and ‘natural’ prey mortality was thus not corrected  
243 for in trials with predators. The ‘predator’ and ‘prey supply’ terms were retained in the top  
244 model of prey consumption (both relative variable importance = 1). The interaction term  
245 between these factors was removed (relative variable importance < 0.01;  $\Delta\text{AICc} = 32.70$ ).

246 The predator treatment had a significant effect on consumption of *C. pipiens* ( $\chi^2 = 102.69$ ,  $df$   
247 = 3,  $p < 0.001$ ) (Fig. 1). Three *M. albidus* consumed significantly more mosquito prey than  
248 single *M. albidus* ( $p < 0.001$ ), but consumption by three copepods did not differ significantly  
249 from single *C. flavicans* ( $p > 0.05$ ). Single *C. flavicans* consumed significantly more prey  
250 than single *M. albidus* ( $p < 0.001$ ), and consumption by individual chaoborids did not differ  
251 significantly from that of *C. flavicans* when present alongside three *M. albidus* ( $p > 0.05$ ).

252 However, *C. flavicans* consumption alongside three *M. albidus* was significantly greater than  
253 either single or triple *M. albidus* treatment levels (both  $p < 0.001$ ). Prey consumption also  
254 increased significantly under greater prey supplies ( $\chi^2 = 307.89$ ,  $df = 5$ ,  $p < 0.001$ ).

255 All functional responses were categorised as Type II, owing to significantly negative linear  
256 coefficients (Table 1). Whilst attack rates were relatively similar between individual *M.*  
257 *albidus* and *C. flavicans*, handling times were considerably reduced for *C. flavicans* (Table  
258 1). Accordingly, individual *C. flavicans* exhibited a substantially higher functional response  
259 ratio compared to individual *M. albidus*. Attack rates were also similar between con- and

260 heterospecific multiple predator groups, whilst handling times were considerably lower in the  
261 latter group, containing both *M. albidus* and *C. flavicans* (Table 1). Therefore, the functional  
262 response ratio was highest under the heterospecific multiple predator group, indicating  
263 greater effects on mosquito prey by copepods in the presence of the higher chaoborid  
264 predator.

265 Individually, functional responses of *M. albidus* and *C. flavicans* did not overlap above prey  
266 densities of approximately eight (Fig. 2a), and so functional responses (i.e., predation rates)  
267 of *C. flavicans* were significantly greater than *M. albidus* at higher densities (i.e.,  
268 significantly lower handling times and higher maximum feeding rates). The functional  
269 response curve of three *M. albidus* was well-predicted from the individual functional  
270 response curve (Fig. 2b). Here, predicted confidence intervals overlapped with those  
271 observed across all prey densities, indicative of non-significant differences and thus additive  
272 multiple predator effects in copepods. Similarly, for three *M. albidus* in the presence of  
273 individual *C. flavicans*, predicted and observed functional response confidence intervals  
274 overlapped under all prey densities (Fig. 2c). Again, this indicated that multiple predator  
275 consumption rates were well-predicted from individual predator treatments.

276

## 277 **Discussion**

278 Robust quantifications of multiple predator interactions are crucial to understanding  
279 interaction strengths at the community-level (Sih et al., 1998; Bolker et al., 2003; Wasserman  
280 et al., 2016; Sentis and Boukal, 2018). In a natural enemy context, predator-predator  
281 interactions may alter the efficacy of biological control agents, with implications for  
282 organism population and economic or sanitary risk. In the present study, we first quantified  
283 the interaction strengths of two widespread natural enemies towards the disease vector *C.*

