

1 *Running head:* Social information drives coexistence

2 **Social information drives ecological outcomes among competing species**

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11

## 12 **Abstract**

13 Through its behavior, an organism intentionally or unintentionally produces information. Use of  
14 this ‘social information’ by surrounding conspecifics or heterospecifics is a ubiquitous  
15 phenomenon that can drive strong correlations in fitness-associated behaviors, such as predator  
16 avoidance, enhancing survival within and among competing species. By eliciting indirect  
17 positive interactions between competing individuals or species, social information might alter  
18 overall competitive outcomes. To test this potential, we present new theory that quantifies the  
19 effect of social information, modeled as predator avoidance signals/cues, on the outcomes from  
20 intraspecific and interspecific competition. Our analytical and numerical results reveal that social  
21 information can rescue populations from extinction and can shift the long-term outcome of  
22 competitive interactions from mutual exclusion to coexistence, or vice versa, depending on the  
23 relative strengths of intraspecific and interspecific social information and competition. Our  
24 findings highlight the importance of social information in determining ecological outcomes.

25 **Keywords:** public information; social behavior, Allee effect, density dependence, coexistence,  
26 mutualism, facilitation, competition, functional response, stability theory

27

## 28 **Introduction**

29 The mere presence and even simple behaviors of an individual animal produce sensory  
30 information that becomes publicly available to surrounding individuals (Danchin et al. 2004,  
31 Dall et al. 2005, Goodale et al. 2010). Such ‘social information’ has long been a central topic of  
32 interest in select study systems in which individuals intentionally produce signals (Templeton  
33 and Giraldeau 1995, Magrath et al. 2015). However, recent empirical and theoretical evidence  
34 from various systems indicates that social information use extends far beyond intentional  
35 signaling and appears to be a general phenomenon in systems in which individuals that cohabit a

36 landscape share needs (Seppänen et al. 2007, Goodale et al. 2010, Gil et al. 2017, Gil and Hein  
37 2017, Kane and Kendall 2017, Gil et al. 2018). Perhaps the best studied and most common  
38 individual need that is enhanced by social information is predator avoidance: alarm calls warn of  
39 approaching predators in avian and primate systems (Zuberbühler 2001, Danchin et al. 2004,  
40 Magrath et al. 2015), postures, evasive movements, or the use of predator-free space  
41 inadvertently provide information on the proximity of threats in avian, mammalian, and fish  
42 systems (Griffin 2004, Schmitt et al. 2016, Gil and Hein 2017), and even plants can use chemical  
43 cues from damaged neighboring plants to induce defenses to protect against herbivores (Karban  
44 et al. 2000, Dicke and Bruin 2001). Because social information typically enhances the fitness of  
45 receiving individuals, and, because any individual in a population can repeatedly receive such  
46 benefits, social information could affect the dynamics of populations (Gil et al. 2018). Thus,  
47 understanding the degree to which social information can affect population dynamics is a  
48 pressing question in ecology.

49 Social information creates the potential for indirect positive interactions within and  
50 across species and might drive positive density dependence. Positive density dependence (i.e., an  
51 ‘Allee effect’) occurs when a greater density of individuals in a population enhances the growth  
52 rate of that population (Courchamp et al. 1999, Stephens et al. 1999). This simple process can  
53 drive profound changes to the dynamics of a population, affecting not only a population’s  
54 carrying capacity but also its likelihood of sudden change or collapse (Stephens and Sutherland  
55 1999, Schreiber 2003). For example, under positive density dependence, loss of individuals (e.g.,  
56 due to harvesting) can become increasingly detrimental to a population, even leading to negative  
57 population growth when a population falls below a critical threshold (i.e., a ‘strong Allee effect’;  
58 Stephens et al. 1999). Positive density dependence and the critical population thresholds they can  
59 cause are putatively common though difficult to rigorously identify in natural systems and are,

60 therefore, of particular interest to natural resource conservation and management (Stephens and  
61 Sutherland 1999, Berec et al. 2007, Gregory et al. 2010). Positive density dependence has been  
62 classically attributed to non-information-mediated mechanisms, such as mate limitation or  
63 habitat amelioration, and to information-mediated mechanisms in species that form cohesive  
64 groups, such as flocks or schools (Courchamp et al. 1999, Stephens and Sutherland 1999,  
65 Stephens et al. 1999, Gascoigne and Lipcius 2004b). Yet, positive density dependence can arise  
66 due to social information regardless of whether or not individuals form cohesive groups or are  
67 conspecifics. Social information typically enhances individual survival or reproduction and  
68 increases with the density of information-producing individuals (Kenward 1978, Jackson et al.  
69 2008, Kazahari and Agetsuma 2010, Lister 2014, Berdahl et al. 2016, Gil et al. 2017, Gil et al.  
70 2018).

71 Social information use is most likely between individuals in similar guilds (e.g., those on  
72 the same trophic level with shared predators) and, thus, typically occurs in the context of  
73 intraspecific and interspecific competition for resources. As a negative interaction, competition  
74 counters the effects of social information. Effects of both competition and social information are  
75 density dependent, but in opposing ways. Social information typically is most beneficial at low  
76 to intermediate population densities, where information is less redundant or its benefits less  
77 ephemeral. In contrast, competition typically is most detrimental at higher densities, where  
78 resources are more limited (Gil et al. 2018). Thus, we expect social information to have stronger  
79 net per capita effects when population densities are low, as they often are in human-altered  
80 landscapes (Courchamp et al. 1999). Nonetheless, to measure the net impact of social  
81 information requires knowing the strength of competition. Furthermore, competition and the  
82 exchange of social information can occur to varying degrees both within species and across  
83 species (Monkkonen et al. 1999, Seppänen et al. 2007, Goodale et al. 2010). Therefore, to

84 understand the ecological consequences of social information requires that we examine the joint  
85 effects of intraspecific and interspecific social information and intraspecific and interspecific  
86 competition.

87         Population models offer a framework through which to explore the population- and  
88 community-level consequences of social information use in wild animals. Classic models that  
89 measure the demographic effects of predator functional response, positive density dependence,  
90 and facilitation provide conceptual precursors to the study of social information. Noy-Meir  
91 (1975) showed that the deceleration of a generalist predator's attack rate across low prey  
92 densities (a Type II functional response (Holling 1966) can generate a strong Allee effect (Noy-  
93 Meir 1975)). In this model, and in most population models, this deceleration of the predator's  
94 attack rate with prey density is attributed to properties of the predator (e.g., satiation, handling  
95 time; (Oaten and Murdoch 1975)). However, this deceleration could be driven by properties of  
96 the prey themselves (i.e., if more prey better help one another avoid predation). More recently,  
97 models exploring the demographic effects of mutualism have shown that even when positive  
98 interspecific interactions are constrained to low and narrow population density ranges, they can  
99 quantitatively and qualitatively affect the fate of one or both interacting populations (Hernandez  
100 1998, Hernandez and Barradas 2003, Zhang 2003, Zhang et al. 2007, Hernandez 2008, Holland  
101 and DeAngelis 2009, Holland and DeAngelis 2010). Social information provides a possible  
102 mechanism for density dependent mutualism, but with the added complexity of being shared not  
103 only between species but also within species (Gil et al. 2018). The two existing population  
104 models that explicitly account for social information (Schmidt et al. 2015, Schmidt 2017) focus  
105 on the case of enhanced breeding habitat selection among conspecifics and show that social  
106 information can drive strong Allee effects. Evaluating whether such critical thresholds occur in

107 multi-species systems with social information requires building on this theory to explicitly model  
108 social information in a multispecies context.

109         Here, we use models of a single species and of competing species to build a theory of the  
110 demographic consequences of social information use in wild animals. We focus on the  
111 widespread use of social information about predators. We modify a framework developed in Gil  
112 et al (2018), where we demonstrated that social information can alter qualitative expectations for  
113 population and community dynamics in specific cases, to thoroughly and comprehensively  
114 quantify, and develop metrics for, when such qualitative changes are expected to occur. We first  
115 quantify the intraspecific effects of this social information using a reparameterization of the  
116 classic Noy-Meir model to address the question: under what conditions does this common form  
117 of social information affect the existence of critical thresholds, equilibrium densities or  
118 persistence of a population? We then expand to a two-species population model, in which  
119 competition and the exchange of social information can occur within and between species, to  
120 address the question: how does social information affect the nature and outcome of species  
121 interactions? Our study reveals that social information can alter competitive outcomes and  
122 generate multiple alternative stable states in a predictable manner depending on the relative  
123 strengths of intra- and interspecific competition, intra- and interspecific social information, and  
124 predation. Our modeling framework is general, meaning it is not system-specific, and our  
125 findings lay the groundwork for further theoretical and empirical investigation of how social  
126 information scales up to affect the ecology and conservation of natural systems.

## 127 **Methods**

### 128 *Effects of social information on single species dynamics*

129 To lay the groundwork for our two-species model, we begin with the dynamics of a single  
130 species with population size  $N$  that exhibits logistic growth, determined by intrinsic per-capita

131 growth rate  $r$  and intraspecific competition coefficient  $\alpha$  (the carrying capacity is  $1/\alpha$ ). The  
132 population also experiences mortality due to a generalist predator at a maximal rate  $p$ , and per-  
133 capita mortality decays with prey density, through the sharing of social information (e.g., alarm  
134 calls, evasive movements; Danchin et al. 2004, Goodale et al. 2010, Magrath et al. 2015), and the  
135 per-capita strength of social information  $b$ . In other words, social information reduces per-capita  
136 predation rates by extending capture time. Thus, the single species dynamics are

$$137 \quad \frac{dN}{dt} = rN(1 - \alpha N) - \frac{Np}{1+bN}. \quad \text{Eq. 1}$$

138 Here, per-capita predation risk saturates at high prey densities because prey reach the maximal  
139 per-capita benefit of social information on predator avoidance (i.e., diminishing returns on  
140 information due to redundancy, ephemeral benefits or occlusion of information motivate a  
141 saturating functional form; Kenward 1978, Seppänen et al. 2007, Jackson et al. 2008, Lister  
142 2014, Berdahl et al. 2016). The model assumes the predator population size remains constant,  
143 independent of prey density,  $N$ , and that the predator has a linear functional response. However,  
144 if we assume the predator exhibits a Type II functional response, then we still get the same  
145 functional form of the predation term in Eq. 1 (Type II) but with new parameters (see Appendix  
146 S1 for details). Furthermore, while Eq. 1 allows social information to drive the predation rate to  
147 zero, an unlikely outcome in most natural systems, this equation is mathematically equivalent to  
148 a functional form in which social information causes predation rate to level off at a nonzero  
149 value, determined by an additional parameter (see Appendix S1 for details). Thus, all of our  
150 results about Eq. 1 also apply to models with a Type II predator functional response and a  
151 minimal predation level even when social information is high.

### 152 *Effects of social information on competing species with shared predators*

153 We expand upon the model presented in Eq. 1 to measure how social information can affect the  
154 long-term dynamics of two competing species. We follow population sizes  $N_i$  of each species  $i$ ,

155 where within-species population growth,  $r_i$ , density dependence,  $\alpha_{ii}$ , and a maximal per-capita  
156 predation rate,  $p_i$ , follow the same dynamics and notation as Eq. 1, but these species compete  
157 with one another at a rate  $\alpha_{ij}$ , which represents the per-capita negative effect of the  $j$ -th species on  
158 the  $i$ -th species, where  $i \neq j$ . Both species experience per-capita mortality due to predation at a  
159 rate that decays with increasing densities of both species (the two-species analog of the mortality  
160 term in Eq. 1); i.e., both conspecifics and heterospecifics share and use social information (e.g.,  
161 from alarm calls or evasive movements) to enhance predator avoidance (Danchin et al. 2004,  
162 Goodale et al. 2010, Magrath et al. 2015). Note that this functional form of mortality could also  
163 be used to model non-information-mediated interactions, such as species-specific prey handling  
164 times by the predator, or group defenses that increase with density. Here,  $b_{ii}$  represents the  
165 magnitude of the effect of intraspecific social information and  $b_{ij}$  ( $i \neq j$ ) that of interspecific  
166 social information, such that the dynamics of the  $i$ -th species are

167 
$$\frac{dN_i}{dt} = r_i N_i (1 - \alpha_{ii} N_i - \alpha_{ij} N_j) - \frac{N_i p_i}{1 + b_{ii} N_i + b_{ij} N_j}, \text{ where } i, j = 1, 2 \text{ and } i \neq j. \text{ Eq. 2}$$

168 We provide a mechanistic derivation of this two-species model by considering transitions  
169 between informed and uninformed behavioral states of individuals in the community (Appendix  
170 S1). Note that Eq. 2 is equivalent to a version of the model that includes predator handling time  
171 (i.e., a Type II functional response) under special cases (Appendix S1, Eq. S3).

### 172 *Analysis of models*

173 For the single species model in Eq. 1, we conduct a global bifurcation analysis for different  
174 values of  $b$ , to determine under what conditions social information about predators can alter the  
175 persistence of a population, generate a strong Allee effect, and alter the equilibrium density of a  
176 persisting population. For the mathematical and numerical analysis of the competing species  
177 model in Eq. 2, we focus primarily on the case that the species are symmetric, i.e.,  $r_1 = r_2 = r$ ,  
178  $\alpha_{11} = \alpha_{22} = \alpha$ ,  $\alpha_{12} = \alpha_{21} = \tilde{\alpha}$ ,  $b_{11} = b_{22} = b$ ,  $b_{12} = b_{21} = \tilde{b}$ ,  $p_1 = p_2 = p$ . For this two-



179 species model, we analytically derive conditions for different community outcomes and develop  
180 an analytically-based numerical method to identify all equilibria and their stability. We use these  
181 methods in conjunction with numerically computed isoclines to determine how social  
182 information affects the nature and outcome of species interactions. Specifically, we compare  
183 individual and combined effects of intraspecific and interspecific social information under  
184 different relative strengths of intraspecific and interspecific competition.

185

## 186 **Results**

### 187 *Single-species model of social information use*

188 In the single-species model, social information can enhance persistence likelihood, with  
189 threshold dynamics, and equilibrium population size (Fig. 1). When the intrinsic per-capita  
190 growth rate  $r$  is greater than the maximal per-capita predation rate  $p$ , the population persists at a  
191 stable equilibrium for all positive initial densities. Our mathematical analysis (see Appendix S2  
192 for details) implies that this stable equilibrium density always increases with social information  
193 (Fig. 1b; Appendix S2: Fig. S1a).

