

On multiple infections by parasites with complex life cycles

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Statement of Authorship

Both authors developed the theory.

P.L.N developed and implemented the computational model.

Both authors wrote the manuscript.

1 **Abstract:** Host manipulation is a common strategy of parasites with complex
2 life cycles. It directly affects predator-prey dynamics in trophically transmitted
3 parasites. Theoretical studies suggest that predation-enhancing manipulation of-
4 ten decimates the prey population, making parasites prone to extinction. Host
5 manipulation, however, can also reduce predation due to conflicting interests
6 when multiple parasites infect a host, which is often neglected in theoretical stud-
7 ies. Misaligned interests of coinfecting parasites can occur due to limited carrying
8 capacity or parasitoid developmental stage. Including this realistic complexity in
9 a mathematical model, the results depart from previous studies substantially.
10 We show that coinfecting multi-trophic parasites can preserve the predator-prey
11 system and themselves through manipulation and reproduction parameters. Our
12 study highlights the necessity of and provides the means for incorporating the
13 reality of multiple parasites and their multi-trophic life cycles into the theory of
14 parasite ecology.

15 **Introduction**

16 Parasites infect life on earth ubiquitously, and many of these parasites have complex life cycles
17 (Zimmer, 2001). While a complex life cycle can be defined as abrupt ontogenetic changes in
18 morphology and ecology (Benesh, 2016), it typically involves numerous host species that
19 a parasite needs to traverse to complete its life cycle. This complex life cycle results in
20 the evolution of various strategies that enable successful parasite transmission from one
21 host species to another. ~~One Host manipulation is a~~ famous strategy that inspires many
22 science fiction movies and novels~~is host manipulation~~, where a parasite can alter its host's
23 morphology and/or behaviour to enhance its transmission to the next host (Hughes et al.,
24 2012). Host manipulation has been shown in many host-parasite systems, from parasites
25 with simple life cycles to those with a complex life cycle that involves more than one host
26 species (Hughes et al., 2012; Molyneux and Jefferies, 1986). For instance, sand flies infected
27 by *Leishmania* parasites bite more and take more time for a blood meal from mammals (the
28 definitive host of *Leishmania*) compared to their uninfected counterparts (Rogers and Bates,
29 2007). Copepods infected by cestode parasites are more active and accessible to sticklebacks
30 (the cestodes' definitive hosts) than uninfected copepods (Wedekind and Milinski, 1996).

31 Theoretical studies have long attempted to understand the ecological and evolutionary
32 consequences of host manipulation. Roosien et al. (2013) and Hosack et al. (2008) showed
33 that manipulative parasites could increase the disease prevalence in an epidemic. Gandon
34 (2018) studied the evolution of the manipulative ability of infectious disease parasites, show-
35 ing different evolutionary outcomes depending on whether the pathogen can control its vector
36 or host. Hadeler and Freedman (1989); Fenton and Rands (2006) and Rogawa et al. (2018)
37 showed that host manipulation could stabilise or destabilise the predator-prey dynamics de-
38 pending on how manipulation affects the predation response function and the reproduction of
39 the infected definitive host. Seppälä and Jokela (2008) showed that host manipulation could
40 evolve even when it increases the risk of the intermediate host being eaten by a non-host
41 predator, given that the initial predation risk is sufficiently low.

42 Most studies mentioned above have not explicitly considered a crucial aspect of parasite
43 dynamics – multiple infections (Kalbe et al., 2002) i.e. the presence of multiple individual
44 parasites within a single host. Multiple infections are a norm rather than an exception in
45 parasitism. They result in the coinfection of more than one parasite inside a host, which may
46 alter the manipulative outcomes (figure 1). An alignment of interest between coinfecting
47 parasites may enhance manipulation, while a conflict of interest may reduce the manipulative
48 effect. Indeed, Hafer and Milinski (2015) showed that copepods infected by two cestode
49 parasites reduce the activity of copepods when both parasites are at the same noninfectious
50 stage, i.e. both parasites are not ready to transmit. When two infectious parasites infect the
51 copepods, the copepods' activity increases, and so does the predation risk for the copepod.
52 However, when the copepods are infected by one infectious and one noninfectious parasite,
53 their interests clash, and the infectious parasite wins.

54 Theoretical work that considers multiple infections often focuses on the evolution of viru-
55 lence (van Baalen and Sabelis, 1995; Alizon et al., 2013; Alizon and van Baalen, 2008; Choisy
56 and de Roode, 2010; Alizon, 2012), while host manipulation in trophically transmitted par-
57 asites receives less attention. Even though host manipulation and virulence correlate with
58 parasite transmission, there are subtle differences, such that virulence implies an addition to
59 the natural mortality rate of the infected host, whereas manipulation links to the immediate
60 death of the intermediate host due to predation. Host manipulation in trophically transmitted
61 parasites, therefore, strongly affects the entire predator-prey dynamics. Theoretical studies
62 regarding host manipulation rarely consider multiple infections. Studies incorporating this
63 feature neglect the predator-prey dynamics, which will likely have important feedback on the
64 evolution of host manipulation (Parker et al., 2003; Vickery and Poulin, 2009). Moreover,
65 these models assume that transmission from definitive hosts to intermediate hosts is due to
66 direct contact between the two types of hosts (Rogawa et al., 2018; Hadeler and Freedman,
67 1989; Fenton and Rands, 2006). This is often not the case in nature, as parasites are re-
68 leased from the definitive hosts into the environment. Transmission thus happens only when

