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The evolution of host manipulation by parasites: a game theory analysis

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Abstract Many parasites are known to manipulate the behaviour of intermediate hosts in order to increase their probability of transmission to definitive hosts. This manipulation must have costs. Here we explore the combined effects of three such costs on the amount of effort a parasite should expend on host manipulation. Manipulation can have direct costs to future reproductive success due to energy expended to manipulate the host. There may also be indirect costs if other parasites infect the host and profit from the manipulation without paying the cost of manipulation. These "free riders" may impose a third cost by competing with manipulators for resources within the host. Using game theory analysis and several different competition models we show that intrahost competition will decrease the investment that a parasite should make in manipulation but that manipulation can, under some circumstances, be a profitable strategy even in the presence of non-manipulating competitors. The key determinants of the manipulator's success and its investment in manipulation are the relatedness among parasites within the host, the ratio of the passive transmission rate to the efficiency of increasing transmission rate and the strength of competitive effects. Manipulation, when exploited by others, becomes an altruistic behaviour. Thus we suggest that our model may be generally applicable to cases where organisms can exploit the investment of others (possibly kin) while also competing with the organism whose investment they exploit.

Keywords Parasite · Host · Manipulation · Competition, mathematical model · Game theory · Altruism

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Introduction

Parasites, particularly macroparasites, are known to manipulate the behaviour of their hosts in ways that increase their probability of transmission (Poulin 1998; Lafferty 1999; Moore 2002; Thomas et al. 2005). In the best documented cases, parasitic worms alter the behaviour of their intermediate host in ways that make it more likely to be eaten by the parasite's definitive host (Lafferty 1999; Moore 2002). The ability to manipulate host behaviour has evolved independently several times, both across and within numerous parasite phyla (Poulin 1998; Moore 2002). Host manipulation must therefore confer substantial benefits to parasites to account for its repeated appearance over evolutionary time. Brown (1999) pointed out that this manipulation is likely to be costly to the parasite in two ways (see also Poulin 1994). First, manipulation requires some effort by the parasite and probably reduces its own growth rate within the host, decreasing its survival and/or reproductive success in its definitive host. Manipulation is often induced via substances produced by the parasite and acting on the host's nervous system (e.g., Helluy and Holmes 1990; Thompson and Kavaliers 1994; Øverli et al. 2001; Helluy and Thomas 2003); the development of specialized tissues and the secretion of these substances must come with a cost. Second, manipulators are open to exploitation by conspecifics who infect the same host but who don't manipulate host behaviour. These non-manipulators will also be transmitted to their definitive host due to the efforts of the manipulator but do not pay the cost of manipulation. Brown (1999) proposed a model of this behaviour in which manipulators made up for their losses through benefits gained by the group in which they lived; the model contrasted individual selection with kin or group selection. Here we propose to add possible competitive effects among parasites within a single host (Parker et al. 2003; Michaud et al. 2006) to this model. Like Brown (1999) we will consider both types of cost to manipulators and we will model both linear and non-linear effects on parasite transmission rates.

We intend our model to apply primarily to trematode parasites which have a complex life-cycle typically involving at least three different organisms (see Kearn 1998; Combes 2001). Following the infection of a first intermediate host (usually a snail) by a single trematode egg, the parasite begins to multiply asexually, producing cercariae that will be responsible for finding and infecting the second intermediate host. Infected snails release from a few dozen to a few thousand cercariae per day, often for months or years. Cercariae usually penetrate the second intermediate host, where they encyst as metacercariae. The life cycle is completed when an infected second intermediate host is ingested by a vertebrate definitive host, in which the parasites develop into adult worms. Two well-documented aspects of the trematode life cycle are relevant to our models. First, many trematode species have been shown capable of manipulating the behaviour of their second intermediate host in order to increase transmission rates to their definitive hosts (e.g, Webber et al. 1987; Lafferty and Morris 1996; Mouritsen and Jensen 1997; Helluy and Thomas 2003; see exhaustive review in Moore 2002). Second, there is evidence that metacercariae can compete for resources within the second intermediate host, resulting in reduced growth and future fecundity (Sandland and Goater 2000; Brown et al. 2003; Fredensborg and Poulin 2005). In addition, the asexual reproduction of trematodes within their snail host, coupled with the low mobility of snails and the limited dispersal capabilities of cercariae, means that the second intermediate host may be infected by several individuals of a given parasite clone. For instance, for both the trematodes *Maritrema novaezealandensis* and *Coitocaecum parvum* in amphipods, more than one metacercariae of the same clone are regularly identified in the same individual host using microsatellite

DNA markers (Keeney et al. 2007; Lagrue et al. 2009). In our models we will consider cases in which a host may be infected by members of one or more clones. When two or more different clones are present, benefits will be shared with parasites of other genotypes. We expect the presence of other clones within the host to lower the investment in host manipulation because parasites should be less willing to help non-kin.