194 When the maximal per-capita predation rate exceeds the intrinsic rate of growth, the  
195 extinction equilibrium is stable, and the population tends to extinction whenever the initial  
196 population density is low. Social information, however, can generate a strong Allee effect and  
197 allow the population to persist whenever the maximal per-capita predation rate lies below  
198 threshold value (see Appendix S2 for details)

$$199 \quad p^* = \frac{r}{4} \left( \sqrt{\frac{b}{\alpha}} + \sqrt{\frac{\alpha}{b}} \right)^2. \quad \text{Eq. 3}$$

200 Equation 4 implies that social information that is strong relative to competition ( $b > \alpha$ ) can  
201 prevent extinction for a population at sufficiently high density (Fig. 1b; Appendix S2: Fig. S1b).

202 When the maximal per-capita predation rate,  $p$ , exceeds the critical threshold  $p^*$ , the population  
203 goes extinct for all initial population densities (Appendix S2: Fig. S1c); population persistence is  
204 not possible. When there is a strong Allee effect (i.e.  $r < p < p^*$ ), social information has opposing  
205 effects on the unstable equilibrium (below which the population tends to extinction) and the  
206 positive stable equilibrium. The population density at the unstable equilibrium decreases with  
207 increasing social information, while the density at the stable equilibrium increases (see Appendix  
208 S2 for a proof; compare dashed and solid curves in Fig. 1b). Thus, with more social information,  
209 a population can recover from larger disturbances that reduce their densities and can ultimately  
210 approach higher densities. This pattern of social information causing positive density dependence  
211 and rescuing populations under high predation is robust to the functional form of the reduction of  
212 predation due to social information (Appendices S1 & S2; Appendix S2: Fig. S1 & S2, including  
213 the functional form used in Gil et al 2018, where the results here indicate the level of social  
214 information necessary to produce the type of qualitatively distinct behavior in the example case  
215 study of Gil et al. 2018 Box 2).

#### 216 *Two-species model of social information use*

217 Whether and how social information changes the qualitative outcome from competition within  
218 and between species depends on its strength and type. Our mathematical analyses of the two-  
219 species model (Eq. 2; Fig. 2a) when the competing species are symmetric provide information  
220 about the invasibility of the single-species equilibria and the multiplicity of equilibria on the  
221 single-species axes and on the two-species symmetric ( $N_1 = N_2$ ) axis (see Appendix S3 for  
222 details). These analyses identify under what conditions increasing the maximal per-capita  
223 predation rate changes the ecological dynamics in two ways. First, we identify when increasing  
224 the predation rate shifts the system from coexistence via mutual invasibility (i.e. each species can  
225 invade the equilibrium determined by the other species) to mutual exclusion (i.e. each of the

226 single species equilibria are stable), or vice versa. Second, we identify when increasing this  
227 predation rate leads to alternative stable states supporting both species or alternative states only  
228 supporting a single species. This analysis reveals that the dynamics of the system depend  
229 qualitatively on the joint effects of social information and competition via two simple net  
230 interaction indices whose form depends on the strength of social information. When both  
231 intraspecific and interspecific social information are weak (i.e.,  $\frac{b}{\tilde{\alpha}} < 1$  and  $\frac{b+\tilde{b}}{\tilde{\alpha}+\alpha} < 1$ ; see Appendix  
232 S3 for details), the interaction index equals

$$233 \quad I_w = (\tilde{b} - b) - (\tilde{\alpha} - \alpha). \quad \text{Eq. 4}$$

234 When at least one form of social information (intraspecific and/or interspecific) is strong (i.e.,  $\frac{b}{\tilde{\alpha}}$   
235  $> 1$  and/or  $\frac{b+\tilde{b}}{\tilde{\alpha}+\alpha} > 1$ ; see Appendix S3 for details), the interaction index equals

$$236 \quad I_s = \frac{\tilde{b}}{b} - \frac{\tilde{\alpha}}{\alpha}. \quad \text{Eq. 5}$$

237 As detailed below, these net interaction indices serve two distinct purposes: 1) their signs  
238 determine the sequence of possible dynamics a symmetric system can exhibit (i.e., whether  
239 social information will push a system toward competitive exclusion or coexistence), and 2)  
240 depending on the strength of social information and predation, these indices can mark the  
241 boundary between coexistence and mutual exclusion or the boundary between persistence (of  
242 one or both species) and extinction. We first explore the effect of social information under  
243 neutral competition and then evaluate the full array of outcomes under non-neutral competition,  
244 closing with a description of the contexts in which we would expect social information to alter  
245 competitive outcomes.

#### 246 *Effects of social information in competitively neutral communities*

247 For the neutral dynamics (Fig. 2b), because  $\tilde{\alpha} - \alpha = 0$  and  $\frac{\alpha}{\tilde{\alpha}} = 1$ , the signs of  $I_w$  and  $I_s$  always  
248 agree, and this index is positive only if interspecific social information is stronger than

249 intraspecific social information (i.e.,  $\tilde{b} - b > 0$ , or, equivalently,  $\frac{\tilde{b}}{b} > 1$ ). In this case,  
250 interspecific social information, which effectively decreases competitiveness between species by  
251 countering this negative effect, causes each species to have a positive per-capita growth rate  
252 when it is rare and its competitor is common (Fig. 2c). At high densities, diminishing returns of  
253 social information (e.g., due to redundancy, ephemeral benefits or occlusion of information;  
254 Kenward 1978, Seppänen et al. 2007, Jackson et al. 2008, Lister 2014, Berdahl et al. 2016) will  
255 saturate the positive effects of heterospecific density (Fig. 2c) and competition will ultimately  
256 constrain population growth. Therefore, for  $I_w > 0$  or equivalently  $I_s > 0$ , social information  
257 promotes coexistence: e.g., even weak interspecific social information ( $\frac{b+\tilde{b}}{\alpha+\alpha} < 1$ ; see Appendix  
258 S3 for details) shifts competitively neutral Lotka-Volterra dynamics (Fig. 2b) to coexistence (Fig.  
259 2c). Conversely, if intraspecific social information is greater than interspecific social information  
260 (i.e.,  $\frac{\tilde{b}}{b} < 1$ ), such that  $I_w < 0$  or, equivalently,  $I_s < 0$ , then intraspecific social information, which  
261 effectively increases competitiveness between species by countering negative interactions within  
262 species, causes each species to have a negative per-capita growth rate when rare and its  
263 competitor is common. Therefore, even weak intraspecific social information ( $\frac{b}{\alpha} < 1$ ; Appendix  
264 S3) shifts neutral coexistence to exclusion (Fig. 2d).

### 265 *Effects of strong social information in competitively non-neutral communities*

266 Under non-neutral Lotka-Volterra competitive dynamics (i.e., that lead to coexistence or mutual  
267 exclusion, depending on competitive strength, given our assumption of symmetric competitors),  
268 social information interacts with the relative strengths of intraspecific and interspecific  
269 competition for symmetric species to determine the sign of  $I_s$ , and the outcomes further depend  
270 on the maximal per-capita predation rate ( $p$ ). Increasing  $p$  strengthens the effects of both  
271 intraspecific and interspecific social information, relative to the effects of competition and, thus,

272 leads to different qualitative outcomes for the effect of social information on competitive  
273 dynamics. Below, we evaluate the effects of social information first when neither form  
274 (intraspecific or interspecific) is strong, then when only one form is strong, and, finally, when  
275 both forms are strong.

276 When neither form of social information is strong, prey populations persist only when  $r >$   
277  $p$ , and, in this case, the sign of  $I_w$  (Eq. 4) determines whether one prey species can drive the other  
278 to extinction or the two competing species can coexist (Fig. 3a). When either form of social  
279 information is strong or both forms are strong, whether competing prey species will coexist or go  
280 extinct depends on predation level and on the sign of  $I_s$  (Fig. 3b, Eq. 5), which determines the  
281 suite of possible dynamics the system can exhibit, as detailed below.

282 When only one form of social information is strong, that form determines the sign of  $I_s$ . If  
283 intraspecific social information is strong and interspecific social information is weak (i.e.,  $\frac{b}{\tilde{\alpha}} > 1$   
284 and  $\frac{b+\tilde{b}}{\tilde{\alpha}+\alpha} < 1$ ), then  $I_s$  is negative and social information promotes mutual exclusion as  $p$  increases  
285 (Fig. 4a). Alternatively, if interspecific social information is strong and intraspecific social  
286 information is weak (i.e.,  $\frac{b}{\tilde{\alpha}} < 1$  and  $\frac{b+\tilde{b}}{\tilde{\alpha}+\alpha} > 1$ ), then  $I_s$  is positive and social information promotes  
287 coexistence as  $p_i$  increases (Fig. 4b, where Fig. 4biii is the specific case study in Gil et al 2018  
288 Box 3 using a different functional form for the social information feedback).

289 With either form of strong social information, once the predation rate ( $p$ ) exceeds the  
290 intrinsic rate of growth ( $r$ ) of the two prey species, alternative stable states occur (as in the  
291 single-species model: Fig. 1), while both species would go extinct without social information.  
292 When  $I_s$  is negative, there are three alternative stable states: each species persisting in isolation or  
293 mutual extinction, and coexistence can no longer occur (Fig. 4aiv). In other words, when  
294 predation is sufficiently high, strong intraspecific social information alone can cause competitors

295 to become ‘obligate excluders’ (i.e., the only equilibria require competitive exclusion).  
296 Conversely, when  $I_s$  is positive, single-species equilibria are eliminated, and there are two  
297 alternative stable states: species coexistence or extinction of all species (Fig. 4biv). Thus, strong  
298 interspecific social information alone can cause competitors to become obligate mutualists (i.e.,  
299 the only equilibria require coexistence) at this critical level of predation.

300 Further increasing the predation rate results in the extinction of all species as the only  
301 outcome (see single-species analog in Appendix S2: Fig. S1c). Where exactly the extinction  
302 threshold for the two-species system occurs depends, again, on the sign of  $I_s$ . When  $I_s$  is  
303 negative, system-wide extinction occurs when the predation level  $p$  exceeds the critical predation  
304 level  $p^*$  that we found for the single-species model (Eq. 3). When  $I_s$  is positive, the critical  
305 predation level is

$$306 \quad p^{**} = \frac{r}{4} \left( \sqrt{\frac{b+\bar{b}}{\bar{\alpha}+\alpha}} + \sqrt{\frac{\bar{\alpha}+\alpha}{b+\bar{b}}} \right)^2, \quad \text{Eq. 6}$$

307 (see Appendix S3 for additional details).

308 When both forms of social information are strong ( $\frac{b}{\bar{\alpha}} > 1$  and  $\frac{b+\bar{b}}{\bar{\alpha}+\alpha} > 1$ ), their opposing  
309 effects generate greater dynamical complexity with the introduction of additional alternative  
310 stable states. As before, when  $I_s$  is negative (i.e., intraspecific social information is stronger than  
311 interspecific social information; Fig. 5a, Appendix S3: Fig. S2a) and as  $p$  increases, even a  
312 system with low interspecific competition will shift from outcomes at equilibrium that can  
313 include stable coexistence (Fig 5ai,ii & Appendix S3: Fig. S2ai-iii) to those that include only  
314 mutual exclusion or extinction (Fig. 5aiii,iv & Appendix S3: Fig. S2aiv-viii). Conversely, when  
315  $I_s$  is positive (i.e., intraspecific social information is weaker than interspecific social information;  
316 Fig. 5b, Appendix S3: Fig. S2b) and as  $p$  increases, even a system with high interspecific  
317 competition will shift from outcomes at equilibrium that can include mutual exclusion (Fig. 5bi,ii

318 & Appendix S3: Fig. S2bi,ii) to those that include only coexistence or extinction (Fig. 5biii,iv &  
319 Appendix S3: Fig. S2biii.-viii). As before (Fig. 4), the system goes extinct when  $I_s$  is negative  
320 and  $p$  exceeds  $p^*$  (Eq. 3; Appendix S3: Fig. S2aviii), or when  $I_s$  is positive and  $p$  exceeds  $p^{**}$  (Eq.  
321 6; Appendix S3: Fig. S2bviii).

322 When predation rate,  $p$ , exceeds the intrinsic rate of growth,  $r$ , strong social information  
323 of both forms further increases the range of parameters where persistence and coexistence can  
324 occur (Fig. 5), in comparison to when only one form of social information is strong (Fig. 4).  
325 When  $I_s$  is negative, coexistence equilibria do not vanish until predation rate exceeds  $p^{**}$  (Eq. 6,  
326 the system-wide extinction threshold when only interspecific social information is strong), while  
327 single-species equilibria remain. When  $I_s$  is positive, single-species equilibria do not vanish until  
328 predation rate exceeds  $p^*$  (Eq. 3, the system-wide extinction threshold when only intraspecific  
329 social information is strong), while coexistence equilibria remain. Thus, when both forms of  
330 social information are strong, a greater diversity of prey community states are possible at high  
331 predation rates (Fig. 5), relative to cases when only one form of social information is strong (Fig.  
332 4), or neither form is strong (in which case, system-wide extinction occurs when  $p > r$ , which is  
333 represented by the vertical dashed line in Fig. 4, 5; Appendix S3: Fig. S1, S2). Furthermore,  
334 while conditions that give rise to obligate excluders or obligate mutualists also emerge when  
335 both forms of social information are strong (Appendix S3: Fig. S2avi,vii, and Fig. S2bvi,vii),  
336 they generally do so over a narrower range of predation rates than when only one form of social  
337 information is strong.

### 338 *Context dependent effects of social information on competitive outcomes*

339 Overall, qualitative shifts in competitive outcomes can occur under each of two conditions (Fig.  
340 6, Appendix S3: Fig. S3): (1) predation exceeds population growth such that the positive effects  
341 of social information can rescue the system from extinction (Fig. 6, Appendix S3: S3a,b), or (2)

342 strengths of intraspecific and interspecific social information are asymmetric in favor of an  
343 outcome that opposes that of competition. Regarding the second condition, high intraspecific  
344 social information can cause mutual exclusion under low interspecific competition [below the  
345 dashed line in Fig. 6c], or high interspecific social information can cause coexistence under high  
346 interspecific competition [above the dashed line in Fig. 6d]; Appendix S3: Fig. S3). As the  
347 strength of social information increases, greater asymmetries between intraspecific and  
348 interspecific social information are needed to qualitatively shift outcomes from expectations  
349 based on competition alone (see curved boundaries between coexistence and mutual exclusion:  
350 Fig. 6).

