VOL. 192, NO. 2 THE AMERICAN NATURALIST AUGUST 2018

SYMPOSIUM

The Role of Phenotypic Plasticity in Moderating Evolutionary Conflict*

Troy Day[1,†] and David V. McLeod[2]

1. Department of Mathematics and Statistics, Department of Biology, Queen's University, Kingston, Ontario K7L 3N6, Canada;
2. Institut für Integrative Biologie, ETH Zürich, Zürich, Switzerland

Submitted October 26, 2017; Accepted March 6, 2018; Electronically published May 29, 2018

ABSTRACT: Evolutionary conflicts arise when the fitness interests of interacting individuals differ. Well-known examples include sexual conflict between males and females and antagonistic coevolution between hosts and parasites. A common feature of such conflicts is that compensating evolutionary change in each of the parties can lead to little overt change in the interaction itself. As a result, evolutionary conflict is expected to persist even if the evolutionary dynamic between the parties reaches an equilibrium. In these cases, it is of interest to know whether certain kinds of interactions are expected to lead to greater or lesser evolutionary conflict at such evolutionary stalemates. Here we present a theoretical analysis showing that when one of the interacting parties can respond to the other through adaptive phenotypic plasticity, evolutionary conflict is reduced. Paradoxically, however, it is the party that does not express adaptive plasticity that experiences less conflict. Conflict for the party displaying adaptive plasticity can increase or decrease, depending on the situation.

Keywords: evolutionary theory, sexual conflict, host-parasite conflict, arms race, sexual selection, interlocus conflict.

Introduction

Evolutionary conflicts arise when the fitness interests of interacting individuals differ (Strassman et al. 2011). Such conflicts can occur among individuals of different species (e.g., predator-prey, host-parasite), among competing individuals within the same species (e.g., resource competition), between mates (e.g., sexual conflict; Arnqvist and Rowe 2005), between parents and offspring (Trivers 1974), among siblings (Mock and Parker 1997), and even among different genetic elements within an organism (intragenomic conflict; Burt and Trivers 2006).

A commonly studied subset of evolutionary conflicts are those that arise through the pairwise interaction of two different kinds of individuals. For example, in the context of sexual conflict, a male might transfer seminal fluid proteins (SFPs) during mating that increase the female's investment in current reproduction, whereas a female might counter this strategy by producing enzymes that degrade the male's SFPs (i.e., interlocus conflict; Chapman et al. 1995; Rice 1996; Rice and Holland 1997; Civetta and Clark 2000; Swanson and Vacquier 2002; Chapman et al. 2003; Wigby and Chapman 2005; Chapman 2006; Parker 2006; Rice 2013; Sirot et al. 2014). Similarly, in the context of host-parasite conflict, a unicellular parasite might employ certain surface molecules as a means of infecting its host, whereas the host might mount an adaptive immune response that targets these surface molecules (Frank 2002; Schmid-Hempel 2011). In all such conflicts, the fitness of each party is determined by an interaction between the two, and their fitness interests are not completely aligned.

The above type of evolutionary conflict is expected to generate antagonistic coevolution between the two interacting parties, but, interestingly, this antagonism will often be difficult to detect (Arnqvist and Rowe 2002; Rowe et al. 2003; Rowe and Day 2006; Frank and Crespi 2011; Dougherty et al. 2017). For instance, if the evolutionary change in female strategy effectively neutralizes the evolutionary change in male strategy, then there will be no overt signs that an evolutionary conflict between the two exists. Only by manipulating one of the parties—for example, by altering the expression of the male-produced SFPs—would one see the underlying conflict (Arnqvist and Rowe 2002; Gaba and Ebert 2009; Frank and Crespi 2011; Dougherty et al. 2017). For instance, an increase in male SFP production might result in an increase in male reproductive success and a decrease in the reproductive success of females, while an increase in the production of female SFP-degrading enzymes might produce the opposite pattern. The key observation is

* These articles originated as the 2017 Vice Presidential Symposium presented at the annual meetings of the American Society of Naturalists in Portland, Oregon.

† Corresponding author; email: day@queensu.ca.

Am. Nat. 2018. Vol. 192, pp. 230–240.
DOI: 10.1086/698170

that at evolutionary equilibrium, each party has reduced fitness as a result of the actions of the other party.

The above type of manipulation for uncovering conflict can also provide insight into the magnitude of the evolutionary conflict between the two parties. For example, if the fitness changes described above are relatively small in magnitude, then it would be natural to conclude that the conflict is relatively weak and vice versa. This then raises an interesting question: Are there certain features of interactions that result in strong conflict and others that tend to moderate its effects? One such possibility is the presence of adaptive phenotypic plasticity in the traits that underlie the interaction (McNamara et al. 2006; McLeod and Day 2017). For example, after a male transfers SFPs to a female during mating, the female can alter her physiological response plastically (and adaptively), depending on what the male has transferred. Similarly, in some host-parasite interactions, the parasite commits to a particular set of surface molecules or to some replication rate, but the host can then respond plastically to the parasite's strategy through an adaptive immune response. At first glance, we might expect such plasticity to buffer the interaction and so lead to reduced evolutionary conflict. As we will show, theory supports this general view, but plasticity moderates the strength of the evolutionary conflict in a rather counterintuitive way. In both examples above, there is an inherent asymmetry in the interaction in that one party can respond plastically to the other but not vice versa. It turns out that in this case, it is the party that does not exhibit adaptive phenotypic plasticity that always benefits from reduced conflict. The conflict experienced by the party exhibiting the plasticity can actually increase.

To elucidate these ideas, below we do two things. First, we provide a definition of what we mean by pairwise evolutionary conflict. Second, we proceed to show how adaptive phenotypic plasticity alters the extent of this conflict. Throughout we use a running example of host-parasite coevolution to make the ideas concrete, but we summarize the results in a general setting in appendixes A–C. Our findings build on the pioneering work of Sjerps and Haccou (1993) and McNamara et al. (1999, 2006), who studied this same question in the context of competitive interactions. The results also generalize the findings of McLeod and Day (2017), who studied this question in the context of sexual conflict. We return to the connection between these previous studies and our current results in the discussion.

What Is Evolutionary Conflict?

Evolutionary conflict has been defined previously by several authors, particularly in the context of sexual interactions (Parker 1979; Chapman et al. 2003; Pizzari and Snook 2003, 2004; Arnqvist 2004; Arnqvist and Rowe 2005; Parker 2006; Rowe and Day 2006; Fricke et al. 2009; Rice 2013; Kokko and Jennions 2014; McLeod and Day 2017). Roughly speaking, evolutionary conflict occurs when the fitness interests of interacting individuals differ. Therefore, to make this idea more precise, we first need to specify the two potentially conflicting parties as well as the nature of their interaction (and the traits that affect this interaction). Once this is done, we must then specify a measure of fitness for each party so that we can determine if and when their fitness interests differ. Although this latter step is obviously critical to making the idea of evolutionary conflict precise, it can be a subtle issue. The reproductive success of an individual typically depends not only on the trait values of itself and those of the party with which it directly interacts but also on the composition of the entire population as well. As a result, it is not necessarily a simple matter to obtain a fitness measure that is broadly applicable and yet still allows for a meaningful definition of evolutionary conflict between the two interacting parties. We will revisit this issue in the discussion, but for now we simply take it as a given that such a fitness measure can be obtained for each party.

