

POPULATION GENETICS OF A PARASITIC CHROMOSOME:
THEORETICAL ANALYSIS OF PSR IN SUBDIVIDED POPULATIONS

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Abstract.—An assemblage of non-Mendelian sex ratio elements occurs in natural populations of the parasitoid wasp *Nasonia vitripennis*. These include Maternal Sex Ratio (MSR), a cytoplasmic element that causes nearly all-female families, and Paternal Sex Ratio (PSR), a B chromosome that causes all-male families. The PSR chromosome is transmitted via sperm but causes destruction of the paternal chromosomes (except itself) shortly after egg fertilization. Owing to haplodiploidy, this results in the conversion of diploid (female) eggs into haploid (male) eggs. Paternal Sex Ratio is an extreme example of a selfish genetic element. Theoretical analysis shows that subdivided population structures reduce PSR frequency. Paternal Sex Ratio cannot exist in subdivided populations (with temporary mating demes lasting one generation) when foundress number is less than three. The equilibrium frequency of PSR depends strongly on fertilization proportion (x). In populations producing the Hamiltonian evolutionarily stable strategy ($x = [(N - 1)(2N - 1)/N(4N - 1)]$), PSR never achieves frequencies over 3% for any deme size. In contrast, if the population produces a high fertilization proportion (i.e., greater than 90%, as produced by MSR), then PSR can achieve frequencies over 90% when deme size is three or larger. Results also show that PSR selects against the MSR cytoplasmic element in populations with small deme size, which results in polymorphic equilibria for both elements.

There is growing evidence that a variety of genetic elements exist that have no function other than their own propagation within the genome and therefore can be considered “genomic parasites” or “selfish genetic elements” (Doolittle and Sapienza 1980; Orgel and Crick 1980; Werren et al. 1988). Parasitic genetic elements illustrate how selection can favor individual genes, even if they are detrimental to the organism. These genetic parasites can also have detrimental effects on populations carrying them. Thus, they can potentially be used to quantitatively study selection operating at different hierarchical levels—for example, gene, individual, and population levels of selection. So far, few studies have investigated the effect of hierarchical selection on parasitic elements.

Paternal Sex Ratio (PSR) is a nonvital supernumerary chromosome that occurs in some natural populations of the parasitic wasp *Nasonia vitripennis* (Werren et al. 1987; Nur et al. 1988; Werren 1991). The PSR chromosome is the most extreme

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example of a selfish genetic element so far described (Godfray and Harvey 1988). Males who carry this chromosome fail to transmit their genetic material (other than PSR) to the next generation because PSR destroys the paternal set of chromosomes, except itself, in the egg shortly after fertilization (Werren et al. 1987). Like other hymenopterans, *Nasonia* has haplodiploid sex determination. Therefore, the result of PSR action is that diploid fertilized eggs, which would have developed into females, are converted into haploid PSR males. The new haploid complement is maternally derived, and it will subsequently be destroyed in the next generation because it is associated with PSR. Thus, PSR "jumps" from one haploid set to another, always destroying the genome with which it is associated. This characteristic imparts a drive to the chromosome under certain population structures, as will be shown below.

Nasonia adjust the sex among their offspring in response to changes in local population structure in ways that are generally consistent with sex ratio theory (Wylie 1966; Walker 1967; Holmes 1972; Werren 1980, 1983; but see Parker and Orzack 1985; Orzack and Parker 1986). Indeed, sex ratio evolution in *N. vitripennis* (and other organisms with subdivided populations) has been a focus of debate in the controversy over levels of selection because it can be interpreted in terms of either individual selection or group selection (Colwell 1981; Charnov 1982; Werren 1983; Wilson 1983; Nunney 1985; Maynard Smith 1987a).

In addition to this "normal" sex ratio adjustment of *N. vitripennis* (which is presumably under autosomal genetic control), an assemblage of non-Mendelian sex ratio distorters occurs in the wasp, including (1) Son-Killer, a maternally transmitted bacterium that prevents the development of unfertilized (male) eggs (Skinner 1985; Werren et al. 1986; Gherna et al. 1991), (2) Maternal Sex Ratio (MSR), a cytoplasmically inherited agent of unknown etiology that causes female wasps to produce nearly 100% daughters (Skinner 1982, 1983), and (3) Paternal Sex Ratio (Werren et al. 1987; Nur et al. 1988; Werren 1991).