351

## 352 **Discussion**

353 Our theoretical models reveal that the simple and ubiquitous use of social information by  
354 individual animals (e.g., using the alarm calls or flight responses of others to avoid danger) can  
355 scale up to qualitatively affect population and community outcomes. Specifically, our results  
356 indicate that by having positive effects on per capita population growth, even when net positive  
357 effects are restricted to low population densities, social information typically raises equilibrium  
358 population sizes and allows persistence, with Allee effects, when extinction would otherwise  
359 occur (due to either predation or interspecific competition in our models; Fig. 1, 6). These effects  
360 of social information on population and community stability arise because social information can  
361 decrease mortality and can give rise to critical population thresholds, and if a population or  
362 community falls below such a threshold it will have insufficient information from conspecifics or  
363 heterospecifics to grow and, thus, will be susceptible to sudden and rapid collapse (Fig. 1, 4, 5).  
364 Furthermore, we show that the community-level consequences of social information are strongly  
365 context dependent, where new metrics, the net interaction indices (Eq. 4 & 5), which measure



366 relative strengths of intraspecific and interspecific social information and competition, determine  
367 the direction in which social information influences competition (towards coexistence or mutual  
368 exclusion) and, therefore, the suite of qualitative outcomes that are possible in a multi-species  
369 system (Fig. 3-6). Thus, social information can qualitatively change the long-term outcome of  
370 species interactions from mutual exclusion to coexistence or from coexistence to mutual  
371 exclusion, by allowing systems to overcome net effects of competition (i.e., intraspecific social  
372 information counters effects of intraspecific competition, and interspecific social information  
373 counters effects of interspecific competition; Fig. 6).

374         The types of qualitative differences in population and community dynamics with social  
375 information illustrated for two specific case studies in Gil et al (2018) can occur under a broad  
376 range of parameters, including a range of competitive interactions. As we develop this new  
377 theory, it is important to recognize the challenges of empirically measuring effects of social  
378 information in many natural systems. While notable work has been done to quantify behavioral  
379 effects of social information in the form of vocalizations in avian systems (Betts et al. 2008,  
380 Magrath et al. 2015), and this work has been used to inform demographic models of socially-  
381 enhanced resource acquisition (Schmidt et al. 2015, Schmidt 2017), social information is shared  
382 through more nuanced behaviors, such as movements, in many systems. Fortunately, recent  
383 advances in the collection of large, high-resolution datasets on individual behaviors in the wild,  
384 combined with probabilistic models, are able to reveal strong information-mediated behavioral  
385 effects that emerge from subtle individual movements (Strandburg-Peshkin et al. 2015, Gil and  
386 Hein 2017, Hein et al. 2018). These and other advances could aid in determining the functional  
387 form and parameter values of system-specific models that extrapolate these effects to their  
388 demographic consequences and test the theory we develop here.

389 *Single-species model*

390 Our findings on the effects of social information on a single species expand upon the results of  
391 (Schmidt et al. 2015, Schmidt 2017), which showed that eavesdropping on breeding habitat  
392 quality can affect the dynamics and persistence of a population. Here, we model the use of  
393 intentional signals or unintentional cues about predators and show that social information could  
394 be a driver of positive density dependence and critical thresholds in relevant natural populations  
395 (Courchamp et al. 1999, Gascoigne and Lipcius 2004a, Suding and Hobbs 2009, Kelly et al.  
396 2015).

397 Our findings further suggest that social information could serve as a stabilizing  
398 mechanism for predator-prey interactions: high levels of predation that would otherwise reduce  
399 prey populations to extinction and, consequently, threaten predator populations can be sustained  
400 when there is sufficient social information available to prey (Fig. 1, 3-6). Thus, social  
401 information about predators would be most important to the coexistence of predators and prey in  
402 systems in which predators can exert high pressure on individual prey populations (e.g., Van de  
403 Koppel et al. 2005, Sandin et al. 2008). Because we assume non-dynamic predators,  
404 demographic effects of social information in the face of such factors as dynamic predators and  
405 differential social information use across trophic levels remain important, unexplored topics for  
406 further research. Nonetheless, our models are representative of instances in which predator and  
407 prey populations are demographically decoupled (e.g., due to wide-dispersing or ranging  
408 predators; Hixon et al. 2002, Van de Koppel et al. 2005) and provide an important first step  
409 toward understanding how predation pressure can interact with effects of social information and  
410 competition to shape how populations of prey species grow, persist, and interact.

#### 411 *Two-species model*

412 Ecologists have long recognized that the qualitative nature of species interactions (negative,  
413 positive, neutral) are not static in space or time, but vary on a continuum in nature (Bronstein

414 1994, 2001). Understanding the context dependence of species interactions that shape  
415 fundamental rates at the population, community and ecosystem levels remains an open but  
416 pressing challenge in the discipline of ecology (Agrawal et al. 2007). Here, we provide theory  
417 that shows that a common driver of animal behavior, social information, can be a powerful force  
418 that shapes the strength or sign of species interactions.

419 We show that the fate of competing species can be determined not by the relative  
420 strengths of intraspecific and interspecific competition, per se (as we conventionally expect), but  
421 instead by the interplay between competition and social information (Fig. 4, 5). Further, we show  
422 that because positive effects of social information can strongly affect demographics at low to  
423 moderate population densities, while negative effects of competition are strongest at high  
424 densities, these opposing effects do not simply cancel one another out but instead interact to give  
425 rise to a range of stable population states. For example, we show that strong intraspecific relative  
426 to interspecific competition can fail to cause long-term coexistence, as we would otherwise  
427 expect, if the effect of intraspecific social information is stronger than the effect of interspecific  
428 social information (Fig. 4a, 5a). In nature, this scenario could result when predators of competing  
429 species differ to enough of a degree that social information about predators is more valuable  
430 when it comes from conspecifics than when it comes from heterospecifics, or in the extreme case  
431 that intraspecific social information, alone, is of value (Seppänen et al. 2007). Conversely, we  
432 show that weak intraspecific competition relative to interspecific competition can fail to drive a  
433 system to long-term mutual exclusion, as we would otherwise expect, if the effect of intraspecific  
434 social information is weaker than the effect of interspecific social information (Fig. 4b, 5b). In  
435 nature, such a scenario could result when individuals are distributed in space such that they are  
436 more likely to be proximate to (and, thus, privy to information from) heterospecifics than  
437 conspecifics (e.g., in mixed-species bird flocks; Graves and Gotelli 1993, Greenberg 2000,

438 Templeton and Greene 2007, Martínez et al. 2018). Effects of interspecific (relative to  
439 intraspecific) social information can be further enhanced by phenotypic differences among  
440 species, allowing some species heightened sensory abilities and/or more effective means of  
441 transmitting information (Seppänen et al. 2007, Goodale et al. 2010). In either case, surrounding  
442 species can come to rely upon such information producers; for example, various bird species are  
443 highly responsive to even the nuances of alarm calls from keystone informant species  
444 (Templeton et al. 2005, Templeton and Greene 2007), and similarly, zebras respond strongly to  
445 simple movements of giraffes (i.e., body postures directed at predators), which possess a much  
446 higher vantage point to spot shared predators (Schmitt et al. 2016). Thus, while we may typically  
447 expect the strength of the effect of social information on prey demographics to be more  
448 pronounced in individuals that more frequently aggregate (e.g., in cohesive flocks, herds or  
449 schools), highly useful information (e.g., that prevents predation) could have strong demographic  
450 effects even when it is received infrequently.

451 To simplify our presentation and for analytical tractability (Appendix S3), we primarily  
452 focus on symmetrically competing populations. However, the same principles revealed above  
453 apply to cases when competing populations exhibit differences in competitive ability: social  
454 information counters effects of competition, within or between species, and, consequently, can  
455 tip the scales in favor of competitively inferior species or strengthen the dominance of  
456 competitively superior species (Appendix S4: Fig. S1). Furthermore, we assume that competing  
457 species share a generalist predator and that social information reduces encounter rates with this  
458 predator. However, a specialist predator would create dissimilarities in the value of social  
459 information between species, such that the prey species that is preferred by the predator would  
460 exhibit a stronger positive response to social information than the less-preferred prey species,  
461 and this can affect the long-term outcome for both prey populations (Appendix S4: Fig. S2). It is

462 also true that when social information enhances resource acquisition (Dall et al. 2005, Goodale et  
463 al. 2010), instead of or in addition to enhancing predator avoidance, it could exacerbate resource  
464 or interference competition in certain contexts (Gil et al. 2017). Consequently, other factors, such  
465 as the abundance and distribution of resources, could strongly influence the overall effect of  
466 social information on competitive outcomes. In summary, our models show that when net effects  
467 of social information exceed and oppose net effects of competition, social information can affect  
468 the qualitative outcome at equilibrium, but there remains vast opportunity to expand our  
469 framework to incorporate specific features of natural history of various systems.

#### 470 *Conclusions*

471 Mounting empirical and theoretical evidence suggests that social information, a ubiquitous driver  
472 of animal behavior and fitness (Goodale et al. 2010, Magrath et al. 2015), can play a significant  
473 role in the ecology of natural systems (Gil et al. 2018). Yet, our paper is the first to our  
474 knowledge to formalize the inclusion of social information in both single and multi-species  
475 population models and to rigorously characterize the demographic effects thereof. Our study  
476 provides an important step in our understanding of the potential for social information to underlie  
477 the persistence, coexistence and diversity of species across systems.

478 Our study also highlights a multifaceted potential impact of social information on  
479 expectations for conservation management. Social information can raise population size and  
480 allow persistence that we would not otherwise expect (e.g., due to high predation and/or  
481 competition); however, under conditions of high predation, social information can cause  
482 putatively common critical population thresholds (Courchamp et al. 1999, Gascoigne and  
483 Lipcius 2004a, Suding and Hobbs 2009, Kelly et al. 2015) that, if not identified by resource  
484 managers, can lead to unrealized risks of sudden population collapse (Holt 2007). The  
485 probability of such information-mediated local extinctions could increase with demographic or

486 environmental stochasticity (Gilpin and Soulé 1986, Lande 1998). Furthermore, the demographic  
487 effects of social information that we reveal suggest that environmental changes that simply  
488 inhibit social cueing/signaling among individuals (e.g., anthropogenic increases in turbidity or  
489 disruption of chemical cues in aquatic systems (Kimbell and Morrell 2015, Chivers et al. 2016),  
490 urban noise masking auditory signals in terrestrial systems (Patricelli and Blickley 2006)) could  
491 drive unexpected changes to extinction risk, the outcome of competition, and ultimately the  
492 community state (Holt 2007). Furthermore, by changing the expected community structure as it  
493 depends on competitive and predation rates, social information could affect the expected  
494 ecological outcome of an invasive predator or competitor. The directionality of this effect on  
495 expected invasiveness and invasive impact will inevitably depend on the interplay between  
496 competition and social information, as described above. Consequently, our findings point to  
497 social information as an important factor that could affect how we conserve and manage natural  
498 resources, particularly for endangered species at small population sizes where social information  
499 is more likely to influence demographic rates.

## 500 **Acknowledgements**

501 We thank Andrew Hein, Andy Sih and Orr Spiegel for helpful feedback in early discussions of  
502 this model. This research was funded by a National Science Foundation Postdoctoral Research  
503 Fellowship awarded to MAG.

504

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656

### 657 **Figure Legends:**

658 **Fig. 1:** How social information can affect the dynamics of a single population. Inclusion of  
659 effects of social information on per-capita mortality due to predation can give rise to positive  
660 density dependence in the per-capita population growth rate (a). This can expand, relative to the  
661 logistic model with predation (grey line), the conditions under which a population can persist,  
662 and it increases population size at equilibrium across a range of conditions (blue line in (a), with  
663 equilibrium population size plotted in (b)). When the predation rate exceeds the population  
664 growth rate ( $p > r$ ), as it does in (a), social information can give rise to a strong Allee effect,  
665 causing alternative stable states (e.g., stable equilibria represented by a solid curve and a solid  
666 line at  $N = 0$  for  $r = 0.2$  or  $0.3$  in (b)). The alternative stable states are separated by unstable  
667 equilibria (e.g., the dashed curves corresponding to  $r = 0.2$  and  $0.3$  in (b)), which represent the  
668 Allee threshold: if a population exceeds this threshold it will grow (represented by the up arrow)  
669 and if it falls below this threshold it will collapse (represented by the down arrow). When  $r \geq p$ ,  
670 social information simply increases the stable population size at equilibrium (shown for  $r = 1, 3$   
671 in (b)). Parameter values:  $\alpha = 0.01$ ,  $r = 0.8$  (for a only),  $b = 0$  (black line) or  $0.05$  (blue curve; for  
672 a only), and  $p = 1$ .

673 **Fig. 2:** Outline of the two-species social information model (Eq. 2), including distinct effects of  
674 intraspecific social information (blue) and interspecific social information (green). (a) Boxes  
675 indicate the two population state variables, and arrows indicate dynamics and are labeled with  
676 the associated parameters. Each population exhibits logistic growth, engages in intraspecific  
677 competition ( $\alpha_{ii}$ ) and interspecific competition ( $\alpha_{ij}$ ), and is consumed by the same predator at a  
678 maximal per-capita rate  $p_i$ . These competing species can also reduce their mortality rate due to  
679 predation by sharing intraspecific social information ( $b_{ii}$ , in blue) and/or interspecific social  
680 information ( $b_{ij}$ , in green); e.g., through alarm calls or evasive movements that provide early  
681 warnings of attacks). In (b)-(d), we show example phase plane plots of the competitive dynamics  
682 without social information (b), with only intraspecific social information,  $I_s = -1$  (c), and with  
683 only interspecific social information,  $I_s = \text{infinity}$  (d). In these phase plane plots, colored lines are  
684 nullclines that indicate where each population exhibits a zero growth rate ( $\frac{dN_1}{dt} = 0$ : red  
685 line/curve,  $\frac{dN_2}{dt} = 0$ : yellow line/curve; these intersect at equilibria) and grey arrows denote the  
686 trajectories populations take through time, starting from the edges of the plotted area. Open  
687 points denote unstable equilibria, and closed points denote stable equilibria. Parameter values:  $r_1$   
688  $= r_2 = 1$ ,  $p_1 = p_2 = 0.5$ ,  $\alpha_{11} = \alpha_{22} = \alpha_{12} = \alpha_{21} = 0.01$  with  $b_{11} = b_{22} = 0$  (b, c) or 0.1 (d) and  $b_{12} = b_{21}$   
689  $= 0$  (b, d) or 0.1 (c).