284 *pipiens* mosquito complex. Larval chaoborids and cyclopoid copepods are known to co-occur  
285 and engage in predatory interactions in freshwater environments (Moore et al., 1994), and  
286 these groups are well-adapted to temporary aquatic systems which mosquitoes also colonise  
287 (Sunahara et al., 2002; Marten and Reid, 2007). Accordingly, both groups have importance as  
288 natural enemies for mosquitoes across various aquatic environments. Both the cyclopoid  
289 copepod *M. albidus* and larval chaoborid midge *C. flavicans* displayed predatory Type II  
290 functional responses towards larval mosquito prey, although the functional response  
291 magnitude (i.e., maximum feeding rate) was significantly higher in *C. flavicans*. Predation by  
292 conspecific copepod groups was additive, with observed multiple predator consumption well-  
293 predicted from simulations based on the functional response of individuals. Similarly, the  
294 presence of the predator at a higher trophic level, *C. flavicans*, did not result in significant  
295 differences in observed predation compared to expectations based on single predator groups.  
296 Accordingly, the predator at a higher trophic level did not result in alterations to copepod-  
297 mosquito interaction strengths in the present study, and multiple coexisting copepods did not  
298 cause reductions to mosquito prey risk *via* interference. Our results thus indicate that these  
299 predator species can be used in combination and that copepod density can be increased  
300 without affecting their *per capita* effects on mosquito populations.

301 Overall consumption rates of chaoborids were significantly higher than cyclopoid copepods  
302 in the present study. This is not surprising owing to their larger size and different prey  
303 handling strategy. Whilst both focal predator species are ambush consumers that detect prey  
304 through hydromechanical cue reception (Riessen et al., 1984; Hwang and Strickler, 2001;  
305 Cuthbert et al., 2018a), chaoborids ingest prey whole using prehensile antennae and mandibles,  
306 with initial ingestion occurring in the thoracic crop before subsequent regurgitation (Riessen  
307 et al., 1984). This enables many individual prey items to be simultaneously packed into the  
308 crop, and enables a relatively high predatory effect compared to other trophically analogous

309 invertebrates (Dodson, 1972; von Ende and Dempsey, 1981; Cuthbert et al., 2019b). On the  
310 other hand, *M. albidus* has chewing mouthparts, using mandibles to tear prey items into  
311 digestible pieces (Fryer, 1957). Accordingly, it is likely that lower handling time constraints  
312 facilitate higher offtake rates towards mosquito prey by chaobiorids as compared to cyclopoid  
313 copepods. Nevertheless, despite significant differences in handling times between the two  
314 predators, attack rates were more similar between the species, which, combined with Type II  
315 functional responses, corresponds to high levels of ecological impact at low prey densities.  
316 Indeed, in the context of biological control, Type II functional responses are desirable as  
317 they are, at least theoretically, associated with population-destabilising effects on target  
318 organisms (Cuthbert et al., 2018d). The functional response ratio has recently been identified  
319 as a novel approach to balance information from both functional response parameters in  
320 predictions of ecological impact (Cuthbert et al. 2019a). Here, functional response ratios  
321 peaked under the heterospecific multiple predator group. Accordingly, greater predator  
322 diversities were conducive to the highest ecological impacts in the present study, with the  
323 presence of *C. flavicans* bolstering the predatory effects of conspecific copepod groups on  
324 larval mosquitoes.

325 The predictability of multiple copepod functional responses from individual interaction  
326 strengths suggests that, at least under densities used in the present study, this group of species  
327 does not respond to the presence of conspecifics in a predation context. This lack of predator-  
328 predator interference corroborates with the reported efficacy of cyclopoid copepods in  
329 mosquito population management, wherein a high numerical response facilitates high  
330 predatory effects when copepods reach high abundances (Marten and Reid, 2007; Nam et al.,  
331 2012; Cuthbert et al. 2018d). Owing to their sit-and-wait prey capture strategy, this lack of  
332 predator-predator interference is not surprising, with multiple predator effects shown to be  
333 dependent on the particular behavioural characteristics of species (Wasserman et al., 2016). In