As well as obvious negative effects on the wasp genome, PSR also can have negative effects on populations carrying it. If it becomes common in a population the number of females (and therefore reproductive potential of the population) is severely reduced. In the extreme case in which PSR goes to or near fixation, populations carrying it will go extinct.

Nasonia vitripennis is a small parasitoid wasp that lays its eggs into the pupae of various fly species (Whiting 1967). Evidence indicates that *N. vitripennis* has a subdivided population structure in nature (Skinner 1983; Werren 1983). Thus, the PSR chromosome apparently has antagonistic selective pressures operating on it at different levels; gene-level selection favors its increase but it has negative effects on the fitness of individuals and populations. These characteristics make PSR an excellent system for quantifying the process of selection operating at different levels.

In this article we present a theoretical analysis of the population dynamics of PSR in subdivided populations and discuss how the force of selection may be hierarchically partitioned. Several predictions of the model presented here have been tested experimentally (Beukeboom and Werren 1992).

PATERNAL SEX RATIO IN RANDOM-MATING POPULATIONS

Theoretical dynamics of PSR in random-mating populations are surprisingly simple (Skinner 1987; Werren 1987a). A key feature determining its dynamics is that PSR is transmitted only to fertilized eggs. Therefore, its transmission rate is negatively related to the proportion of unfertilized eggs (males) produced. An increase in the proportion of unfertilized eggs also negatively affects PSR frequency because it results in a greater number of (normal) males who compete with PSR males for mates. These two features are present in the derivation below. If x is the proportion of eggs fertilized by inseminated females (in the absence of PSR these develop into females), t is the proportion of PSR male sperm that carry the chromosome, and w is the mating success of PSR males relative to normal males, and it is assumed that the remaining proportion $(1 - t)$ of eggs fertilized by sperm of PSR males develops into females, then the frequency of PSR in one generation (p) yields the frequency in the next (p') according to the formula

$$p' = pxtw/(pxtw + 1 - x) \quad (1)$$

and equilibrium frequency (p^*) is

$$p^* = [x(tw + 1) - 1]/xtw. \quad (2)$$

Estimates for t are between 0.9 and 1.0, and for w are 1.0 (Werren and Assem 1986; Beukeboom and Werren 1993). If these two parameters are assumed to equal 1.0, then the formula simplifies to $p^* = (2x - 1)/x$. The basic conclusion from the formula is that PSR cannot exist in panmictic populations unless the proportion of fertilized eggs (normal proportion females) is greater than 0.5. These results form a baseline for the following analysis of PSR dynamics in subdivided populations.

PATERNAL SEX RATIO IN SUBDIVIDED POPULATIONS

Assume a "metapopulation" composed of many temporary demes. Each generation, individual demes are formed of N inseminated "foundress" females, which produce progeny and then die. Mating occurs only among progeny of the natal deme, and then inseminated females disperse and randomly assort to form new demes. Therefore each deme lasts only one generation. This population structure was first modeled by Hamilton (1967) in studies of sex ratio selection under "local mate competition" and will henceforth be referred to as a "Hamiltonian" population.

For the purposes of the model it is assumed that females mate only once, or that if they do mate more than once they effectively use the sperm from only one male. This assumption generally holds for *Nasonia* (Assem and Visser 1976). We will further assume that PSR-inseminated and normal inseminated (non-PSR-inseminated) females produce equivalent family sizes, and that PSR and normal males have equal survival, which as an approximation is supported by data (Werren and Assem 1986; Beukeboom and Werren 1993). The metapopulation is composed of a very large (effectively infinite) number of demes.

