



DIGITAL ACCESS TO SCHOLARSHIP AT HARVARD

Host Plant Specialization Driven by Sexual Selection

The Harvard community has made this article openly available.
[Please share](#) how this access benefits you. Your story matters.

Citation	Quental, Tiago B., Manus M. Paten, and Naomi E. Pierce. 2007. Host Plant Specialization Driven by Sexual Selection. <i>American Naturalist</i> 169(6): 830-836.
Published Version	doi:10.1086/516654
Accessed	February 17, 2015 1:50:40 PM EST
Citable Link	http://nrs.harvard.edu/urn-3:HUL.InstRepos:2560813
Terms of Use	This article was downloaded from Harvard University's DASH repository, and is made available under the terms and conditions applicable to Other Posted Material, as set forth at http://nrs.harvard.edu/urn-3:HUL.InstRepos:dash.current.terms-of-use#LAA

(Article begins on next page)

Notes and Comments

Host Plant Specialization Driven by Sexual Selection

Tiago B. Quental,^{*} Manus M. Patten,[†] and Naomi E. Pierce[‡]

Department of Organismic and Evolutionary Biology, Museum of Comparative Zoology, Harvard University, Cambridge, Massachusetts 02138

Submitted September 15, 2006; Accepted December 18, 2006;
Electronically published April 3, 2007

ABSTRACT: We propose a new mechanism based on sexual selection to explain the evolution of diet breadth in insects. More specifically, we show that mate choice in females for certain diet-derived male pheromones can be exploited by maternal effect genes that preferentially place offspring on a specific host plant, resulting in specialization. Our analytical model also suggests that the process is more likely to occur with species that show male-congregating mating strategies, such as lekking and hilltopping. The model offers a new explanation for the similarity between the composition of male lepidopteran pheromones and the chemistry of their host plants and also suggests a novel mechanism of host plant shift. This is the first time that sexual selection has been proposed to drive host plant specialization and the first time that a mechanism with selection acting solely on the adult stage has been shown to be capable of determining larval feeding habits.

Keywords: maternal effects, pheromone, Lepidoptera, diet breadth, host shift, specialization.

The evolution of diet breadth in insects has long fascinated ecologists and evolutionary biologists, and multiple factors have been suggested to promote specialist or generalist diets in different contexts. Among the former are the ability to deal with plant chemistry (Ehrlich and Raven 1964), competition for resources (Karbon 1986), and enemy-free space (Atsatt 1981; Jeffries and Lawton 1984). Among the latter are habitat unpredictability (Strong et al. 1984), the necessity for certain nutritional requirements (Bernays et

al. 1997), and resource availability (Thompson 1982). Many phytophagous insects have restricted diets (Janzen 1988; Thompson 1994), and feeding specialization has been argued to be a central force driving their evolution (Ehrlich and Raven 1964; Nosil 2002).

Insects are well known for their dependence on chemical communication. Mating signals are among the most essential chemical messages exchanged between individual insects, and it is important to understand the origin and composition of these signals. In the case of Lepidoptera, males produce courtship pheromones that are often structurally similar to compounds found in certain plants (Baker 1989). The arctiid moth *Utetheisa ornatrix* is particularly well known in this regard (Conner et al. 1981; Eisner and Meinwald 1987, 1995; Dussourd et al. 1988, 1991), but other species, as either larvae or adults, also acquire host plant chemicals for the production of pheromones. For example, some species of arctiid moths are known to sequester chemicals during the larval stage for later use as pheromones or as precursors of pheromones (Baker 1989; Landolt and Phillips 1997), and adult males of danaine and ithomiine butterflies actively collect chemicals (usually alkaloids in plant material such as rotting fruits or broken twigs) to use as pheromones (Edgar and Culvenor 1974; Pliske 1975).