334 a similar vein, the ambush-style capture strategy of chaoborids likely also limited interference  
335 between predators in the present study, with intraguild predation only observed in one  
336 instance. Furthermore, whilst chaoborids often forage in pelagic water zones, many cyclopoid  
337 copepods, including *M. albidus*, are benthic foragers, therefore potentially enabling spatial  
338 separation between the two predator types, which further limits antagonistic interactions (see  
339 Schmitz, 2007). Applications of natural enemies which occupy different parts of waterbodies  
340 could enhance mosquito control *via* reductions in predator free space, yet these effects may  
341 be further altered by habitat characteristics such as water volume. Experimental arena size  
342 can directly influence the strength of predator-prey interactions (e.g., Uiterwaal and DeLong,  
343 2018), and it is therefore probable that choice of volume can influence experimental  
344 quantifications of multiple predator effects in aquatic systems through, for example,  
345 modulating predator-predator encounter rates. Given the particular tendency for *C. pipiens* to  
346 spend time at the water surface (Yee et al., 2004), effects of different experimental water  
347 depths may be especially profound in mediating interaction strengths. Nevertheless,  
348 comparative studies which examine feeding rates phenomenologically (see Jeschke et al.,  
349 2002) across standardised experimental conditions provide useful insights into predatory  
350 interactions, whilst omitting search area as a confounding variable. Further, as the present  
351 study used relatively small arena sizes, it is unlikely that larger volumes would alter the  
352 additive nature of predator-predator interactions through changes to encounter rates.

353 Although not significantly different to single chaoborid treatments, consumption levels  
354 towards mosquitoes tended to peak under the combined copepod and chaoborid predator  
355 treatment group in the present study. Therefore, both increased abundances and diversity of  
356 predators resulted in the greatest interaction strength towards medically important  
357 mosquitoes. Alongside general studies on the biological control of crop pests (Snyder et al.,  
358 2003, 2006, 2008; Finke and Denno, 2004), a number of studies have examined the combined



359 efficacy of multiple antagonists towards larval mosquitoes (Nilsson and Soderstrom, 1988;  
360 Culler and Lamp, 2009; Barry and Roberts, 2014; Brahma et al., 2015; Bofill and Yee, 2019).  
361 Yet, there has been a lack of application of functional responses in quantifications of multiple  
362 predator effects towards mosquitoes, despite the inherent density-dependence of consumer-  
363 resource interactions (Holling, 1959). Whilst antagonistic predator-predator interactions have  
364 been reported in previous studies, our results suggest that the promotion of cyclopoids and  
365 chaoborids for the control of medically important mosquitoes could further enhance  
366 biological control efforts *via* additive effects. However, the *per capita* interaction strength of  
367 chaoborids was far higher to that of copepods, with the latter group contributing relatively  
368 little to combined interactions. Importantly, both focal predator types in the present study are  
369 capable of colonising a broad range of lentic aquatic habitats where vector mosquitoes breed,  
370 including ephemeral container-style habitats (Sunahara et al., 2002; Marten and Reid, 2007).  
371 In particular, aerial dispersal by chaoborids during their adult stage could enable effective  
372 colonisation of discrete habitat patches which other predators cannot reach. Equally, many  
373 cyclopoid copepods are able to enter periods of diapause during phases of temporary drying  
374 between hydroperiods, reducing the potential for exploitation of predator-free habitats by  
375 mosquito colonists (Marten and Reid, 2007). Indeed, diapausing copepods are known to  
376 survive for months in the absence of water (Frisch, 2002).

377 In conclusion, the predatory effect of cyclopoid copepods is not significantly altered by either  
378 the presence of conspecifics or predators at a higher trophic level. Both predator types  
379 exhibited additive functional responses towards common mosquito prey, conducive to high  
380 predictability from individual interaction strengths and a lack of interference among  
381 consumers. Accordingly, their combined promotion in aquatic habitats could further assist in  
382 mosquito population management strategies through bolstering of predatory effects. Such  
383 insights into multiple predator interactions offer improved quantifications of the overall

384 effects of natural enemies upon target species, further informing as to the efficacy of selected  
385 biological control agents before their release into empirical systems.