690 **Fig. 3:** The interaction indices, which integrate the intraspecific and interspecific competition  
691 and social information, determine the coexistence-exclusion boundary when both forms of social  
692 information (intraspecific and interspecific) are weak ( $I_w = 0$ , A) and the persistence-extinction  
693 boundary when at least one form of social information is strong ( $I_s = 0$ , B). Parameter values:  $r =$   
694  $1$ ;  $p = 0.999999$  (A), 1.002271 (B);  $\alpha = 0.011$  (A), 0.010 (B);  $\tilde{\alpha} = 0$  to 0.1;  $b = 0.010$  (A), 0.011  
695 (B);  $\tilde{b} = 0$  to 0.1.

696 **Fig. 4:** Phase plane plots of nullclines at which the population of each competing species exhibits  
697 zero net growth ( $N_1$  nullcline in red,  $N_2$  nullcline in yellow) when only one type of social  
698 information is strong in the system: intraspecific social information (a) or interspecific social  
699 information (b). Nullcline intersections mark equilibrium points (open points denote unstable  
700 equilibria; closed points denote stable equilibria). The type of social information that is strong  
701 determines the sign of interaction indices  $I_s$  or  $I_w$  (Eq. 4 & 5) and, thus, the progression of  
702 equilibrium outcomes that a system can experience, as the predation rate,  $p$ , which is affected by  
703 social information, increases (bottom x-axis). At the vertical dashed line, predation rate  $p$   
704 exceeds the intrinsic growth rate  $r$  such that the extinction of all species would occur without  
705 social information. For  $p < r$ , coexistence would occur without social information in (a), and  
706 mutual exclusion would occur without social information in (b). Parameter values used are  
707 provided in the extended version of this figure (Appendix S3: Fig. S1).

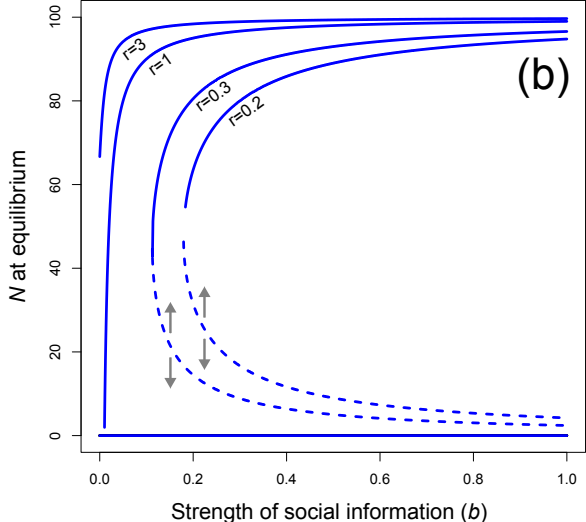
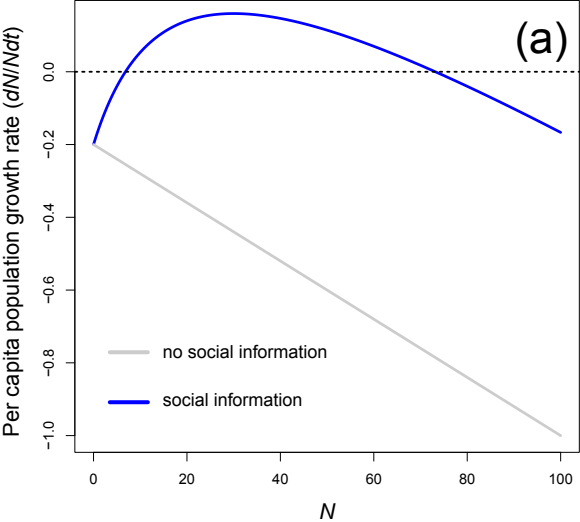
708 **Fig. 5:** Phase plane plots of nullclines at which the population of each competing species exhibits  
709 zero net growth ( $N_1$  nullcline in red,  $N_2$  nullcline in yellow) when both intraspecific and  
710 interspecific social information are strong. Nullclines intersections mark equilibrium points  
711 (open points denote unstable equilibria; closed points denote stable equilibria). The sign of the  
712 net interaction index,  $I_s$  or  $I_w$  (calculated from the relative effects of social information and  
713 competition; Eq. 4 & 5), determines the progression of equilibrium outcomes that a system can  
714 experience, as the predation rate,  $p$ , which is affected by social information, increases (bottom x-  
715 axis). In (a), the interaction index is negative and promotes mutual exclusion. In (b), the  
716 interaction index is positive and promotes coexistence. At the vertical dashed line,  $p$  exceeds the  
717 intrinsic growth rate  $r$  such that the extinction of all species would occur without social  
718 information. For  $p < r$ , coexistence would occur without social information in (a), and mutual

719 exclusion would occur without social information in (b). Parameter values used are provided in  
720 the extended version of this figure (Appendix S3: Fig. S2).

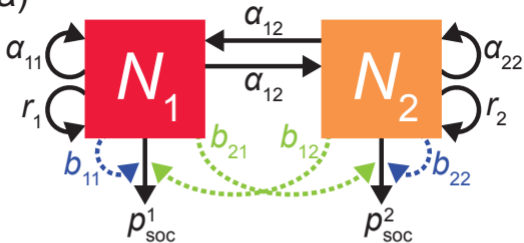
721 **Fig. 6.** Social information drives qualitative shifts in the dynamics of competing species. The  
722 outcomes at equilibrium for competing populations respond to the relative strengths of social  
723 information types (intraspecific: x-axes; interspecific: y-axes). These responses depend on  
724 interspecific competition (columns: low (left; a, c):  $\alpha > \tilde{\alpha}$ , such that coexistence would occur  
725 without social information; and high (right; b, d):  $\alpha < \tilde{\alpha}$ , such that mutual exclusion would occur  
726 without social information), and predation (rows: high (top; a, b):  $p > r$ , such that system-wide  
727 extinction would occur without social information; and low (bottom; c, d):  $p < r$ ). Furthermore,  
728 the direction in which social information influences the competitive outcome (towards  
729 coexistence or competitive exclusion), and therefore the suite of qualitatively distinct dynamics  
730 that the system can exhibit (e.g., Fig. 4a vs. 4b, Fig. 5a vs. 5b; Appendix S3: Fig. S1a vs. S1b,  
731 Fig. S2a vs. S2b), depends on the sign of the net interaction indices  $I_s$ ,  $I_w$  (Eq. 4 & 5), where  $I_s =$   
732 0 along the dashed line,  $I_s < 0$  below the dashed line, and  $I_s > 0$  above the dashed line. Parameter  
733 values:  $r = 1$ ,  $\alpha = 0.01$ ,  $\tilde{\alpha} = 0.009$  (left side; a, c) or 0.011 (right side; b, d),  $p = 1.2$  (top row; a, b)  
734 or 0.9 (bottom row; c, d).

735

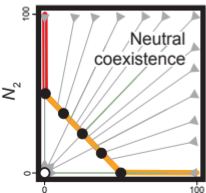




(a)



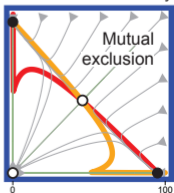
(b) Social info. absent



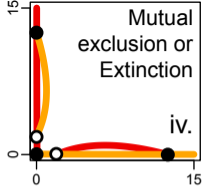
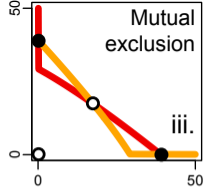
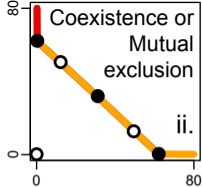
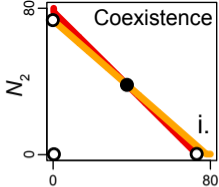
(c) + Interspecific social info. only



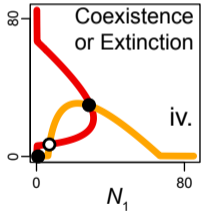
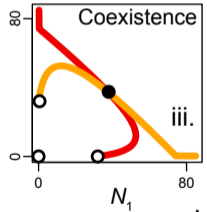
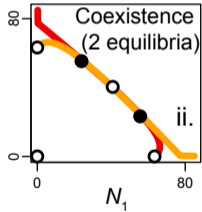
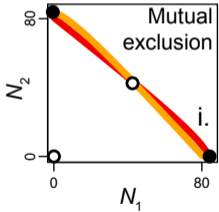
(d) + Intraspecific social info. only



(a) Strong intraspecific social information ( $I < 0$ )



(b) Strong interspecific social information ( $I > 0$ )

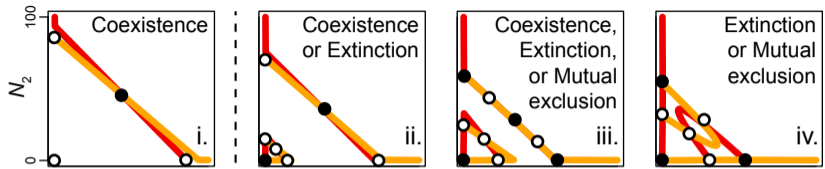


- unstable equilibrium
- stable equilibrium
- $N_1$  nullcline
- $N_2$  nullcline

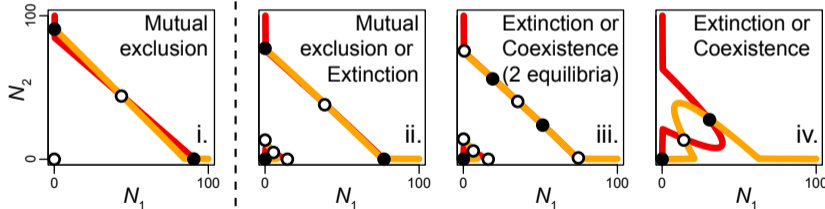
predation rate affected by social information

# Strong intraspecific and interspecific social information

(a) Net negative interaction ( $I < 0$ )



(b) Net positive interaction ( $I > 0$ )



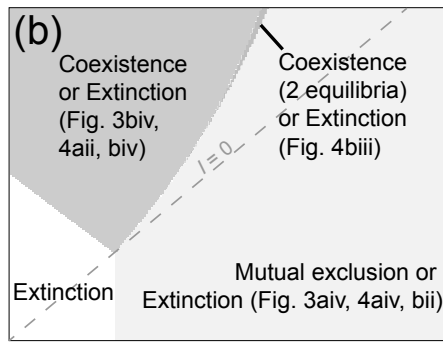
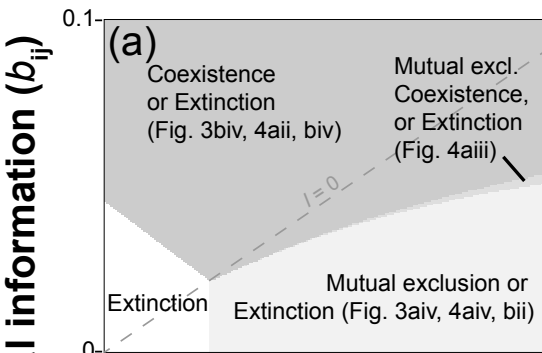
- unstable equilibrium
- stable equilibrium

—  $N_1$  nullcline  
—  $N_2$  nullcline

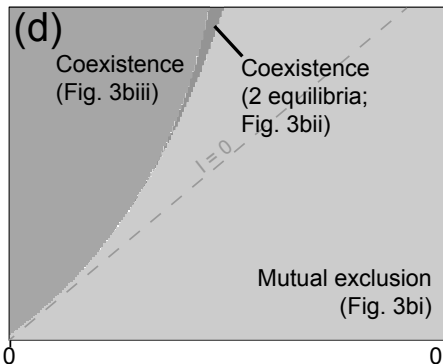
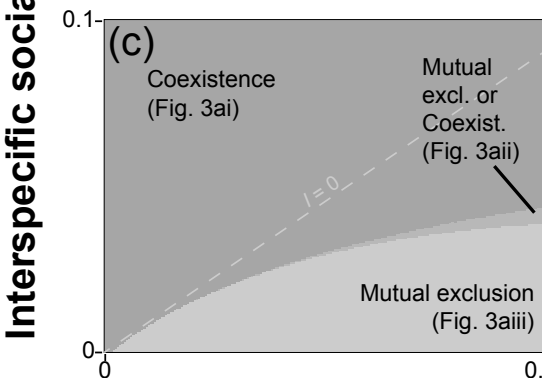
predation rate affected by social information

### Low interspecific competition

### High interspecific competition



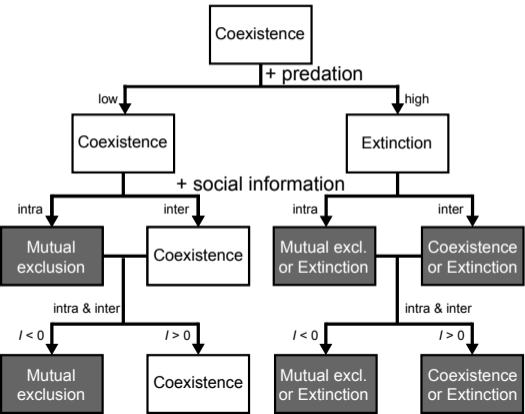
High predation



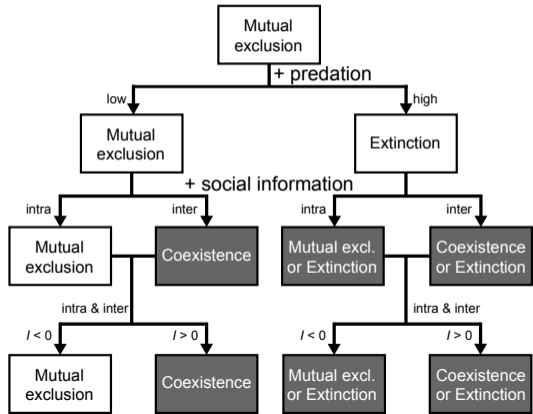
Low predation

Intraspecific social information ( $b_{ii}$ )

**(a) Low interspecific competition**



**(b) High interspecific competition**



## Supporting Information. Appendix S1: Mechanistic derivation and re-parameterizations.

Michael A. Gil, MARRISA L. BASKETT, and Sebastian J. Schreiber. 2019. Social information drives ecological outcomes among competing species. Submitted to *Ecology*

In this Appendix, we provide a mechanistic derivation of the predation term for the models in the main text, and describe how these models can account for a minimal level of predation as well as a type II functional response. We do the re-parameterizations separately to minimize the amount of notation.

