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INFLUENCE OF GENERATION TIME ON THE RATE OF RESPONSE TO SELECTION

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Abstract.—We examined the influence of generation time on the rate of evolution of a trait under intense natural selection: pesticide resistance in arthropod pests. Previous empirical and theoretical analyses supported a positive linear relationship between the number of generations per year and the rate of evolution of pesticide resistance. To test this relationship, we assembled a data base that integrated information on resistance evolution, generation time, and other biological parameters for 682 North American arthropod pests. The data did not support a linear relationship between generations per year and the evolution of resistance, revealing instead a nonlinear and highly variable relationship, with peak rates of resistance evolution for species with intermediate generation times. This result was independent of the difference between introduced and native species and of differences among the major arthropod taxonomic orders in ability to evolve resistance. A reevaluation of evidence from analytical and computer-simulation models of resistance evolution suggests that the linear relationship between generations per year and resistance evolution is also without foundation in theory. An extension of a simple analytical model of resistance evolution suggests instead that the rate of resistance evolution is independent of generation time. We also find little support for the suggestion that species with many generations per year are regularly subject to elevated levels of selection for pesticide resistance. Per-generation fitness values for genotypes conferring resistance to pesticides or genotypes conferring increased fitness in response to any density-independent selective agent are related exponentially to generation time, resulting in the independence of generation time and the rate of response to selection in the simplest-case model. Generation time can influence the rate of resistance evolution; however, rather than acting in a simple, uniform manner, generation time interacts with a variety of genetic, ecological, and operational factors to produce a multitude of effects.

The molecular-clock hypothesis has spurred a continuing controversy regarding the rate of evolutionary change in lineages with different cohort generation times. Most studies attempting to resolve this issue have been conducted at the molecular level and have examined genetic changes that are arguably selectively neutral (Sarich and Wilson 1973; Wu and Li 1985; Easteal 1988; Graur et al. 1989; see also Palumbi 1989). The degree to which the rate of molecular evolution of neutral traits is constant is important because rate constancy must be assumed to reconstruct evolutionary trees with correct topologies and to infer the phylogenetic divergence times of taxa of known molecular similarity.

The influence of generation time on the evolution of nonneutral traits is also a

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theoretically important question. Variation in generation time is one of several factors that could cause the rate of adaptive evolution to vary in different lineages. If the fitness values of given alleles are independent of generation time, then lineages with a larger number of generations per year (GPY) exhibit greater annual changes in allele frequencies. Rate constancy of evolution for selectively important traits would argue against the claim that a constant rate of evolution is consistent only with a neutral theory of evolution (Hartl and Dykhuizen 1979; Gillespie 1986; Zuckerkandl 1987). The effect of generation time on the rate of adaptation of populations could also influence the evolution of life-history strategies. If a larger GPY increases evolutionary plasticity, shorter generation times could be favored over longer generation times. Shorter generation times might therefore be favored evolutionarily for one of the same primary reasons that sexual reproduction has been hypothesized to be favored over asexual reproduction (Maynard Smith 1984; Nunney 1989). Nevertheless, few studies have attempted to assess the influence of generation time on the rate of adaptive evolution. In a seminal study, Hartl and Dykhuizen (1979; Dykhuizen and Hartl 1981) found that adaptation of *Escherichia coli* to a novel habitat was a function of absolute time rather than the number of elapsed generations. These authors were able to change generation time by manipulating the rate of nutrient flow into bacterial cultures in a chemostat. Similar experimental tests of the influence of generation time on adaptive evolution have not been performed with higher eucaryotes.

The evolution of pesticide resistance in arthropod pests provides an opportunity to test the influence of generation time on the evolution of a selectively important trait. The economic importance of pesticide resistance has resulted in the documentation of resistance in a large number of arthropod species (Georghiou 1981); these data reveal the results of a large-scale natural experiment in organic evolution, observed at the organismal rather than the molecular level.

Generation time has been identified as one of the few factors that appears to influence resistance evolution in a strong and consistent manner. Empirical and theoretical analyses have uniformly supported a positive linear relationship between GPY and the rate of resistance evolution (Comins 1979; Georghiou 1980; Tabashnik and Croft 1982, 1985; May and Dobson 1986; Hartl 1988; Tabashnik 1990). Here we present an empirical analysis of resistance evolution in North American arthropod pests that challenges this view. We reevaluate existing theory in light of our results and show that it fails to support a consistent relationship between generation time and the rate of resistance evolution. Finally, we extend our conclusions to a broad array of traits influenced by selective forces that operate in a density-independent manner. Elsewhere we present the results of computer simulations elucidating the various influences of generation time on resistance evolution (Rosenheim and Tabashnik 1990).