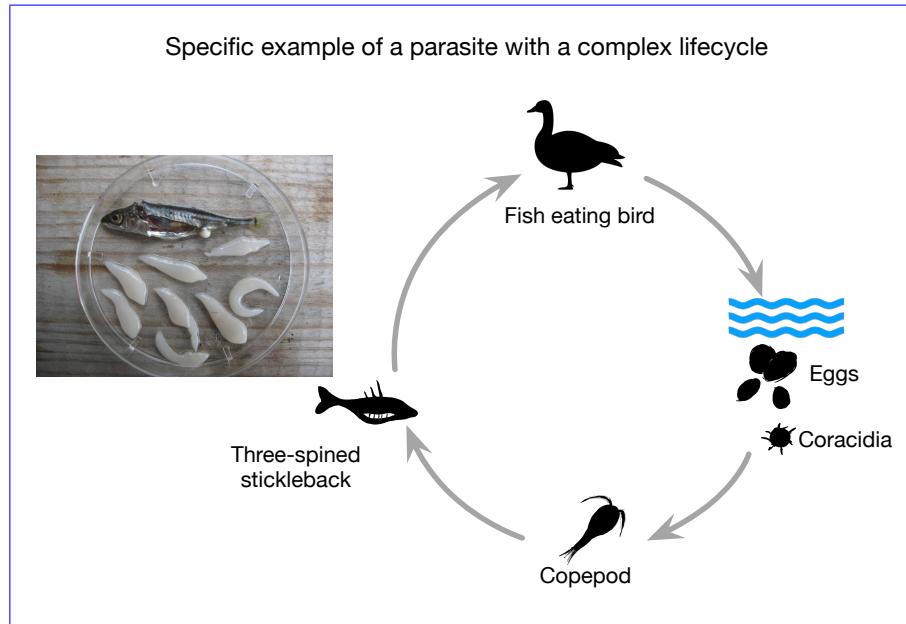


Figure 1: Who is in control? Schistocephalus eggs hatch into microscopically tiny swimming larvae. These larvae are eaten by copepods, where they develop to the second larval stage. However, the copepod is only the first intermediate host. The larvae are then eaten by sticklebacks, reaching the third larval stage and growing prominently in size and weight. For the parasite to successfully reach its final host, a warm-blooded animal like a bird, it manipulates its intermediate hosts. The presence of multiple parasites in the same host can lead to competition and strategic decisions pertaining to about investment in manipulation and growth. Indeed, a stickleback can be infected by numerous parasites, all vying for control, as shown and photographed by Martin Kalbe (Kalbe et al., 2002). While this is a specific example of a parasite with a complex life cycle, our model abstracts the concept to generic multi-host life cycles with an environmental component.

69 intermediate hosts have contact with this free-living parasite pool. The inclusion of this free-
 70 living stage could have a profound effect on the dynamics of the whole predator-prey-parasite
 71 system.

72 Our study addresses the gap in the theoretical work on host manipulation in trophically
 73 transmitted parasites. We include multiple infections of the same parasite species and con-
 74 sider the dynamics of the free-living parasite pool. Our compartment model helps illustrate
 75 a parasite's complex life cycle with two host species: an intermediate host preyed upon
 76 by a definitive host. Transmission from the intermediate host to the definitive host occurs

77 when predation on infected intermediate hosts happens. Reproduction only happens in the
78 definitive hosts. New parasites then enter the environment, where the cycle continues. We
79 focus on the intermediate host manipulation, such that the parasite increases the uptake of
80 the intermediate host by the definitive host to increase its transmission rate. We then anal-
81 yse the effect of host manipulation on the ecological dynamics in the predator-prey-parasite
82 system. We found that sabotage in host manipulation almost always pushes the dynamical
83 system toward bistability, provided the reproduction in a single infection is sufficiently small.
84 The bistable nature suggests that the predator-prey parasite system is finely balanced and
85 susceptible to extinction via ecological disturbances. Initially surprising, we showed that co-
86 operation in host manipulation and enhanced reproduction in co-infecting parasites is not
87 always beneficial and might expose the parasite population to the risk of extinction.

88 Model

89 Our model concerns the complex life cycle of a trophically transmitted parasite that requires
90 two hosts: an intermediate host and a definitive host. Reproduction only happens inside the
91 definitive hosts, releasing new parasitic progeny in the environment. An intermediate host
92 can be infected if it encounters this free-living parasite pool. Finally, when a definitive host
93 consumes an infected intermediate host, the definitive host gets infected, and the parasite
94 completes its life cycle.

95 For simplicity, we assume that hosts can be infected by one (single infection) or, at
96 most, two parasites [of the same species](#) (double infections). Thus, while I_s and D_s are the
97 susceptible intermediate and definitive hosts, their singly and doubly infected counterparts
98 are denoted by I_w and D_w and I_{ww} and D_{ww} respectively. Our model is, therefore, more
99 relevant to the macroparasitic system. Figure (2) illustrates the transmission dynamics, and
100 details of the model's variables and parameters are shown in Table 1. Note that multiple
101 infections in nature often involve more than two parasites. Typically, the number of parasites
102 in multiple infections follows a negative binomial distribution, i.e. most hosts are infected

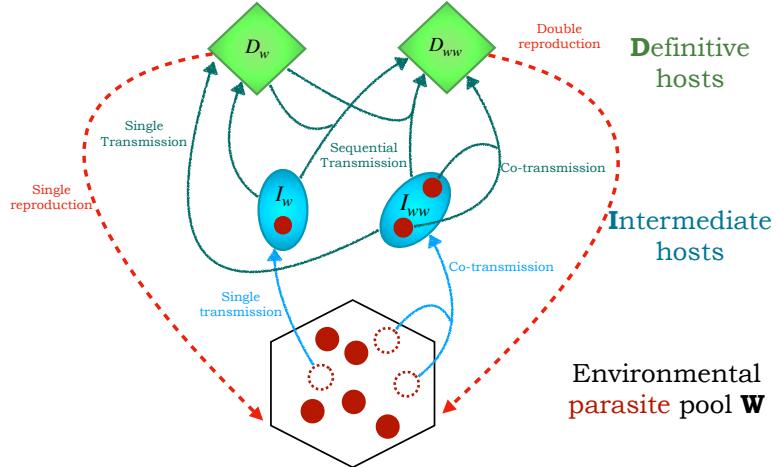


Figure 2: Schematics of the transmission routes. Blue ovals represent the intermediate hosts, while green diamonds represent the definitive hosts. The hexagon represents the parasite pool compartment, with the red circles illustrating the free-living individual parasites. The parasites infect the intermediate hosts singly (I_w) or doubly (I_{ww}) upon encounter between the intermediate hosts and the parasite pool (blue arrows). These intermediate hosts are then predated upon by the definitive hosts (green arrows), thus moving the parasites to the final host (either as D_w or D_{ww}) where they can reproduce and reenter the free-living stage in the environmental pool W (red dashed arrows).

with a few parasites ~~while very~~ and few hosts are infected with many parasites (Wilson et al., 1996). However, since we use a compartmental model, enabling binomial distribution would mean infinitely many differential equations, making it impossible to formulate and analyze the model. Instead, we focus on another aspect of multiple infections, that is, co-transmission, which has been shown to affect the evolutionary trajectories of parasites in infectious disease (Alizon, 2012). Given an infection, the probability that two parasites from the parasite pool co-transmit to an intermediate host is denoted by p . Thus, $1 - p$ is the probability that a single parasite enters an intermediate host. When a definitive host consumes an intermediate host infected by two parasites, there is a probability q that the parasites co-transmit to the definitive host. With probability $1 - q$, only one parasite successfully transmits. This formulation assumes that infection always happens when intermediate hosts encounter free-living parasites and when definitive hosts consume infected intermediate hosts (Figure. 2). The dynamics of a complex life cycle parasite that requires two host species is described by

116 the following system of equations, firstly for the intermediate host as,

$$\begin{aligned}\frac{dI_s}{dt} &= R(I_{total}) - dI_s - P_s(D_{total})I_s - \eta I_s \\ \frac{dI_w}{dt} &= (1-p)\eta I_s - (d + \alpha_w)I_w - P_w(D_{total}, \beta_w)I_w \\ \frac{dI_{ww}}{dt} &= p\eta I_s - (d + \alpha_{ww})I_{ww} - P_{ww}(D_{total}, \beta_{ww})I_{ww}\end{aligned}\quad (1)$$