Research on the relationship between pheromone composition and larval diet has typically focused on understanding how host plant characteristics (e.g., plant chemistry) could give rise to pheromone composition and how this could affect mating behavior. Host plant and pheromone chemical similarity has been explained in the context of the exploitation of a preexisting female sensory system that is geared to find and identify host plants (Edgar et al. 1974; Conner et al. 1981; Boppre and Schneider 1985; Eisner and Meinwald 1987, 1995; Dussourd et al. 1988, 1991; Baker 1989; Krasnoff and Dussourd 1989; Landolt and Phillips 1997). Here we invoke sexual selection as a new evolutionary route to the evolution of specialization in larval feeding. This line of reasoning reverses the causal chain in the conventional explanation for the resemblance between pheromones and host plant chemicals. We argue that preexisting mate choice mechanisms in females for

* E-mail: tqental@oeb.harvard.edu.

† E-mail: mpatten@oeb.harvard.edu.

‡ E-mail: npierce@oeb.harvard.edu.

Table 1: Genetic and fitness scheme for the selection model

	Genotype					
	WZ	WZ*	ZZ	ZZ*	Z*Z	Z*Z*
Frequency	$(1 - p_s)$	p_s	$(1 - p_d)(1 - p_s)$	$(1 - p_d)p_s$	$p_d(1 - p_s)$	$p_d p_s$
Fitness	1	$1 - s$	1	1	$1 + t$	$1 + t$

certain male pheromones can be exploited by maternal effect genes that preferentially place male offspring in a plant environment suited to incorporating the necessary chemicals to produce such pheromones.

The Model

To model this possible mechanism, we start with a population of a generalist lepidopteran species and introduce a mutant oviposition preference allele. We consider the case of Z linkage for oviposition preference genes because all studies of such genes in butterflies show sex linkage (Sperling 1994; Janz 1998; Prowell 1998 and references therein). We denote a Z chromosome bearing this novel mutant as Z^* and one with a wild-type allele as Z . The mutant occurs in frequency p . Female genotypes Z^*W and ZW occur in the frequencies p_s and $(1 - p_s)$, while male genotypes Z^*Z^* , Z^*Z , ZZ^* , and ZZ occur in the frequencies $p_d p_s$, $p_d(1 - p_s)$, $(1 - p_d)p_s$, and $(1 - p_d)(1 - p_s)$, respectively. We use subscripts s and d to denote sire derived and dam derived because this avoids the confusion of m 's and f 's (Mothers? Males? Females? Fathers?). Plants come in two varieties, α and β . The α variety represents one species or one clade, and β represents one or many different species or clades; together, α and β make up the set of established oviposition sites for the generalist species. The WZ^* mothers oviposit exclusively on α host plants, while wild-type mothers oviposit on both types of plants. Host plants α and β can differ in one of two ways, either by the presence in α of a unique chemical that can be later modified into a mating pheromone or in the relative ratios of the same host plant chemicals that go into making the pheromonal suite of the adult male. Males developing on α host plants experience increased fitness relative to males developing on host plant β , reflecting the attractiveness of the pheromone in the adult stage and a pre-existing preference in females for this pheromone. The fitness of preferred males can be modeled as a fixed constant, as we do below for ease of presentation, or it can be drawn from a fitness function (see appendix).

The Z chromosome has different fitness consequences in the two sexes. In females, it is the sire-derived copy, the lone Z in heterogametic females, that causes fitness variation. We assign a reduced fitness, $1 - s$, to females bearing the Z^* version of this chromosome to reflect a cost of searching for a suitable oviposition site. Fitness

variation also exists between the dam-derived Z chromosomes, which are present only in males, to the extent that they reflect a bias for where these males have developed. All sons of WZ^* mothers are reared on α , while only a fraction of sons of WZ mothers are reared there by chance, according to α host plant density. Thus, males with a dam-derived Z^* have fitness $1 + t$, and males with a dam-derived Z have an average fitness of 1. Table 1 gives the genotype frequencies and fitness values for all possible individuals.