### A mechanistic derivation

Here, we show how the functional form of our predation term in the two species model can be derived from first principles. For illustrative purposes, assume that the population of species  $i$  consists of individuals that are vulnerable to predation (with density  $V_i$ ) and informed individuals (with density  $I_i$ ) that are invulnerable to predation; in the next section, we describe how to account for a minimal level of predation on all individuals (i.e., even informed individuals are subject to some level of predation). We have that  $N_i = V_i + I_i$ . Invulnerable individuals return to being vulnerable at a characteristic rate  $\gamma_i$  corresponding to their tendency to return to less informed behavior. Alternatively, vulnerable individuals by interacting with intra- and inter-specific individuals gain social information about the dangers of predation. If the movement between these behavioral stages occurs at a faster time scale than changes in population densities, then we can describe shifts between these behavioral states as

$$\begin{aligned}\frac{dV_i}{dt} &= \gamma_i I_i - (\beta_{ii} N_i + \beta_{ij} N_j) V_i \\ \frac{dI_i}{dt} &= (\beta_{ii} N_i + \beta_{ij} N_j) V_i - \gamma_i V_i\end{aligned}$$

where  $\beta_{ii}, \beta_{ij}$  are the per-capita influence of intra- and interspecific individuals (via social information) on switching from vulnerable to informed. Over the faster behavioral time scale, these behavioral dynamics converge to a unique equilibrium which satisfies

$$\begin{aligned}0 &= \gamma_i I_i - (\beta_{ii} N_i + \beta_{ij} N_j) V_i \\ 0 &= \gamma_i (N_i - V_i) - (\beta_{ii} N_i + \beta_{ij} N_j) V_i \\ (\gamma_i + \beta_{ii} N_i + \beta_{ij} N_j) V_i &= \gamma_i N_i \\ V_i &= \frac{\gamma_i N_i}{\gamma_i + \beta_{ii} N_i + \beta_{ij} N_j}.\end{aligned}$$

Dividing the numerator and denominator of the final expression by  $\gamma_i$ , we get

$$V_i = \frac{N_i}{1 + \frac{\beta_{ii}}{\gamma_i} N_i + \frac{\beta_{ij}}{\gamma_i} N_j}.$$

As only vulnerable individuals experience predation, the net predation rate on species  $i$  equals

$$a_i P V_i = \frac{a_i P N_i}{1 + b_{ii} N_i + b_{ij} N_j}$$

where  $b_{ii} = \beta_{ii}/\gamma_i$ ,  $b_{ij} = \beta_{ij}/\gamma_i$ , and  $P$  is the predator density. This functional form is used in all of the models in the main text.

## Accounting for minimal predation

First, we show how a model which includes a minimal level of predation  $p_{\min}^i$ , for each species  $i = 1, 2$ , that occurs irregardless of social information corresponds to a re-parameterization of the model presented in the Models and Methods. As in the model presented in the main manuscript (single-species model: Eq. 1, two-species model: Eq. 2),  $r_i$  is the intrinsic growth rate of species  $i$ ,  $\alpha_{ij}$  is the per-capita competition coefficient for the effect of species  $j$  on species  $i$ ,  $p_i$  is the additional maximal predation level that occurs when there is no social information, and  $b_{ij}$  determines the per-capita reduction of predation on species  $i$  due to social information from species  $j$ . This model is given by

$$\begin{aligned}\frac{dN_1}{dt} &= N_1 \left( r_1 (1 - \alpha_{11}N_1 - \alpha_{12}N_2) - p_{\min}^1 - \frac{p_1}{1 + b_{11}N_1 + b_{12}N_2} \right) \\ \frac{dN_2}{dt} &= N_2 \left( r_2 (1 - \alpha_{22}N_2 - \alpha_{21}N_1) - p_{\min}^2 - \frac{p_2}{1 + b_{22}N_2 + b_{21}N_1} \right).\end{aligned}\tag{S1}$$

Assume  $r_i > p_{\min}^i$  for  $i = 1, 2$ . Define  $\tilde{r}_i = r_i - p_{\min}^i$  and  $\tilde{\alpha}_{ij} = \alpha_{ij}r_i/(r_i - p_{\min}^i)$ . Then  $\tilde{r}_i\tilde{\alpha}_{ij} = r_i\alpha_{ij}$  and we get

$$\begin{aligned}\frac{dN_1}{dt} &= N_1 \left( \tilde{r}_1 (1 - \tilde{\alpha}_{11}N_1 - \tilde{\alpha}_{12}N_2) - \frac{p_1}{1 + b_{11}N_1 + b_{12}N_2} \right) \\ \frac{dN_2}{dt} &= N_2 \left( \tilde{r}_2 (1 - \tilde{\alpha}_{22}N_2 - \tilde{\alpha}_{21}N_1) - \frac{p_2}{1 + b_{22}N_2 + b_{21}N_1} \right),\end{aligned}\tag{S2}$$

which has the same form of the model shown in Eq. 2 in the main text.

## Accounting for a type II functional response

To account for a type II functional response for the generalist predator, we begin with the single species model and then discuss the two species model. For the single species model, we shall show that it is equivalent, via re-parameterization, to the model studied in the main manuscript. For the two species model, we shall show that it is equivalent to the model presented in the main text under special circumstances that allow some of the analysis to extend to the two species model with a type II functional response.

For the single species model, let  $h$  be the handling time of the predator. The attack rate of the predator is a decreasing function of intraspecific social information  $a/(1 + bN)$  where  $a$  is the maximal attack rate of the predator. Under these assumptions the functional response of the predator is given by

$$\frac{\frac{a}{1+bN}N}{1 + h\frac{a}{1+bN}N} = \frac{aN}{1 + (ha + b)N}.$$

If  $P$  is the total density of the generalist predator, then the model becomes

$$\frac{dN}{dt} = rN(1 - \alpha N) - \frac{aNP}{1 + (ha + b)N}$$

Setting  $\tilde{p} = aP$  and  $\tilde{b} = ha + b$ , we get

$$\frac{dN}{dt} = rN(1 - \alpha N) - \frac{\tilde{p}N}{1 + \tilde{b}N}$$



that is equivalent to Eq. 1 in the main text.

Now, consider the two species model where the generalist predator has a handling time  $h_i$  on species  $i$ , and an attack rate  $a_i/(1 + b_{ii}N_i + b_{ij}N_j)$  on species  $i$ . Then its functional response with respect to species 1, for example, is

$$\begin{aligned} & \frac{\frac{a_1}{1+b_{11}N_1+b_{12}N_2}N_1}{1 + h_1\frac{a_1}{1+b_{11}N_1+b_{12}N_2}N_1 + h_2\frac{a_2}{1+b_{22}N_2+b_{21}N_1}N_2} \\ &= \frac{a_1N_1}{1 + b_{11}N_1 + b_{12}N_2 + h_1a_1N_1 + h_2\frac{a_2(1+b_{11}N_1+b_{12}N_2)}{1+b_{22}N_2+b_{21}N_1}N_2} \end{aligned} \quad (\text{S3})$$

Unlike the functional response with a single prey species, the term  $\frac{a_2(1+b_{11}N_1+b_{12}N_2)}{1+b_{22}N_2+b_{21}N_1}$  in the denominator of equation (S3) implies that this expression for the predator's functional response does not always simplify to an expression equivalent to the functional response in Eq. 2 in the main text. Two special cases where it does are as follows. First, if inter- and intraspecific social information terms are equal (i.e.  $b_{11} = b_{22} = b_{12} = b_{21}$ ), then the ratio  $\frac{a_2(1+b_{11}N_1+b_{12}N_2)}{1+b_{22}N_2+b_{21}N_1}$  reduces to  $a_2$  and this functional response is equivalent to the one presented in the main text. Second, if there is symmetry in the social information cues (i.e.  $\alpha_{11} = \alpha_{22}$  and  $\alpha_{12} = \alpha_{21}$ ) and both species have equal densities (i.e.  $N_1 = N_2 =: N$ ), then the ratio  $\frac{a_2(1+b_{11}N_1+b_{12}N_2)}{1+b_{22}N_2+b_{21}N_1}$  also reduces to  $a_2$ . It follows that the bifurcation analysis of the symmetric model along the  $N_1$ ,  $N_2$ ,  $N_1 = N_2$  axes in Supplementary Information S3 still applies where  $h_1 = h_2$ ,  $a_1 = a_2$ ,  $p_i$  is replaced with  $a_iP$ ,  $b_{ii}$  is replaced with  $h_ia_i + b_{ii}$ , and  $b_{ij}$  is replaced with  $h_ia_i + b_{ij}$ . In particular, the interaction index in this case is given by  $I_s = \frac{h_ia_i + b_{ij}}{h_ia_i + b_{ii}} - \frac{\alpha_{ij}}{\alpha_{ii}}$ .

**Supporting Information. Appendix S2: Analysis of single species model.** Michael A. Gil, MARRISA L. BASKETT, and SEBASTIAN J. SCHREIBER. 2019. Social information drives ecological outcomes among competing species. Submitted to *Ecology*

In this Appendix, we analyze the single-species model presented in the main text and numerically explore an alternative formulation of the model. Although the main model is mathematically equivalent to the model of Noy-Meir [1975], our analysis of the two possible types of bifurcations and the first order approximation of the positive equilibrium are novel.

**The bifurcation analysis.** Recall, the single species model is

$$\frac{dN}{dt} = N \left( r(1 - \alpha N) - \frac{p}{1 + bN} \right) \quad (\text{S1})$$

where  $N$  is the population density,  $r$  is the intrinsic rate of growth,  $\alpha$  is the strength of intraspecific competition,  $p$  corresponds to the maximal predation level which can be reduced to near zero by social information, and  $b$  is the per-capita reduction in predation due to intraspecific social information. Positive equilibria of (S1) must satisfy

$$(r - r\alpha N)(1 + bN) = p, \quad (\text{S2})$$

or equivalently

$$(1/\alpha - N)(1/b + N) = p/(rab) \quad (\text{S3})$$

As the left hand side is a quadratic with roots at  $1/\alpha$  and  $-1/b$  and a maximum of  $(1/\alpha + 1/b)^2/4$  at  $(1/\alpha - 1/b)/2$ , we get two possible sequences of bifurcations as  $p$  increases from zero to infinity (Figure S1):

*Weak social information* ( $b/\alpha < 1$ ): If  $p < r$ , then the population persists at a globally stable positive equilibrium  $n^*$ . If  $p > r$ , then the population goes extinct as  $n = 0$  is a globally stable equilibrium.

*Strong social information:* Assume  $b/\alpha > 1$ . If  $p < r$ , then the population persists at a globally stable feasible equilibrium  $n^*$ . If  $r < p < r(\sqrt{b/\alpha} + \sqrt{\alpha/b})^2/4 =: p^*$  (the same as Eq.3 in the main text), there are two feasible equilibria  $n_* < n^*$ , such that initial conditions below  $n_*$  go to extinction and initial conditions above  $n_*$  converge to the stable equilibrium  $n^*$ . If  $p > p^*$ , then the population goes asymptotically extinct for all initial conditions as  $n = 0$  is globally stable.

Note that the critical value  $p^*$  is proportional to  $r$ , and increases from the value of  $r$  up to  $\infty$  as  $b/\alpha$  goes from 1 to  $\infty$ . Namely, the stronger the social information, the higher level of predation that the population can withstand.

**Effects of social information on equilibrium densities.** To understand the effect of social information  $b$  on the non-zero equilibria of the model, let  $R$  denote the per-capita growth rate of the population i.e.

$$R(N, b) = r(1 - N/K) - \frac{p}{1 + bN}.$$

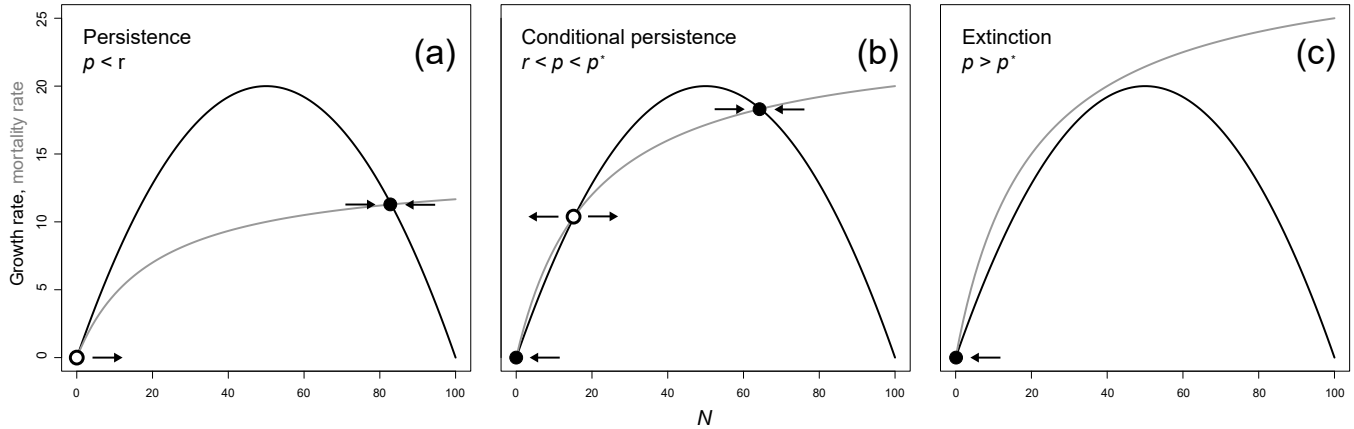


Figure S1: Social information can have quantitative or qualitative effects on a population. If social information is absent (i.e.,  $b = 0$  in Eq. 1), the prey mortality rate increases linearly with the prey population, with the slope =  $p$ . However, when social information is present, it causes the prey mortality rate (grey curves, with initial slope =  $p$ ) to decelerate with prey density ( $N$ ,  $x$ -axis), allowing for either a greater population size at equilibrium (a; a quantitative effect) or conditional persistence when we would otherwise expect extinction (b; a qualitative effect), if  $p < p^*$  (Eq. 3 in the main text). However, when  $p > p^*$ , social information has no effect (i.e., the population goes extinct whether or not social information is available; c).