117 where $R(I_{total})$ represents the birth rate of the intermediate hosts, a function of both infected
 118 and uninfected individuals $I_{total} = I_s + I_w + I_{ww}$. Intermediate hosts die at a natural rate
 119 d , and parasites cause additional mortality rate α_w in single infection and α_{ww} in double
 120 infection. P_s , P_w , P_{ww} are the predation functions of definitive hosts on susceptible, singly
 121 infected and doubly infected intermediate hosts. The predation function depends on the
 122 density of all definitive hosts $D_{total} = D_s + D_w + D_{ww}$ and the manipulative strategies of
 123 parasites in the intermediate hosts. In particular, if a single parasite infects an intermediate
 124 host, the manipulation strategy is β_w . However, if the intermediate host is co-infected, the
 125 manipulation strategy is β_{ww} . We assume no specific relationship between β_w and β_{ww} to
 126 explore all possible ecological outcomes of the system. The force of infection by parasites in
 127 the environment is denoted by $\eta = \gamma W$, where γ represents the infection rate of free-living
 128 parasites. The force of infection is a term often used in epidemiology, which represents
 129 the rate at which a host gets infected by the parasites. Since parasites can manipulate
 130 intermediate and definitive hosts, whenever we mention host manipulation, it specifically
 131 refers to the manipulation in intermediate hosts, which correlates to the predation rate.

132 For the definitive hosts, we have,

$$\begin{aligned}\frac{dD_s}{dt} &= B(D_{total}, I_{total}) - \mu D_s - (\lambda_{ww} + \lambda_w)D_s \\ \frac{dD_w}{dt} &= (\lambda_w + (1-q)\lambda_{ww})D_s - (\mu + \sigma_w)D_w - ((1-q)\lambda_{ww} + \lambda_w)D_w \\ \frac{dD_{ww}}{dt} &= q\lambda_{ww}D_s + ((1-q)\lambda_{ww} + \lambda_w)D_w - (\mu + \sigma_{ww})D_{ww}\end{aligned}\quad (2)$$

133 where $B(D_{total}, I_{total})$ represents the birth rate of definitive hosts. The birth rates depend
 134 on the density of both intermediate and definitive hosts, infected or uninfected. The natural
 135 mortality rate of definitive hosts is represented by μ , and parasites induce additional mortality
 136 rates σ_w and σ_{ww} in single and double infection, respectively. The force of infection that
 137 corresponds respectively to singly infected intermediate host (I_w) and doubly infected inter-
 138 mediate hosts (I_{ww}) is denoted respectively by $\lambda_w = h(\rho + \beta_w)I_w$ and $\lambda_{ww} = h(\rho + \beta_{ww})I_{ww}$,
 139 where ρ is the baseline predation rate, i.e. the basic constitutive level of predation, and h
 140 is the probability that the parasite successfully establishes inside the host. Without manipu-
 141 lation, that is, $\beta_w = \beta_{ww} = 0$, the parasite is still transmitted via the baseline predation ρ .
 142 The dynamics of the free-living parasites in the environment are then given by,

$$\frac{dW}{dt} = f_w D_w + f_{ww} D_{ww} - \delta W - \eta I_s \quad (3)$$

143 where f_w and f_{ww} are the reproduction rates of parasites in single and double infection,
 144 respectively, and parasites die naturally at a rate δ .

145 Here, we focus on manipulation that enhances transmission from intermediate hosts to
 146 definitive hosts; we thus simplify the transmission from the parasite pool to intermediate
 147 hosts so that no sequential infection occurs. This assumption is motivated because the
 148 prey's life cycle is often shorter than the predator's. A prey likely encounters the free-living
 149 parasite pool once and then dies due to predation, making sequential transmission less likely
 150 at this state. Sequential infection can happen when parasites transmit from intermediate
 151 hosts to definitive hosts. Therefore, a singly infected definitive host can be further infected
 152 by another parasite if it consumes infected intermediate hosts.

153 Basic reproduction ratio R_0 of the parasites

154 The basic reproduction ratio R_0 (or basic reproduction number as often used in epidemiology)
 155 indicates parasite fitness. It can be understood as the expected number of offspring a parasite

156 produces during its lifetime when introduced to a susceptible host population. We calculate
 157 the basic reproduction ratio R_0 using the next-generation method (Diekmann et al., 1990,
 158 2009; Hurford et al., 2010) (See SI1 for details).

$$R_0 = \underbrace{\gamma I_s^* \frac{pqh(\rho + \beta_{ww})}{\alpha_{ww} + d + P_{ww}} \frac{D_s^*}{\mu + \sigma_{ww}} \frac{f_{ww}}{\delta + \gamma I_s^*}}_{\text{Double infections}} + \\ \underbrace{\gamma I_s^* \left(\frac{(1-p)h(\rho + \beta_w)}{\alpha_w + d + P_w} + \frac{p(1-q)h(\rho + \beta_{ww})}{\alpha_{ww} + d + P_{ww}} \right) \frac{D_s^*}{\mu + \sigma_w} \frac{f_w}{\delta + \gamma I_s^*}}_{\text{Single infection}} \quad (4)$$

159 where I_s^* and D_s^* are the densities of susceptible intermediate and definitive hosts at the
 160 disease-free equilibrium. Here, the expression of R_0 contains the possible reproduction routes
 161 of a parasite, which can be via double or single infections. The first component corresponds
 162 to the double infections route, in which the focal parasite co-transmits with another parasite
 163 into a susceptible intermediate host, then co-transmits into a susceptible definitive host and
 164 reproduces. Here, parasites are so rare that only co-transmission matters and the compart-
 165 ments with sequential infections are neglected. The second component corresponds to the
 166 single infection route, wherein the focal parasite infects a susceptible intermediate host via
 167 single or double infections. The parasite then transmits alone into the susceptible definitive
 168 host and eventually reproduces.

169 If $R_0 > 1$, a parasite spreads when introduced into the disease-free equilibrium of prey and
 170 predator. Intuitively, the higher the density of susceptible intermediate and definitive hosts,
 171 the larger the value of R_0 as the infection reservoir is more extensive. In contrast, regardless
 172 of the explicit form of the predation function, the higher the predation rate P_w and P_{ww} , the
 173 lower the value of R_0 given the smaller reservoir of intermediate hosts. The effect of host
 174 manipulation on the value of R_0 is more complex; as host manipulation becomes efficient,
 175 the transmission rate from the intermediate host to the definitive host increases, but so does
 176 the predation rate. A higher predation rate results in a smaller intermediate host reservoir
 177 for the parasites to infect. To understand the effect of manipulation on parasites' fitness

178 and the system's ecological dynamics, we next specify the predation functions. We consider
179 linear functions for predation to begin with,

$$P_s(D_{total}) = \rho D_{total}$$

$$P_w(D_{total}, \beta_w) = (\rho + \beta_w)D_{total}$$

$$P_{ww}(D_{total}, \beta_{ww}) = (\rho + \beta_{ww})D_{total}$$

180 where ρ is the baseline capture rate of the predator on the prey. If an intermediate host is
181 infected, it is captured by the definitive hosts with rate $\rho + \beta_w$ if it is singly infected and with
182 rate $\rho + \beta_{ww}$ if it is doubly infected. Zero values for β_w and β_{ww} suggest no manipulation,
183 and predation is at the baseline value ρ .