386

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389

### 390 **Contribution of authors**

391 RC conceived the designed the experiment. RC performed the experiment. RC analysed the  
392 data. RC and AS did the modelling. AC, AS, AD and JD contributed materials and analysis  
393 tools. RC wrote the first draft of the manuscript, and all authors contributed substantially to  
394 revisions. The authors declare that they have no conflicts of interest.

395

### 396 **References**

397 Abrams, P.A. (1982) Functional responses of optimal foragers. *American Naturalist*, 120,  
398 382–390.

399 Alexander, M.E., Dick, J.T.A. & O'Connor, N.E. (2013) Trait-mediated indirect interactions  
400 in a marine intertidal system as quantified by functional responses. *Oikos*, 122, 1521–  
401 1531.

402 Arnott, S.E. & Vanni, M.J. (1993) Zooplankton assemblages in fishless bog lakes – influence  
403 of biotic and abiotic factors. *Ecology*, 74, 2361–2380.

404 Barrios-O'Neill, D., Dick, J.T.A., Emmerson, M.C., Ricciardi, A., MacIsaac, H.J., Alexander,  
405 M.E. & Bovy H.C. (2014) Fortune favours the bold: a higher predator reduces the

406 impact of a native but not an invasive intermediate predator. *Journal of Animal*  
407 *Ecology*, 83, 693–701.

408 Barry, M.J. & Roberts, D.M. (2014) Indirect interactions limit the efficiency of Odonata as  
409 natural control agents for mosquito larvae. *Journal of Insect Behaviour*, 27, 626–638.

410 Bartoń, K. (2015) MuMIn: Multi-model inference. R package.

411 Bofill, C.E. & Yee, D.A. (2019) An army of one: predaceous diving beetle life history stages  
412 affect interactions with shared mosquito prey. *Hydrobiologia*, 827, 201–209.

413 Bolker, B.M. (2008) *Emdbook: ecological models and data in R*. Princeton University Press,  
414 Princeton, United States.

415 Bolker, B., Holyoak, M., Křivan, V., Rowe, L. & Schmitz, O. (2003) Connecting theoretical  
416 and empirical studies of trait-mediated interactions. *Ecology*, 84, 1101–1114.

417 Borkent, A. (1980) The potential use of larvae of *Chaoborus cooki* Sakther (Diptera:  
418 Chaoboridae) as a biological control of mosquito larvae. *Mosquito News* 40, 634–635.

419 Brahma, S., Sharma, D., Kundu, M., Saha, N., Aditya, G. & Saha, G.K. (2015) Mosquito  
420 prey vulnerability in intraguild predation between *Ranatra filiformis* and *Anisops*  
421 *bouvieri*: implications in biological control. *Proceedings of the Zoological Society*,  
422 68, 36–44.

423 Burnham, K.P. & Anderson, D.R. (2002) *Model Selection and Multi-model Inference: A*  
424 *Practical Information-Theoretic Approach*. Springer, New York, United States.

425 Culler, L. & Lamp, W.O. (2009) Selective predation by larval *Agabus* (Coleoptera:  
426 Dytiscidae) on mosquitoes: support for conservation-based mosquito suppression in  
427 constructed wetlands. *Freshwater Biology*, 54, 2003–2014.

428 Cuthbert, R.N., Callaghan, A. & Dick, J.T.A. (2018a) Dye another day: the predatory impact  
429 of cyclopoid copepods on larval mosquito *Culex pipiens* is unaffected by dyed  
430 environments. *Journal of Vector Ecology*, 43, 334–336.