METHODS

Data-Base Compilation

Our analysis is based on a data base that integrates information on biology and resistance evolution for North American arthropod pests. We used Davidson and

Lyon's (1987) extensive list of pest species as the foundation for the data base. All pests of agriculture, stored products, and human or animal health were included. Pests of ornamental shrubs and trees, rangelands, and forest trees were included only if subject to pesticidal control. For each pest species, we then sought five pieces of information: (1) a measure of ability to evolve resistance, (2) an estimate of GPY, (3) a measure of pest severity, (4) whether the species was introduced or native, and (5) the species' taxonomic order.

An index of each species' ability to evolve resistance was generated by counting the number of insecticide/acaricide classes to which at least some North American field populations had been reported as resistant (Georghiou 1981). Thirty-six pest species reported as resistant by Georghiou (1981) but not present in Davidson and Lyon (1987) were added to the data base. Pesticides were grouped into six classes following Georghiou (1981): (1) DDT and analogues, (2) benzene hexachloride and cyclodienes, (3) organophosphates, (4) carbamates, (5) pyrethroids, and (6) other miscellaneous compounds, including binapacryl, chlordimeform, ovex, propargite, quinomethionate, sulfenone, and tetradifon. Resistances to inorganic, botanical, and microbial insecticides, which are relatively uncommon, were excluded. Although we feel that our measure of ability to evolve resistance is unbiased with respect to species GPY, the index is not without limitations. Most important, the exposure of different pests to pesticide selection pressures probably varied within and between different managed ecosystems. We have attempted to accommodate variable selection intensity by including in the analyses a measure of pest severity. We analyzed the data base first as a single unit and then grouped species by pest type and crop attacked (see below).

Estimates of each species' GPY were compiled from the literature. For cases in which a range of GPY associated with latitude was cited, or when different studies produced different GPY estimates, the arithmetic mean of the observations was used. No attempts were made to estimate GPY from laboratory studies or egg-to-adult development rates. We estimated GPY for 90 species for which literature references could not be found by using the mean value reported for congeners. This approximation was not applied to mosquitoes, which demonstrated large within-genus variation in GPY. In this article, we use the terms GPY and generation time to refer to the same biological parameter; however, because many arthropods undergo diapause for part of the year, the inverse relationship between GPY and generation time will not be exact. This distinction, although potentially significant in some cases (Rosenheim and Tabashnik 1990), is not important to the current discussion. It should be noted, however, that our data base included values for GPY and not generation time per se.

The remaining three parameters were included to explain variation in resistance evolution not related to GPY. The third parameter, an index of pest severity, was generated by summing the number of times a species was cited in the *Review of Applied Entomology,* 1950–1953 (Hall 1950–1953*a*, 1950–1953*b*). The severity index was included because more important pests may be subject to more intense selection pressure from pesticide applications and, further, because all other things being equal, resistance in more important pests may be more likely to be documented by researchers. Only North American field studies or laboratory

studies published in North American journals were tallied. A time period before the major onset of resistance (1950–1953) was chosen to minimize the extent to which a species' ability to evolve resistance would inflate its severity score. To cross-reference current taxonomic names with those used in the 1950–1953 volumes of the *Review of Applied Entomology,* all names were amended to their 1950 forms using reviews of economic entomology from that period and taxonomic works providing historical data on name synonymies. Thirty species not clearly defined taxonomically in 1950 were excluded.

Population bottlenecks that occur when exotic species are introduced to new regions can have profound effects on a population's genetic structure. We therefore included a fourth parameter that grouped native and introduced species. This categorization was obtained from the North American Introduced Arthropod Database (NAIAD, an unpublished data base compiled by R. I. Sailer and the United States Department of Agriculture; Sailer 1978, 1983) and from Furniss and Carolin (1977), Clausen (1978), and Davidson and Lyon (1987). Species listed in NAIAD as having invaded by a continuous range expansion were categorized as native because population bottlenecks were unlikely to have occurred and gene flow with indigenous populations was unlikely to have been obstructed. Twelve pests introduced after the advent of synthetic organic pesticides in 1945 were excluded.

Finally, to assess the possibility that different arthropod taxonomic orders have different abilities to evolve resistance, species were grouped by order following the systematic scheme of Borror et al. (1981). The final data set included 888 species; GPY estimates were obtained for 682 species. The portion of the data base describing resistance evolution for pests of cotton is presented as an example in the Appendix; the full data base with complete literature citations is available from the first author.