If p is the frequency of PSR-mated females in the metapopulation, T_p is the frequency of PSR among all males in the metapopulation, D_a is the frequency of demes founded by a PSR-inseminated females and $N - a$ normal inseminated females, M_a is the number of males (\times mating success) produced in a -type demes, and F_a is the number of females produced in a -type demes, then the frequency of PSR-mated females in the next generation is given by

$$p' = \sum_{a=1}^N D_a axtwF_a / M_a N[x(1 - pt)], \quad (3)$$

where

$$M_a = N(1 - x) + axtw \quad (4)$$

and

$$F_a = (N - a)x + ax(1 - t). \quad (5)$$

The frequency of PSR in the next generation is determined by summing the contributions of PSR matings over all demes in the metapopulation. Basically, PSR will increase in frequency if the number of PSR-mated females produced per PSR-mated foundress is greater than the average number of females produced per foundress.

It is worthwhile to consider what happens in a single deme containing a PSR-mated foundresses and $N - a$ normal mated foundresses (fig. 1). What are the consequences of increasing a in such a deme? First, as the number of PSR-mated founding females increases, the number of female progeny dispersing from that deme decreases (fig. 1A). This means there will be fewer mates available for PSR males. Second, the number of males competing for mates in the deme increases and the proportion of PSR males among these males increases, but at a declining rate (fig. 1B). In other words, there are two negative frequency-dependent effects of PSR on its own propagation from demes: (1) a reduced number of females and (2) increased competition for mates (fig. 1A and B). Multiplying the proportion of PSR males by the proportion of females gives the relative "PSR productivity" of a deme—that is, the number of dispersing PSR-mated females (fig. 1C). Recall that PSR will increase in a metapopulation so long as the average number of PSR-mated females produced per PSR-mated foundress exceeds the average number of females produced per foundress. The contribution of a deme with a PSR-mated foundresses to that average can be visualized graphically in figure 1C by drawing a line through the origin with slope $px(1 - t) + x(1 - p)$, which is the average number of females produced per foundress. Those demes with PSR output above the line make a net increase to PSR frequency, whereas those below the line make a net decrease. For illustrative purposes, a line with slope 0.75 is shown in the figure. It can be seen that at higher frequencies PSR has a negative frequency-dependent effect on itself.

Clearly the frequency distribution of PSR-mated foundresses among demes is crucial to PSR population dynamics. An overdispersed pattern would favor an increase of PSR because it would minimize the negative frequency dependent