In this paper we construct general models for the evolution of host manipulation with intra-host competition, inspired by the biological features of trematodes and applicable to other trophically transmitted parasites capable of manipulation, such as cestodes and acanthocephalans. We expect that the models may apply to a much larger class of behaviours in which an individual's investment in its own fitness can be exploited by its competitors, thus making such investments seem altruistic or cooperative. Our analyses of the effect of competition on manipulative effort can thus also apply to the evolution of cooperation among kin who compete with each other (Queller 1994; West et al. 2001; West and Buckling 2003). In order to attain a certain amount of generality in our models we evaluate several possible competition models and both linear and non-linear effects of manipulation on transmission probability.

The model

We start with a model of fitness (W) similar to Brown et al. (2002) in which we change one parameter and to which we add the effects of competition within hosts:

$$W = \left(1 - x - {}^{N}\!/_{K}\right)(p_0 + bN\bar{x}). \tag{1}$$

Here, the first right-hand term accounts for losses due both to the investment effort, x, and to resource competition, N/K, within the host. The second term accounts for the increase in the probability of transmission to the new host. The term x is measured as the cost to the parasite in reduced future reproduction (either by increased probability of mortality before reproduction or decreased fecundity in the definitive host). This manipulation increases the probability that the parasite's host will be eaten by its definitive host by an amount proportional to the loss of fecundity, say bx (b can be interpreted as the efficiency of manipulation). Further, each parasite which sacrifices a proportion x of its future fecundity increases the probability that the current host will be consumed by a definitive host by $b\,x$. So in total, if N parasites in a host each sacrifice on average $\bar{x}$, the increase in probability will be $bN\bar{x}$. We define p_0 as the passive transmission rate (the probability of being passed to the definitive host if no sacrifice is made by any parasite). Finally, K accounts for within host competition among parasites. The parameter is borrowed from the logistic population growth model and causes a linear reduction in fecundity as the number of parasites per host increases. Our approach is the same as that adopted by Anderson and May (1978) to account for intra-host competition (our parameter K is $1/\mu$ in their notation).

Because the success of each parasite depends on the strategy adopted by the other parasites within the host it is appropriate to use game theory (see Maynard Smith 1982 Eq. 2.11, Brown 2001 or Brown et al. 2002) in order predict the amount of effort which each parasite is likely to invest in manipulation. Game theory analysis predicts an unbeatable strategy, that is, a strategy which, if adopted by all members of a group, prevents all rare invading strategies from achieving greater success than they do. We will refer to such an unbeatable strategy as an ESS (evolutionary stable strategy). To find the ESS investment (see Maynard Smith 1982, Eq. 2.11) in parasite manipulation we calculate, using Eq. 1, the fitness of an invading mutant, using strategy x, in a group whose mean strategy is $\bar{x}$. Differentiating this equation with respect to x, and setting the differential equal to zero allows us to find the best response x to the ESS, $\bar{x}$. Then setting $\bar{x}$ equal to x and solving for x gives us the ESS.

The first stage of this process shows that the best response to the ESS will be

$$x_c = 1 - {}^{N}\!/_{K} - \frac{p_0}{bN^{\partial\bar{x}}\!/_{\partial x}} - \frac{\bar{x}}{{}^{\partial\bar{x}}\!/_{\partial x}}. \tag{2}$$

It is important to note that in Eq. 1 $\bar{x}$ is in fact a function of x because as an individual changes its strategy the mean strategy of the group also changes. In fact the change can be measured as $\frac{1+(N-1)r}{N}$where r is the mean relatedness of a focal individual to all other individuals in the group (see Brown 2001). The term $(N-1)r/N$ in this equation accounts for changes in the mean due to relatives of the focal individual. Substituting this value for ${}^{\partial\bar{x}}\!/_{\partial x}$ and solving for $\bar{x} = x$ gives us an ESS, in the presence of competition, of

$$x_c^* = \frac{(K-N)(1+(N-1)r)}{K(1+(N-1)r+N)} - \frac{p_0}{b(1+(N-1)r+N)}. \tag{3}$$