We separately examine allele frequency changes after selection in males and females. We apply selection according to the above fitness regime. This will give the frequency of Z^* in sperm as

$$\begin{aligned} p'_s &= \frac{[p_d p_s + p_d(1 - p_s)/2](1 + t) + [(1 - p_d)p_s/2]}{\overline{w_m}} \\ &= \frac{p_d(1 + p_s)(1 + t) + (1 - p_d)p_s}{2\overline{w_m}}. \end{aligned} \quad (1)$$

This frequency is also the frequency of sire-derived alleles in the next generation of zygotes. Average male fitness is $\overline{w_m} = 1 + p_d t$.

Second, we apply selection to females to generate the subsequent frequencies of alleles in their eggs. This will be the dam-derived frequency in zygotes. We apply selection according to the scheme above to give

$$p'_d = \frac{1}{w_f} p_s(1 - s), \quad (2)$$

in which average female fitness is $\overline{w_f} = 1 - p_s s$. The timing of the selection on females is inconsequential because we make an assumption of random mating among genotypes. Thus, selection could occur on females pre-mating or post-mating.

Subtracting p_s from p'_s and p_d from p'_d gives equations for the change in sire-derived and dam-derived allele frequencies:

$$\begin{aligned} \Delta p_s &= p'_s - p_s \\ &= \frac{[p_d(1 + p_s)(1 + t) + (1 - p_d)p_s] - 2p_s \overline{w_m}}{2\overline{w_m}}, \\ \Delta p_d &= p'_d - p_d \\ &= \frac{p_s(1 - s) - p_d \overline{w_f}}{\overline{w_f}}. \end{aligned} \quad (3)$$

Combining the above equations in a weighted average (one Z chromosome in females and two Z chromosomes in males) gives a precise one-generation change in an allele's population-wide frequency, p , for any starting values and allows us to look for equilibria:

$$\begin{aligned} \Delta p &= \frac{1}{3} \Delta p_d + \frac{2}{3} \Delta p_s \\ &= \frac{1}{3w_f w_m} [p_d(1+t)\overline{w}_f + p_s(1-s)\overline{w}_m - (p_d + p_s)\overline{w}_f \overline{w}_m]. \end{aligned} \tag{4}$$

When s is 0, the cost to mothers of being specialists is nonexistent, and the above reduces to

$$\Delta p = \frac{1}{3w_m} [p_d(1-p_d)(1+t) - p_d(1-p_d)], \tag{5}$$

which, by inspection, is always greater than or equal to 0 if t is positive, suggesting that if the cost of searching for α plants is sufficiently low, the evolution of specialization will always be obtained.

When the cost of choosy oviposition is entered in equation (4), we see that the change in p is greater than or equal to 0 provided that

$$p_d(1+t)\overline{w}_f + p_s(1-s)\overline{w}_m - (p_d + p_s)\overline{w}_f \overline{w}_m > 0. \tag{6}$$

This can be rearranged to form the following inequality:

$$\frac{t}{s} > \frac{p_s(1-p_s)\overline{w}_m}{p_d(1-p_d)\overline{w}_f}. \tag{7}$$

The above inequality indicates that provided that s , the direct costs to maternal fitness, are small or that t , the indirect benefits to sons of host plant choice, are relatively large, the evolution of specialization is attainable by the indirect selection mechanism described here.

For the case of absolute fitness benefits to males, that is, when t is constant, we can ask whether such a selection scheme permits any internal equilibria. At equilibrium, equation (2) can be rewritten as

$$\hat{p}_d = \frac{1}{w_f} \hat{p}_s(1-s). \tag{8}$$

The above permits only the trivial equilibria at $p_d, p_s = 0, 1$. For certain combinations of the fitness parameters s and t the oviposition behavior becomes selectively neutral. This gives rise to another situation in which equation (7) is expected to return an equality rather than

an inequality. The function relating s and t that makes the behavior neutral is given by rewriting equation (7) as an equality and using the substitution in equation (8):

$$s = \frac{t}{1+t}. \tag{9}$$

Figure 1 plots equation (9) and shows the parameter space that permits specialization to evolve.