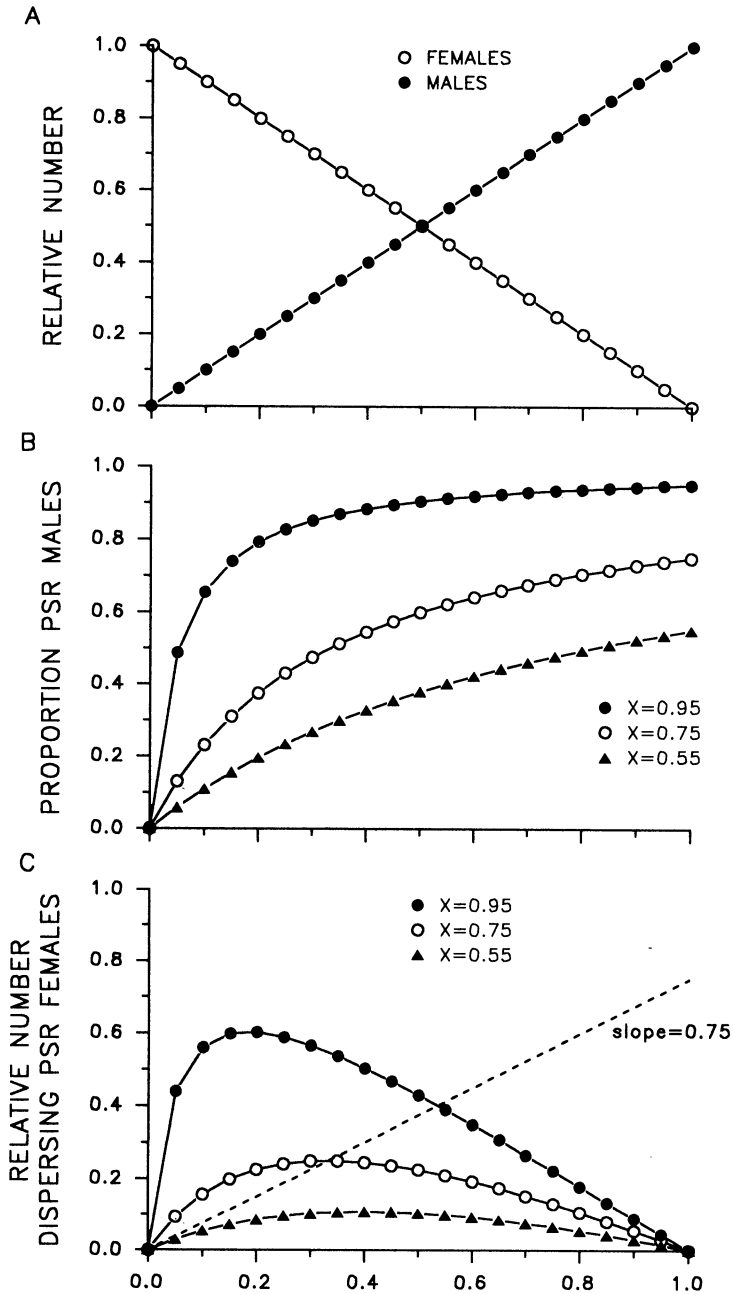


FIG. 1.—Effect of PSR-mated female frequency on (A) relative number of males and females in a deme, (B) proportion PSR males in a deme for three different fertilization proportions ($x = 0.55$, $x = 0.75$, and $x = 0.95$), and (C) relative number of dispersing females from a deme for those fertilization proportions. A line through the ordinate with slope $x(1 - p)$ (with the assumption that $t = 1.0$) indicates the proportion of daughters produced by an average female in the population. Demes with PSR productivity above the line yield a net increase in PSR frequency, whereas those below the line yield a net decrease. An illustrative line is shown for $x = 0.75$.

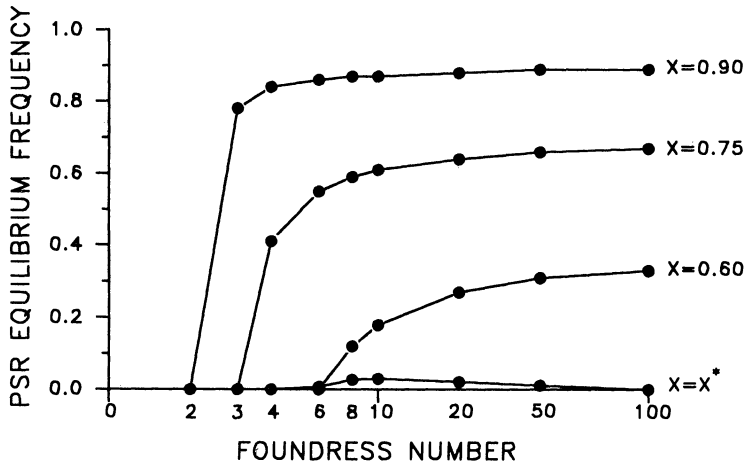


FIG. 2.—Influence of deme structure and fertilization proportion on equilibrium PSR frequency (frequency of PSR-mated females; see text) for four different fertilization proportions (x). Included is PSR equilibrium frequency when the organisms produce the ESS fertilization proportion for haplodiploids in a Hamiltonian population (x^*).

effects of PSR upon itself in local demes. An underdispersed pattern of PSR foundresses would reduce frequency of the chromosome. If it is assumed that foundresses disperse randomly into new demes, then a binomial distribution is appropriate. Given this assumption or any other frequency distribution, the formula above can be iterated to determine the population dynamics and equilibrium frequency of PSR.