Our main objective here is to evaluate the effects of intrahost competition. We can see this by differentiating x_c^* with respect to K. The resulting expression is always positive showing that investment should increase as K increases. Increasing values of K represent decreases in competition. Thus, as the strength of intrahost competition increases, investment in host manipulation should decrease. This decrease can be quantified by the difference between x_n^*, the expected (ESS) investment in the absence of competition, and x_c^*.. It is easily shown that

$$x_n^* = \frac{(1+(N-1)r)}{(1+(N-1)r+N)} - \frac{p_0}{b(1+(N-1)r+N)}. \tag{4}$$

So the proportional decrease in investment due to intrahost competition should be:

$$\frac{\left(x_n^* - x_c^*\right)}{x_n^*} = \frac{N}{K}. \tag{5}$$

Figure 1 illustrates the reduction in investment due to intrahost resource competition. Note that intrahost competition not only reduces the investment in host manipulation (see Fig. 1b) but also reduces the range of passive transmission rates and parasite loads for which manipulation is profitable (best seen by comparing Fig. 1a, with competition, and the upper graph in 1b, without competition). Furthermore, intrahost resource competition reduces the range of passive transmission rates for which increased parasite load will lead to higher investment in manipulation (compare the lower left-hand side of Fig. 1a, with competition, with the lower left-hand side of the upper graph in 1b, without competition).

It is also of interest to see how intrahost competition may affect the way in which other parameters influence the model. Brown et al. (2002) showed, for a slightly different form of this model, that virulence, which should respond roughly the same way investment in manipulation does in our model, could either increase or decrease as group size (N) increased. For our model, by differentiating Eq. 4 with respect to N we can see that x_n^* will increase with increasing N whenever

$${}^{p_0}\!/_{b} > {}^{(1-r)}\!/_{(1+r)}; \tag{6}$$

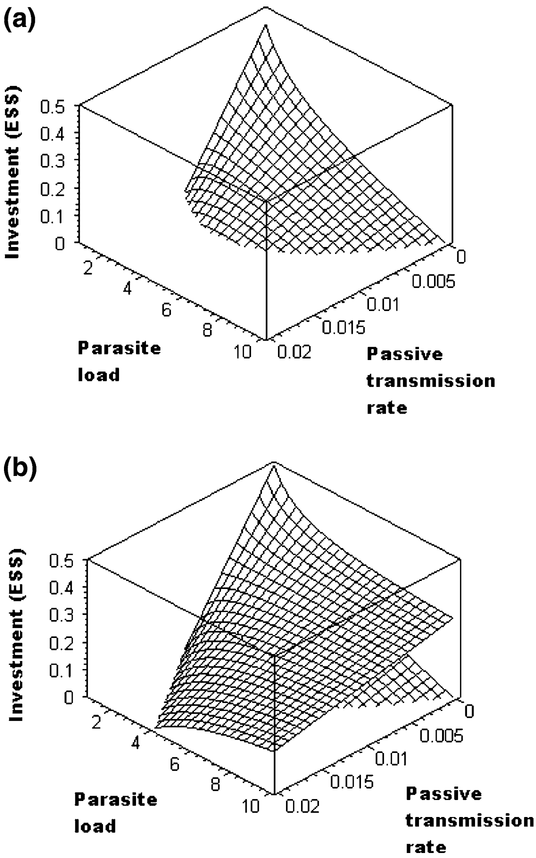

Fig. 1 The effect of parasite load and passive transmission rate on investment in host manipulation based on the linear model (Eq. 1). **a** with intrahost resource competition ($r = 1/3$, $b = 1/100$ and $K = 10$) and **b** without intrahost resource competition compared to with intrahost resource competition. Note that 1**b** shows that the investment without resource competition is greater than the investment with competition for every combination of parameter values

and x_n^* will decrease as N increases when this relation is reversed. A similar analysis could be done with Brown et al.'s (2002) model adding precision to their assertion that parasite virulence will not necessarily decrease as parasite load (N) increases.

In the presence of intrahost competition, the condition for x_c^* to increase with N becomes

$$p_0/_b > \frac{1-r}{1+r} + \frac{(1-r)^2}{K(1+r)} + \frac{rN(N(1+r)+2(1-r))}{K(1+r)}. \qquad (7)$$

Thus, with intrahost competition, manipulative effort is less likely to increase as parasite load increases than when such competition is absent. This result suggests that manipulative effort will increase with increased parasite load only when competition is weak (large K) and parasites are closely related (high r).

When only a single clone infects a given host Eq. 7 simplifies to $p_0/_b > \frac{N^2}{K}$ implying that manipulative effort will increase with parasite load only when parasite load is very small relative to the capacity of the host.