This model has some minor but important assumptions. First, we assume no allelic variation for the male trait (the ability to produce the pheromone). All males are capable of producing pheromones from the host plant chemicals, and the differences in pheromone composition between males are completely determined by the host plant environment. Second, the pheromonal suites of males reared on both α and β plants contain a shared component necessary for species recognition. The difference between males reared on either plant is not so large that females fail to recognize α -reared males as conspecifics. This assumption is not problematic since, as mentioned before, there are many examples in Lepidoptera where the male sequesters chemicals from the host plant to use as pheromones and where these pheromones can be composed of a mixture of chemicals (Baker 1989 and references therein; Nishida et al. 1996). Third, larval feeding on any of the possible host plants does not result in viability differences. All fitness differences due to host plants are ex-

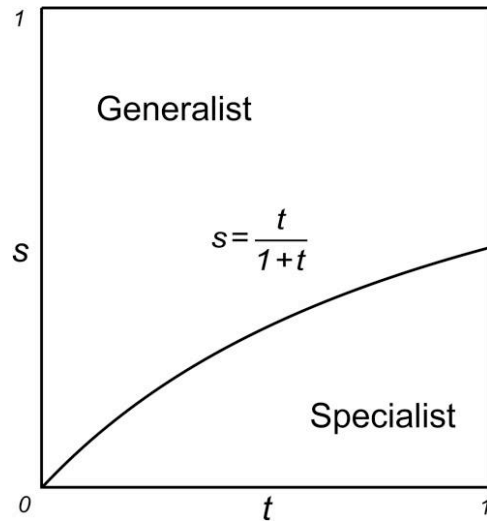


Figure 1: Parameter combinations of s (direct cost of oviposition search) and t (male fitness benefit) and their associated oviposition behaviors in females. The equation shown in the figure was used to draw the line dividing the parameter space. For values above this line, we have a combination of parameters that favors generalist behavior; for values below the line, we get the evolution of specialization.

perienced by adults. Fourth, we have chosen to make no assumption on how plant density affects the search cost to mothers or on the frequency with which generalist mothers oviposit on α plants according to density. We have instead assigned costs and benefits in a general sense, such that s and t could both become functions of a plant density parameter. An assumption of a linear effect of α plant density in both males and females was explored (not shown) and found to make no difference to our result. The main assumption of our model is the preexisting female preference for a particular pheromone blend in mates. In our model, we do not present an explicit explanation for that initial preference. Rather, we assume the existence of this mating preference and explore its consequences in the presence of allelic variation for oviposition behavior.

Discussion

Our model not only shows that the evolution of host plant specialization through sexual selection is possible but also suggests a certain range of values for the direct search costs imposed on females and the indirect benefits provided by their sexy sons for which this mechanism could work (fig. 1). That relationship also permits predictions of which taxa the sexual selection mechanism of host plant specialization is more likely to work for.

Many butterfly species show mating strategies, such as lekking and hilltopping (Shields 1967; Rutowski 1991; Wiklund 2003), that involve male congregations. These mating strategies are likely to impose the strong sexual selection (see also appendix) required for the mechanism proposed here to work and could drive host plant specialization, even in cases where the costs are relatively high. The facts that ZW species are especially prone to sexual selection (Reeve and Pfennig 2003; Kirkpatrick and Hall 2004) and that lekking and hilltopping are common behaviors make butterflies a good candidate for the study of the mechanism proposed here. In addition, any feature that decreases female searching cost should predispose the evolution of host plant specialization by the mechanism proposed here. In this respect, lineages that have acquired traits or that inhabit environments that diminish female searching costs are also good candidates to use in the study of our mechanism of host plant specialization. We should mention that there are some species where other aspects of the mating biology render our proposed mechanism irrelevant. Pupal mating butterflies are one such example. Here, males sit on female pupae and compete to fertilize the females as they emerge (Gilbert 1991; Deinert et al. 1994; Deinert 2003). In such species, precopulatory female choice is absent, and our model does not apply.