In figure 2, results are presented from a series of computer iterations using various biologically realistic values for the proportion of eggs fertilized and foundress number and assuming (1) a binomial distribution of foundresses among demes, (2) $t = 1.0$, and (3) $w = 1.0$. Repeated simulations (not presented) have shown that, for any given x and N , a single equilibrium frequency of PSR is achieved independently of the starting frequency. In addition, the equilibrium is rapidly approached, usually within 10 generations. Equilibrium frequencies of PSR are shown for several different fertilization proportions. Paternal Sex Ratio cannot be maintained in subdivided populations when x is equal to or smaller than 0.5. For $x = 0.60, 0.75$, and 0.90 , PSR cannot exist in populations with deme sizes equal to or smaller than six, three, and two foundresses, respectively. For larger demes, increasing N results in an increasing equilibrium PSR frequency. The reason is that a small foundress number results in a greater local mating disadvantage for the PSR chromosome. For example, the presence of even a single PSR-mated foundress in a small deme causes a large decrease in the number of dispersing females and an increase in the number of competing males in that deme.

Hamiltonian Sex Ratios and PSR Frequency

Which population structures allow for an increase in the frequency of a rare PSR chromosome? If $t = 1$ and $w = 1$, then PSR can invade a demic population

whenever

$$x > N/2(N - 1). \quad (6)$$

It is clear that the smaller the deme size, the more female biased a sex ratio must be in order for a rare PSR chromosome to increase in frequency. Indeed, PSR cannot exist in populations of $N \leq 2$. Hamilton (1972) and others (Taylor 1981; Herre 1985; Frank 1986; Werren 1987*b*) have derived the sex ratio expected in an evolutionarily stable strategy (ESS) for various foundress numbers in haplodiploid species. These models assume autosomal genetic control of the sex ratio expressed in females, random mating within the deme, and also that non-Mendelian sex ratio distorters are absent. According to the version given in an earlier article (Werren 1987*b*), the ESS proportion of daughters (x^*) is given by

$$x^* = (N - 1)/(1 + G)N, \quad (7)$$

where G is a measure of the genetic relatedness of females to daughters relative to sons. Relatedness to sons and daughters is asymmetrical in haplodiploid organisms. On the basis of calculations of Suzuki and Iwasa (1980), $G = 2N/(2N - 1)$, and therefore

$$x^* = 1 - [(N - 1)(2N - 1)/N(4N - 1)]. \quad (8)$$

If one contrasts formulae (6) and (8), it is clear that PSR can invade populations producing the Hamiltonian ESS sex ratio when $6 < N < \infty$. The equilibrium PSR frequency in populations producing the Hamiltonian ESS is shown in figure 2 for various foundress numbers. This was determined by iteration of the structured population formula (eq. [2]), with binomial distribution of foundresses assumed. As can be seen, in populations producing the Hamiltonian sex ratio, PSR cannot exist in populations for which $N < 6$. Neither does it achieve frequencies greater than 3% even in populations with intermediate deme sizes. It should be emphasized that the Hamiltonian ESS is based on the assumption that PSR is absent. Presence of PSR may itself select for more female-biased sex ratios, since it can reduce the effective number of foundresses in a deme.

Nevertheless, a surprising result is that, in populations producing the Hamiltonian sex ratio, PSR will never achieve appreciable frequencies. This contrasts with the outcome when foundresses produce MSR-like sex ratios—that is, fertilize nearly all their eggs ($x = 0.90$). Under these circumstances, PSR will achieve very high frequencies (up to 90%). Hence, the presence of the cytoplasmic sex ratio distorter MSR gives a major boost to PSR frequency.

Measuring the Effect of Deme Structure on PSR Frequency

It is worthwhile to partition and quantify the effect of deme structure on PSR frequency. This is best accomplished by comparing the frequency of PSR to what it would have been if the population were panmictic. Given the frequency of PSR-mated females in any generation, the frequency in the next generation in a panmictic population (p_p) versus the frequency in a Hamiltonian demic population (p_d) is determined by recourse to equations (1) and (3), respectively. The

effect of a Hamiltonian population structure (R) is simply the ratio of these two, p_d/p_p .

The effect of a subdivided population structure is to reduce PSR frequency. For example, when the metapopulation is at equilibrium with $N = 3$ and $x = 0.75$, then $R = 0.31$. This means that PSR frequency in the next generation is 31% what it would be if the population were panmictic. Similarly, if $N = 12$ and $x = 0.75$ then $R = 0.72$. As a general pattern, deme structure has the most adverse effects on PSR frequency when fertilization proportion is low and founding number is small.