Statistical Analysis

Resistance scores were transformed as the log(resistance score + 1.0) before regression analyses to satisfy the assumption of homoscedasticity. Analyses of transformed and untransformed data yielded identical results; therefore, only the results from the transformed data analyses are presented. To test for a linear relationship between resistance evolution and GPY, we performed multiple linear regressions and partial regression analyses of resistance scores (dependent variable) on GPY and pest severity (independent variables). The data base was analyzed as a single unit and by grouping species by pest type (i.e., key pests, operationally defined as species with severity score ≥ 8, and pests of agriculture, stored products, and human or animal health) or by crop attacked. To test for a nonlinear relationship between resistance and GPY, we performed polynomial regressions of the residuals from a linear regression of resistance on pest severity (dependent variable) on GPY (independent variable). Residuals were analyzed as a means of removing the influence of confounding independent variables (in this case, pest severity). Effects of taxonomic order were investigated by averaging across all species within each order the residual value from a multiple regression of resistance score (dependent variable) on pest severity and GPY, with GPY

TABLE 1

MULTIPLE-REGRESSION ANALYSIS OF THE INFLUENCE OF GENERATIONS PER YEAR (GPY) ON RESISTANCE EVOLUTION

Pest Group Type and Independent Variables	Regression Coefficient	SE	t	P	r^{2}*
All species (682):					
Pest severity	.0063	.0006	10.22	<.001	.14
GPY	.0017	.0012	1.50	.13	.01
Agriculture (586):					
Pest severity	.0087	.0009	9.95	<.001	.15
GPY	.0011	.0011	.93	.35	.01
Stored products (37):					
Pest severity	.0087	.0064	1.36	.18	.06
GPY	.0162	.0165	.99	.33	.02
Human and animal health (59):					
Pest severity	.0039	.0011	3.70	<.001	.22
GPY	.0044	.0059	.75	.46	.04
Key pests (70):					
Pest severity	.0039	.0012	3.13	<.01	.13
GPY	.0015	.0043	.36	.72	.01
Cotton (36):					
Pest severity	.0085	.0019	4.60	<.001	.39
GPY	−.0021	.0045	−.48	.64	.00
Grains and corn (81):					
Pest severity	.0078	.0019	4.12	<.001	.18
GPY	−.0020	.0032	−.62	.54	.00
Pome fruits (apple and pear) (56):					
Pest severity	.0071	.0019	3.81	<.001	.22
GPY	.0114	.0049	2.32	.02	.09
Solanaceous crops (primarily potato, tomato, tobacco) (37):					
Pest severity	.0081	.0028	2.84	.01	.20
GPY	.0012	.0076	.15	.88	.01

NOTE.—Number of species in parentheses.

* r^{2} values are given for both significant ($P < .05$) and nonsignificant variables. For regressions with one or no significant independent variables, r^{2} values reflect the contribution of each independent variable considered alone (i.e., simple bivariate linear regression); note that in these cases t and P values continue to refer to the results of the multiple regression analysis. For the regression with two significant independent variables (pests of pome fruits), partial correlation coefficients are reported.

included as a cubic polynomial (independent variables). All analyses were conducted using the BMDP computer statistics package (Dixon 1985).

RESULTS AND DISCUSSION

Data-Base Analysis

Multiple linear regression of resistance score on pest severity and GPY revealed a consistent positive effect of pest severity on resistance score (table 1). However, except for one case, pests of pome fruits, GPY had no significant effect on resistance score. The two independent variables, pest severity and GPY, were themselves almost completely uncorrelated (for all species, $r^{2} = 0.026$); thus, species with rapid generation turnover were not, in general, more severe pests,

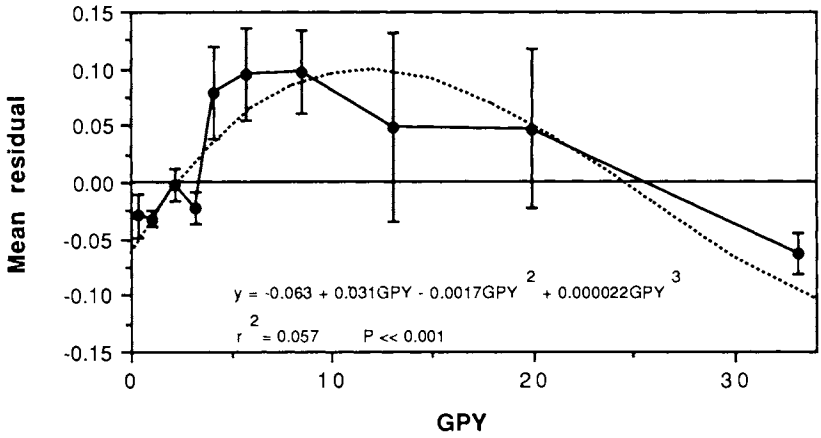

FIG. 1.—Mean residuals (±SE) from a regression of log-transformed resistance score on pest severity for 682 arthropod pests. *Circles*, mean residual values for pests grouped by GPY value. Classes are formed with upper boundaries at generations-per-year values of: 0.5, $n = 32$; 1.5, $n = 276$; 2.5, $n = 129$; 3.5, $n = 90$; 4.5, $n = 37$; 6.5, $n = 40$; 10.5, $n = 34$; 15.5, $n = 13$; 25.5, $n = 9$; >25.5, $n = 16$. *Dashed line*, fitted third-order polynomial regression curve.