184 For simplicity, we also consider a linear function of the birth of definitive hosts

$$B(D_{total}, I_{total}) = \rho c D_{total} I_{total}$$

185 where c is the efficiency of converting prey into predator's offspring. It is important to note
186 that host manipulation affects population dynamics via its influence on the predation rate,
187 not the physiological aspect of the definitive host, i.e., the predator. The birth rate of the
188 predators thus depends on the capture rate, but it is not affected by host manipulation; to
189 our best knowledge, there is no supporting evidence to consider otherwise.

190 The explicit form of I_s^* and D_s^* , capturing the predator-prey dynamics, depends on the
191 precise form of all birth and predation functions B, R, P_s, P_w and P_{ww} . However, it does
192 not depend on the ability to manipulate or any other parameter of the parasite. Given that
193 the birth rate of the predator and the predation rate are linear functions in prey and predator
194 density, the form of the birth rate R of the prey has a significant effect on the susceptible
195 intermediate and definitive host dynamics.

196 **Birth function of intermediate hosts**

197 The simplest form of the prey's birth rate is a linear function, in which case the disease-free
198 equilibrium is always in a cyclic regime (see SI 2). This follows from the Lotka-Volterra
199 system using linear functions for prey birth and predation ([Lotka, 1920](#)). Since the disease-
200 free dynamics is cyclic, it is difficult to analyse the spread of a parasite using the basic
201 reproduction ratio, which is evaluated when the disease-free state is stable. Here, $R_0 > 1$
202 happens when γ , the transmission rate from the environment to intermediate hosts, and the
203 reproduction rates f_w, f_{ww} are quite large (as compared to the theoretical threshold shown by
204 the mathematical conditions in [SI3SI.3](#)). However, even when this condition is satisfied, the
205 parasite may not be able to spread and persist in cyclic susceptible host dynamics (Figure
206 [SI1SI.1](#)). This result agrees with the conclusion in ([Ripa and Dieckmann, 2013](#)), which
207 suggests that it is difficult for a mutant to invade a cyclic resident population. In our case,
208 it is not the invasion of a mutant in a resident population but the invasion of a parasite in
209 a cyclic disease-free host population; the argument, however, remains valid in both cases.
210 This issue deserves a more thorough investigation, which is out of the scope of this article.
211 Therefore, we choose a non-linear birth function of the intermediate hosts to obtain a stable
212 disease-free state and focus on the effect of host manipulation on the ecological dynamics
213 (Figure 3).

214 The logistic growth for the non-linear birth function follows by

$$R(I_{total}) = rI_{total}(1 - kI_{total})$$

215 where [r is the intrinsic growth rate of the intermediate hosts, and](#) k is the intraspecific
216 competition coefficient. The disease-free equilibrium is as follows,

$$I_s^* = \frac{\mu}{c\rho} ; D_s^* = \frac{c\rho(r - d) - k\mu r}{c\rho^2}$$

217 This equilibrium is positive and stable if components of the parasite, such as reproduction
218 and transmission, are sufficiently small; details of the condition can be found in section SI 4.
219 Here, as the reproduction and transmission ~~value-values~~ of the parasite are not sufficient, it
220 goes extinct (Figure 3A, B), leaving the predator-prey dynamics attaining equilibrium (Figure
221 3C, D)

222 When a parasite appears in the disease-free equilibrium, it spreads if its reproduction ratio
223 $R_0 > 1$ (Figure 4). Since the expression is complicated, we could only obtain analytical
224 solutions for this inequality with assumptions. We assume the same parasite virulence,
225 $\alpha_w = \alpha_{ww}$, $\sigma_w = \sigma_{ww}$, and reproduction in double infection as a linear function concerning
226 reproduction in single infections, $f_{ww} = \epsilon f_w$. When $\epsilon > 1$, reproduction in double infections
227 is enhanced compared to in single infections, whereas for $\epsilon \leq 1$, it is suppressed or equal to
228 reproduction in single infections. We found that the parasite can establish if its reproduction
229 value in a single infection f_w is more significant than a threshold (Figure 5, see section SI 5
230 and Eq. (SI.19)).

231 Our numerical results show that the parasite reproduction is substantial compared to
232 other parameters (Figure 5A). For instance, in the parameter set used to generate Figure
233 5, to spread in the predator-prey system, the value of parasite reproduction (f_w) has to
234 be at least 20 times the value of intermediate host reproduction $r = 2.5$, given that both
235 these parameters represent the *per capita* growth rate of the parasite and the intermediate
236 host population. This observation suggests that trophically transmitted parasites should
237 release many offspring into the environment to persist. Interestingly, bistability occurs if
238 the reproduction rate of the parasite in double infections is enhanced. Bistability suggests
239 that the parasite population is vulnerable to extinction. Specifically, if sufficient parasites are
240 introduced into the disease-free predator-prey populations, the parasite population persists
241 and reaches a stable equilibrium. In contrast, if only a few parasites are introduced into the
242 disease-free populations, or if sufficient disturbance occurs when the parasite population is
243 already established, the parasite population could go extinct (Figure 5C).