Then the growth rate is  $G(N, b) = NR(N, b)$ . A positive equilibrium density  $N^*(b)$  for this model satisfies  $R(N^*(b), b) = 0$  and is stable if

$$0 > \frac{\partial G}{\partial N}(N^*(b), b) = N^*(b) \frac{\partial R}{\partial N}(N^*(b), b) \quad (\text{S4})$$

and unstable if

$$0 < N^*(b) \frac{\partial R}{\partial N}(N^*(b), b). \quad (\text{S5})$$

To understand how  $N^*(b)$  varies with  $b$ , we can implicitly differentiate with respect to  $b$

$$\begin{aligned} \frac{d}{db} 0 &= \frac{d}{db} R(N^*(b), b) \\ 0 &= \frac{\partial R}{\partial N} \frac{dN^*}{db} + \frac{\partial R}{\partial b} \end{aligned}$$

Therefore, whenever  $\frac{\partial R}{\partial N} \neq 0$ ,

$$\frac{dN^*}{db} = - \frac{\frac{\partial R}{\partial b}}{\frac{\partial R}{\partial N}}. \quad (\text{S6})$$

As

$$\frac{\partial R}{\partial b} = \frac{pN}{(1 + bN)^2} > 0,$$

equations (S4)–(S6) imply that  $\frac{dN^*}{db} > 0$  when  $N^*$  is stable and  $\frac{dN^*}{db} < 0$  when  $N^*$  is unstable.

**An alternative functional form of the model.** As an alternative functional form of the effect of social information on predation, we also consider an inverse normal function to model cases in which reductions in per capita mortality due to social information manifest at low densities but are completely negated at higher densities (e.g., due to false alarms and/or occlusion of information [Rosenthal et al., 2015]). In this form,  $p_{\max}$  sets the effect of social information on reducing mortality due to predation (analogous to  $p$  in Eq. 1 in main text),  $b$  controls the strength of the effect of social information and the (symmetric) strength of compensation, and  $N^*$  is the population size at which mortality due to predation is minimized by social information, such that the effective predation rate is determined by the second term in the model:

$$dN/dt = rN(1 - \alpha N) - Np_{\max}(1 - \exp(-b^2(N - N^*)^2)) \quad (\text{S7})$$

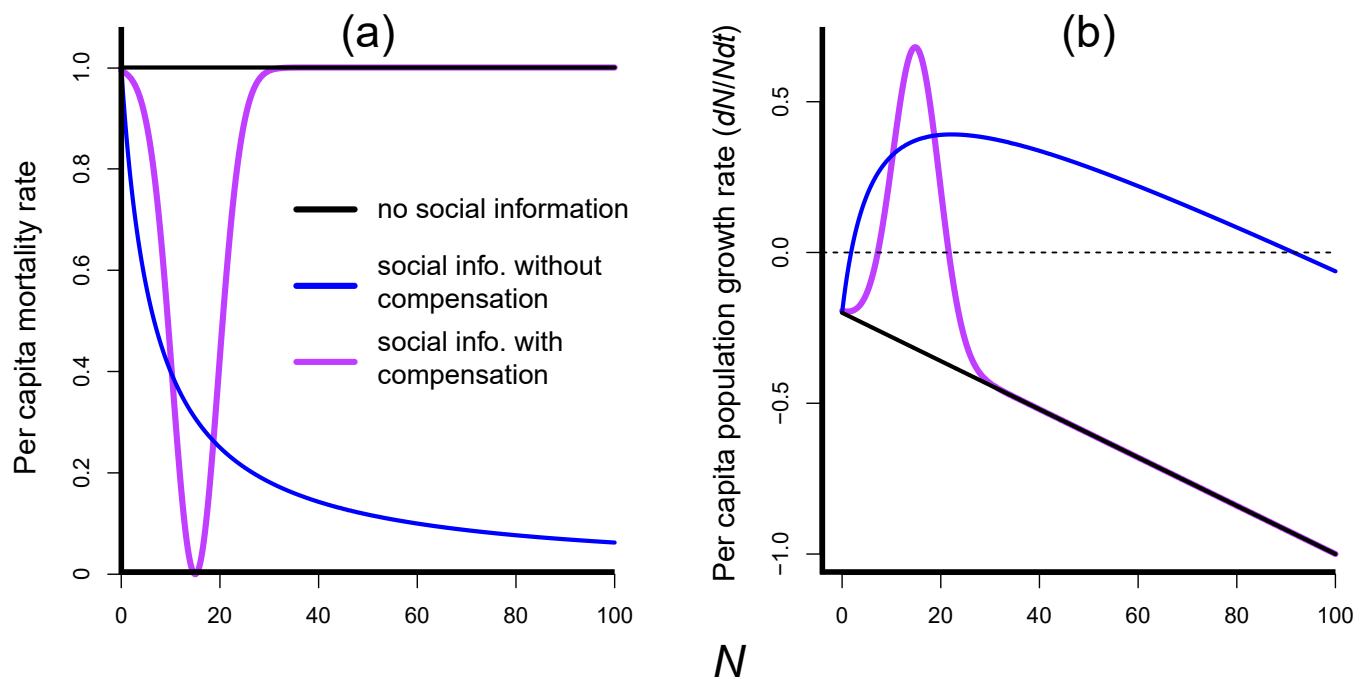


Figure S2: Effects of social information on population dynamics are robust across functional forms. Inclusion of effects of social information on per capita mortality due to predation in two distinct functional forms (a) gives rise to positive density dependence in the per capita population growth rate (b) and expands, relative to the logistic model with predation (black line), the conditions under which a population can persist. In particular, when predation rate exceeds population growth rate ( $p > r$  for the model with social information [blue curves] or  $p_{\max} > r$  for the model with social information and compensation [purple curves]), as it does in (b), social information can give rise to alternative stable states. Thus, social information can prevent population collapse if population size does not fall below an unstable equilibrium that represents a critical threshold (where the blue and purple curves first intersect the dotted line at  $y = 0$  in (b); a ‘strong Allee effect’). For these calculations, we set  $r = 0.8$ ,  $\alpha = 0.01$ ,  $p = p_{\max} = 1$ ,  $N^* = 15$ , and  $b = 0$  (Eq. 1 and Eq. 2–8 in the main text) for ‘no social information’, or  $b = 0.15$  for both models with social information. Note that the inverse normal functional form (purple curve) has the additional property of bistability between low and high population sizes over a narrow range of  $p$ , when  $p > r$ .

Note that complete compensation for effects of social information is likely less common than cases of partial compensation (i.e., when benefits of social information are only partially negated at higher densities) [Kenward, 1978, Seppänen et al., 2007, Jackson et al., 2008, Lister, 2014, Berdahl et al., 2016]. Thus, the functional form of predation in Eq. S7 can be considered a lower bound of the demographic consequences of social information. Nonetheless, this functional form with compensation drives the same qualitative pattern as the monotonic form (without compensation; Eq. 1; Fig. S2): it allows for a greater carrying capacity of the population (relative to the logistic + predation model) and can prevent extinction, when predation exceeds the intrinsic rate of growth ( $p_{\max} > r$ ; Fig. S2).

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**Supporting Information. Appendix S3: Analysis of two-species model.** Michael A. Gil, MARRISA L. BASKETT, and Sebastian J. Schreiber. 2019. Social information drives ecological outcomes among competing species. Submitted to *Ecology*

In this Appendix, we analyze the two-species competition model presented in the main text. Recall, this model is given by

$$\begin{aligned}\frac{dN_1}{dt} &= N_1 \left( r_1 (1 - \alpha_{11}N_1 - \alpha_{12}N_2) - \frac{p_1}{1 + b_{11}N_1 + b_{12}N_2} \right) \\ \frac{dN_2}{dt} &= N_2 \left( r_2 (1 - \alpha_{22}N_2 - \alpha_{21}N_1) - \frac{p_2}{1 + b_{22}N_2 + b_{21}N_1} \right)\end{aligned}\tag{S1}$$

where  $r_i$  is the intrinsic rate of growth of species  $i$ ,  $\alpha_{ij}$  is the strength of the competitive effect of species  $j$  on species  $i$ ,  $p_i$  is the maximal predation level in the absence of social information, and  $b_{ij}$  is the per-capita effect of social information from species  $j$  to species  $i$ .

### Bifurcation Analysis of the Symmetric Case.

Consider the symmetric case i.e.  $r_1 = r_2 =: r$ ,  $p_1 = p_2 = p$ ,  $b_{11} = b_{22} =: b$ ,  $b_{12} = b_{21} =: \tilde{b}$ ,  $\alpha_{11} = \alpha_{22} =: \alpha$ , and  $\alpha_{12} = \alpha_{21} =: \tilde{\alpha}$ .

Under these assumptions, there is an invariant line  $N_1 = N_2 =: N$  for the dynamics, and the dynamics on the line are given by

$$\frac{dN}{dt} = N \left( r(1 - (\alpha + \tilde{\alpha})N) - \frac{p}{1 + (b + \tilde{b})N} \right)\tag{S2}$$

Our analysis of the symmetric model is divided into two parts. First, we identify when increasing  $p$  can cause the non-zero nullclines to cross on the single species axis. When intraspecific information is weak (i.e.  $b/\alpha < 1$  cf. the analysis in Appendix S2), this bifurcation corresponds to the system switching from bistability (i.e. both single species equilibria are stable) to coexistence in the sense of mutual invasibility (i.e. both single species equilibria are unstable), or vice-versa. Second, we study the equilibrium structure on the single species axes and the  $N_1 = N_2$  axis. Together, these analyses provide the analytical scaffolding for the results presented in the main text. These analyses, however, do not address the structure of the asymmetric equilibria, i.e. pairs of equilibria of the form  $(N_1, N_2) = (a, b)$  and  $(N_1, N_2) = (b, a)$  with  $a > b > 0$ .

**Bifurcations along the single species and symmetric axes.** As equation (S2) is the same as the single species model but with  $\alpha$  replaced by  $\alpha + \tilde{\alpha}$  and  $b$  replaced by  $b + \tilde{b}$ , we can classify the bifurcations as  $p$  increases into 4 types. For this classification, we define two critical predation levels:

$$p^* = \frac{r}{4} \phi \left( \frac{b}{\alpha} \right) \quad (\text{single species axes: Eq.3 in main text})$$

$$p^{**} = \frac{r}{4} \phi \left( \frac{b + \tilde{b}}{\alpha + \tilde{\alpha}} \right) \quad (\text{symmetric axis: Eq.6 in main text})$$

where  $\phi(x) = (\sqrt{x} + 1/\sqrt{x})^2$ .

As  $\phi(x)$  in an increasing function for  $x \geq 1$ ,  $p^{**} > p^*$  when  $\frac{b+\tilde{b}}{\alpha+\tilde{\alpha}} > \frac{b}{\alpha} > 1$  and, conversely,  $p^{**} < p^*$  when  $\frac{b+\tilde{b}}{\alpha+\tilde{\alpha}} < \frac{b}{\alpha} > 1$ . Furthermore, notice that

$$\begin{aligned} \frac{b+\tilde{b}}{\alpha+\tilde{\alpha}} &> \frac{b}{\alpha} \\ \alpha b + \alpha\tilde{b} &> \alpha b + \tilde{\alpha} b \\ \alpha\tilde{b} &> \tilde{\alpha} b \\ \frac{\tilde{b}}{b} &> \frac{\tilde{\alpha}}{\alpha} \end{aligned}$$

Thus, the interaction index  $I_s = \frac{\tilde{b}}{b} - \frac{\tilde{\alpha}}{\alpha}$  defined in Eqn. 5 in the main text is positive if and only if  $\frac{b+\tilde{b}}{\alpha+\tilde{\alpha}} > \frac{b}{\alpha}$ , and  $I_s < 0$  if and only if  $\frac{b+\tilde{b}}{\alpha+\tilde{\alpha}} < \frac{b}{\alpha}$ . Based on these observation, we get the following cases:

*Weak intra and interspecific information* ( $\frac{b}{\alpha} < 1$  and  $\frac{b+\tilde{b}}{\alpha+\tilde{\alpha}} < 1$ ): If  $r > p$ , then there are positive equilibria on each of these axes. If  $r < p$ , then there are no positive equilibria on these axes and extinction occurs for all initial conditions. As in this case, there is at most one positive equilibrium on each of the single species axes, our earlier analysis implies that the sign of interaction index  $I_w$  determines whether predation can shift the system from coexistence to bistability ( $I_w < 0$ ) or vice-versa ( $I_w > 0$ ).

*Strong intra and weak interspecific information* ( $\frac{b}{\alpha} > 1$  and  $\frac{b+\tilde{b}}{\alpha+\tilde{\alpha}} < 1$ ): As one increases  $p$ , one goes from a unique positive equilibrium on each axis (when  $p < r$ ), to having no equilibria on the symmetric species axes and two positive equilibria on each of the single species axes (when  $r < p < p^*$ ), to finally having no positive equilibria on any axis (when  $p > p^*$ ). Notice that  $I_s < 0$  in this case as  $\frac{b+\tilde{b}}{\alpha+\tilde{\alpha}} < 1 < \frac{b}{\alpha}$ . See Figure S1a.

*Weak intra and strong interspecific information* ( $\frac{b}{\alpha} < 1$  and  $\frac{b+\tilde{b}}{\alpha+\tilde{\alpha}} > 1$ ): As one increases  $p$ , one goes from a unique positive equilibrium on each axis (when  $p < r$ ), to having no equilibria on the single species axes and two equilibria on the symmetric axis (when  $r < p < p^{**}$ ), to finally having no positive equilibria on any axis (when  $p > p^{**}$ ). Notice that  $I_s > 0$  in this case as  $\frac{b+\tilde{b}}{\alpha+\tilde{\alpha}} > 1 > \frac{b}{\alpha}$ . See Figure S1b.

*Strong intra and interspecific information* ( $\frac{b}{\alpha} > 1$  and  $\frac{b+\tilde{b}}{\alpha+\tilde{\alpha}} > 1$ ): If  $p < r$ , then there is a unique positive equilibrium on each axis. If  $r < p < \min\{p^*, p^{**}\}$ , there are two positive equilibria on all three axes. If  $p > p^*$ , then all initial conditions on the single species axis go to extinction. If  $p > p^{**}$ , then all initial conditions on symmetric two species axis go to extinction. Depending on whether  $p^* > p^{**}$  or  $p^* < p^{**}$  one gets different orders of the bifurcations. If  $I_s < 0$ , then  $p^* > p^{**}$  and one first loses the positive equilibria on the symmetric axis followed by the positive equilibria on the single species axes (Fig. S2a). If  $I_s > 0$ , then  $p^{**} > p^*$  and one first loses the positive equilibria on the singles species axes and then the positive equilibria on the symmetric axis (Fig. S2b).