and the pest severity variable could not hide an important contribution by GPY. For pests of pome fruits, GPY explained only 9% of the observed variance in resistance scores. Given that nine regressions were computed, a single significant result is not compelling evidence; if we maintain overall $\alpha = 0.05$ by applying Bonferroni's inequality (Dixon 1985) to the data in the table, the critical P value becomes .05/9 = .004, and the result for pome fruits ($P = .02$) is not significant. Thus, the data do not support a linear relationship between resistance evolution and generation time.

An examination of the residuals from a regression of resistance score on pest severity for all species combined revealed a pattern of positive residuals for species with intermediate GPY values (i.e., GPY = 3.5–10.5; fig. 1). The magnitude of the effect (largest mean residual was 0.097 for $6.5 \leq \text{GPY} \leq 10.5$; fig. 1) was similar to that of pest severity: key pests with severity scores of 10–73 yielded predicted increases in resistance scores of 0.063–0.441 (from table 1, regression for all species combined). A polynomial regression of residuals on GPY yielded a curvilinear relationship, which although highly significant ($P < .001$ for the linear, quadratic, and cubic terms) explained only 5.7% of the variation in residuals. Thus, although generation time does influence resistance evolution, the effect appears to be nonlinear and highly variable.

The influences of two variables that might complicate the demonstration of a significant effect for generation time were investigated. First, the native species/introduced species dichotomy proved to be highly significant, with introduced species exhibiting a decreased ability to evolve resistance (J. A. Rosenheim, M. W. Johnson, R. F. L. Mau, B. E. Tabashnik, and S. C. Welter, unpublished data). However, no significant linear effect for GPY was detected for either native

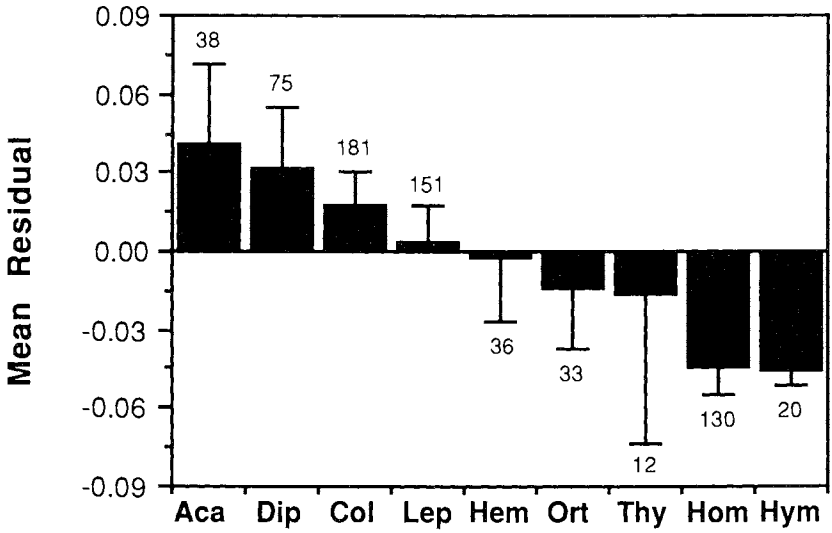

FIG. 2.—Mean residuals (±SE) from a regression of log-transformed resistance score on pest severity and a third-order polynomial in generations per year for nine major arthropod taxonomic orders. The number above or below each bar is the sample size. *Aca,* Acarina; *Dip,* Diptera; *Col,* Coleoptera; *Lep,* Lepidoptera; *Hem,* Hemiptera; *Ort,* Orthoptera; *Thy,* Thysanoptera; *Hom,* Homoptera; *Hym,* Hymenoptera. Only the mean residuals for the Homoptera and Hymenoptera differ significantly from zero ($t = 3.93$, $P < .01$, and $t = 9.38$, $P < .001$, respectively).

or introduced pests alone, and the subtle curvilinear relationships between resistance score and GPY were not significantly different for the two species groups. Thus, the different abilities of native and introduced species to evolve resistance did not mask an important role for generation time.