Effect of Virgin Females

Unmated or poorly mated females that produce all-male families occur in many parasitoid wasps (Godfray 1990). Virgins occur at about 5% in natural populations of *Nasonia vitripennis* in Utah (Skinner 1983; J. H. Werren, unpublished data), and similar frequencies are found in many laboratory population experiments (Werren and Assem 1986; Beukeboom and Werren 1993). Therefore, it is worthwhile to determine their effect on PSR frequency. In an earlier article (Werren 1987a) it was shown that, in panmictic populations, virgin females have an adverse effect on PSR frequency, although the effect when virgin frequency is around 5% is small. We have investigated the virgin effect in demic populations by modifying the deme population formula to include virgin females and iterating until equilibrium frequency is achieved. Figure 3 shows the outcome for three different fertilization proportions (of the mated females) and three founding female numbers. Increasing the frequency of unmated females decreases PSR frequency, although the effect is small (around 10%) for an increase in virgin frequencies of around 5%.

Codynamics of PSR and MSR

Analysis indicates that the MSR cytoplasmic element, which is cytoplasmically inherited through females and causes nearly all-female families, greatly enhances spread of the PSR chromosome. Indeed, on the basis of results for populations producing Hamiltonian ESS sex ratios, it can be concluded that the PSR chromosome may not be able to exist in appreciable frequency under many population structures unless MSR-like elements are also present.

Factors that regulate the frequency of the MSR element are still poorly understood. Unless there is some negative frequency-dependent effect of MSR on itself, then the MSR cytotype is expected to go to fixation within a population, even though this could eventually lead to extinction of the population owing to an absence of males (Hamilton 1967; Bull 1983; Werren 1987a). The MSR cytotype is favored over those that produce less female-biased sex ratios because the cytotype is maternally inherited. Therefore, any cytotype that effectively increases the number of females produced will have a selective advantage. This contrasts with nuclear genes, which are inherited through both sexes (Werren 1987a).