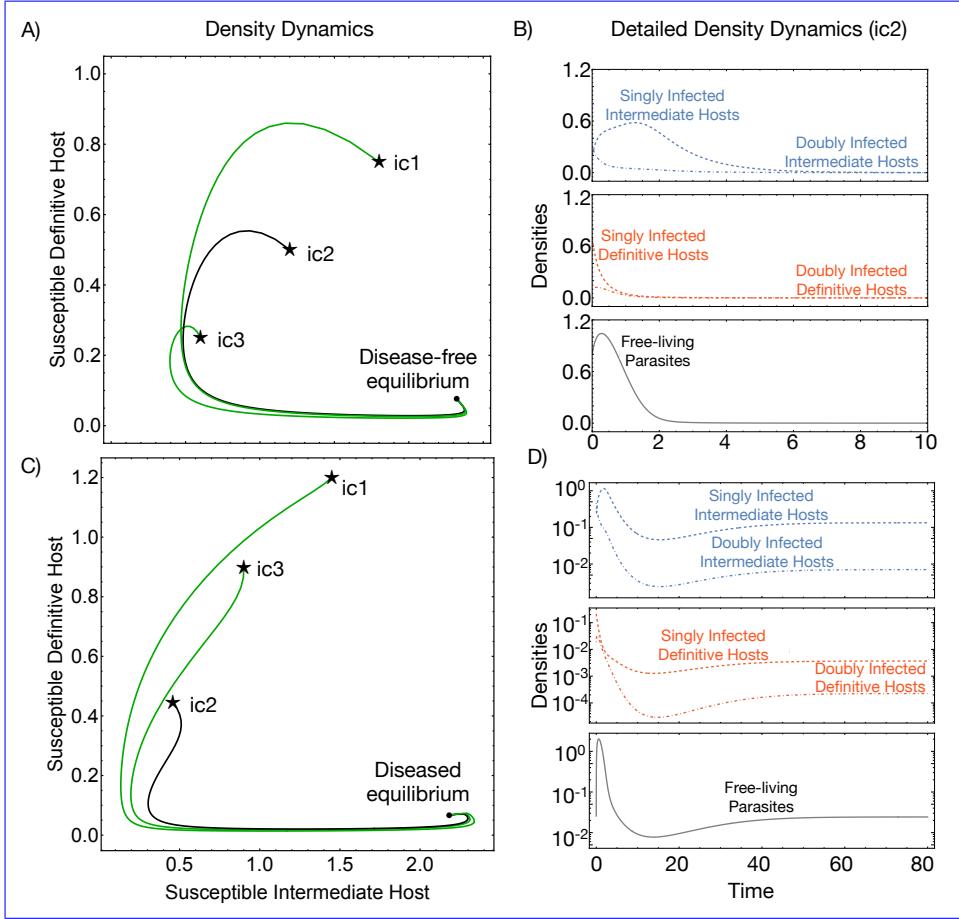


Figure 3: Ecological dynamics of the predator-prey-parasite system. On the left, we show the density dynamics of the susceptible intermediate and definitive hosts at different initial conditions (ic1, ic2, and ic3). The detailed dynamics of infected compartments are further shown for specific initial conditions (ic2), including the free-living parasite dynamics. A-B) A case of a disease-free equilibrium being reached from different initial conditions (ic). C-D) A case where the parasite survives. Parameters for disease free equilibrium $\rho = 1.2$, $d = 0.9$, $r = 2.5$, $\gamma = 2.9$, $\alpha_w = \alpha_{ww} = 0$, $\beta_w = \beta_{ww} = 1.5$, $p = 0.05$, $c = 1.4$, $\mu = 3.9$, $\sigma_w = \sigma_{ww} = 0$, $q = 0.05$, $f_w = f_{ww} = 7.5$, $\delta = 0.9$, $k = 0.26$, $h = 0.6$. Disease stable equilibrium has the same parameter values except for higher host manipulation $\beta_w = \beta_{ww} = 4.5$ and parasite reproduction $f_w = f_{ww} = 45$

244 The effect of host manipulation on ecological dynamics

245 Host manipulation can be cooperative; two parasites increase the predation rate on inter-
 246 mediate hosts, or $\beta_{ww} > \beta_w$ ([Hafer and Milinski, 2015](#)). However, it can also be unco-
 247 operative; the predation rate on doubly-infected intermediate hosts is lower than that on

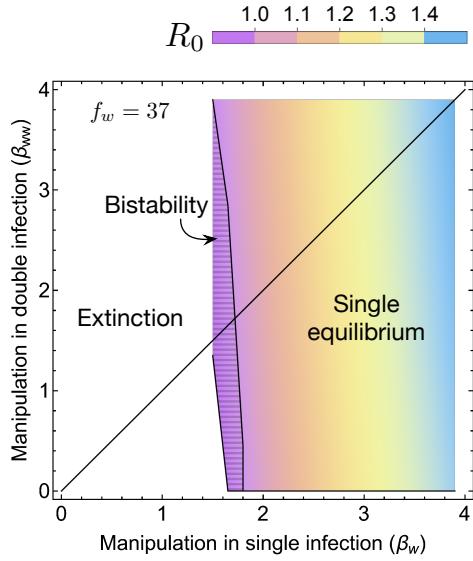


Figure 4: Effect of manipulation in single and double infections on the reproduction ratio R_0 . R_0 values increase with more efficient manipulation in single and double infection. The hatched area indicates the bistable region. As manipulation in single infection increases, the system only has one stable equilibrium. On the black line, the manipulation level is equal between single and double infection ($\beta_w = \beta_{ww}$). In the upper triangular area, parasites cooperate, and in the lower triangular area, parasites sabotage. Common parameter: $\rho = 1.2$, $d = 0.9$, $r = 2.5$, $\gamma = 2.9$, $\alpha_w = 0$, $\alpha_{ww} = 0$, $p = 0.05$, $c = 1.4$, $\mu = 3.9$, $\sigma_w = 0$, $\sigma_{ww} = 0$, $q = 0.05$, $\delta = 0.9$, $k = 0.26$, $f_w = 37$, $\epsilon = 4.5$, $h = 0.6$.

248 singly-infected ones or $\beta_{ww} < \beta_w$ (Hafer and Milinski, 2015). Cooperation in parasite ma-
 249 nipulation increases the parasite's basic reproduction ratio R_0 , but the manipulation in a
 250 single infection substantially affects the value of R_0 (Figure 4, see section SI 6 for analytical
 251 results). Intuitively, if the manipulation in a single infection is minor, there is not enough
 252 transmission, and the parasite goes extinct. However, we could suppose that the ability to
 253 manipulate the host in a single infection is enough for the parasite population to escape
 254 extinction. In that case, the system is in a bistable state where intermediate cooperation
 255 in host manipulation cannot guarantee a single equilibrium (Hatched area Figure 4). In the
 256 bistable region, the basic reproduction ratio can be less than one, implying that the parasite
 257 with manipulative values within this range, i.e. weak manipulation ability, cannot spread.
 258 When the This is due to the Allee effect (Stephens et al., 1999) where the parasite spreads