**Bifurcations from coexistence to bistability and vice versa.** The invasion growth rates change sign as one increases  $p$  if and only if there is a  $p$  value at which the  $N_1$  and  $N_2$  nullclines intersect at the same point on the  $N_1$  axis (by symmetry, this intersection also occurs on the  $N_2$  axis). When such an intersection occurs, one has that  $N_1 = x$  satisfies

$$(1 - \alpha x)(1 + bx) = (1 - \tilde{\alpha}x)(1 + \tilde{b}x) = p/r.$$

Equivalently,

$$(b - \alpha)x - \alpha bx = (\tilde{b} - \tilde{\alpha})x - \tilde{\alpha}\tilde{b}x = p/r - 1.$$

From the first equality, we get

$$x(\Delta b + \Delta\alpha - (\tilde{\alpha}\tilde{b} - \alpha b)x) \text{ where } \Delta b = \tilde{b} - b \text{ and } \Delta\alpha = \alpha - \tilde{\alpha}$$

and either  $x = 0$  (in which case  $p = r$ ) or

$$x = \frac{\Delta b + \Delta\alpha}{\tilde{\alpha}\tilde{b} - \alpha b}$$

A nullcline crossing at  $N_1 = x$  is only of interest if  $x > 0$ . Hence, we get two cases. First, if  $\tilde{\alpha}\tilde{b} > \alpha b$ , then  $x$  is positive if and only if  $\Delta b + \Delta\alpha > 0$ . Notice that the quantity  $\Delta b + \Delta\alpha$  corresponds to the interaction index  $I_w = \tilde{b} - b - (\tilde{\alpha} - \alpha)$  presented in Eq. 4 of the main text. Second, if  $\tilde{\alpha}\tilde{b} < \alpha b$ , then  $x$  is positive if and only if  $I_w < 0$ .

These observations have two implications. Recall that  $\Delta b > 0$  means interspecific information is greater than intraspecific information, and  $\Delta\alpha > 0$  means that intraspecific competition is greater than interspecific competition. If  $\Delta\alpha < 0$  (i.e. bistability in the absence of predation) and  $\Delta b > 0$ , then predation can reverse the sign of the invasion growth rates (i.e. make them positive and thus allow for coexistence) only if  $I_w > 0$ . Second, if  $\Delta\alpha > 0$  (i.e. coexistence in the absence of predation) and  $\Delta b < 0$ , then the sign of the invasion growth rates are reversed (i.e. both negative resulting in bistability) only if  $I_w < 0$ .



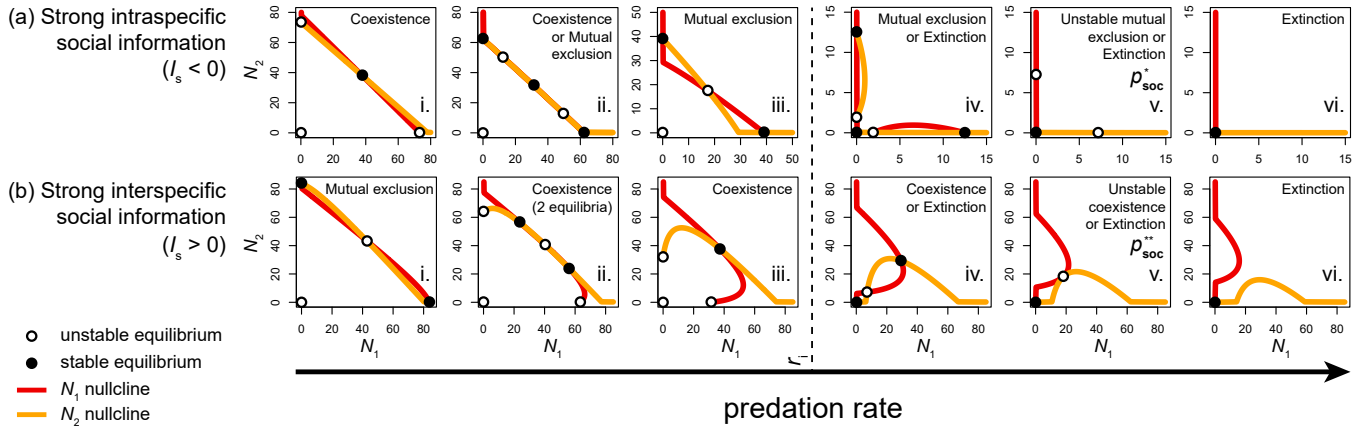


Figure S1: Phase plane plots of nullclines at which the population of each competing species exhibits zero net growth ( $N_1$  nullcline in red,  $N_2$  nullcline in yellow). Where nullclines intersect mark equilibrium points (open points denote unstable equilibria; closed points denote stable equilibria). Qualitatively distinct dynamics emerge when only one type of social information is strong in the system, intraspecific social information (a) or interspecific social information (b). The type of social information that is strong determines the sign of  $I_s$  (Eq. 5 in main text) and, thus, the progression of equilibrium outcome that a system can experience, as the predation rate affected by social information,  $p$ , increases (bottom  $x$ -axis). When only intraspecific social information is strong (a),  $p^*$  (Eq. 3 in main text) marks the threshold predation level (av), above which the populations go extinct (avi), and when only interspecific social information is strong (b),  $p^{**}$  (Eq. 5 in main text) marks the threshold predation level (bv) above which the populations go extinct (bvi). Parameter values:  $r = 1$ ; (a):  $\alpha = 0.013$ ;  $\tilde{\alpha} = 0.012$ ;  $b = 0.016$ ;  $\tilde{b} = 0.008$ ; (b):  $\alpha = 0.01$ ;  $\tilde{\alpha} = 0.012$ ;  $b = 0.01$ ;  $\tilde{b} = 0.1$ ;  $p = 0.1$  (ai), 0.38 (a ii), 0.8 (a iii), 1.004 (a iv), 1.010817 (av), 1.1 (avi), 0.3 (bi), 0.6 (b ii), 0.9 (b iii), 1.5 (b iv), 1.8 (bv), 2 (bvi). Based on these parameters and Eq. 5,  $I_s = -0.42$  (a) or 8.8 (b).

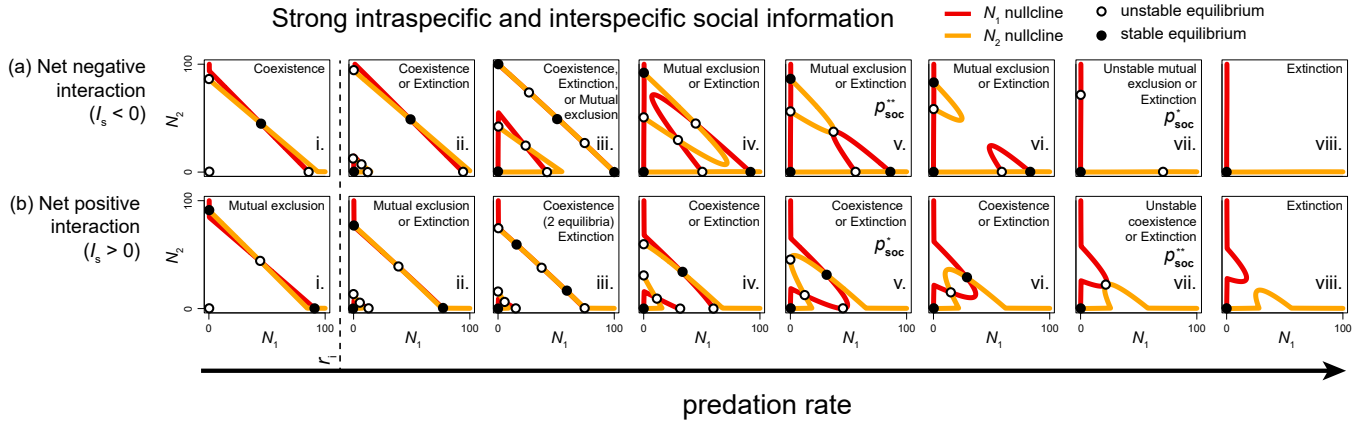


Figure S2: Phase plane plots of nullclines at which the population of each competing species exhibits zero net growth ( $N_1$  nullcline in red,  $N_2$  nullcline in yellow). Where nullclines intersect mark equilibrium points (open points denote unstable equilibria; closed points denote stable equilibria). Qualitatively distinct dynamics emerge when both intraspecific and interspecific social information are strong in the system. Under these conditions, as before (Fig. S1), it is whether the sign of the net interaction index,  $I_s$  (calculated from the relative effects of social information and competition; Eq. 5 of main text), is negative (a) or positive (b) that determines the progression of equilibrium outcomes that a system can experience, as the predation rate affected by social information,  $p$ , increases (bottom x-axis). Here, equilibria on the single species axes vanish once predation exceeds  $p^*$  (avii, bv; Eq. 3 of main text), and equilibria on the symmetric two-species axis (the 1:1 line) vanish once predation exceeds  $p^{**}$  (av, bvii; Eq. 6 of main text). Parameter values:  $r = 1$ ; (a):  $\alpha = 0.011$ ;  $\tilde{\alpha} = 0.010$ ;  $b = 0.18$ ;  $\tilde{b} = 0.15$ ; (b):  $\alpha = 0.010$ ;  $\tilde{\alpha} = 0.011$ ;  $b = 0.10$ ;  $\tilde{b} = 0.15$ ;  $p = 0.9$  (ai), 2 (a ii), 2.15 (a iii), 2.7 (a iv), 3.025 (a v), 3.2 (a vi), 3.49719 (a vii), 3.6 (a viii), 0.9 (bi), 3 (b ii), 4 (b iii), 4.35 (b iv), 4.444481 (b v), 4.5 (b vi), 4.606187 (b vii), 4.7 (b viii). Based on these parameters and Eq. 5 of main text,  $I_s = -0.08$  (a) or 1.39 (b).

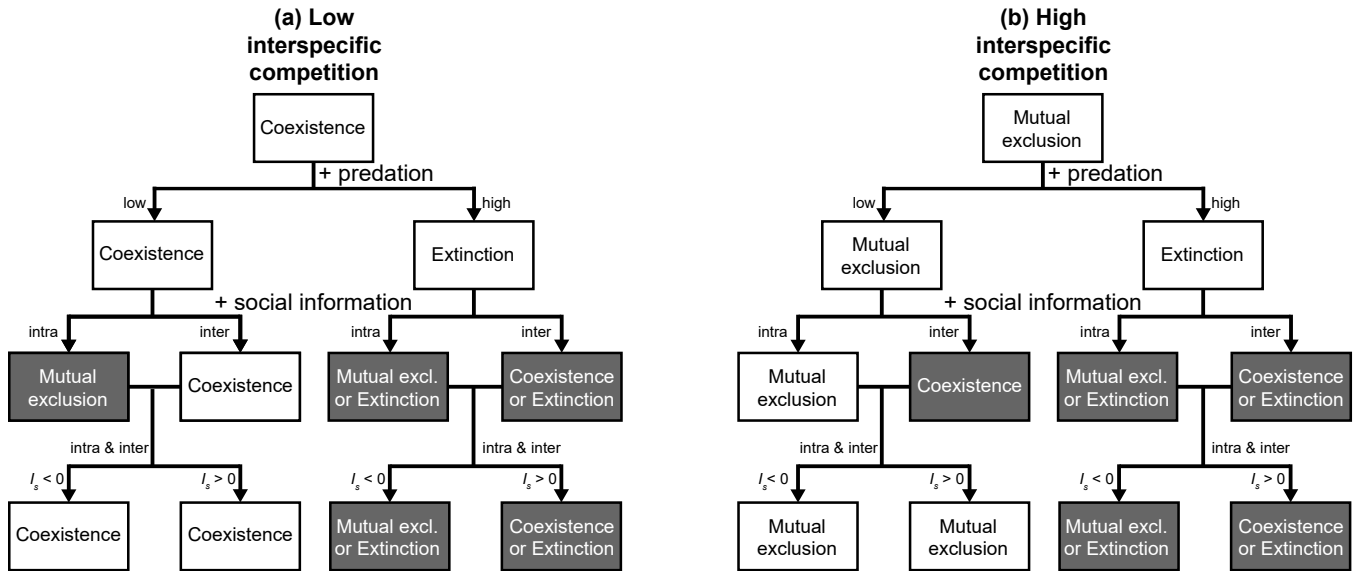


Figure S3: Summary of effects of different types of social information (intraspecific and/or interspecific) on the fate of populations of competing species at equilibrium, under low interspecific competition (a;  $\alpha > \tilde{\alpha}$ ) or high interspecific competition (b;  $\alpha < \tilde{\alpha}$ ), and under low predation ( $r > p$ ; left branches) or high predation ( $r < p$ ; right branches). Here, when social information is added to the system in either form (3rd row) or both forms (4th row), it is relatively strong (i.e., intra alone:  $b/\tilde{\alpha} > 1$  and  $(b + \tilde{b})/(\tilde{\alpha} + \alpha) < 1$ , inter alone:  $b/\tilde{\alpha} < 1$  and  $(b + \tilde{b})/(\tilde{\alpha} + \alpha) > 1$ , intra & inter:  $b/\tilde{\alpha} > 1$  and  $(b + \tilde{b})/(\tilde{\alpha} + \alpha) > 1$ , see Appendix S3 for details; Eq. 2; Fig. 2). The inclusion of social information can drive qualitative shifts in the fate of the system (denoted by shaded boxes). Note that such shifts from coexistence to mutual exclusion (a) or vice versa (b) are generally expected at low to intermediate levels of social information (e.g., bottom-left corners of Fig. 6c, d; just beyond the white ‘Extinction’ region in Fig. 6a, b) and become less likely at high levels of both types of social information, unless there is sufficiently high predation or there are strong asymmetries in information types (e.g., see right edges of Fig. 6a, c and top edges of Fig. 6b, d). Qualitative shifts (grey boxes) in the 3rd row follow (from left to right) from Fig. S3-1 aiii, aiv, biii, biv, and qualitative shifts in the 4th row follow from Fig. S3-2 aiv-avii, biv-bvii.