Our model of host plant specialization offers a new

explanation for some patterns described in the literature. One interesting phenomenon accommodated by our model is the frequently observed mismatch between oviposition preference and larval performance (Thompson 1988). Since, in our model, the forces acting on the evolution of larval host plant specialization are solely determined by selection on the adult stage, there is no a priori reason to expect that plants that have potentially useful pheromone precursors would also be the ones that confer the best performance in the larval stage. Our hypothesis explaining this mismatch is not mutually exclusive with others, such as the enemy-free space model (Lawton and McNeil 1979; Atsatt 1981). Further, having Z-linked oviposition preferences means that any fitness cost associated with host plant choice need only be paid for by increased fitness in males—not females, since they do not inherit the maternal Z chromosome (Miller et al. 2006)—suggesting that host plants with sexually antagonistic consequences in favor of sons are suitable substrates on which butterflies may specialize. The Z linkage may consequently expand the realm of possible plants on which butterflies can specialize and help explain the mismatch between host plant choice and larval performance. This also suggests that our mechanism of host plant specialization through sexual selection could be more common in insects where females are the heterogametic sex and oviposition genes are located on the Z chromosome. A further theoretical exploration of autosomal linkage may prove fruitful.

Our model also offers an alternative explanation for the similarity between insect pheromone chemistry and host plant compounds. The existing explanation is based on the idea that males are able to exploit the female sensory mechanism for finding host plants by essentially mimicking the plants (Edgar et al. 1974; Baker 1989; Krasnoff and Dussourd 1989) and assumes that specialization in females happens before the male acquisition of specific pheromones derived from larval feeding. According to our model, the similarity of pheromone and host plant chemicals can be explained by a reverse series of events in which a preexisting preference in females favoring a plant-derived pheromone would drive specialization on that host plant by indirectly selecting for oviposition preference genes; the chemical resemblance between pheromones and host plants is an outcome of this process under our model. Using a phylogeny for comparative analysis offers a way to test these two views of the acquisition of male courtship pheromone communication and the evolution of specialization. If sexual selection is the mechanism driving host plant specialization, we would expect to find pheromone communication and the ability to change host plant chemicals into attractive pheromones evolving before host plant specialization. The opposite result would falsify our hypothesis and lend support to the current explanation of

similarity between host plant chemistry and pheromone composition. Comparative methods may not be able to fully resolve these two hypotheses, given that the order of acquisition of these characteristics might be lost in the reconstruction of a particular clade. A complementary approach would be to study generalist species that exhibit quantitative variation in the use of host plants among populations and look for covariance between this trait and female preference for host plant–derived pheromones. Our hypothesis predicts a positive association between male offspring fitness and female oviposition preference. If our sexual selection hypothesis is correct, it should be possible to identify signs of sexual selection before specialization. In contrast, the alternative hypothesis would assume that sexual selection could play a role only after host plant specialization has been achieved.

Although our model was developed explicitly to describe the evolution of host plant specialization from a generalist strategy, it also suggests a novel mechanism of host plant shift. Consider a scenario in which α and β represent a novel host plant and an established host plant, respectively. Under this reworked scenario, the same mechanism presented above for specialization would describe the evolution of a host plant shift from β to α as an outcome of sexual selection on the adult stage.

To our knowledge, this is the first time that sexual selection on male secondary traits has been proposed to drive host plant specialization. We suggest that it might be an important and overlooked mechanism in Lepidoptera and in those species where we observe a mismatch between larval performance and oviposition preference. Our model was developed explicitly for butterflies and moths, but in principle, a sexual selection mechanism of host plant specialization could work in any insect taxon where (1) adult male secondary sexual traits are affected by the larval stage, (2) those traits are a product of gene and host plant environment interactions, (3) female choice is possible, and (4) oviposition choice has a strong genetic component.