As an example, consider a host species and a microparasite that infects the host (fig. 1). To define the traits of interest, we begin by specifying a model for how the interaction between the two parties occurs. Denote the density of susceptible hosts by S and the density of hosts infected by the parasite by I. A simple dynamical model for how these change over time is then (van Baalen 1998; Day and Burns 2003; Wild et al. 2007)

$$\frac{dS}{dt} = b(S + I) - dS - \beta SI + cI, \tag{1a}$$

$$\frac{dI}{dt} = \beta SI - (d + c + v)I. \tag{1b}$$

Here b is the per capita birth rate, d is the per capita death rate, β is the transmission rate of the parasite between infected and susceptible hosts, v is the virulence of the para-

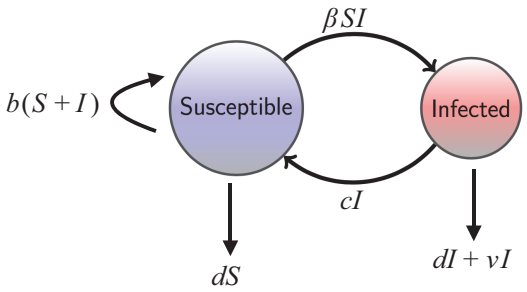

Figure 1: Flow diagram for the host-parasite model embodied by equations (1). Arrows depict flow of individuals with the rate of flow indicated.

site (defined as the parasite-induced per capita death rate), and c is the rate at which infected hosts clear the infection and become susceptible again.

Given the interaction described by equations (1), we can now define the traits of interest. We suppose that the clearance rate c is under the genetic control of the host and that there is a trade-off between birth rate b and clearance rate c (high values of c are associated with low values of b). We also suppose that the virulence v is under the genetic control of the parasite and that there is a trade-off between transmission rate β and virulence v (low values of v are associated with low values of β).

Finally, from equations (1) we can derive a measure of fitness for each party. It can be shown (see app. A) that the parasite genotype that produces the largest possible value of $\beta/(d + c + v)$ is the evolutionarily stable strategy (ESS). Likewise, the host genotype that produces the largest possible value of $(b - d)(d + c + v)/[\beta(d + v - b)]$ is the ESS. Thus, we define the two fitness functions

$$P(c, v) = \frac{\beta(v)}{d + c + v}, \tag{2a}$$

$$H(c, v) = \frac{(b(c) - d)(d + c + v)}{\beta(d + v - b(c))}. \tag{2b}$$

It is optimal for each party to maximize its respective fitness function in equations (2) if possible.

Given two fitness functions such as those in equations (2), how should we then define and quantify evolutionary conflict? One possibility is to suppose that although c and v are private traits (i.e., each is expressed by only one of the two parties), together they might influence a shared trait (e.g., the duration of an infection). If selection acts differently on this shared trait in the two parties, then we would say that evolutionary conflict occurs (Rowe et al. 2003; Arnqvist and Rowe 2005; Rowe and Day 2006; Frank and Crespi 2011).

Here we instead take a slightly more general approach, following McLeod and Day (2017). Rather than defining an intermediary shared trait through which the two private traits map to fitness, we simply ask how selection acts on both traits in each of the two parties as a result of the traits' effects on fitness. Even though each trait is private, we can still ask how an individual's fitness changes as we alter either of the two traits. Indeed, the manipulation protocol described in the introduction does exactly this (Arnqvist and Rowe 2002; Gaba and Ebert 2009; Frank and Crespi 2011; Dougherty et al. 2017). For example, if increasing parasite virulence v increases parasite fitness but decreases host fitness, then we would conclude that conflict exists (at least with respect to this trait). The existence of conflict is reflected by the fact that each individual would have a higher fitness if only its partner had a different trait value. This definition is also, in effect, a formalization of the idea put forth by Kokko and Jennions (2014) that conflict exists if a hypothetical cost-free tool that allowed one party to control the trait value of the other would be selectively advantageous.

To make these ideas more concrete, consider the fitness contour plots of two arbitrary parties as a function of two arbitrary private traits. Figure 2 presents a hypothetical ex-

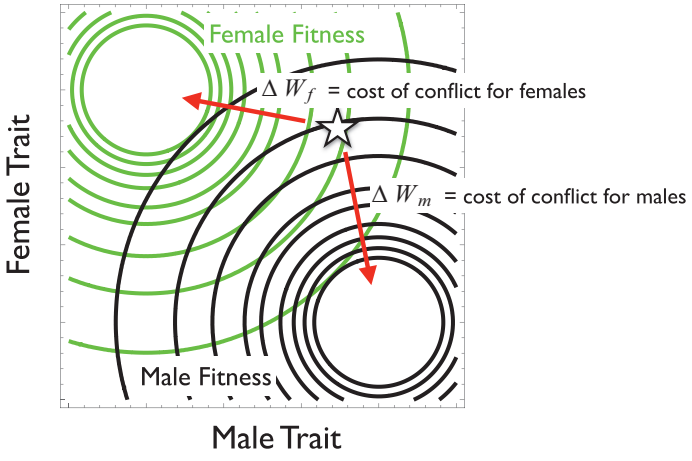

Figure 2: Hypothetical plot of fitness contours for males and females engaged in an evolutionary conflict, as a function of the male and female trait. Black lines give male fitness, and green lines give female fitness (smaller concentric rings correspond to higher fitness). Star indicates current trait values in the population. Arrows indicate the direction of selection on the two traits in males and females. The existence of evolutionary conflict is revealed by the arrows pointing in different directions. The magnitude of conflict experienced by each party is given by the change in fitness that would result when moving the traits to their preferred values for each sex (ΔW_f for females and ΔW_m for males).

ample for a male-female interaction. The current (mean) trait values in the population are indicated by the star. We can see that the highest fitness for each party is attained for different values of the two traits, and because selection is acting in different directions on the traits in the two parties, we conclude that evolutionary conflict exists. Figure 1 also leads to the observation that the extent and nature of the conflict depends on the current trait values in the population (Rowe et al. 2003; Rowe and Day 2006).