Second, different arthropod taxonomic orders exhibited similar abilities to evolve resistance (fig. 2). Of the nine orders with sample sizes greater than 10, only two, the Homoptera and Hymenoptera, showed mean residuals from the regression of resistance score on severity and a third-order polynomial in GPY that differed significantly from zero. The retarded resistance evolution observed in the Homoptera was not due to a higher proportional representation by introduced species ($G = 0.09$, $P > .5$). However, 12 of 20 hymenopteran species were introduced, a significantly greater proportion of introduced species than observed for other orders (other orders, 149 of 662 species were introduced; $G = 12.48$, $P < .001$). Thus, the negative mean residual observed for the Hymenoptera may in part reflect the decreased ability of introduced species to evolve resistance. The magnitude of the taxonomic order effect was small compared to the effect of GPY (largest absolute value for a mean residual for a taxonomic order was 0.046 [fig. 2], half as large as the maximum mean residual for GPY [fig. 1]). Thus, variation in resistance evolution capacities among different taxonomic orders also did not appear sufficient to mask possible underlying linear effects for GPY.

In summary, a survey of field data on resistance evolution in 682 North American arthropod pests did not support a significant linear relationship between GPY

and resistance evolution. A modest curvilinear relationship was identified; species with intermediate GPY values showed increased abilities to evolve resistance. This relationship accounted for only 5.7% of the observed variation in residuals, however, suggesting that the effect was highly variable. Thus, available empirical evidence does not support previous theoretical analyses, which predict a linear relationship between GPY and the rate of resistance evolution.

Reappraisal of Existing Evidence

Empirics.—Previous empirical support for a linear relationship between GPY and resistance evolution is of limited scope. May and Dobson (1986) argued that the number of generations required for resistance to evolve in arthropods, avian coccidia, and nematodes was less variable than the corresponding absolute time requirements. Their data set, however, included only three data points for arthropod species for which the number of generations required to develop field resistance was known. Georghiou (1980) described a linear relationship between GPY and the time required for resistance evolution to aldrin/dieldrin in seven soil-dwelling insect species occurring in different crop systems in different countries. The time required to manifest resistance to azinphosmethyl among 12 pest and 12 beneficial arthropods in North American apple orchards also supported a direct influence of generation time (Tabashnik and Croft 1985). This latter example is of special interest; despite being derived from a different measure of resistance evolution and a different sample of arthropod species, the data in table 1 also identified pests of pome fruits as a group significantly influenced by GPY. Although we cannot fully explain why such an effect should exist for apple arthropods other than as a chance event, the agreement between our study and the earlier one (Tabashnik and Croft 1985) is suggestive. Generation time interacts with various genetic, ecological, and operational factors to produce an array of effects on resistance evolution (Rosenheim and Tabashnik 1990); it is therefore possible that conditions in apple orchards result in a positive relationship between GPY and resistance evolution. Because of the predominantly cool climates in which apples and pears are grown, none of the 56 pome fruit pests had a GPY value greater than 12; of the remaining 626 species in the data base, 37 had GPY values greater than 12. The positive role of GPY observed for pests of pome fruits may therefore simply reflect the increasing trend in resistance score for species with low to moderate GPY (fig. 1).

Analytical models.—The dominant view regarding the importance of generation time has been most lucidly expressed by May and Dobson (1986), who derived a basic formula relating generation time, T_g, to the absolute time required for resistance to appear, T_R. Because of the crucial role that this theory has played in shaping thought on resistance evolution, we review May and Dobson's (1986) analysis. We then demonstrate how a simple extension of their model can explain the observed absence of a linear relationship between GPY and resistance evolution.

In their simplest-case model, May and Dobson (1986) analyzed resistance conferred by one locus with two alleles, a resistant allele R and a susceptible allele S, existing at frequencies p_t and q_t, respectively, in generation t. The population

was assumed to be diploid and closed to gene flow. The per-generation fitnesses, w, of the three genotypes RR, RS, and SS in the presence of pesticide were assumed to satisfy the condition $w_{RR} \geq w_{RS} \geq w_{SS}$. Standard population-genetics theory (Hedrick 1983) then relates the R allele frequency in successive generations as

$$p_{t+1} = (w_{RR}p_t^2 + w_{RS}p_tq_t)/(w_{RR}p_t^2 + 2w_{RS}p_tq_t + w_{SS}q_t^2). \quad (1)$$

Two approximations will be generally valid during the early stages of resistance: first, $p_t \ll q_t$, and, second, $q_t \simeq 1.0$. Equation (1) can therefore be reduced to

$$p_{t+1}/p_t \simeq w_{RS}/w_{SS}. \quad (2)$$

Equation (2) can be applied to successive generations to obtain a relationship describing the number of generations, n, required for the R allele frequency to increase from its initial frequency, p_0, to a final frequency at which resistance may be considered to have evolved, p_f:

$$p_f/p_0 \simeq (w_{RS}/w_{SS})^n. \quad (3)$$

Noting that $n = T_R/T_g$, equation (3) may be rearranged to yield

$$T_R \simeq T_g \ln(p_f/p_0)/\ln(w_{RS}/w_{SS}). \quad (4)$$

May and Dobson (1986) completed their derivation with this equation and concluded therefore that a linear relationship exists between time to evolve resistance, T_R, and generation time, T_g. They furthermore concluded that the influence of generation time should be strong compared to the influences of other variables present in equation (4), which are related only logarithmically to T_R.