431 Cuthbert, R.N., Dalu, T., Wasserman, R.J., Coughlan, N.E., Callaghan, A., Weyl, O.L.F. &  
432 Dick, J.T.A. (2018b) Muddy waters: efficacious predation of container-breeding  
433 mosquitoes by a newly-described calanoid copepod across differential water clarities.  
434 *Biological Control*. 127, 25–30.

435 Cuthbert, R.N., Dick, J.T.A. & Callaghan, A. (2018c) Interspecific variation, habitat  
436 complexity and ovipositional responses modulate the efficacy of cyclopoid copepods  
437 in disease vector control. *Biological Control*, 121, 80–87.

438 Cuthbert, R.N., Dick, J.T.A., Callaghan, A. & Dickey, J.W.E. (2018d) Biological control  
439 agent selection under environmental change using functional responses, abundances  
440 and fecundities; the Relative Control Potential (RCP) metric. *Biological Control*, 121,  
441 50–57.

442 Cuthbert, R.N., Dickey, J.W.E., Coughlan, N.E., Joyce, P.W.S. & Dick, J.T.A. (2019a) The  
443 Functional Response Ratio (FRR): advancing comparative metrics for predicting the  
444 ecological impacts of invasive alien species. *Biological Invasions*, 21, 2543–2547.

445 Cuthbert, R.N., Ortiz-Perea, N., Dick, J.T.A. & Callaghan, A. (2019b) Elusive enemies:  
446 Consumptive and ovipositional effects on mosquitoes by predatory midge larvae are  
447 enhanced in dyed environments. *Biological Control*, 132: 116–121.

448 Dick, J.T.A., Alexander, M.E., Jeschke, J.M., Ricciardi, A., MacIsaac, H.J., Robinson, T.B.  
449 et al. (2014) Advancing impact prediction and hypothesis testing in invasion ecology  
450 using a comparative functional response approach. *Biological Invasions*, 16, 735–753.

- 451 Dodson, S.I. (1972) Mortality in a population of *Daphnia rosea*. *Ecology*, 53, 1011–1023.
- 452 Dussart, B.H. & Defaye, D. (2001) *Introduction to the Copepoda. Guides to the Identification*  
453 *of the Microinvertebrates of the Continental Waters of the World*. Backhuys  
454 Publishers, Kerkwerve, Netherlands.
- 455 Finke, D.L. & Denno, R.F. (2004) Predator diversity dampens trophic cascades. *Nature*, 429,  
456 407–410.
- 457 Frisch, D. (2002) Dormancy, dispersal and the survival of cyclopoid copepods (Cyclopoida,  
458 Copepoda) in a lowland floodplain. *Freshwater Biology*, 47, 1269–1281.
- 459 Fryer, G. (1957) The food of some fresh water cyclopoid copepods and its ecological  
460 significance. *Journal of Animal Ecology*, 26, 263–286.
- 461 Gabowski, J.H. (2004) Habitat complexity disrupts predator – prey interactions but not the  
462 trophic cascade on oyster reefs. *Ecology*, 85, 995–1004.
- 463 Holling, C. (1959) The components of predation as revealed by a study of small-mammal  
464 predation of the European Pine Sawfly. *The Canadian Entomologist*, 91, 293–320.
- 465 Hwang, J.S. & Strickler, J.R. (2001) Can copepods differentiate prey from predator  
466 hydromechanically? *Zoological Studies*, 40, 1–6.
- 467 Jeschke J.M., Kopp M. & Tollrian R. (2002) Predator functional responses: discriminating  
468 between handling and digesting prey. *Ecological Monographs*, 72, 95–112.
- 469 Juliano, S.A. (2001) Nonlinear curve fitting: predation and functional response curves. In:  
470 Scheiner, S.M. & Gurvitch, J. (eds) *Design and analysis of ecological experiments*.  
471 Oxford University Press, Oxford, United Kingdom, pp. 178–196.