If there is conflict, we can also ask about the strength of conflict by considering how much the fitness of each party changes as we alter the trait values in the direction that is selectively advantageous for each party. This leads to a second observation, namely that we can consider the strength of conflict separately for the two parties. For example, in figure 2 we can quantify the strength of conflict from the perspective of females by determining how much female fitness changes as we move the population trait values to the female optimum (ΔW_f). Similarly, we can quantify the strength of conflict from the perspective of males by determining how much male fitness changes as we move the population trait values to the male optimum (ΔW_m). Notice that these measures of conflict need not be equal. For example, if the population were located close to the female optimum, then evolutionary conflict from the female's perspective would be weaker than that from the male's perspective.

Returning to the host-parasite example, the fitness contours for each party as a function of c and v are shown in figure 3*a* for a particular choice of the functions $\beta(v)$ and $b(c)$. We can see that the optimal trait values for the parasite are different than those for the host, setting the stage for potential evolutionary conflict.

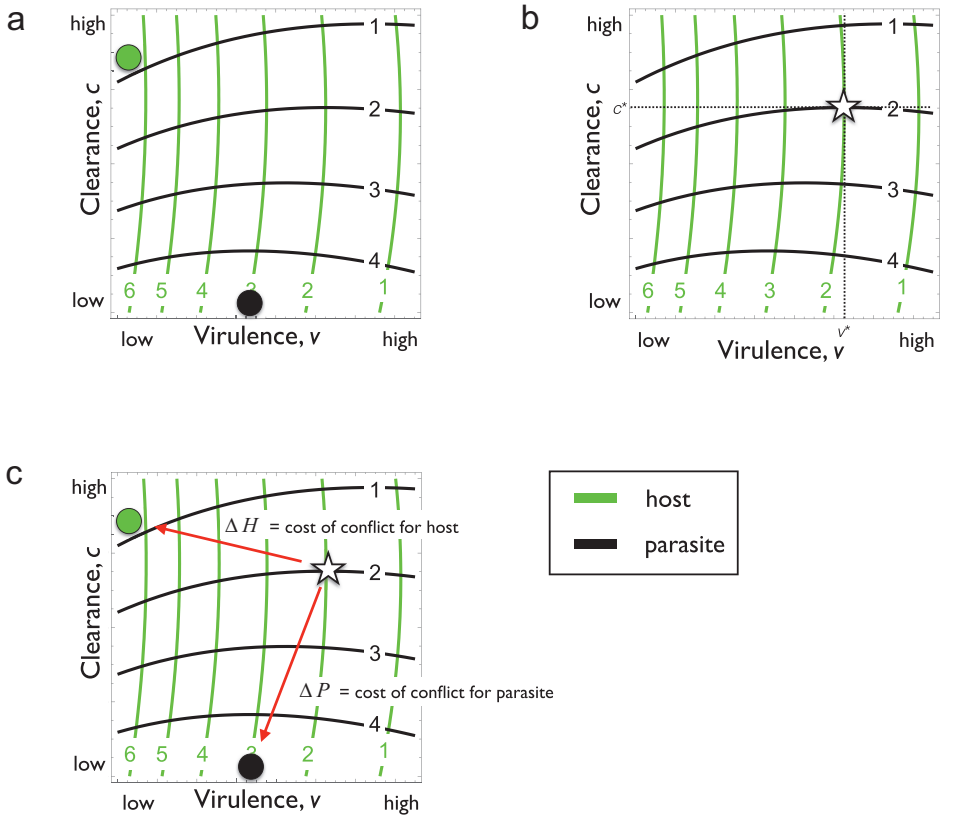

Figure 3: Fitness contours for host and parasite assuming that $\beta(v) = v^{1/2}$ and $b(c) = b_0 - ac^2$. Parameter values are arbitrary. Black lines give parasite fitness, and green lines give host fitness. Green and black circles represent the optimal trait values (those that give the highest possible fitness) for host and parasite, respectively. *a*, Optimal trait values for host and parasite. *b*, Star indicates evolutionarily stable strategy trait values c^* and v^*. Specifically, if we fix the value of v at v^*, then host fitness (green lines) is maximized at c^*. Likewise, if we fix the value of c at c^*, then parasite fitness (black lines) is maximized at v^*. *c*, Existence of evolutionary conflict is revealed by arrows pointing in different directions. The magnitude of conflict experienced by each party is given by the change in fitness that would result when moving the traits to their preferred values (ΔH for hosts and ΔP for parasites).

Our primary interest is in examining the level of conflict that exists when the population is at evolutionary equilibrium, and so we would like to quantify this conflict at the ESS trait values v^* and c^*. In this example, we can identify this ESS pair of trait values directly from the fitness contour plot. The star in figure 3*b* indicates these ESS values. At this ESS the parasite has achieved its maximum possible fitness as a function of virulence v, given that the host is using clearance rate c^*. Likewise, the host has achieved its maximum possible fitness as a function of clearance rate c, given that the parasite is using virulence v^*. Figure 3*c* shows that evolutionary conflict exists at this ESS because selection is acting in different directions in the parasite and host. Also notice that although one might initially think the ESS ought to lie in between the optima for each party, this is not necessarily the case. Each party has control over only one of the two traits, and so the ESS value of each need not be a compromise of the optimal values for each party.

Now that we have defined evolutionary conflict, we can address the main question of interest. What happens to the predicted level of conflict if one of the parties can respond plastically (and adaptively) to the actions of the other?

The Effect of Adaptive Phenotypic Plasticity on Evolutionary Conflict

As explained in the introduction, we are interested in cases where there is an asymmetry in the interaction between the two parties such that one individual plays first and the other is then able to respond plastically (and adaptively). In game theory, this is sometimes referred to as a sequential game, and it stands in contrast to a simultaneous or sealed-bid game, in which both parties play their strategies simultaneously, without knowledge of what their opponent is going to do. In the context of our running example, we will suppose that during an infection, the parasite exhibits a fixed level of virulence v and that the host then responds plastically through an adaptive immune response so as to employ the clearance rate c that maximizes host fitness. If instead we were to consider the simultaneous game, the host clearance rate would not respond plastically to the level of virulence of the parasite.

The adaptive phenotypic response of the host to the level of virulence exhibited by the parasite can be visualized using the host fitness contour plot (fig. 4). The host should employ a clearance rate c that corresponds to the highest possible contour for any given value of v. This results in the optimal reaction norm $c = r(v)$ shown in figure 4.