Intrahost competition can potentially affect the way in which other factors influence investment in host manipulation. For instance, when competition is present relatedness among parasites within a host does not increase investment nearly as much as when competition is absent (Fig. 2). However, we do note that as mean relatedness with other

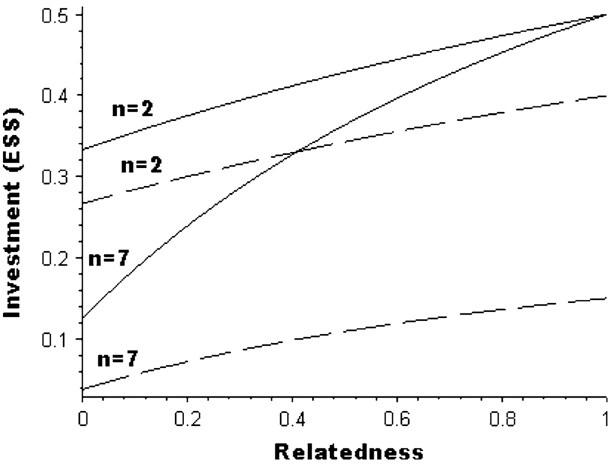

Fig. 2 The effect of relatedness on investment at two parasite loads (**n**) ($b = 1/100$, $K = 10$ and $p = 0$). Note that when parasites do not compete within the host (*solid lines*) investment converges on a maximal value as relatedness approaches 1. However, competition within the host (*dashed lines*) prevents this convergence, keeping investment, in fact near zero as relatedness approaches 1

parasites in the host increases investment increases for all values of r and N for which investment is worthwhile.

Differentiating both x_c^* and x_n^* with respect to b and to p_0 shows that investment in manipulation should increase as b increases (Fig. 3) and decrease as p_0 increases (Fig. 1 a, b) regardless of whether or not there is intrahost competition. In both cases, as parasite load, and thus intrahost competition, increases the rate of increase in investment slows down.

Alternate models

Equation 1 assumed that intra-host competition had a logistic form (following Anderson and May (1978)). In order to assure that our results do not depend strictly on the choice of this one model, we repeated the analysis presented above using four other competition models (Appendix 1): a single-species Monod model, a Ricker model, a Hassel model, and a shared-resources model. The latter assumed reproductive success decreased geometrically as the number of parasites in the host increased. The Ricker and the shared resources model were not constrained to parasite loads less than K, as were the other models. Our analyses also cover the Beverton-Holt model which is a special case of the Hassell model.

Analyses of these additional models have many points in common with the analysis of the logistic model. In all cases, competition reduces the expected (ESS) level of investment in manipulation. In all models, investment increased with increases in mean relatedness (r) and efficiency of manipulation (b) but decreased with increases in passive transmission rate (p_0). Investment also decreased as the strength of competition increased (as K decreased) in all models except Ricker where K had no effect and the shared resource model which lacks this parameter. That all these models produce similar results suggests that our analyses may apply quite generally to the effects of competition on investment in parasite manipulation.

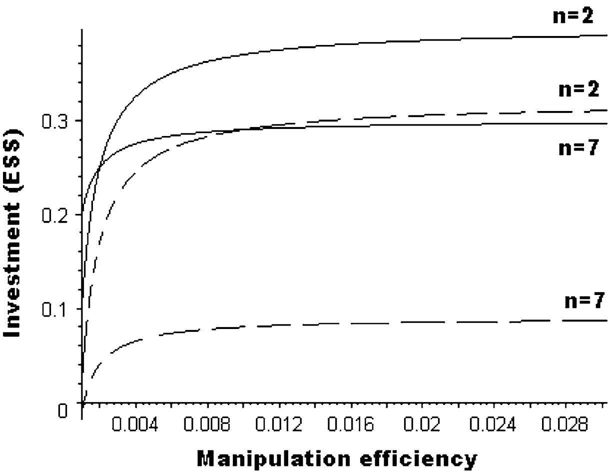

Fig. 3 The effect of manipulation efficiency on investment at two parasite loads (**n**). ($r = 1/3$, $K = 10$ and $p = 1/1000$) (No competition, *solid lines*; Competition, *dashed lines*). Note that as efficiency increases, investment also increases and that the reduction in investment due to competition increases as parasite load increases

Models with independent effects

If the loss due to competition is independent of that due to manipulative effort fitness can be evaluated using the model

$$W = \left((1-x)\left(1-{}^{N}\!/_{K}\right)\right)(p_0 + bN\bar{x}). \tag{8}$$

Analysis of this model shows that competition has no effect on manipulative effort. This is the result of the assumption that the effects of competition and manipulative effort are independent. The result applies not only to the logistic model in Eq. 8 but also to all the models in Appendix 1 if they are adjusted so that these two factors operate independently.