- 472 Kay, B. & Nam, V.S. (2005) New strategy against *Aedes aegypti* in Vietnam. *Lancet*, 365,  
473 613–617.
- 474 Losey, J.E. & Denno, R.F. (1998) Positive predator – predator interactions: enhanced  
475 predation rates and synergistic suppression of aphid populations. *Ecology*, 79, 2143–  
476 2152.
- 477 Marten, G.G. & Reid, J.W. (2007) Cyclopoid copepods. *Journal of the American Mosquito*  
478 *Control Association*, 23, 65–92.
- 479 McCoy, M.W., Stier, A.C. & Osenberg, C.W. (2012) Emergent effects of multiple predators  
480 on prey survival: the importance of depletion and the functional response. *Ecology*  
481 *Letters*, 15, 1449–1456.
- 482 Medlock, J.M. & Snow, K.R. (2008) Natural predators and parasites of British mosquitoes –  
483 a review. *European Mosquito Bulletin*, 25, 1–11.
- 484 Moore, M.A., Yan, N.D. & Pawson, T. (1994) Omnivory of the larval phantom midge  
485 (*Chaoborus* spp.) and its potential significance for freshwater planktonic food webs.  
486 *Canadian Journal of Zoology*, 72, 2055–2065.
- 487 Murdoch, W.W. & Oaten, A. (1975) Predation and population stability. *Advances in*  
488 *Ecological Research*, 9, 1–131.
- 489 Nam, V.S., Yen, N.T., Duc, H.M., Tu, T.C., Thang, V.T., Le, N.H. et al. (2012) Community-  
490 based control of *Aedes aegypti* by using *Mesocyclops* in Southern Vietnam. *The*  
491 *American Journal of Tropical Medicine and Hygiene*, 86, 850–859.
- 492 Nilsson, A.N. & Söderström, O. (1988) Larval consumption rates, interspecific predation, and  
493 local guild composition of egg-overwintering *Agabus* (Coleoptera, Dytiscidae)  
494 species in vernal ponds. *Oecologia*, 76, 131–137.

- 495 Nyberg, P. (1998) Biotic effects in planktonic crustacean communities in acidified Swedish  
496 forest lakes after liming. *Water Air and Soil Pollution*, 101, 257–288.
- 497 O’Neil, R.J. (1990) Functional response of arthropod predators and its role in the biological  
498 control of insect pests in agricultural systems. In: Dunn, P.E. & Baker, R.R. (eds) *New*  
499 *directions in biological control: alternatives for suppressing agricultural pests and*  
500 *diseases*. Alan R. Liss, Inc., New York, United States, pp. 83–96.
- 501 Peacor, S.D. & Werner, E.E. (2001) The contribution of trait-mediated indirect effects to the  
502 net effects of a predator. *Proceedings of the National Academy of Sciences of the*  
503 *United States of America*, 98, 3904– 3908.
- 504 Pritchard, D.W., Paterson, R.A., Bovy, H.C. & Barrios-O’Neill, D. (2017) FRAIR: an R  
505 package for fitting and comparing consumer functional responses. *Methods in*  
506 *Ecology and Evolution*, 8, 1528–1534.
- 507 R Development Core Team (2018) R: A language and environment for statistical computing.  
508 Vienna, Austria.
- 509 Riessen, H.P., O’Brien, J. & Loveless, B. (1984) An analysis of the components of  
510 *Chaoborus* predation on zooplankton and the calculation of relative prey  
511 vulnerabilities. *Ecology*, 65, 514–522.
- 512 Rogers, D. (1972) Random search and insect population models. *Journal of Animal Ecology*,  
513 41, 369–383.
- 514 Schmitz, O.J. (2007) Predator diversity and trophic interactions. *Ecology*, 88, 2415–2426.
- 515 Schmitz, O.J., Krivan, V. & Ovadia, O. (2004) Trophic cascades: the primacy of trait-  
516 mediated indirect interactions. *Ecology Letters*, 7, 153–163.