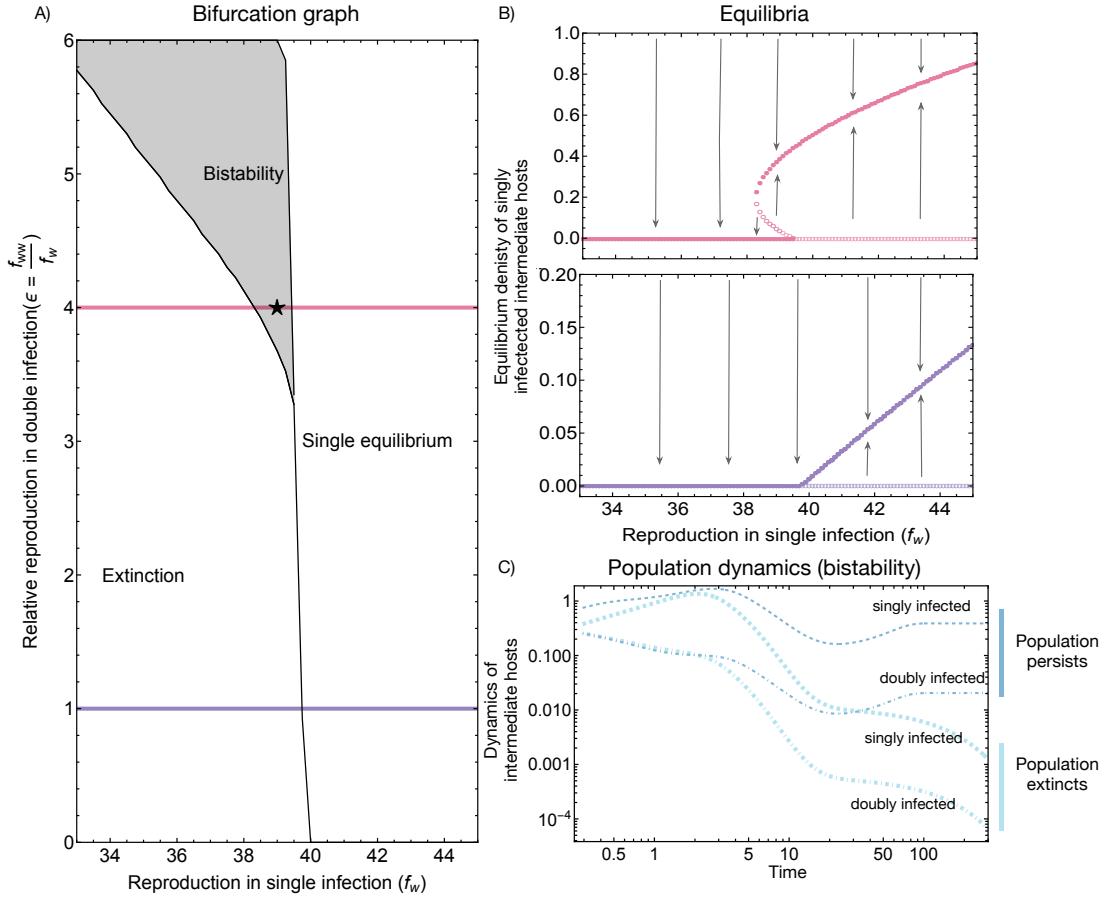


Figure 5: Effect of parasite reproduction on the ecological dynamics. A) A bifurcation graph for different reproduction values in single and double infections. B) Equilibrium density of intermediate host when $\epsilon = 4$ when bistability occurs at high values of f_w (in pink), and $\epsilon = 4$ when only one stable equilibrium exists at high values of f_w (in purple). C) Details of the parasite population dynamics in the case of bistability shown through the infected intermediate hosts. When the parasites start at high density, the parasite population persists, whereas when they start at lower density, they perish. Filled circles indicate stable **equilibrium**, and open circles indicate unstable equilibrium. Parameter $\rho = 1.2$, $d = 0.9$, $r = 2.5$, $\gamma = 2.9$, $\alpha_w = 0$, $\alpha_{ww} = 0$, $\beta_w = 1.5$, $\beta_{ww} = 1.5$, $p = 0.05$, $c = 1.4$, $\mu = 3.9$, $\sigma_w = 0$, $\sigma_{ww} = 0$, $q = 0.05$, $\delta = 0.9$, $k = 0.26$, $h = 0.6$.

259 and persists if, initially, there are sufficient parasites in the free-living pool as well as in the
 260 intermediate and definitive hosts. On the contrary, if the initial populations of parasites are
 261 insufficient, the parasite will perish (Figure S1.2). In addition, when the system encounters

262 bistability, the parasite population risks extinction if there is a disturbance in the community.
263 In the following parts, we will explore scenarios where bistability may occur.

264 Besides manipulation, co-infecting parasites can influence each other in different life his-
265 tory traits. Parasites can have an enhanced reproduction rate in coinfections, i.e. $f_{ww} > f_w$
266 (upper part of the horizontal line in all panels Figure 6). Likewise, they can compete for re-
267 sources, so reproduction in double infection is suppressed compared to single infection (lower
268 parts of the horizontal lines in all panels Figure 6). Without any assumption on the link be-
269 tween manipulative ability and reproduction, and a linear relationship between manipulation
270 in single and double infections, we explore all possible combinations of cooperation-sabotage
271 range in manipulation and suppressed-enhanced range in reproduction. This results in four
272 scenarios of parameter combinations: i, parasites sabotage manipulation but have enhanced
273 reproduction – manipulative incoordination (top left quadrants in all panels Figure 6), ii,
274 parasites cooperate to increase manipulation and enhance reproduction – coordination (top
275 right quadrants in all panels Figure 6), iii, parasites cooperate in manipulation but suppress
276 reproduction – reproductive incoordination (bottom right quadrants in all panels Figure 6),
277 and iv, parasites sabotage manipulation and suppress reproduction – discordance (bottom
278 left quadrants in all panels Figure 6).

279 If coinfecting parasites are discordant, i.e. uncooperative in manipulations and show sup-
280 pressed reproduction, they cannot persist (bottom left quadrants Figure 6A-D). On the other
281 extreme, where they are highly cooperative in manipulation and show enhanced reproduction,
282 i.e., an extreme level of coordination, there is a guaranteed single equilibrium for parasite
283 existence (top right quadrants Figure 6A-D). Note that this happens at the combination
284 of $\beta_{ww}/\beta_w \rightarrow \infty$ and $f_{ww}/f_w \rightarrow \infty$, a scenario that is rather impossible in reality. We
285 often expect intermediate levels of coordination where a bistable area could occur (top right
286 quadrant in Figure 6A, C, D). However, the size of this area is sensitive to the value of
287 reproduction and manipulation in a single infection. In particular, higher values of these two
288 parameters reduce the bistability area so that sufficiently large reproduction in a single infec-

tion can guarantee single equilibrium when parasites coordinate (Figure 6 B, D). In contrast, slightly reducing values of either reproduction or manipulation in a single infection increases the bistability area (Figure 6A, C, D). If the parasites sabotage each other, the system is highly prone to bistability and only has a single equilibrium when reproduction is enhanced. Interestingly, reproductive incoordination, *i.e.* ~~with~~ depressed reproduction and sufficient manipulative cooperation, always leads to a single equilibrium of the system (bottom right quadrants Figure 6A, ~~B~~, note that if we extend the relative manipulation in Figure C and D, we also obtain single equilibrium in this area). While a single equilibrium guarantees the existence of a parasite population, bistability indicates that a disturbance of the system may likely lead to the extinction of the parasite population. This suggests that the benefits of coordination in reproduction and manipulation are context-dependent. Coordinating is advantageous if no significant tradeoffs and reproduction or manipulation in single infections are large enough.