Non-linear effects

Our model in Eq. 1 assumes that the combined effect of several parasites in one host is simply the sum of the effects of the individual parasites. This may not always be true. We explore this possibility by generating a non linear version of Eq. 1 (see Appendix 2), $W = \left(1 - x - {}^{N}\!/_{K}\right)(p_0 + bN^a\bar{x})$.

The non-linear model leads to the same conclusions as the linear model except with respect to the conditions under which investment should increase as parasite load increases. The latter conditions fall into two categories. When the combined effect of several parasites has an asymptote (is less than the sum of the individual effects), investment should decrease with increased parasite load at all passive transmission rates. Further, the range of passive transmission rates and parasite loads for which manipulation is profitable is greatly reduced compared to the linear model (compare Figs. 4a and 1b). On the other hand, when the combined effect of several parasites is synergistic (greater than the sum of the individual effects), lower passive transmission rates (compared to the linear model) can generate increased manipulation as a function of increased parasite load and manipulation

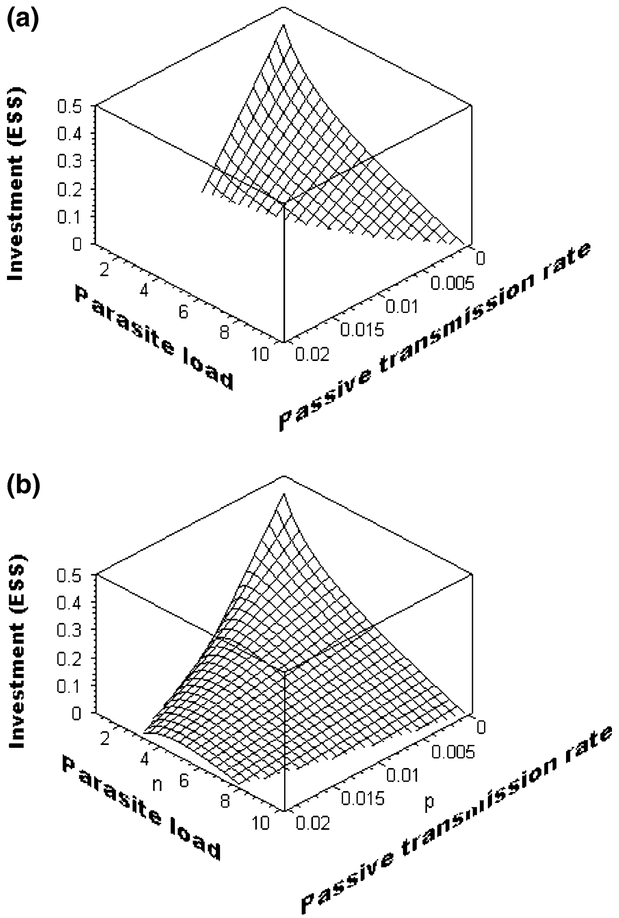

Fig. 4 The effect of parasite load and passive transmission rate on investment in host manipulation based on the nonlinear model (Eq. 7). **a** the combined manipulative effect of several parasites is less than the sum of the individual effect ($x = 2/3$) and **b** the combined manipulative effect of several parasites is greater than the sum of the individual effect ($x = 3/2$). (Competition is present in both (**a**) and (**b**); $r = 1/3$, $b = 1/100$ and $K = 10$)

will be profitable under a wider range of passive transmission rates and parasite loads (compared to the linear model see Figs. 4b versus 1b).

Discussion

The ability to manipulate host behaviour has evolved independently several times, in many different parasite lineages (Poulin 1998; Moore 2002). Yet, not all parasites have this ability, even when their close relatives do. Assuming that host manipulation is not constrained genetically or otherwise, there must be conditions under which it is favoured, and conditions under which it is not. Analysis of our simple model in the absence of competition would suggest that a lone parasite should sacrifice up to ½ of its fecundity in order to manipulate host behaviour. However, our model clearly shows that competition reduces the investment which a parasite should make towards manipulating its host. This result occurs in all variants of our model. We surmise that competition reduces the parasite's expected gain if it succeeds in infecting its definitive host, thus making manipulation a less interesting prospect and reducing the investment a parasite will make in host manipulation.

While resource competition should always reduce manipulative effort and restrict the conditions under which manipulation will be profitable, it will not necessarily negate the advantages of manipulating. In fact manipulation can remain profitable despite competition among kin provided that parasites do not reach the carrying capacity of their host. Manipulation can even be so profitable that manipulative effort will increase as parasite load increases. This occurs because the benefits shared among kin due to manipulation more than counterbalance losses due to competition. However, competition reduces the range of parameter (r, b, p_0 and N) values over which manipulative effort should increase as parasite load increases. This is particularly clear in the linear (Fig. 1a) or asymptotic (Fig. 4a) models but synergistic effects among parasites can counteract this tendency (Fig. 4b).