- 517 Sentis, A. & Boukal, D.S. (2018) On the use of functional responses to quantify emergent  
518 multiple predator effects. *Scientific Reports*, 8, 11787.
- 519 Shalaan, E.A-S. & Canyon, D.V. (2009) Aquatic insect predators and mosquito control.  
520 *Tropical Biomedicine*, 26, 223–261.
- 521 Sih, A., Englund, G. & Wooster, D. (1998) Emergent impacts of multiple predators on prey.  
522 *Trends in Ecology and Evolution*, 13, 350–355.
- 523 Schmitz, O.J. (2007) Predator diversity and trophic interactions. *Ecology*, 88, 2415–2426.
- 524 Smyly, W.P. (1979) Food and feeding of aquatic larvae of the midge *Chaoborus flavicans*  
525 (Meigen) (Diptera: Chaoboridae) in the laboratory. *Hydrobiologia*, 70, 179–188.
- 526 Snyder, G.B., Finke, D.L. & Snyder, W.E. (2008) Predator biodiversity strengthens aphid  
527 suppression across single-and multiple-species prey communities. *Biological Control*,  
528 44, 52–60.
- 529 Snyder, W.E. & Ives, A.R. (2003) Interactions between specialist and generalist natural  
530 enemies: parasitoids, predators, and pea aphid biocontrol. *Ecology*, 84, 91–107.
- 531 Snyder, W.E., Snyder, G.B., Finke, D.L. & Straub, C.S. (2006) Predator biodiversity  
532 strengthens herbivore suppression. *Ecology Letters*, 9, 789–796.
- 533 Soetaert, K. & Petzoldt, T. (2010) Inverse modelling, sensitivity and Monte Carlo analysis in  
534 R using package FME. *Journal of Statistical Software*, 33, 1–28.
- 535 Solomon ME (1949) The natural control of animal populations. *Journal of Animal Ecology*,  
536 18, 1–35.
- 537 Soluk, D.A. (1993) Multiple predator effects: predicting combined functional response of  
538 stream fish and invertebrate predators. *Ecology*, 74, 219–225.



- 539 Soluk, D.A. & Collins, N.C. (1988) Synergistic interactions between fish and stoneflies –  
540 facilitation and interference among stream predators. *Oikos*, 52, 94–100.
- 541 Suarez, M.F., Marten, G.G. & Clark, G.G. (1992) A simple method for cultivating freshwater  
542 copepods used in biological control of *Aedes aegypti*. *Journal of the American*  
543 *Mosquito Control Association*, 8, 409–412.
- 544 Sunahara, T., Ishizaka, K. & Mogi, M. (2002) Habitat size: a factor determining the  
545 opportunity for encounters between mosquito larvae and aquatic predators. *Journal of*  
546 *Vector Ecology*, 27, 8–20.
- 547 Tang, S., Pawar, S. & Allesina, S. (2014) Correlation between interaction strengths drives  
548 stability in large ecological networks. *Ecology Letters*, 17, 1094–1100.
- 549 Trexler, J.C., McCulloch, C.E. & Travis, J. (1988) How can the functional response best be  
550 determined? *Oecologia*, 76, 206–214.
- 551 Trussell, G.C., Ewanchuk, P.J., Bertness, M.D. & Silliman, B.R. (2004) Trophic cascades in  
552 rocky shore tide pools: distinguishing lethal and nonlethal effects. *Oecologia*, 139,  
553 427–432.
- 554 Trussell, G.C., Ewanchuk, P.J. & Matassa, C.M. (2008) Resource identity modifies the  
555 influence of predation risk on ecosystem function. *Ecology*, 89, 2798–2807.
- 556 Uiterwaal, S.F. & DeLong, J.P. (2018) Multiple factors, including arena size, shape the  
557 functional responses of ladybird beetles. *Functional Ecology*, 55, 2429–2438.
- 558 Van Driesche, R. & Bellows, T.S. (2011) *Biological control*. Springer, Berlin, Germany.
- 559 von Ende, C.N. & Deanpsey, D.O. (1981) Apparent exclusion of the cladoceran *Bosmina*.  
560 *longirostris* by the invertebrate predator *Chaoborus americanus*. *American Midland*  
561 *Naturalist*, 105, 240–248.