These conclusions rely, however, on the assumption that the ratio of fitnesses (w_{RS}/w_{SS}) remains constant for all values of T_g, or, in other words, that the per-generation selection intensity is the same for species with different generation times. This might be true for laboratory selection experiments, but it does not generally hold in the field. An example will demonstrate this. Assume that in the absence of pesticides $w_{RS} = w_{SS}$ and that a single pesticide application kills 50% of SS individuals and 0% of RS individuals; for each application of pesticide per generation, the ratio of per-generation fitnesses, w_{RS}/w_{SS}, will therefore increase by a factor of two. Consider three pests in an agro-ecosystem that is sprayed twice per year at 6-mo intervals. Species A has two generations per year ($T_g = 0.5$ yr); thus, each generation is sprayed once, $w_{RS}/w_{SS} = 2$, and equation (4) can provide an expression for the time to resistance for species A, $T_R(A)$,

$$\begin{aligned} T_R(A) &\simeq 0.5 \ln(p_f/p_0)/\ln 2 \\ &\simeq 0.72 \ln(p_f/p_0). \end{aligned} \quad (5)$$

For the purposes of this discussion, let $\ln(p_f/p_0) = k$, some constant, for all species. Equation (5) may then be rewritten as $T_R \simeq 0.72k$. Consider now species B in the same agro-ecosystem, with $T_g = 1$ yr. Each generation of species B will experience both of the annual sprays; w_{RS}/w_{SS} is therefore equal to $(2)^2$ or 4. From equation (4), $T_R(B) \simeq 1k/\ln(4) = 0.72k$, exactly the same result as for

species A. A third species, species C, with $T_g = 4$ yr, experiences eight sprays per generation; w_{RS}/w_{SS} is then $(2)^8 = 256$, and $T_R(C) \simeq 4k/\ln(256) = 0.72k$. The time to resistance is clearly independent of generation time. Although this example presents the case of regularly spaced, discrete sprays, our argument is independent of the temporal pattern of pesticide-induced mortality. The crucial element is that species with longer generation times will, on the average, suffer greater per-generation pesticide-induced mortality than species with shorter generation times.

We can generalize this result within the analytical framework of May and Dobson (1986). Let b denote the number of pesticide applications per year, and a denote the (fractional survival of RS individuals per pesticide application)/(fractional survival of SS individuals per pesticide application). Assume that these parameters are constant across species within an agro-ecosystem. Then the ratio of per-generation fitnesses can be expressed as

$$w_{RS}/w_{SS} = a^{(T_g b)}, \tag{6}$$

and substituting into equation (4)

$$\begin{aligned} T_R &\simeq T_g \ln(p_f/p_0)/\ln(a^{(T_g b)}) \\ &\simeq T_g \ln(p_f/p_0)/(T_g b \ln a) \\ &\simeq \ln(p_f/p_0)/(b \ln a). \end{aligned} \tag{7}$$

Observe that T_g has dropped out of equation (7). This simplest-case model predicts, therefore, that the time to resistance is independent of generation time.

The theoretical analysis of Comins (1979) also suggested that the rate of selection for resistance could be independent of generation time. Comins (1979), however, went on to assume that species with rapid generation turnover require more intense pesticidal suppression, because of their population's high intrinsic growth rate, and therefore exhibit rapid selection for resistance. Expressed in terms of the parameters in equation (7), Comins's argument is that b, the number of pesticide applications per year, is a species-specific parameter, inversely proportional to each species' generation time.

Although Comins's (1979) argument may be applicable to some pest species (see, e.g., Longstaff 1988), we do not believe it is generally applicable for two reasons. First, the typical crop is attacked by a large number of arthropod species, only a handful of which become "key" pests, that is, pests requiring pesticidal suppression. The relatively large number of secondary pests continues, however, to experience the pesticide applications directed at the key pests. Although not all secondary pests are susceptible to all pesticide applications (Rosenheim and Hoy 1986), secondary pest populations are commonly suppressed by at least some pesticide applications. The timing of these pesticide applications is, however, completely independent of life-history parameters of secondary pests, including their generation times. Thus, there is no causal link between generation time and pesticide-application frequency for the large majority of pests that are not the primary targets of pesticide applications and therefore do not influence the decision of when to apply pesticides.