Now, given that the host always uses the optimal reaction norm, we can see from figure 5 that the level of virulence predicted in figure 3*b* is no longer an ESS. Specifically, in the case of figure 5*a*, a parasite with higher virulence can now achieve a higher fitness because the adaptive response

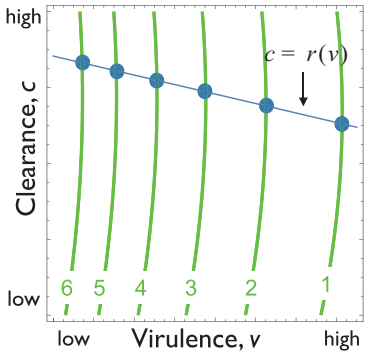

Figure 4: Optimal reaction norm for host clearance rate c as a function of parasite virulence v. Green lines show host fitness as a function of the two traits, and blue line indicates the optimal reaction norm $c = r(v)$. For example, each circle on this reaction norm gives the value of clearance c that produces the highest host fitness (i.e., the lands on the highest host fitness contour) for that particular value of v.

that this induces in the host allows the parasite to move up its fitness contours. By definition this means that the parasite will then experience less conflict. Paradoxically, however, although plasticity essentially provides the host with more information about the parasite (e.g., McNamara and Dall 2009), the level of conflict experienced by the host actually increases (it moves down its fitness contours). This occurs despite the fact that the plasticity exhibited by the host is always adaptive. This counterintuitive outcome stems from the fact that when the host exhibits plasticity, even though this plasticity is adaptive, it provides a mechanism through which the parasite can manipulate the private trait of the host.

It is also clear from figure 5*a* that the outcome for the host, in terms of the conflict it experiences, depends on the slope of the reaction norm $c = r(v)$. If instead the slope is positive, as in figure 5*b*, then again the level of virulence that is predicted in the absence of the plasticity is no longer an ESS. In this case, however, both parties end up experiencing less conflict.

Our conclusions so far have relied on a particular set of contour plots, but the above qualitative conclusions hold in general. To see this, let us put the above specifics aside and consider two general fitness functions, $P(c, v)$ and $H(c, v)$ (see also app. B). In the absence of plasticity, the ESS trait values v^* and c^* satisfy the conditions

$$P(c^*, v) \le P(c^*, v^*), \tag{3a}$$

$$H(c, v^*) \le H(c^*, v^*) \tag{3b}$$

for all possible values of v and c such that $v \neq v^*$ and $c \neq c^*$. The first-order derivative conditions corresponding to equations (3) are

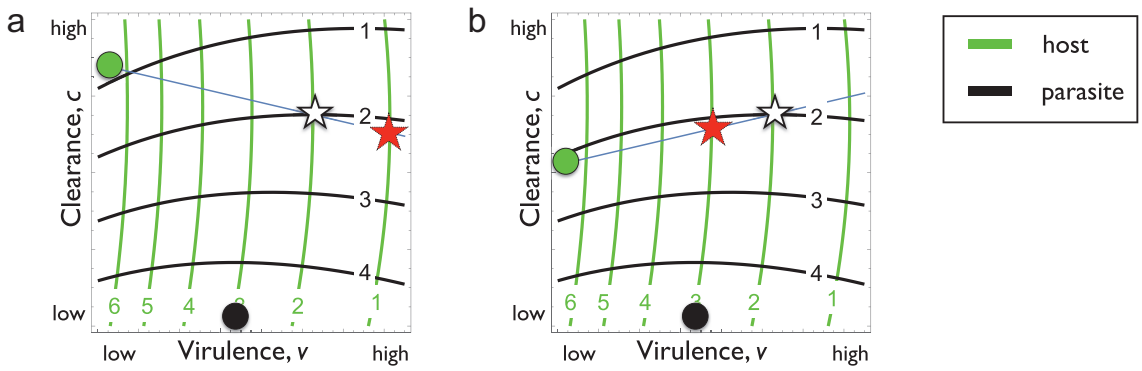

Figure 5: Effect of host adaptive plasticity in clearance rate on evolutionary conflict. Black lines give parasite fitness, and green lines give host fitness. Star indicates evolutionarily stable strategy trait values c^* and v^* in the absence of host plasticity from figure 3*b*. Red star indicates direction in which evolution will occur. Green and black circles represent the optimal trait values for host and parasite, respectively. *a*, Host reaction norm has a negative slope. At the red star, the parasite has moved up its fitness contours. Paradoxically, however, the host has moved down its fitness contours, despite its plastic response being adaptive. *b*, Host reaction norm has a positive slope. At the red star, the parasite has moved up its fitness contours. The host has moved up its fitness contours as well.

$$\frac{\partial P(c^*, v^*)}{\partial v} = 0, \tag{4a}$$

$$\frac{\partial H(c^*, v^*)}{\partial c} = 0. \tag{4b}$$

Now in order for conflict to exist at this ESS, we require that the fitness of each party can be increased with a change (either up or down) in the trait value expressed by its partner. In the context of the host-parasite example, at the ESS the host fitness can be increased by decreasing parasite virulence. Likewise, parasite fitness can be increased by decreasing host recovery rate. Therefore, without any loss of generality, we can assume that the traits c and v are defined such that we have $\partial H(c^*, v^*)/\partial v < 0$ and $\partial P(c^*, v^*)/\partial c < 0$.

With this scenario in mind, we can now consider what happens if the host responds plastically in an adaptive way to the virulence exhibited by the parasite. We have the optimal reaction norm $c = r(v)$ for some function $r(v)$, and by definition we also have $c^* = r(v^*)$. With this optimal reaction norm, the host is always maximizing its fitness no matter what the parasite does. Therefore, all that remains is to find out how selection acts on the parasite. If there exists a value of v different from v^* that increases parasite fitness, then this will spread and so conflict for the parasite will decrease. The corresponding clearance rate for the host will then be given by $c = r(v)$.

Consider a mutation with small effect, such that the mutant's value of v is close to v^*. The change in fitness for the parasite is $P(r(v), v) - P(c^*, v^*)$. Using a first-order approximation for P, we obtain

$$P(r(v), v) \approx P(c^*, v^*) + \left(\frac{\partial P(c^*, v^*)}{\partial c}\frac{dr}{dv} + \frac{\partial P(c^*, v^*)}{\partial v}\right)(v - v^*).$$

Therefore, making use of equations (4), we find that the change in parasite fitness simplifies to

$$\frac{\partial P(c^*, v^*)}{\partial c}\frac{dr}{dv}(v - v^*). \tag{5}$$

Now recall that by definition when there is conflict at the ESS, we have $\partial P(c^*, v^*)/\partial c < 0$. Therefore, we can see that the parasite can always increase its fitness (and thus decrease the level of conflict it experiences). In particular, if the reaction norm has a positive slope (i.e., $dr/dv > 0$), then the parasite can increase its fitness by using $v < v^*$. On the other hand, if the reaction norm has a negative slope (i.e., $dr/dv < 0$), then the parasite can increase its fitness by using $v > v^*$. Thus, by manipulating the host's clearance rate through its adaptive plastic response, the parasite is always able to achieve a higher fitness and so less conflict.