562 Werner, E.E. & Peacor, S.D. (2003) A review of trait-mediated indirect interactions in  
563 ecological communities. *Ecology*, 84, 1083–1100.

564 Vance-Chalcraft, H.D. & Soluk, D.A. (2005) Multiple predator effects result in risk reduction  
565 for prey across multiple prey densities. *Oecologia*, 144, 472–480.

566 Vázquez, D.P., Ramos-Jiliberto, R., Urbani, P. & Valdovinos, F.S. (2015) A conceptual  
567 framework for studying the strength of plant–animal mutualistic interactions. *Ecology*  
568 *Letters*, 18, 385–400.

569 Wasserman, R.J., Alexander, M.E., Dalu, T., Ellender, B.R., Kaiser, H. & Weyl, O.L.F.  
570 (2016) Using functional responses to quantify interaction effects among predators.  
571 *Functional Ecology*, 30, 1988–1998.

572 Yan, N.D., Keller W., MacIsaac H.J. & McEachern L.J. (1991) Regulation of zooplankton  
573 community structure of an acidified lake by *Chaoborus*. *Ecological Applications*, 1,  
574 52–65.

575 Yee, D.A., Kesavaraju, B. & Juliano, S.A. (2004) Larval feeding behaviour of three co-  
576 occurring species of container mosquitoes. *Journal of Vector Ecology*, 29, 315–322.

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583 **Table 1.** First order term results from logistic regression to determine functional response  
 584 types, alongside rounded parameter estimates and functional response ratios resulting from  
 585 Rogers' random predator equation.

Predator treatment	First order term, $p$	Attack rate ( $a$ ), $p$	Handling time ( $h$ ), $p$	Functional response ratio ( $a/h$ )
<i>M. albidus</i> ( $\times 1$ )	-0.03, < 0.001	0.85, < 0.05	0.18, < 0.001	4.67
<i>C. flavicans</i> ( $\times 1$ )	-0.01, < 0.05	0.95, < 0.001	0.02, < 0.05	57.68
<i>M. albidus</i> ( $\times 3$ )	-0.03, < 0.001	1.94, < 0.001	0.07, < 0.001	27.82
<i>C. flavicans</i> ( $\times 1$ ) + <i>M. albidus</i> ( $\times 3$ )	-0.03, < 0.001	1.69, < 0.001	0.02, < 0.001	79.99

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594 **Fig. 1.** Larval *Culex pipiens* consumption under four observed predator treatments across all  
595 densities: 1 × *Macrocyclus albidus* (Ma); 1 × *Chaoborus flavicans* (Cf); 3 × *Macrocyclus*  
596 *albidus*; 3 × *Macrocyclus albidus* + 1 × *Chaoborus flavicans*. In the boxplots, the horizontal  
597 bar displays the median, the box gives the interquartile ranges and the whiskers show the  
598 largest and smallest values up to 1.5 times the interquartile range.

599

600 **Fig. 2.** Functional responses of *Macrocyclus albidus* (Ma) and *Chaoborus flavicans* (Cf)  
601 towards larval *Culex pipiens*, individually (a: solid, *M. albidus*; dotted, *C. flavicans*), or in  
602 con/heterospecific predatory units (b: solid, *M. albidus* (× 3) observed; dashed, 3 *M. albidus*  
603 (× 3) predicted; c: solid, *M. albidus* (× 3) and *C. flavicans* (× 1) observed; dashed, *M. albidus*  
604 (× 3) and *C. flavicans* (× 1) predicted). Shaded areas are 95 % confidence intervals.