We now explore the effect of co-transmission probability on the bistability of the system (Figure 7). First, extinction is more likely with varying levels of co-transmission from the parasite pool to the intermediate host, p , compared to varying levels of co-transmission from the intermediate host to the definitive host, q . For exceptionally high levels of cooperation and intermediate values of p and q , the predator-prey-parasite system will always persist with one stable equilibrium. However, limitations and trade-offs are often unavoidable, and such high values of cooperation may be impossible, putting the system in the parameter space where bistability likely occurs. When the parasite sabotages manipulation, the bistable area decreases with increasing p and q . However, this bistable area disappears with high values of q but not with high values of p . When parasites cooperate in manipulation, reducing p almost always leads to bistability, whereas reducing q can lead to a single equilibrium if cooperation is sufficiently large. Bistability indicates vulnerability to disturbance, so cooperation in manipulation may be beneficial when q , the co-transmission from the intermediate host to the definitive host, decreases. However, cooperation in manipulation may still harm

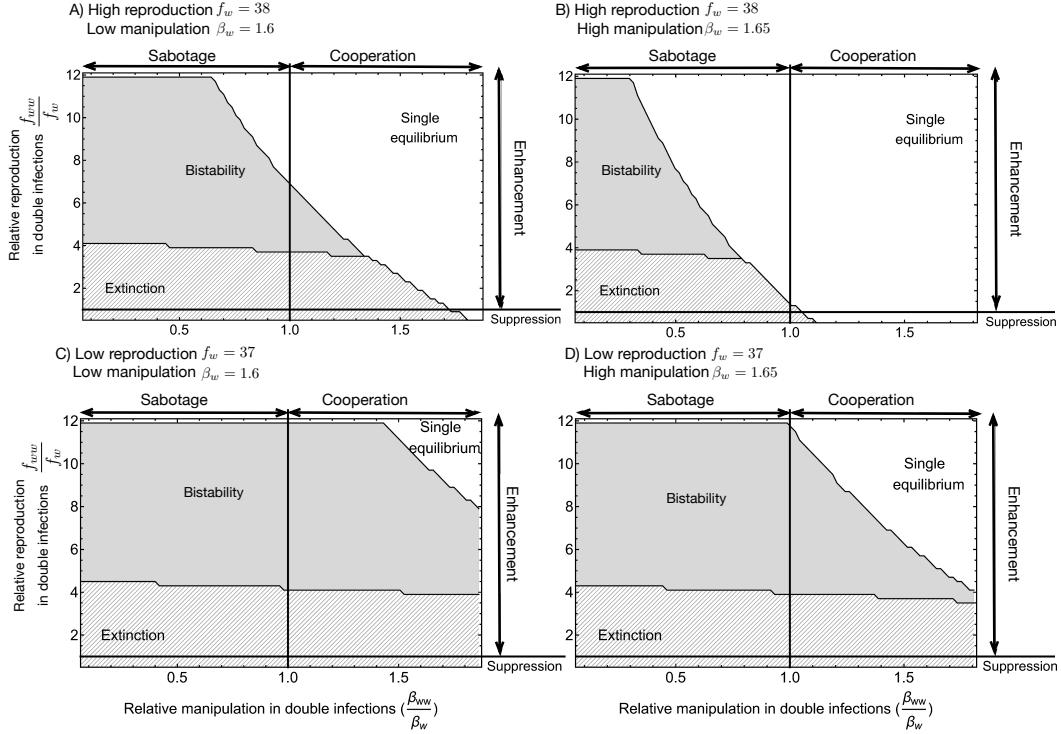


Figure 6: Effect of manipulation and reproduction on bistability. The bistability area (shaded areas) reduces as the reproduction rate (f_w) and manipulation (β_w) in a single infection increases. Reproduction in single infection decreases from the upper panels (A, B) to the lower panels (C, D), while manipulation in single infection increases from the left panels (A, C) to the right panels (B, D). Manipulation and reproduction levels are equal between single and double infection on the vertical and horizontal lines. On the left side of the vertical line, $\beta_{ww} > \beta_w$, indicating cooperation, whereas on the right side of the vertical line, $\beta_{ww} < \beta_w$, indicating sabotage. On the upper part of the horizontal line, $f_{ww} > f_w$, indicating enhanced reproduction, whereas, on the lower part of the horizontal line, $f_{ww} < f_w$, indicating suppressed reproduction. Common parameter: $\rho = 1.2$, $d = 0.9$, $r = 2.5$, $\gamma = 2.9$, $\alpha_w = 0$, $\alpha_{ww} = 0$, $p = 0.05$, $c = 1.4$, $\mu = 3.9$, $\sigma_w = 0$, $\sigma_{ww} = 0$, $q = 0.05$, $\delta = 0.9$, $k = 0.26$, $\beta_w = 1.65$, $h = 0.6$.

316 the population by reducing p , the co-transmission from the parasite pool to the intermediate
 317 host.

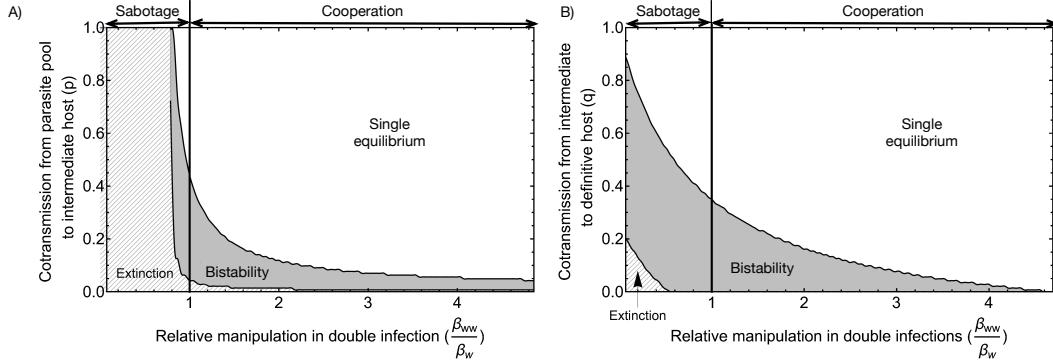


Figure 7: A) Effect of cotransmission from parasite pool to intermediate host. B) Effect of co-transmission from intermediate to the definitive host. On the left side of the vertical line, $\beta_{ww} > \beta_w$, indicating cooperation, whereas on the right side of the vertical line, $\beta_{ww} < \beta_w$, indicating sabotage. Common parameters: $\rho = 1.2$, $d = 0.9$, $r = 2.5$, $\gamma = 2.9$, $\alpha_w = 0$, $\alpha_{ww} = 0$, $p = 0.05$, $c = 1.4$, $\mu = 3.9$, $\sigma_w = 0$, $\sigma_{ww} = 0$, $q = 0.05$, $\delta = 0.9$, $k = 0.26$, $\epsilon = 4.5$, $\beta_w = 1.45$, $f_w = 38$, $h = 0.6$.

318 Discussion & Conclusion

319 Host manipulation is a ubiquitous phenomenon suggested to affect predator-prey dynamics in
 320 trophically transmitted parasites. In particular, manipulation of infected intermediate hosts
 321 to increase the predation rate of definitive hosts may result in a heavy burden of predators
 322 on the intermediate host population. This pressure can make parasites more vulnerable to
 323 extinction (Hadeler and Freedman, 1989; Fenton and Rands, 2006).

324 Our model shows that parasites cannot spread quickly in a cyclic predator-prey system.
 325 This delay is an expected result since even though the parasite's basic reproduction ratio R_0
 326 is larger than one, it is estimated at the predator and prey's unstable equilibrium (or cyclic
 327 equilibrium). Thus, when the density of the prey and predator is at the minimum value of
 328 the cycle, the "effective" R_0 of the parasite can be smaller than one. Another interesting
 329 result is that the reproduction value is much larger than other parameter values, such as
 330 the *per capita* reproduction rate of the intermediate host. This result is likely due to the
 331 introduction of a free-living parasitic pool. Our model shows that in making the system more
 332 realistic, we also obtain a more realistic quantitative value for parasitic reproduction.