Acknowledgments

We extend special thanks to B. Koiller for developing a simulation model that gave rise to the analytical model presented here and for her support, comments, and generosity. We thank D. Haig, B. Lemos, S. Ramírez, F. Úbeda, and R. Vila for valuable discussions and helpful comments on earlier drafts of the manuscript. T.Q. was supported by a fellowship from the Department of Organismic and Evolutionary Biology at Harvard, M.P. was supported by a National Science Foundation (NSF) predoctoral fellowship, and T.Q. and N.P. were supported by NSF grant DEB-0447242.

APPENDIX

Models for Fixed Relative Preferences and the Best-of- N Males

In the body of the article, we present the simplest possible selection scheme in which t , the fitness benefit to males of being sexy, is not related to the frequency of sexy males. This choice was made to simplify the presentation of the underlying workings of the model. However, most models of sexual selection assume that the benefit of sexiness to a male is in some way related to the frequency of the preferred trait in the population. What we do here is model t as a function of the frequency f of sexy males in the population. The frequency of sexy males is given as the sum of the frequency of sons of specializing mothers and that fraction of sons ϕ who were randomly oviposited on the α plant by generalist mothers:

$$f = p_a + (1 - p_a)\phi,$$

$$1 - f = (1 - p_a)(1 - \phi).$$

Let U_i be the proportion of females that mate with a male in class i , where $i = 1$ for nonsexy males and 2 for sexy males. We will use two different behavioral rules to calculate U . The fitness W_i of the two classes of male is given by

$$W_1 = \frac{U_1}{(1 - f)},$$

$$W_2 = \frac{U_2}{f},$$

and we can calculate t as

$$t = \frac{W_2}{W_1} - 1.$$

To explore the consequences of imposing our first behavioral rule, fixed relative preferences in females (sensu Kirkpatrick 1982), we let a be the propensity of a female to mate with a sexy male rather than with a nonsexy male. Verbally, this means she is a times more likely to mate with a sexy male. The U_i are

$$U_1 = \frac{1 - f}{(1 - f) + af},$$

$$U_2 = \frac{af}{(1 - f) + af}.$$

Male fitness is given by

$$W_1 = \frac{1}{(1-f) + af},$$

$$W_2 = \frac{a}{(1-f) + af}.$$

The above shows that absolute male fitness is negatively frequency dependent for both types of male. However, taking the ratio gives $t = a - 1$, a fixed constant. Thus, under a fixed relative mating preference scheme in which all females are choosy, the fitness of a sexy male at any frequency is constant, and equations (4) and (7) apply. This means that fixation of the specializing allele is deterministically a possibility in our infinite population provided that a is sufficiently high.

A second rule of mate choice captures the behavior at a lek (Seger 1985). We sample a pair of males at random from the population, and the female mates with one of them according to the following preference. If the pair is heterogeneous, one sexy and one nonsexy male, then the female chooses the sexy male with probability $(1 + c)/2$. When $c = 0$, mating is random, and when $c = 1$, the female mates with the sexy male with certainty. For this case, the U_i are given by

$$U_1 = (1 - f) - cf(1 - f),$$

$$U_2 = f + cf(1 - f);$$

male fitnesses are given by

$$W_1 = 1 - cf,$$

$$W_2 = 1 + c(1 - f);$$

and the fitness parameter t is given by

$$\begin{aligned} t &= \frac{1 + c(1 - f)}{1 - cf} - 1 \\ &= \frac{c}{1 - cf}. \end{aligned}$$

In the “best of two” mating scheme, we capture the positive frequency dependence that Seger found (1985). Thus, the “best of two” rule augments the probability of the evolution of specialization.