Second, even for key pests, the relationship between generation time and pesticide-application frequency may be weak. Generation time has a strong influence on the intrinsic rate of population growth (Price 1984). However, many factors may cause the realized rate of population growth to fall below the intrinsic growth rate, and it is the realized population growth rate, not the intrinsic growth rate or the generation time per se, which may influence the frequency of pesticide applications. Realized population growth rate is also shaped by the entire range of biotic and abiotic factors that influence development rates and age-specific survival and reproduction, including population interactions with host-plant condition, weather, the farmer's agronomic practices, predators, parasitoids, and pathogens. In addition, there are many instances in which the rate of population rebound following a pesticide application will not affect pest-management decisions. Many crops have relatively narrow temporal windows of susceptibility to pest damage. A single pesticide application made at the onset of plant susceptibility may be sufficient to decrease populations to levels low enough that additional applications are not required until the next crop cycle. The rate of population rebound outside the window of susceptibility does not influence the pesticide-application frequency. Thus, for many pest species, not all generations experience pesticide applications. The frequency of pesticide applications may also be influenced by other factors not related to population dynamics, including the type of damage induced by the target pest and the monetary value of the crop.

In summary, Comins's (1979) argument linking pesticide-application frequency to pest-species generation time does not apply to secondary pests and applies to key pests only under the restrictive conditions that (1) generation time is the primary determinant of realized population growth rate and (2) realized population growth rate is the primary determinant of pesticide-application frequency. Perhaps the strongest evidence arguing against the generality of Comins's thesis is our failure to observe a close relationship between GPY and either pest severity or resistance score (table 1). Even for key pests, comprising the 70 species with pest severity scores of 8 or more, there was no significant relationship between GPY and severity score ($r^2 = 0.027$, $P > .1$) or GPY and resistance score. If pesticide-application frequency is generally independent of generation time, our extension of May and Dobson's (1986) analytical model (eq. [7]) suggests that the rate of resistance evolution is independent of generation time. This simplest-case model, although heuristic, does ignore many less direct influences of generation time on resistance evolution, which are explored elsewhere (Rosenheim and Tabashnik 1990).

Computer-simulation models.—The only computer-simulation study explicitly testing the effect of GPY (Tabashnik and Croft 1982) concluded that increasing GPY consistently accelerated resistance evolution under a variety of conditions (with and without immigration, with high or low doses of pesticide). However, in their simulations, increasing GPY resulted in a corresponding increase in the number of pesticide applications per year, and it is clear that increased pesticide applications do accelerate resistance. As discussed above with regard to Comins's (1979) analysis, the assumption of increasing pesticide-application frequency with increasing GPY is not generally valid. Thus, computer-simulation models currently provide no support for a role of generation time in resistance evolution.

Generation Time and Fitness Values

Our conclusion that the evolution of pesticide resistance depends on the absolute time elapsed rather than on the number of generations elapsed parallels that of Hartl and Dykhuizen (1979; Dykhuizen and Hartl 1981) studying adaptation of *Escherichia coli* to a novel environment. Because of the well-defined nature of pesticide-induced selection pressures, we were able to demonstrate analytically that per-generation fitness values for resistant genotypes are related exponentially to species' generation times (eq. [6]). In studies of *E. coli* strains competing for limiting nutrients, Dykhuizen (1978) found that the per-generation selection rate was linearly related to generation time over a wide range of generation times.

If we ignore possible effects of generation time on mutation rates, the question of whether the rate of adaptive evolution is influenced by generation time becomes equivalent to the question of whether generation time influences the fitness values of given genetic variants. The distinction between traits influenced by density-dependent and density-independent selective forces appears to be crucial in this regard.

We do not know whether there is a general relationship between generation time and the relative fitnesses of different genetic variants for traits influenced by selective forces whose intensity is linked to population density. It seems possible that fitness values associated with some such traits, like competitive ability, might be influenced by generation time, whereas fitness values for other such traits, perhaps including those influenced by selection acting on short parts of the life cycle, the duration of which may be only loosely related to total generation time (e.g., gametic selection or sexual selection), might be less likely to show such an influence. For traits shaped by density-dependent selection, the question of the influence of generation time on fitness values of given genetic variants may remain primarily empirical.

We suggest, however, that the relationship between generation time and fitness values that we have demonstrated for pesticide resistance (eq. [6]) is generalizable to traits molded by selection that is decoupled from the species' life history and population dynamics, that is, density-independent selection. This type of selection is generated by many abiotic factors, including harsh weather (e.g., extreme temperature or humidity fluctuations, drought, heavy rain, hail) and various environmental disturbances (e.g., fires, floods, volcanic emissions). Generalist predators and parasites may also act in a density-independent manner if the prey or host species in question consistently forms a small fraction of the total prey or host pool. Finally, interspecific competition may be independent of density if a resource is exploited by another species, the population dynamics of which are unaffected by the species in question. Regardless of the specific selective agent, the per-generation intensity of selection generated by density-independent factors is related exponentially to generation time. For example, in a habitat that experiences periodic freezes, a long-lived plant may, on the average, experience a large number of freezes (selection bouts) per generation, whereas an annual or a short-lived perennial might experience a single freeze or escape selection entirely; in general the number of freezes experienced per generation is directly propor-