333 In the study by [Rogawa et al. \(2018\)](#), a non-manipulative parasite can invade a susceptible
334 prey-predator population and cause the system to cycle. The system stops cycling and
335 approaches a fixed point when the parasite becomes manipulative, and this stability increases
336 with increased manipulation. In our model, non-manipulative parasites cannot persist in the
337 system, and the parasite never leads to cyclic dynamics. These results may contradict with
338 [Rogawa et al. \(2018\)](#), where non-manipulative parasites can still exist via cyclic behaviour.
339 We suggest that the different results may be due to our introduction of a parasite pool and
340 multiple infections, unlike the model of [Rogawa et al. \(2018\)](#). In their system, transmission
341 from the definitive host to the intermediate host was assumed to result from direct contact
342 between the two host species. Such immediate transmission could directly accelerate the
343 feedback loop between prey and predator. Hence, faster predator-prey dynamics occur,
344 which may lead to cyclic dynamics when parasites are introduced.

345 Another study on host manipulation, [Iritani and Sato \(2018\)](#), showed that manipulative
346 parasites persist if they switch from suppressing to boosting predation rate. This theoretical
347 work modelled the ability to change the manipulative strategy of a single parasite inside
348 a host, which can be equal to introducing the developmental state of a parasite, where a
349 suppressed predation rate protects the parasites that are not ready to transmit. That is
350 why decreasing manipulative ability is beneficial and prevents parasite extinction. In our
351 model, sabotaging manipulation also reduces manipulative ability, which only reduces the
352 basic reproduction ratio R_0 and makes the system bistable, exposing the parasite to the risk
353 of extinction. This result contrasts with [Iritani and Sato \(2018\)](#) because in our model, the
354 parasite cannot switch its manipulative strategy, and sabotage decreases the transmission
355 rate from intermediate to definitive host and does not benefit the parasite in any way.

356 In our study, population dynamics exhibit bistability under certain circumstances. This
357 is very likely due to the introduction of co-transmission, which has been shown to result in
358 bistable population dynamics in plant virus [Allen et al. \(2019\)](#) and infectious diseases [Gao
et al. \(2016\)](#). In this bistability region, if the system is disturbed (e.g. migration of the

360 intermediate or definitive hosts or predation of intermediate hosts by other predators), then
361 the density of the infected hosts may crash, leading to parasite extinction. The bistability
362 region widens as parasites show enhanced reproduction but sabotage manipulation. This
363 extension is because the density of the doubly infected hosts is always much smaller than
364 the singly infected hosts, limited by sequential transmission and a small probability of co-
365 transmission. If manipulation in a single infection is insufficient, then the transmission of
366 the parasites depends mainly on the doubly infected hosts, which is rare. So, extinction is
367 possible if manipulation in double infections is low.

368 Finally, our study Our study specifically focuses on the ecological dynamics of a trophically
369 transmitted parasite between two host species. In nature, parasites with complex life cycles
370 can have more than two hosts. However, our model of a single intermediate host species
371 already includes enough complexity to discuss the relationship between transmission and
372 manipulation. In addition, we consider multiple infections of the same parasite species.
373 Although, in nature, a host can be co-infected by multiple parasites of the same or different
374 species, the results of our model stay valid as the key aspect in host manipulation is the
375 alignment or conflict of interest between co-infecting parasites. Here, we introduce more
376 realistic features compared to previous models, such as a free-living parasite pool and multiple
377 infections, regardless of some simplifications, such as multiple infections being limited to at
378 most two parasites. In this way Thus, we can obtain analytical results of the reproduction
379 ratio and mathematical expressions for the existing condition of the parasite.

380 Our model serves as a groundwork for future exploration into more complex and realis-
381 tic systems, where numerical simulation may be the only possible approach. Moreover, the
382 Given that few studies considered measuring different parameters of trophically transmitted
383 parasites (Seppälä et al., 2004; Gopko et al., 2015), our model calls for additional empirical
384 work to measure relevant parameters, especially those from the parasite's perspective. For
385 instance, comparing the reproduction rate of parasites in single versus multiple infections
386 (parameters f_w and f_{ww}) sheds light on parasite cooperation in definitive hosts. Studying

387 the distribution of parasites in the environment (the variable W) informs us about feeding
388 strategies and reflects the distribution of parasites within intermediate hosts. Finally, comparing
389 host condition (parameters α_w , α_{ww} , σ_w , and σ_{ww}) between no infection, single and multiple
390 infections illustrates the magnitude of parasite virulence. Although parasite virulence has
391 been quantified in some studies, none have examined differences between single and multiple
392 infections. Eventually, the results of our ecological model are a baseline for further investiga-
393 tion of the evolution of host manipulation, where introducing the parasite pool may create
394 interesting eco-evolutionary feedback to the system.

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Table 1: Description of variables and parameters

Parameters and Variables	Description	Dimensionality
I_i	Density of intermediate hosts that are susceptible $i = s$, singly infected $i = w$, or doubly infected $i = ww$	$[I_i]t^{-1}$
D_i	Density of definitive hosts that are susceptible $i = s$, singly infected $i = w$, or doubly infected $i = ww$	$[D_i]t^{-1}$
W	Density of parasites released from definitive hosts into the environment	$[W]t^{-1}$
r	Reproduction rate of intermediate host	t^{-1}
k	Competition coefficient	$[I_i]^{-1}$
d	Natural death rate of intermediate hosts	t^{-1}
α_i	Additional death rate of intermediate hosts due to infection by a single parasite ($i = w$) or two parasites ($i = ww$)	t^{-1}
p	Probability that two parasites eotransmit co-transmit from the environment to an intermediate host	dimensionless
γ	Transmission rate of parasites in the environment to intermediate hosts	$[W]^{-1}t^{-1}$
ρ	Baseline capture rate	$[I_i]^{-1}t^{-1}$
c	Coefficient of energy conversion into new definitive host	dimensionless
μ	Natural death rate of definitive hosts	t^{-1}
σ_i	Additional death rate of definitive hosts due to infection by a single parasite ($i = w$) or two parasites ($i = ww$)	t^{-1}
σ_i	Additional death rate of the hosts due to being infected by a singly single parasite ($i = w$) or two parasites ($i = ww$)	t^{-1}
q	Probability that two parasites eotransmit co-transmit from intermediate hosts to definitive hosts	dimensionless
β_i	Transmission rate of parasites from intermediate hosts to definitive hosts	$[I_i]^{-1}t^{-1}$
f_i	Reproduction rate of parasites in singly infected definitive hosts ($i = w$) or doubly infected hosts ($i = ww$)	t^{-1}
δ	Natural death rate of parasites in the environment	t^{-1}
h	Probability that the parasites successfully established inside the definitive host	dimensionless

* $[I_i]$, $[D_i]$, and $[W]$ have the same unit (*individual area⁻¹*)