Literature Cited

- Atsatt, P. R. 1981. Lycaenid butterflies and ants: selection for enemy-free space. *American Naturalist* 118:638–654.
- Baker, T. C. 1989. Origin of courtship and sex pheromones of the oriental fruit moth and discussion of the role of phytochemicals in the evolution of lepidopteran male scents. Pages 401–418 in C. H. Chou and G. R. Waller, eds. *Phytochemical ecology: allelochemicals, mycotoxins and insect pheromones and allomones*. Academia Sinica Monograph Series 9. Institute of Botany, Taipei.
- Bernays, E. A., J. E. Angel, and M. Augner. 1997. Foraging by a generalist grasshopper: the distance between food resources influences diet mixing and growth rate (Orthoptera: Acrididae). *Journal of Insect Behavior* 10:829–840.
- Boppre, M., and D. Schneider. 1985. Pyrrolizidine alkaloids quantitatively regulate both scent organ morphogenesis and pheromone biosynthesis in male *Cretonotos* moths (Lepidoptera, Arctiidae). *Journal of Comparative Physiology A* 157:569–577.
- Conner, W. E., T. Eisner, R. K. Vandermeer, A. Guerrero, and J. Meinwald. 1981. Pre-copulatory sexual interaction in an arctiid moth (*Utetheisa ornatrix*): role of a pheromone derived from dietary alkaloids. *Behavioral Ecology and Sociobiology* 9:227–235.
- Deinert, E. I. 2003. Mate location and competition for mates in a pupal mating butterfly. Pages 91–110 in C. L. Boggs, W. B. Watt, and P. R. Ehrlich, eds. *Butterflies: ecology and evolution taking flight*. University of Chicago Press, Chicago.
- Deinert, E. I., J. T. Longino, and L. E. Gilbert. 1994. Mate competition in butterflies. *Nature* 370:23–24.
- Dussourd, D. E., K. Ubik, C. Harvis, J. Resch, J. Meinwald, and T. Eisner. 1988. Biparental defensive endowment of eggs with acquired plant alkaloid in the moth *Utetheisa ornatrix*. *Proceedings of the National Academy of Sciences of the USA* 85:5992–5996.
- Dussourd, D. E., C. A. Harvis, J. Meinwald, and T. Eisner. 1991. Pheromonal advertisement of a nuptial gift by a male moth (*Utetheisa ornatrix*). *Proceedings of the National Academy of Sciences of the USA* 88:9224–9227.
- Edgar, J. A., and C. C. Culvenor. 1974. Pyrrolizidine ester alkaloid in danaid butterflies. *Nature* 248:614–616.
- Edgar, J. A., T. E. Pliske, and C. C. Culvenor. 1974. Coevolution of danaid butterflies with their host plants. *Nature* 250:646–648.
- Ehrlich, P. R., and P. H. Raven. 1964. Butterflies and plants: a study in coevolution. *Evolution* 18:586–608.
- Eisner, T., and J. Meinwald. 1987. Alkaloid-derived pheromones and sexual selection in Lepidoptera. Pages 251–269 in G. D. Prestwich and G. J. Blumquist, eds. *Pheromone biochemistry*. Academic Press, Orlando, FL.
- . 1995. The chemistry of sexual selection. *Proceedings of the National Academy of Sciences of the USA* 92:50–55.
- Gilbert, L. E. 1991. Biodiversity of Central American *Heliconius* community: pattern, process and problems. Pages 403–427 in P. W. Price, T. M. Lewinsohn, G. W. Fernandes, and W. W. Benson, eds. *Plant-animal interactions: evolutionary ecology in tropical and temperate regions*. Wiley, London.
- Janz, N. 1998. Sex-linked inheritance of host-plant specialization in a polyphagous butterfly. *Proceedings of the Royal Society B: Biological Sciences* 265:1675–1678.
- Janzen, D. H. 1988. Ecological characterization of a Costa Rican dry forest caterpillar fauna. *Biotropica* 20:120–135.
- Jeffries, M. J., and J. H. Lawton. 1984. Enemy free space and the structure of ecological communities. *Biological Journal of the Linnean Society* 23:269–286.
- Karban, R. 1986. Interspecific competition between folivorous insects on *Erigeron glaucus*. *Ecology* 67:1063–1072.
- Kirkpatrick, M. 1982. Sexual selection and the evolution of female choice. *Evolution* 36:1–12.
- Kirkpatrick, M., and D. W. Hall. 2004. Male-biased mutation, sex linkage, and the rate of adaptive evolution. *Evolution* 58:437–440.