## **Appendix S4: Effects of social information on competition in the face of asymmetries**

*for Social information drives ecological outcomes among competing species*

by Michael A. Gil, MARRISA L. BASKETT, and Sebastian J. Schreiber

In this Appendix, we use numerical simulations to examine the effects of social information on competitive dynamics between two species when one species is competitively superior, or when one species is preferentially consumed by a shared specialist predator. Note that in both of these cases of asymmetric competing species, the net interaction indices, as presented in the main text, are no longer sufficient to determine the sequence of dynamics the system can exhibit. However, see Appendix S3 for a modification of the inequality used to create  $I_s$  (Eq. 5) that accounts for species-specific differences in population growth rate and mortality rate due to predation.

### **Superior competitor**

To measure the demographic consequences of social information when two competing species are not competitively equivalent (i.e., symmetric), we use Eq. 2 to model species 1 as a superior competitor ( $\alpha_{12} < \alpha_{21}$ ), whose population,  $N_1$ , has an advantage over the population of species 2 ( $N_2$ ), an inferior competitor, for most initial conditions. When interspecific competition exceeds intraspecific competition (Fig. S1a), species 1 outcompetes species 2 over a greater range of initial conditions (Fig. S1ai), and when intraspecific competition exceeds interspecific competition (Fig. S1b), species 1 and 2 coexist, but  $N_1$  is greater than  $N_2$  over a greater range of initial conditions (Fig. S1bi). These outcomes result from the absence of social information, or from the case when the effects of intraspecific and interspecific social information are equivalent and the same for both species. However, if intraspecific or interspecific social information has a greater effect on one species, this can quantitatively or qualitatively shift competitive outcomes;

when social information provides greater benefits to competitively inferior species, these species can persist or reach the larger of the two population sizes over a greater range of initial conditions than competitively superior species (Fig. S1a<sub>ii</sub>, a<sub>iv</sub>, b<sub>ii</sub>, b<sub>iv</sub>), and when social information provides greater benefits to competitively superior species, these species can exert greater dominance over the inferior competitor, in some cases excluding this species under all initial conditions (Fig. S1a<sub>iii</sub>, b<sub>iii</sub>).

### **Specialist predator**

We use Eq. 2 to model the case when the predator shared between the competing populations specializes on (i.e., prefers) one of the two species; in this case, the predator prefers species 1 over species 2 ( $p_1 > p_2$ ). When interspecific competition exceeds intraspecific competition (Fig. S2a), species 2 can competitively exclude the predator-targeted species 1 over all initial conditions (a<sub>i</sub>), and when intraspecific competition exceeds interspecific competition (Fig. S2b), species 1 and 2 coexist, with  $N_2$  greater than  $N_1$  (Fig. S2b<sub>i</sub>). These outcomes result from the absence of social information, or from the case when the effects of intraspecific and interspecific social information are equivalent and the same for both species. However, if intraspecific or interspecific social information has a greater effect on one species, this can quantitatively or qualitatively shift competitive outcomes; when social information provides greater benefits to the prey species that is preferred by the predator (species 1), this species that could otherwise go extinct can persist and reach the larger of the two population sizes over a greater range of initial conditions than the species that is less preferred by the predator: species 2 (Fig. S2a<sub>iii</sub>, a<sub>v</sub>). When social information provides greater benefits to the species less preferred by the predator (species 2), this species can exert greater dominance over the predator-targeted species (species 1), which

can cause or maintain competitive exclusion of this species over all initial conditions (Fig. S2aii, aiv, bii).

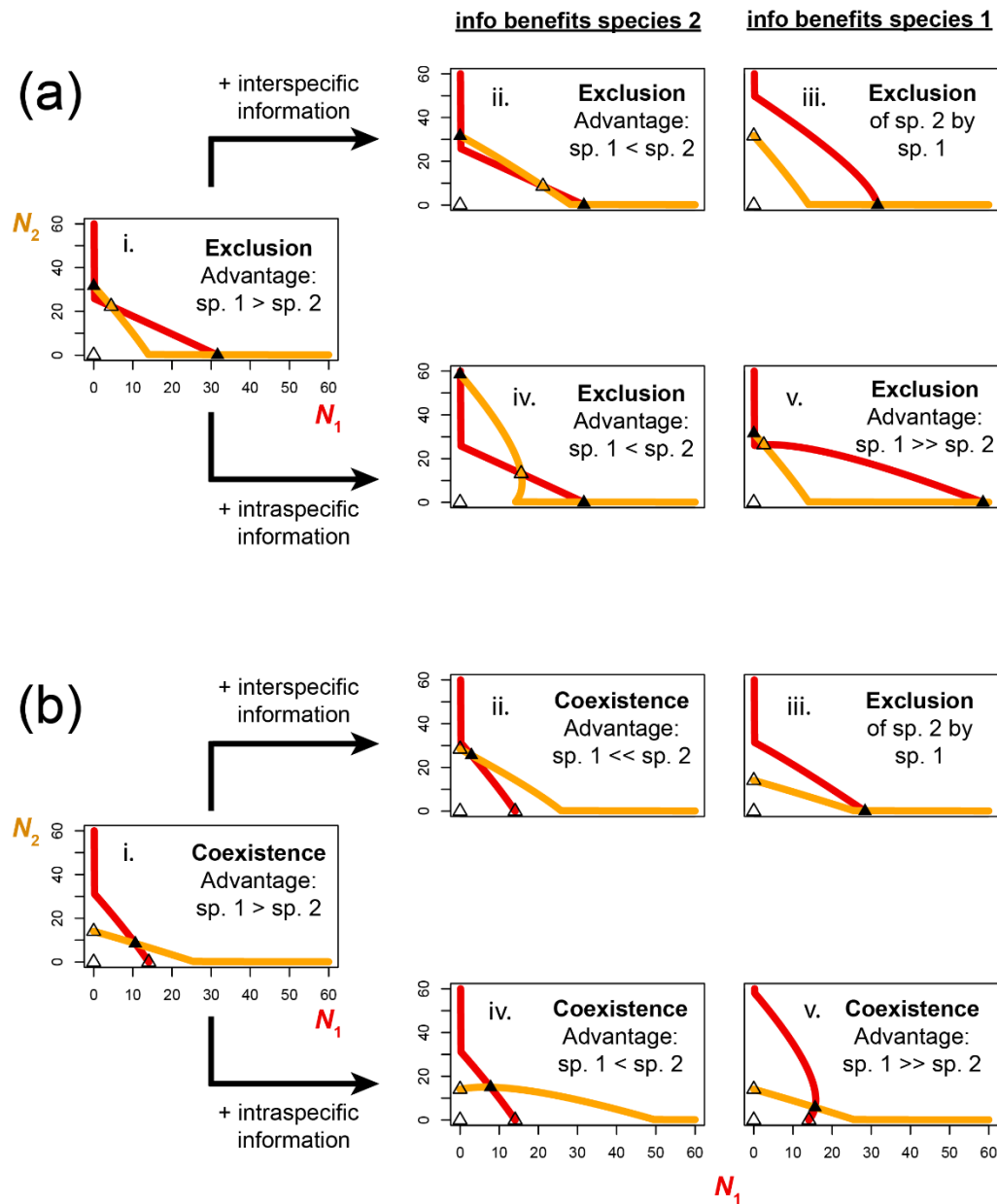


Fig. S1: Effects of social information on the outcomes of asymmetric competition.

Phase plane plots of nullclines at which the population of each competing species exhibits zero net growth ( $N_1$  nullcline in red,  $N_2$  nullcline in yellow); where nullclines intersect mark equilibrium points (open points denote unstable equilibria; closed points denote stable

equilibria). When one species is competitively superior (species 1, in this case), and whether interspecific competition exceeds intraspecific competition (a) or intraspecific competition exceeds interspecific competition (b), asymmetries in effects of social information can determine the outcome of competitive interactions on populations. As in the main text figures,

Parameters used: all panels:  $r = 1$ ,  $p = 0.9$ , (a):  $\alpha_{11} = \alpha_{22} = 0.01$ ,  $\alpha_{12} = 0.011$ ,  $\alpha_{21} = 0.015$ ; (b):  $\alpha_{11} = \alpha_{22} = 0.015$ ,  $\alpha_{12} = 0.010$ ;  $\alpha_{21} = 0.011$ ; (ai, bi):  $b_{11} = b_{22} = 0.01$ ,  $b_{12} = b_{21} = 0.01$ ; (aii, biv):  $b_{11} = b_{22} = 0.01$ ,  $b_{12} = 0.01$ ,  $b_{21} = 0.02$ ; (aiii, bv):  $b_{11} = b_{22} = 0.01$ ,  $b_{12} = 0.02$ ,  $b_{21} = 0.01$ ; (aiv, bii):  $b_{11} = 0.01$ ,  $b_{22} = 0.02$ ,  $b_{12} = b_{21} = 0.01$ ; (av, biii):  $b_{11} = 0.02$ ,  $b_{22} = 0.01$ ,  $b_{12} = b_{21} = 0.01$ .

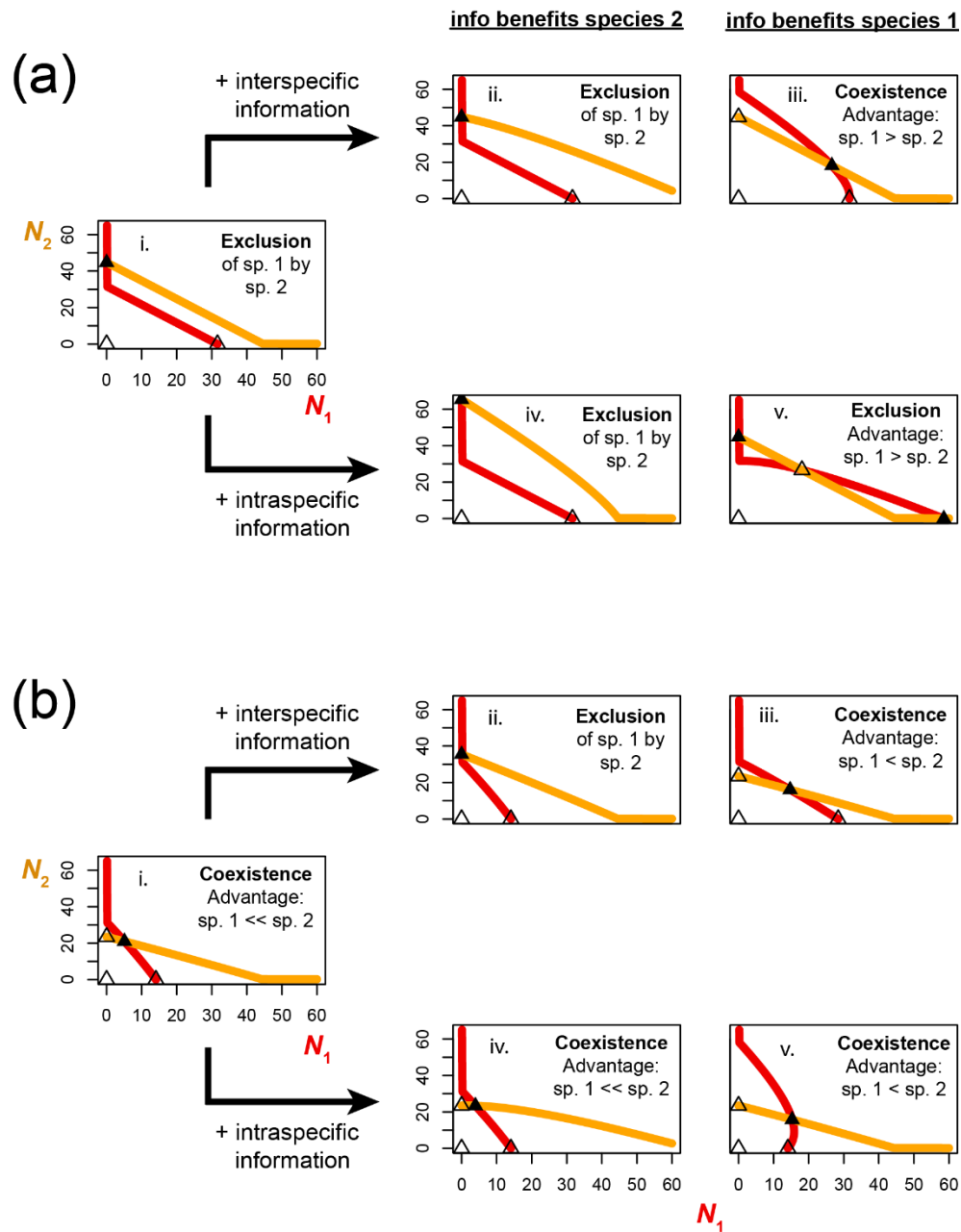


Fig. S2: Effects of social information about a specialist predator. Phase plane plots of nullclines at which the population of each competing species exhibits zero net growth ( $N_1$  nullcline in red,  $N_2$  nullcline in yellow); where nullclines intersect mark equilibrium points (open points denote unstable equilibria; closed points denote stable equilibria). When one prey species (species 1, in this case) is preferentially consumed by a predator that is shared by a second, less-preferred species (species 2), and whether interspecific competition exceeds intraspecific competition (a)



or intraspecific competition exceeds interspecific competition (b), asymmetries in effects of social information can determine the outcome of competitive interactions on populations.

Parameters used: all panels:  $r_1 = r_2 = 1$ ,  $p_1 = 0.9$ ,  $p_2 = 0.8$ ,  $\alpha_{12} = \alpha_{21} = 0.01$ ; (a):  $\alpha_{11} = \alpha_{22} = 0.01$ ;

(b):  $\alpha_{11} = \alpha_{22} = 0.015$ ; (ai, bi):  $b_{11} = b_{22} = 0.01$ ,  $b_{12} = b_{21} = 0.01$ ; (aii, biv):  $b_{11} = b_{22} = 0.01$ ,  $b_{12} =$

$0.01$ ,  $b_{21} = 0.02$ ; (aiii, bv):  $b_{11} = b_{22} = 0.01$ ,  $b_{12} = 0.02$ ,  $b_{21} = 0.01$ ; (aiv, bii):  $b_{11} = 0.01$ ,  $b_{22} =$

$0.02$ ,  $b_{12} = b_{21} = 0.01$ ; (av, biii):  $b_{11} = 0.02$ ,  $b_{22} = 0.01$ ,  $b_{12} = b_{21} = 0.01$ .