In many cases the presence of multiple parasites within a host should decrease the level of manipulative effort per parasite. Brown (1999) pointed out that in the absence of intrahost competition these decreases in manipulation per individual lead to an increase in total manipulation of the host as the rate of decrease is less than proportional to the number of parasites in the host. The result is then that hosts should be more strongly manipulated when they harbour more individuals even though each individual puts less effort into manipulation. This results in greater benefits per individual than when the parasite manipulates on its own. This situation does not necessarily hold when intrahost competition occurs. Figs. 1a, 4a, b show clearly (note that investment approaches or reaches zero as N approaches K) that reductions in individual effort may even reduce total manipulation of the host.

Our model assumes that when a host is infected by several individuals of the same clone, the costs of manipulation are shared equally among individuals, and all reap the same benefits. Although this is likely to hold for most cases, species of the trematode genus *Dicrocoelium* offer one famous exception. In what is now a textbook example, *Dicrocoelium* spp. cause their ant second intermediate hosts to attach to the tips of grass blades, where they are susceptible to grazing herbivores such as sheep that serve as definitive hosts for the parasites (Carney 1969; Romig et al. 1980). Because of the way ants become infected, it is very likely that each ant harbours only individual parasites of a single clone (Wickler 1976; Wilson 1977), although this still needs to be confirmed with genetic data. Within an infected ant, a single parasite induces the manipulation by attaching to the host's brain, while the other parasites remain in the host's body cavity. Following ingestion of the ant by a suitable definitive host, the manipulator invariably dies, whereas the other parasites establish within the definitive host (Wickler 1976; Wilson 1977). This example, and a few others like it (see Poulin et al. 2005), illustrate dramatically how costly it can be for a parasite to invest in manipulation. The *Dicrocoelium*-ant association also shows that in some unusual cases, manipulative effort is not shared equally among all members of the same parasite clone within an intermediate host. It remains, however, possible that each parasite has equal expected cost when it enters the ant/host and that chance determines which individual parasite sacrifices all to the benefit of the others. If this is the case then our model may still apply to this classic example.

One might argue, as has Brown (1999), that a linear model is unrealistic because it can predict transmission probabilities greater than 1 for high levels of effort. We note here that this will not happen in our model provided that $b < (1 - p_0)/N$. Data are needed to evaluate the relationship between manipulative effort and realised transmission. If such data show an approximately linear relation, there is no reason to exclude the linear model (provided that b is sufficiently small).

A brief analysis of the possible consequences a non-linear relation between lost fecundity and increased probability of transfer suggests that our general conclusions will hold both when increased transfer is a function of the square of lost fecundity and when it is a function of the square root. In the former case, the model predicts higher investment in host manipulation (and thus greater lost fecundity) than in the linear model; lower investment in the latter case. However, in both cases within host competition has the same effect as with the linear model.

It is not necessary to suppose that parasites can evaluate the number of conspecifics in each host and adjust their effort accordingly, although our model could apply to this case. It suffices that parasites adapt to the mean (expected) number of parasites per host. Analysis of another version of our model, not presented here, using a negative binomial distribution of parasites among hosts showed that manipulation levels will be the same if we assume that parasites adapt to mean levels or if we let them adapt to the distribution of parasites among hosts.

Our models' predictions apply not only to trematodes but also to any organism whose investment can be exploited by others such as bean weevils burrowing into beans (Ohtsuka and Toquenaga 2008), foraging birds (Fernández-Juricic et al. 2005) whose food is "scrounged" by others (Vickery et al. 1992) and other parasitic worms capable of manipulating their intermediate hosts, such as cestodes and acanthocephalans (e.g., Rosen and Dick 1983; Dezfuli et al. 2001; Parker et al. 2003; Michaud et al. 2006). In these other groups, the genetic relatedness within groups will differ from that observed in trematodes. In acanthocephalans and the majority of cestodes, there is no asexual multiplication in a first intermediate host. Conspecifics sharing the same host may sometimes be full-sibs (see Jäger and Schjørring 2006), but more commonly they will be unrelated individuals as may be the case in foraging birds and possibly burrowing weevils. Thus, for these organisms the relatedness parameter r in our model might be quite low, but our model will still apply.