But consider things from the host's perspective. It will always choose the best possible level of clearance as a function of the virulence used by the parasite, and so the resulting change in its fitness is $H(r(v), v) - H(c^*, v^*)$. Now using a first-order approximation for H, we obtain

$$H(r(v), v) \approx H(c^*, v^*) + \frac{\partial H(c^*, v^*)}{\partial c}(c - c^*) + \frac{\partial H(c^*, v^*)}{\partial v}(v - v^*).$$

Therefore, making use of equations (4), we find that the change in host fitness simplifies to

$$\frac{\partial H(c^*, v^*)}{\partial v}(v - v^*). \tag{6}$$

Again, by definition of conflict occurring at the ESS, we have $\partial H(c^*, v^*)/\partial v < 0$. As a result, host fitness will increase—and thus conflict from the perspective of the host will decrease—only if $v < v^*$. From above we see that this requires that the slope of the reaction norm be positive. Otherwise, the fitness of the host will decrease, and thus it will experience more conflict. Last, we note that the sign of the slope of the optimal reaction norm is determined by the sign of the mixed partial derivative $\partial^2 H(c^*, v^*)/\partial c \partial v$. This measures how selection on the clearance rate of the host changes as parasite virulence increases.

Discussion

Evolutionary conflict between interacting parties is often thought to result in coevolutionary arms races where neither party ultimately gains the upper hand. Despite this seeming stalemate in the evolutionary dynamic, extensive conflict can still persist in that both parties would enjoy higher fitness if only their partner would alter its actions (Arnqvist and Rowe 2002; Gaba and Ebert 2009; Frank and Crespi 2011; Dougherty et al. 2017). In such situations, it is of interest to know the conditions under which the resulting conflict is expected to be strong versus weak. Here we have shown that phenotypic plasticity in the traits underlying the interaction between the parties is expected to lead to reduced conflict. Surprisingly, however, when only one party can exhibit adaptive plasticity, it is the party not displaying the adaptive plasticity that always benefits from less conflict. The conflict experienced by the plastic party can be higher or lower, depending on the situation. This counterintuitive prediction stems from the fact that by displaying adaptive phenotypic plasticity to a partner's actions, one opens oneself up to the possibility of being manipulated.

Our findings generalize previous results by McLeod and Day (2017) who examined this same issue in the context of an explicit model of sexual conflict. We also built on previous work by Taylor et al. (2006), Wild et al. (2007), and McLeod and Day (2015), who examined the role of plasticity in host-parasite interactions but who did not explore the consequences of this plasticity for evolutionary conflict. All of these findings also build on general results by McNamara et al. (1999, 2006), who examined similar questions in the context of what might be called competitive interactions. In their analyses, they examine general pairwise interactions between identical individuals, such as two female insects who oviposit on the same host (Sjerps and Haccou 1993). Similar analyses have also been published in the economic literature, where the interacting individuals might be competing companies (Bulow et al. 1985; Dowrick 1986; Rebelein and Turkay 2016). In each of these studies, because the interacting individuals play identical roles, the primary goal is to determine how plasticity affects which of the two individuals does best in the interaction. This is usually done by comparing the fitnesses of each party to one another.

Our work differs from these previous results in focusing on interactions in which the two conflicting parties play distinctly different roles. In such cases, it is usually not meaningful to ask which individual does best in the presence of plasticity because the fitness of each party is not directly comparable. Instead, it is of interest to determine how plasticity alters the magnitude of conflict between the parties. This can be assessed by comparing fitness in the presence and absence of plasticity within each party rather than comparing the fitnesses of each party with one another. Interestingly, the answer to this question turns out to be much simpler. Although the previous results from competitive interactions show that either the plastic or the nonplastic party can do best, depending on the situation (Bulow et al. 1985; Dowrick 1986; McNamara et al. 2006; Rebelein and Turkay 2016), it is the nonplastic party that always enjoys reduced conflict.

The results presented here make some interesting predictions about the level of conflict we expect to observe in different situations. Any time there is an asymmetry in the interaction between individuals whereby one party can respond plastically to the other, we expect conflict to be reduced for at least one of the parties (the nonplastic one). For example, in the context of sexual conflict, we might broadly assume that postcopulatory conflict tends to fall into this category because males will have played their hand on copulation, and females can then respond adaptively to what the male has done. In contrast, with precopulatory conflict involving morphological traits, there will be less scope for plasticity. Thus, although there will be exceptions, we might broadly expect males to experience less conflict in postcopulatory interactions than in precopulatory interactions mediated by morphology (McLeod and Day 2017).

A similar situation arises in host-parasite interactions. Although many parasites are complex enough to exhibit plastic changes in their phenotype as a function of the environment within a host, for viruses and other simple unicellular parasites it seems reasonable to suppose that such plasticity is limited. Therefore, if this is true, we might broadly expect such parasites to experience less conflict when infecting hosts capable of adaptive plasticity (e.g., through an adaptive immune response) than in those without such a capability.

In many situations, however, both parties might have the ability to respond plastically to their partner. In this case, the analysis becomes considerably more difficult, and un-

ambiguous conclusions are much harder to obtain. To our knowledge, McNamara et al. (1999) were the first to begin addressing this question, and their work (along with more recent studies) suggests that in this case both parties often tend to experience lower conflict than they would if neither party exhibited plasticity (McNamara et al. 1999; Taylor and Day 2004; Pen and Taylor 2005; Taylor et al. 2006; Wild et al. 2007; André and Day 2007; but see Lessells and McNamara 2011 for an example where negotiation over parental care reduces fitness).

Finally, the host-parasite model used here also helps to reveal the limitations of the definition of evolutionary conflict that we use and, indeed, the difficulty of providing any meaningful definition that can be applied more broadly. As mentioned earlier, the reproductive success of an individual typically depends not only on the traits expressed by each party but also on the composition of the population as a whole as well. A key feature of the assumptions embodied by our host-parasite model, however, is that they allowed us to derive fitness functions $H(c, v)$ and $P(c, v)$ that are maximized by natural selection and that do not depend on the composition of the population. As a result, the same trait values are optimal for each party no matter what the composition of the population. Furthermore, the further each party gets from their preferred optimum, the larger the fitness costs of conflict from their perspective will be. The difference between the current and the optimal fitness for each party tells us how strongly selected a mutant would be that had some way of moving both its own private trait and that of its partner to its preferred values (Kokko and Jennions 2014). And if such a mutant spread, then evolutionary conflict for that party would be resolved.