- Krasnoff, S. B., and D. E. Dussourd. 1989. Dihydropyrrrolizine attractants for arctiid moths that visit plants containing pyrrolizidine alkaloids. *Journal of Chemical Ecology* 15:47–60.
- Landolt, P. J., and T. W. Phillips. 1997. Host plant influences on sex pheromone behavior of phytophagous insects. *Annual Review of Entomology* 42:371–391.
- Lawton, J. H., and S. McNeil. 1979. Between the devil and the blue sea: on the problem of being an herbivore. Pages 223–244 in R. M. Anderson, B. D. Turner, and L. R. Taylor, eds. *Population dynamics*. Blackwell, Oxford.
- Miller, P. M., S. Gavrilets, and W. R. Rice. 2006. Sexual conflict via maternal-effect genes in ZW species. *Science* 312:73.
- Nishida, R., S. Schulz, C. S. Kim, H. Fukami, Y. Kuwahara, K. Honda, and N. Hayashi. 1996. Male sex pheromone of a giant danaine butterfly, *Idea leuconoe*. *Journal of Chemical Ecology* 22:949–972.
- Nosil, P. 2002. Transition rates between specialization and generalization in phytophagous insects. *Evolution* 56:1701–1706.
- Pliske, T. E. 1975. Courtship behavior and use of chemical communication by males of certain species of ithomiine butterflies (Nymphalidae-Lepidoptera). *Annals of the Entomological Society of America* 68:935–942.
- Prowell, D. P. 1998. Sex linkage and speciation in Lepidoptera. Pages 309–319 in D. J. Howard and S. H. Berlocher, eds. *Endless forms: species and speciation*. Oxford University Press, New York.
- Reeve, H. K., and D. W. Pfennig. 2003. Genetic biases for showy males: are some genetic systems especially conducive to sexual selection? *Proceedings of the National Academy of Sciences of the USA* 100:1089–1094.
- Rutowski, R. L. 1991. The evolution of male mate-locating behavior in butterflies. *American Naturalist* 138:1121–1139.
- Seger, J. 1985. Unifying genetic models for the evolution of female choice. *Evolution* 39:1185–1193.
- Shields, O. 1967. Hilltopping. *Journal of Research on Lepidoptera* 6: 69–178.
- Sperling, F. A. H. 1994. Sex-linked genes and species-differences in Lepidoptera. *Canadian Entomologist* 126:807–818.
- Strong, D. R., J. H. Lawton, and R. Southwood. 1984. *Community patterns and mechanisms*. Blackwell Scientific, London.
- Thompson, J. N. 1982. *Interaction and coevolution*. Wiley, New York.
- . 1988. Evolutionary ecology of the relationship between oviposition preference and performance of offspring in phytophagous insects. *Entomologia Experimentalis et Applicata* 47:3–14.
- . 1994. *The coevolutionary process*. University of Chicago Press, Chicago.
- Wiklund, C. 2003. Sexual selection and the evolution of butterfly mating systems. Pages 67–90 in C. L. Boggs, W. B. Watt, and P. R. Ehrlich, eds. *Butterflies: ecology and evolution taking flight*. University of Chicago Press, Chicago.

Associate Editor: Stephen B. Heard
 Editor: Michael C. Whitlock