tional to generation time. The argument developed above (eqq. [1]–[7]) for the evolution of pesticide resistance is therefore relevant to the evolution of traits contributing to cold tolerance. In fact, for many traits like cold tolerance, our argument is actually simplified somewhat because there is a greatly reduced likelihood of the species' population dynamics' influencing the frequency or intensity of selection bouts. We conclude that in our simplest-case scenario the rate of evolutionary response to density-independent selection is independent of generation time.

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APPENDIX

AN EXAMPLE OF THE DATA USED TO INVESTIGATE THE INFLUENCE OF THE NUMBER OF GENERATIONS PER YEAR (GPY) ON THE EVOLUTION OF PESTICIDE RESISTANCE: NORTH AMERICAN ARTHROPOD PESTS OF COTTON

Scientific Name	Introduced (i) or Native (n)	GPY*	Pest Severity†	Resistance Score‡	Taxonomic Order§
Heliothis zea (Boddie)	n	4	70	4	Lep
Anuraphis maidiradicis (Forbes)	n	12	0	0	Hom
Petrobia latens (Muller)	n	18.5	4	0	Aca
Lygus lineolaris (Palisot de Beauvois)	n	4	20	1	Hem
Anthonomus grandis grandis Boheman	n	5	47	2	Col
Aphis gossypii Glover	n	31.5	41	1	Hom
Aphis craccivora Koch	i	30.2‖	2	0	Hom
Tetranychus cinnabarinus (Boisduval)	n	20		1	Aca
T. turkestani (Ugarov & Nikolskii)	n	12	4	0	Aca
T. urticae Koch	n	15.5	73	5	Aca
T. pacificus McGregor	n	15	15	2	Aca
T. desertorum Banks	n	15	0	0	Aca
T. tumidus Banks	n	18.5	0	1	Aca
T. schoenei McGregor	n	9	2	2	Aca
T. canadensis (McGregor)	n	18.5	0	1	Aca
Pseudatomoscelis seriatus (Reuter)	n	7	6	1	Hem
Lygus elisus Van Duzee	n	4	4	1	Hem
L. hesperus Knight	n	4	4	3	Hem
Adelphocoris rapidus (Say)	n	2‖	4	0	Hem
A. superbus (Uhler)	n	2‖	0	0	Hem
Alabama argillacea (Hubner)	i	5	11	2	Lep
Pectinophora gossypiella (Saunders)	i	5	4	1	Lep
Estigmene acrea (Drury)	n	2.5	15	2	Lep
Strymon melinus (Hubner)	n	2.5	0	0	Lep
Frankliniella fusca (Hinds)	n	8	3	0	Thy
F. exigua Hood	n	8	1	0	Thy
F. gossypiana Hood	n	8		0	Thy
F. occidentalis (Pergande)	n	6	2	1	Thy
F. tritici (Fitch)	n	12.5	3	1	Thy
Caliothrips fasciatus (Pergande)	n	6	0	0	Thy
Thrips tabaci Lindeman	i	7.5	17	2	Thy
Sericothrips variabilis (Beach)	n		0	0	Thy
Homalodisca triquetra (F.)	n		1	0	Hom
Aulacizes irrorata (F.)	n		0	0	Hom
Oncometopia undata (F.)	n		1	0	Hom
Cuerna costalis (F.)	n		1	0	Hom
Anthonomus grandis thurberiae Pierce	n	3	0	0	Col
Chlorochroa ligata (Say)	n	1	0	0	Hem
Acrosternum hilare (Say)	n	2	0	0	Hem
Euschistus impictiventris (Stal)	n	1	0	0	Hem
Nezara viridula (L.)	i	2.5	2	0	Hem
Chlorochroa sayi Stal	n	2	0	0	Hem
Dysdercus suturellus (Herrich-Schaffer)	n		0	0	Hem
D. mimulus Hussey	n		0	0	Hem
Bucculatrix thurberiella Busck	n	5	0	4	Lep

* Missing values are species for which we were unable to locate estimates of GPY. Full literature citations for GPY estimates are available from the authors.

† Species with missing values were not clearly defined taxonomically in 1950.

‡ The resistance score is the number of insecticide/acaricide classes to which at least some North American field populations have been reported as resistant (Georghiou 1981).

§ Lep, Lepidoptera; Hom, Homoptera; Aca, Acarina; Hem, Hemiptera; Col, Coleoptera; Thy, Thysanoptera.

‖ Values were estimated by using the mean value reported for congeners.