The problem with attempting to use these ideas more broadly as a definition of evolutionary conflict is that the optimal trait values for each party need not be independent of the state of the population. Instead, what is optimal for each party might depend on what other individuals in the population are doing. As an example, let us return to the case of sexual conflict, where males produce SFPs and females produce enzymes that degrade these proteins. One can readily imagine a situation in which the production of SFPs by males and no enzymes by females is optimal from the male's perspective, but only if there are lots of other rival males in the population. On the other hand, if rival males are absent, then we might imagine a situation where it is optimal for males not to produce SFPs (and again no female enzymes). Now consider applying our definition of conflict in this case. Given any composition of the population, we could determine the optimal trait values for males and females. Strong conflict would be measured by a large deviation of the trait values from the optimum of each party. As before, strong conflict would imply that if a mutant had some way of moving both its own private trait and that of its partner to its preferred values, then it would be strongly selected. But even if such a mutant spread through the population, there is no guarantee that, at equilibrium, the conflict for that party would then be resolved (or even reduced; see app. C). This is because once the mutant spreads, the composition of the population will have changed, and the trait values that are optimal for each party might then have changed as well. As a result, it is not clear that such a definition of evolutionary conflict has much biological meaning in this context. In fact, we wonder if it is even possible to obtain a meaningful definition of evolutionary conflict that can be applied in this broad setting.

Acknowledgments

We thank A. Agrawal, S. Dall, J. McNamara, L. Rowe, P. Taylor, and the Queen's Biomath Group for discussions. This work was funded by the Natural Sciences and Engineering Research Council of Canada.

APPENDIX A

To determine the evolutionarily stable host and parasite strains, we first compute the endemic equilibrium for model (1). Setting $dS/dt = 0$ and $dI/dt = 0$ gives the equilibrium values

$$S = \frac{d + c + v}{\beta},$$

$$I = \frac{(b - d)(d + c + v)}{\beta(d + v - b)}.$$

This equilibrium is locally stable, provided that $b > d$ and $b < d + v$ (van Baalen 1998; Day and Burns 2003). Assuming that these conditions hold, we can then determine the parasites' ESS by conducting an evolutionary invasion analysis for a rare mutant parasite in a resident population at the endemic equilibrium (Otto and Day 2007). Doing so shows that the evolutionarily stable parasite is the one that induces the smallest equilibrium value of S (van Baalen 1998; Day and Burns 2003). Equivalently, the evolutionarily stable parasite has the largest possible value of $\beta/(d + c + v)$. In a similar fashion, one can determine the ESS host by conducting an evolutionary invasion analysis for a rare mutant host in a resident population at the endemic equilibrium. Doing so shows that the evolutionarily stable host is the one that induces the largest equilibrium value of I (van Baalen 1998; Day and Burns 2003).

APPENDIX B

Although the calculations in the main text are phrased in terms of host-parasite interactions, nothing in the compu-

tations is specific to this situation. The very same calculations can be followed to show the following general result.

Suppose two parties have fitness functions $M(x, y)$ and $N(x, y)$, where x is the private trait for the M party and y is the private trait for the N party. In the absence of phenotypic plasticity, the ESS pair of trait values x^* and y^* must satisfy

$$\frac{\partial M(x^*, y^*)}{\partial x} = 0,$$

$$\frac{\partial N(x^*, y^*)}{\partial y} = 0.$$

At this ESS, for conflict to be occurring, we require that the fitness of each party can be increased with a change (either up or down) in the private trait value expressed by its partner. Without loss of generality, if there is conflict we can therefore define the traits x and y such that

$$\frac{\partial M(x^*, y^*)}{\partial y} < 0,$$

$$\frac{\partial N(x^*, y^*)}{\partial x} < 0.$$

Now suppose that the N party exhibits adaptive phenotypic plasticity such that the optimal choice of y for any choice of x is given by the reaction norm $y = r(x)$. Then, at the new equilibrium, the level of conflict experienced by the nonplastic M party will always be smaller than at the ESS (x^*, y^*). The level of conflict experienced by the plastic N party will be larger or smaller, depending on the slope of its optimal reaction norm $r(v)$, and this is determined by the sign of the mixed partial derivative, $\partial^2 N(x^*, y^*)/\partial x \partial y$.

APPENDIX C

The definition of evolutionary conflict used in the main text is based on there being fitness functions that, barring any restrictions, are maximized by natural selection (e.g., $H(c, v)$ and $P(c, v)$ in the host-parasite example). Of course there are restrictions in that each party has only one of the two traits under its control. Thus, at evolutionary equilibrium, the fitness function of each party will be maximized with respect to its own private trait but typically not with respect to the trait value of its partner. This constitutes our definition of evolutionary conflict: each individual would have a higher fitness if only its partner had a different trait value. We then quantified the magnitude of conflict for each party by comparing their fitness at this equilibrium with what their fitness could be if they had control over both traits.

In order to better understand the biological significance of this measure of conflict and how it might be extended to cases where there is no fitness function that is maximized by natural selection, it is helpful to first step back and consider how this approach fits into the broader modeling framework of evolutionary game theory. The evolutionary game theory framework begins by considering a population that is monomorphic for a resident type and then asks whether a rare mutant type with different characteristics can invade (Otto and Day 2007). The assumption is that the resident type determines the environmental state into which the mutant attempts to spread. For instance, in the host-parasite example, the environmental state consists of the equilibrium density of susceptible and infected hosts that results when the resident type is present by itself.

To make these ideas more precise, let us measure a mutant's ability to spread by its total lifetime reproductive output (LRO), denoted by R. If $R > 1$, then the mutant more than replaces itself and so it spreads in the population. We use E to represent the environmental state and, in the context of our host-parasite example, the traits of interest are c and v. Therefore, the LRO of a rare mutant host attempting to invade a resident population with trait values $(\hat{c}, \hat{v})$ (which corresponds to an environmental state $\hat{E}$) is given by some function $R_H(c, v; \hat{E})$. Likewise, for the parasite we have an LRO function $R_P(c, v; \hat{E})$. Of course, each type (host or parasite) has control over only one of c or v, but we can nevertheless ask what the fitness of a mutant of each type would be if it had control over both traits. Indeed, according to our definition, conflict exists if each party could increase their LRO by somehow altering both their private trait value and that of their partner. This is, in effect, a formalization of the idea put forth by Kokko and Jennions (2014) that conflict exists if a hypothetical cost-free tool that allowed one party to control the trait value of the other would be selectively advantageous. Finally, also note that by definition $R_P(\hat{c}, \hat{v}; \hat{E}) = 1$ and $R_H(\hat{c}, \hat{v}; \hat{E}) = 1$, reflecting the fact that at equilibrium in a monomorphic population the LRO of both parties must equal 1.