If manipulation is seen as altruistic because it shares its benefits with others (Hamilton 1964) this suggests that altruism can evolve despite inter-kin competition, a problem that has been much debated lately (see Queller 1994; West et al. 2001; West and Buckling 2003 among others). In the broadest sense, our model suggests that the evolution of social behaviour will be influenced by the interaction between benefits given to kin and competition among kin.

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Appendix 1: Comparison of analyses based on five different competition models

(a) Fitness equations used for the competition models

MODEL

$$\text{Logistic} \quad \left(1 - x - {}^{N}\!/_{K}\right)(p_0 + bN\bar{x})$$

$$\text{Monod}\quad \left(\frac{K-N}{a+K-N}-x\right)(p_0+bN\bar{x})$$

$$\text{Ricker}\quad e^{\left(1-x-N/K\right)}(p_0+bN\bar{x})$$

$$\text{Hassell}\quad \left(\frac{1}{\left(1+\frac{(\lambda-1)N}{K}\right)^h}-x\right)(p_0+bN\bar{x})$$

$$\text{Shared resources}\quad \left(\frac{1}{N}-x\right)(p_0+bN\bar{x})$$

(b) ESS investment in host manipulation (x^*)
MODEL

$$\text{Logistic}\quad \frac{(K-N)(1+r(N-1))}{K(N+1+r(N-1))}-\frac{p_0}{b(N+1+r(N-1))}$$

$$\text{Monod}\quad \frac{(K-N)(1+r(N-1))}{(q+K-N)(N+1+r(N-1))}-\frac{p_0}{b(N+1+r(N-1))}$$

$$\text{Ricker}\quad \frac{1+r(N-1)}{N}-\frac{p_0}{bN}$$

$$\text{Hassell}\quad \frac{1+r(N-1)}{(N+1+r(N-1))H}-\frac{p_0}{b(N+1+r(N-1))}\quad \text{where } H=\left(1+\frac{N(\lambda-1)}{K}\right)^h$$

$$\text{Shared resources}\quad \frac{1+r(N-1)}{N(N+1+r(N-1))}-\frac{p_0}{b(N+1+r(N-1))}$$

(c) Proportional decrease in x^* at $p_0 = 0$ due to competition
MODEL

$$\text{Logistic}\quad \frac{N}{K}$$

$$\text{Monod}\quad \frac{q}{q+K-N}$$

$$\text{Ricker}\quad \frac{1+r(N-1)}{N}$$

$$\text{Hassell}\quad 1-{}^{1}\!/_{H}\quad \text{where } H=\left(1+\frac{N(\lambda-1)}{K}\right)^h$$

$$\text{Shared resources}\quad \frac{N-1}{N}$$

(Note: Almost all of these proportions are positive which suggests that competition decreases investment when the passive transmission rate is 0).

(d) dx*/dN (The effect of parasite load on investment in host maipulation) (When the differential is negative, investment should decrease as parasite load increases.)

MODEL

Logistic $$\frac{(1+r)p_0}{b(N+1+r(N-1))^2}-\frac{K(1-r)+r(2N^2-1)+r*(1-r)(N-1)^2}{K(N+1+r(N-1))^2}$$

which is negative when $$p_0/b<\frac{1-r}{1+r}+\frac{(1-r)^2}{K(1+r)}+\frac{rN(N(1+r)+2(1-r))}{K(1+r)}$$

Monod $$\frac{p_0(1+r)}{b(N+1+r(N-1))}+\frac{(q+K-N)((r(K-2N)-(1-r))-(K-N)(1+r)(1+r(N-1)))+(K-N)(1+r(N-1))}{(N+1+r(N-1))}$$

which is negative when

$$p_0/b<\frac{(1-r)K^2-(1-r)(2N-q)K+(1+r)rN^2+(1-r)2rN+(1-r)^2}{(q+K-N)(1+r)}$$

Ricker $$\frac{p_0-b+br}{bN^2}$$

which is negative when $p_0/b<1-r$

Hassell $$\frac{2ph(\lambda-1)}{b(N+1+r(N-1))(K+N(\lambda-1))}-\frac{(1+r(N-1))h(\lambda-1)}{H(N+1+r(N-1))(K+N(\lambda-1))}-\frac{r}{H(N+1+r(N-1))}+\frac{p(1+r)}{b(N+1+r(N-1))^2}-\frac{(1+r)(1+r(N-1))}{H\left(N+1+r(N-1)^2\right)}$$

which is negative when

$$p_0/b<\frac{(N+1+r(N-1))(1+r(N-1))h(\lambda-1)+(1-r)(K+N(\lambda-1))}{H(1+r)(K+N(\lambda-1))}$$