Now it turns out that for the host-parasite example studied earlier, the interaction is such that the LRO of both host and parasite can be written as (van Baalen 1998; Day and Burns 2003)

$$R_P(c, v; \hat{E}) = P(c, v) f(\hat{E}), \tag{C1a}$$

$$R_H(c, v; \hat{E}) = H(c, v) g(\hat{E}) \tag{C1b}$$

for some functions $P(c, v)$, $H(c, v)$, $f(\hat{E})$, and $g(\hat{E})$. The key property of equations (C1) is that the effect of the environmental state on the LRO of a mutant can be entirely separated from the effect of the mutant trait values themselves (i.e., into a product of the separate functions $P(c, v)$ and $f(\hat{E})$ for the parasite and functions $H(c, v)$ and $g(\hat{E})$ for the host). The significance of this property is that it implies that natural selection will maximize some function of the

trait values alone for both host and parasite (Mylius and Diekmann 1995; Metz et al. 2008). Specifically, because we know that $R_P(\hat{c}, \hat{v}; \hat{E}) = 1$ and $R_H(\hat{c}, \hat{v}; \hat{E}) = 1$ at monomorphic equilibrium, this implies that $f(\hat{E}) = 1/P(\hat{c}, \hat{v})$ and $g(\hat{E}) = 1/H(\hat{c}, \hat{v})$. Thus, for example, a mutant parasite can invade only if $R_P(c, v; \hat{E}) > 1$, which is equivalent to the condition $P(c, v) > P(\hat{c}, \hat{v})$. This shows that the function P is maximized by natural selection acting on the parasite. Likewise, the function H is maximized by natural selection acting on the host. Thus, we can determine whether conflict occurs by focusing on the simpler fitness functions P and H, which do not involve any of the epidemiological feedbacks inherent in the interaction. Notice though that technically these are relative fitness functions.

Importantly, we can also use the simpler functions P and H to quantify the magnitude of conflict as well, as we did earlier. To see this, recall that we quantified the magnitude of conflict for each party by comparing their fitness at equilibrium with what their fitness could be if they had control over both traits. Taking the parasite again as an example and considering the monomorphic equilibrium $(\hat{c}, \hat{v})$ (which corresponds to an environmental state $\hat{E}$), we want to compare the biggest possible value of $R_P(c, v; \hat{E}) = P(c, v)f(\hat{E})$ with the value $R_P(\hat{c}, \hat{v}; \hat{E}) = 1$. The difference is $\Delta\hat{W}_P = P(c_{\text{opt}}, v_{\text{opt}})f(\hat{E}) - 1$, where c_{opt} and v_{opt} are the values of c and v that maximize $P(c, v)$. Now consider comparing this level of conflict to the level of conflict that would exist at a different equilibrium $(\tilde{c}, \tilde{v})$ (which corresponds to an environmental state $\tilde{E}$). For this second equilibrium, the magnitude of conflict is $\Delta\tilde{W}_P = P(c_{\text{opt}}, v_{\text{opt}})f(\tilde{E}) - 1$, and therefore the difference in the magnitude of conflict between the two is $\Delta\tilde{W}_P - \Delta\hat{W}_P = P(c_{\text{opt}}, v_{\text{opt}})(f(\tilde{E}) - f(\hat{E}))$. Using the result that $f(\hat{E}) = 1/P(\hat{c}, \hat{v})$ (and similarly for $f(\tilde{E})$), we obtain

$$\Delta\tilde{W}_P - \Delta\hat{W}_P = P(c_{\text{opt}}, v_{\text{opt}})\left(\frac{P(\hat{c}, \hat{v}) - P(\tilde{c}, \tilde{v})}{P(\tilde{c}, \tilde{v})P(\hat{c}, \hat{v})}\right),$$

showing that the change in the magnitude of conflict is proportional to the difference in (relative) fitness of the parasite at the two equilibria $P(\hat{c}, \hat{v}) - P(\tilde{c}, \tilde{v})$. This is precisely what we used to quantify conflict in our host-parasite example. Biologically, this difference in relative fitness tells us how strongly selected a mutant would be that had a tool allowing it to control both its own private trait and that of its partner (Kokko and Jennions 2014).

The above considerations provide an approach for obtaining a biologically meaningful measure of the magnitude of conflict in the special case where there are fitness functions that are maximized by natural selection for both parties. Although this is true for a wide variety of situations, how do things change if the sort of decomposition found in equations (C1) is not possible? Consider again the example of the parasite in a population at the monomorphic equilibrium $(\hat{c}, \hat{v})$. The magnitude of conflict is $\Delta\hat{W}_P = R_P(c_{\text{opt}(\hat{E})}, v_{\text{opt}(\hat{E})}, \hat{E}) - 1$, where $c_{\text{opt}(\hat{E})}$ and $v_{\text{opt}(\hat{E})}$ are the trait values that maximize parasite LRO when the environmental state is $\hat{E}$. Likewise, at a different equilibrium $(\tilde{c}, \tilde{v})$, we have $\Delta\tilde{W}_P = R_P(c_{\text{opt}(\tilde{E})}, v_{\text{opt}(\tilde{E})}, \tilde{E}) - 1$, where $c_{\text{opt}(\tilde{E})}$ and $v_{\text{opt}(\tilde{E})}$ are the trait values that maximize parasite LRO when the environmental state is $\tilde{E}$. Thus, the difference in conflict is $\Delta\tilde{W}_P - \Delta\hat{W}_P = R_P(c_{\text{opt}(\hat{E})}, v_{\text{opt}(\hat{E})}, \hat{E}) - R_P(c_{\text{opt}(\tilde{E})}, v_{\text{opt}(\tilde{E})}, \tilde{E})$. Notice that the optimal choice of trait values is now potentially different for different environmental states E. This contrasts with the previous case in which the optimal choices of c and v were the same, regardless of environmental state. Similar conclusions hold for the host. Unfortunately, this added complexity precludes any sort of general analysis.

Literature Cited

André, J. B., and T. Day. 2007. Perfect reciprocity is the only evolutionarily stable strategy in the continuous prisoner's dilemma. Journal of Theoretical Biology 247:11–22.

Arnqvist, G. 2004. Sexual conflict and sexual selection: lost in the chase. Evolution 58:1383–1388.

Arnqvist, G., and L. Rowe. 2002. Antagonistic coevolution between the sexes in a group of insects. Nature 415:787–789.

———. 2005. Sexual conflict. Princeton University Press, Princeton, NJ.

Bulow, J. I., J. D. Geanakoplos, and P. D. Klemperer. 1985. Multimarket oligopoly: strategic substitutes and complements. Journal of Political Economy 93:488–511.

Burt, A., and R. L. Trivers. 2006. Genes in conflict: the biology of selfish genetic elements. Harvard University Press, Cambridge, MA.

Chapman, T. 2006. Evolutionary conflicts of interest between males and females. Current Biology 16:R744–R754.

Chapman, T., G. Arnqvist, J. Bangham, and L. Rowe. 2003. Sexual conflict. Trends in Ecology and Evolution 18:41–47.

Chapman, T., L. F. Liddle, J. M. Kalb, M. F. Wolfner, and L. Partridge. 1995. Cost of mating in *Drosophila melanogaster* females is mediated by male accessory gland products. Nature 373:241–244.

Civetta, A., and A. G. Clark. 2000. Correlated effects of sperm competition and postmating female mortality. Proceedings of the National Academy of Sciences of the USA 97:13162–13165.

Day, T., and J. G. Burns. 2003. A consideration of patterns of virulence arising from host-parasite co-evolution. Evolution 57:671–676.

Dougherty, L. R., E. van Lieshout, K. B. McNamara, J. A. Moschilla, G. Arnqvist, and L. W. Simmons. 2017. Sexual conflict and correlated evolution between male persistence and female resistance traits in the seed beetle *Callosobruchus maculatus*. Proceedings of the Royal Society B 284:20170132.

Dowrick, S. 1986. Von Stackelberg and Cournot duopoly: choosing roles. RAND Journal of Economics 17:251–260.

Frank, S. A. 2002. Immunology and evolution of infectious diseases. Princeton University Press, Princeton, NJ.

Frank, S. A., and B. J. Crespi. 2011. Pathology from evolutionary conflict, with a theory of X chromosome versus autosome conflict over sexually antagonistic traits. Proceedings of the National Academy of Sciences of the USA 108(suppl. 2):10886–10893.

Fricke, C., J. Perry, T. Chapman, and L. Rowe. 2009. The conditional economics of sexual conflict. Biology Letters 5:671–674.

Gaba, S., and D. Ebert. 2009. Time-shift experiments as a tool to study antagonistic coevolution. Trends in Ecology and Evolution 24:226–232.

Kokko, H., and M. D. Jennions. 2014. The relationship between sexual selection and sexual conflict. Cold Spring Harbor Perspectives in Biology 6:a017517, doi:10.1101/cshperspect.a017517.

Lessells, C. M., and J. M. McNamara. 2011. Sexual conflict over parental investment in repeated bouts: negotiation reduces overall care. Proceedings of the Royal Society B 279:1506–1514.

McLeod, D. V., and T. Day. 2015. Pathogen evolution under host avoidance plasticity. Proceedings of the Royal Society B 282: 20151656, doi:10.1098/rspb.2015.1656.

———. 2017. Female plasticity tends to reduce sexual conflict. Nature Ecology and Evolution 1:0054, doi:10.1038/s41559-016-0054.

McNamara, J. M., and S. R. X. Dall. 2009. Information is a fitness enhancing resource. Oikos 119:231–236.

McNamara, J. M., C. E. Gasson, and A. I. Houston. 1999. Incorporating rules for responding into evolutionary games. Nature 401: 368–371.

McNamara, J. M., E. M. K. Wilson, and A. I. Houston. 2006. Is it better to give information, receive it, or be ignorant in a two-player game? Behavioral Ecology 17:441–451.

Metz, J. A. J., S. D. Mylius, and O. Diekmann. 2008. When does evolution optimize? Evolutionary Ecology Research 10:629–654.

Mock, D. W., and G. A. Parker. 1997. The evolution of sibling rivalry. Oxford University Press, Oxford.

Mylius, S. D., and O. Diekmann. 1995. On evolutionarily stable life histories, optimization and the need to be specific about density dependence. Oikos 74:218–224.

Otto, S. P., and T. Day. 2007. A biologist's guide to mathematical modeling. Princeton University Press, Princeton, NJ.

Parker, G. A. 1979. Sexual selection and sexual conflict. Pages 123–166 *in* M. S. Blum and N. B. Blum, eds. Sexual selection and reproductive competition in insects. Academic Press, New York.

———. 2006. Sexual conflict over mating and fertilization: an overview. Philosophical Transactions of the Royal Society B 361:235–259.

Pen, I., and P. D. Taylor. 2005. Modelling information exchange in worker-queen conflict over sex allocation. Proceedings of the Royal Society B 272:2403–2408.

Pizzari, T., and R. R. Snook. 2003. Sexual conflict and sexual selection: chasing away the paradigm shifts. Evolution 57:1223–1236.

———. 2004. Sexual conflict and sexual selection: measuring antagonistic coevolution. Evolution 58:1389–1393.

Rebelein, R., and E. Turkay. 2016. When do first-movers have an advantage? a Stackleberg classroom experiment. Journal of Economic Education 47:226–240.

Rice, W. R. 1996. Sexually antagonistic male adaptation triggered by experimental arrest of female evolution. Nature 381:232–234.

———. 2013. Nothing makes sense except in light of genomic conflict. Annual Review of Ecology, Evolution, and Systematics 44: 217–237.

Rice, W. R., and B. Holland. 1997. The enemies within: intergenomic conflict, interlocus contest evolutionary (ICE), and the intraspecific Red Queen. Behavioral Ecology and Sociobiology 41:1–10.

Rowe, L., E. Cameron, and T. Day. 2003. Detecting sexually antagonistic coevolution with population crosses. Proceedings of the Royal Society B 270:2009–2016.

Rowe, L., and T. Day. 2006. Detecting sexual conflict and sexually antagonistic coevolution. Philosophical Transactions of the Royal Society B 361:277–285.

Schmid-Hempel, P. 2011. Evolutionary parasitology: the integrated study of infections, immunology, ecology, and genetics. Oxford University Press, Oxford.

Sirot, L. K., A. Wong, T. Chapman, and M. F. Wolfner. 2014. Sexual conflict and seminal fluid proteins: a dynamic landscape of sexual interactions. Cold Spring Harbor Perspectives in Biology 7:1–24.

Sjerps, M., and P. Haccou. 1993. Information determines the optimal clutch sizes of competing insects: Stackleberg versus Nash equilibrium. Journal of Theoretical Biology 163:473–484.

Strassman, J. E., D. C. Queller, J. C. Avise, and F. J. Ayala, eds. 2011. In the light of evolution. Vol. 5. Conflict and cooperation. National Academies, Washington, DC.

Swanson, W. J., and V. D. Vacquier. 2002. The rapid evolution of reproductive proteins. Nature Reviews Genetics 3:137–144.

Taylor, P. D., and T. Day. 2004. Stability in negotiation games and the emergence of cooperation. Proceedings of the Royal Society B 271:669–674.

Taylor, P. D., T. Day, D. Nagy, G. Wild, J. B. André, and A. Gardner. 2006. The evolutionary consequences of plasticity in host-parasite interactions. Theoretical Population Biology 69:323–331.

Trivers, R. L. 1974. Parent-offspring conflict. American Zoologist 14:249–264.

van Baalen, M. 1998. Coevolution of recovery ability and virulence. Proceedings of the Royal Society B 265:317–325.

Wigby, S., and T. Chapman. 2005. Sex peptide causes mating costs in female *Drosophila melanogaster*. Current Biology 15:316–321.

Wild, G., G. Costain, and T. Day. 2007. An epidemiological context for the consequences of phenotypic plasticity in host-pathogen interactions. Evolutionary Ecology Research 9:221–238.

Symposium Editor: Locke Rowe