Shared resources $$\frac{p_0(1+r)}{b(N+1+r(N-1))^2}-\frac{r^2(N-1)^2+(N^2-2)r+(2N+1)}{(N+1+r(N-1))^2N^2}$$

which is negative when $$\left(p_0/b<\frac{r^2(N-1)^2+(N^2-2)r+(2N+1)}{N^2(1+r)}\right)$$

(e) dx*/dr (The effect of relatedness on investment)

MODEL

Logistic $$\frac{N(K-N)(N-1)}{K(N+1+r(N-1))^2}-\frac{p_0(N-1)}{b(N+1+r(N-1))^2}$$ which is positive when $N<K$

Monod $\frac{(N-1)(bN(K-N)+p_0(q+K-N))}{b(q+K-N)(N+1+r(N-1))^2}$ which is positive when $N<K$

Ricker $\frac{N-1}{N}$ which is always positive

Hassell $\frac{(N+1)\left(bN/H+p_0\right)}{b(N+1+r(N-1))^2}$ which is always positive

Shared resources $\frac{(N-1)(b+p_0)}{b(N+1+r(N-1))^2}$ which is always positive

(f) dx*/db (The effect of conversion efficiency on investment in host manipulation)

MODEL

Logistic $\frac{p_0}{b^2(N+1+r(N-1))}$ which is always positive

Monod $\frac{p_0}{b^2(N+1+r(N-1))}$ which is always positive if $p_0 > 0$

Ricker $\frac{p_0}{b^{2N}}$ which is always positive

Hassell $\frac{p_0}{b^2(N+1+r(N-1))}$ which is always positive

Shared resources $\frac{p_0}{b^2(N+1+r(N-1))}$ which is always positive

(g) dx*/dp_0 (The effect of passive transmission rate on investment in host manipulation)

MODEL

Logistic $\frac{-1}{b(N+1+r(N-1))}$ which is always negative

Monod $\frac{-1}{b(N+1+r(N-1))}$ which is always negative

Ricker $\frac{-1}{b(N+1+r(N-1))}$ which is always negative

Hassell $\frac{-1}{b(N+1+r(N-1))}$ which is always negative

Shared resources $\frac{-1}{b(N+1+r(N-1))}$ which is always negative

(h) dx*/dK (The effect of reducing competition intensity (increasing K) on investment in host manipulation)

MODEL

Logistic $\left\{\dfrac{N(rN+1-r)}{K^2(N+1+r(N-1))}\right\}$ which is always positive

Monod $\dfrac{q(1+r(N-1))}{(N+1+r(N-1))(q+K-N)^2}$ which is always positive

Ricker 0 (The strength of competition has no effect on investment in host manipulation.)

Hassell $\dfrac{Nh(\lambda-1)}{HK(K+N(\lambda-1)(N+1+r(N-1)))}$ which is positive when $N < K$

Shared resources (Does not apply)

Appendix 2: Evaluation of non-linear models

We explore possible effects of a non linear version of Eq. 1 using:

$$W = \left(1 - x - {}^{N}\!/_{K}\right)(p_0 + bN^a\bar{x}) \tag{A1}$$

where a is a parameter which describes the shape of the combined effects of all the parasites in the host on the host's susceptibility to predation by the parasite's definitive host. When a exceeds one the combined effect of the parasites exceeds the sum of the individual effects producing a certain synergy; when a is less than one, the combined effect is less than the sum of the individual effects. When $a = 1$, Eq. A1 becomes Eq. 1.

Most of the inferences drawn from Eq. 1 are also supported by analysis of Eq. A1. For all positive values of a, increases in competition should decrease the investment in host manipulation and the proportional decrease is described by Eq. 4. As in the linear model, investment should increase as relatedness, r, and as manipulation efficiency, b, increase; investment should decrease as the passive transmission rate, p_0, increases. Analysis of the non linear model differs from the linear model only with respect to the effect of increases in parasite load. In this case, Eq. 5 describing the conditions under which investment should increase as parasite load increases becomes

$$ {}^{p_0}\!/_{b} > {}^{(1-r)N^a}\!/_{((1+r)aN-(1-a)(1-r))}\cdot \tag{A2}$$

This condition differs greatly from Eq. 5 because of the presence of N on the right hand side of the equation. If $a < 1$, indicating that the combined effect of several parasites is less than the sum of their individual effects, investment should decrease with increased parasite load at all passive transmission rates. Further, the range of passive transmission rates and parasite loads for which manipulation is profitable is greatly reduced compared to the linear model.

On the other hand, when $a > 1$, lower passive transmission rates (compared to the linear model) can generate increased manipulation as a function of increased parasite load while manipulation will be profitable under a wider range of passive transmission rates and parasite loads.

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