Recent empirical findings suggest that the PSR chromosome may have a nega-

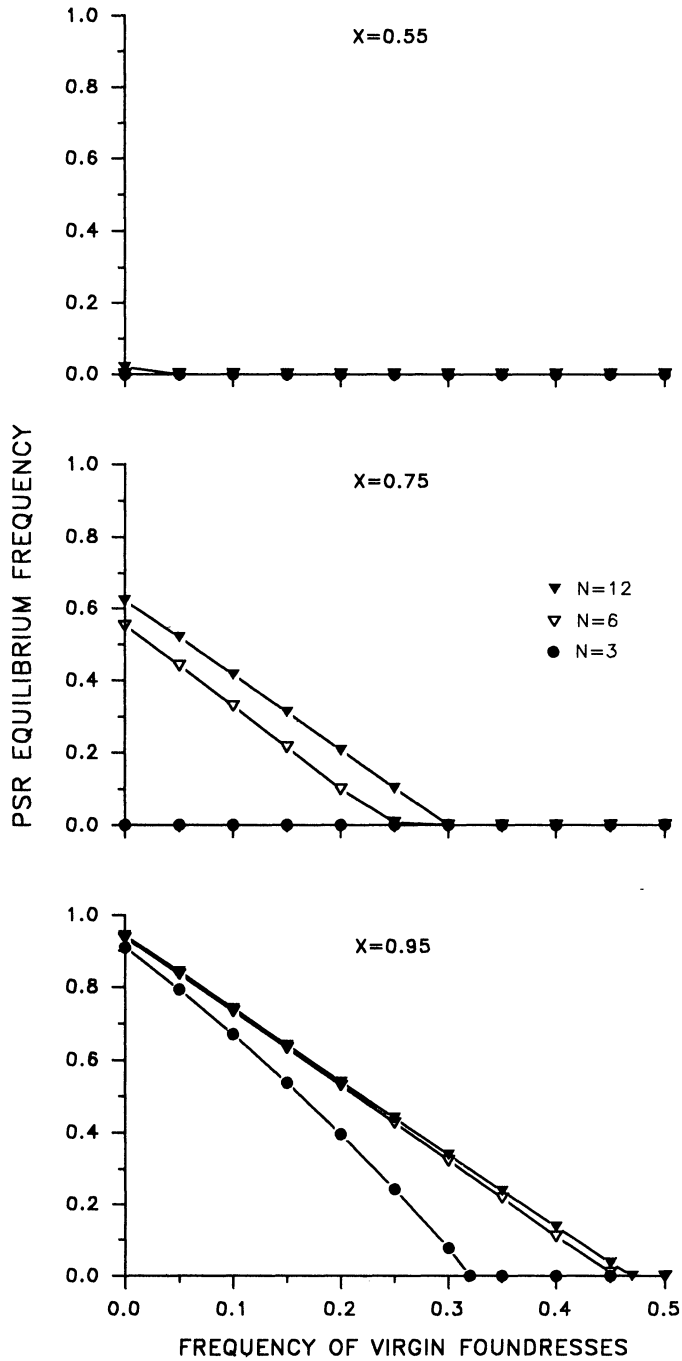


FIG. 3.—Effect of virgin females on equilibrium PSR frequency (frequency of PSR-mated females; see text) in three demic populations ($N = 3$, $N = 6$, and $N = 12$) and for three fertilization proportions ($x = 0.55$, $x = 0.75$, and $x = 0.95$).

tive effect on the frequency of MSR among females under certain population structures, and this interaction could serve as a regulating mechanism. We found (Beukeboom and Werren 1992) that, under highly subdivided populations ($N = 3$), the presence of the PSR chromosome appears to select against the MSR cytotype, whereas in less demic populations (e.g., $N = 12$) it does not.

In order to investigate the codynamics of PSR and MSR in subdivided populations the following additional terms are used: p_m is the proportion of foundresses in the metapopulation that are MSR females mated to PSR males, p_n is the proportion of foundresses in the metapopulation that are normal females mated to PSR males, q is the proportion of foundresses in the metapopulation that are MSR females mated to normal males, $D_{a,b,c}$ is the frequency of demes with a PSR-mated normal foundresses, b PSR-mated MSR foundresses, c non-PSR-mated MSR foundresses, and $N - a - b - c$ non-PSR-mated normal foundresses, and x_m is the proportion of fertilized eggs produced by MSR foundresses. The prime symbol indicates the same proportion for the next generation. Given these definitions and similar ones used previously, the transmission formulae are

$$p'_n = \sum_{c=0}^{N-a-b} \sum_{b=0}^{N-a-c} \sum_{a=0}^{N-b-c} D_{a,b,c}(ax + bx_m)twx \times [(N - a - b - c) + a(1 - t)]/M_{a,b,c}F, \tag{9}$$

$$p'_m = \sum_{c=0}^{N-a-b} \sum_{b=0}^{N-a-c} \sum_{a=0}^{N-b-c} D_{a,b,c}(ax + bx_m)twx_m \times [c + b(1 - t)]/M_{a,b,c}F, \tag{10}$$

and

$$q' = \sum_{c=0}^{N-a-b} \sum_{b=0}^{N-a-c} \sum_{a=0}^{N-b-c} D_{a,b,c}[M_{a,b,c} - (ax + bx_m)tw]x_m \times [c + b(1 - t)]/M_{a,b,c}F, \tag{11}$$

where

$$M_{a,b,c} = a[1 - (1 - t)x] + b[1 - (1 - t)x_m] + c(1 - x_m) + (N - a - b - c)(1 - x) \tag{12}$$

and

$$F = N[qx_m + (1 - p_n - p_m - q)x + p_mx_m(1 - t) + p_nx(1 - t)]. \tag{13}$$

To investigate the codynamics of PSR and MSR these formulae were iterated for two different population structures ($N = 3$ and $N = 12$). These two values of N are presented because they are the same values used in the population experiments (Beukeboom and Werren 1992), and because they reflect an extreme and a moderate demic population structure with respect to sex ratio selection (recall that for $N = 12$ the expected Hamiltonian sex ratio is 0.55, which is

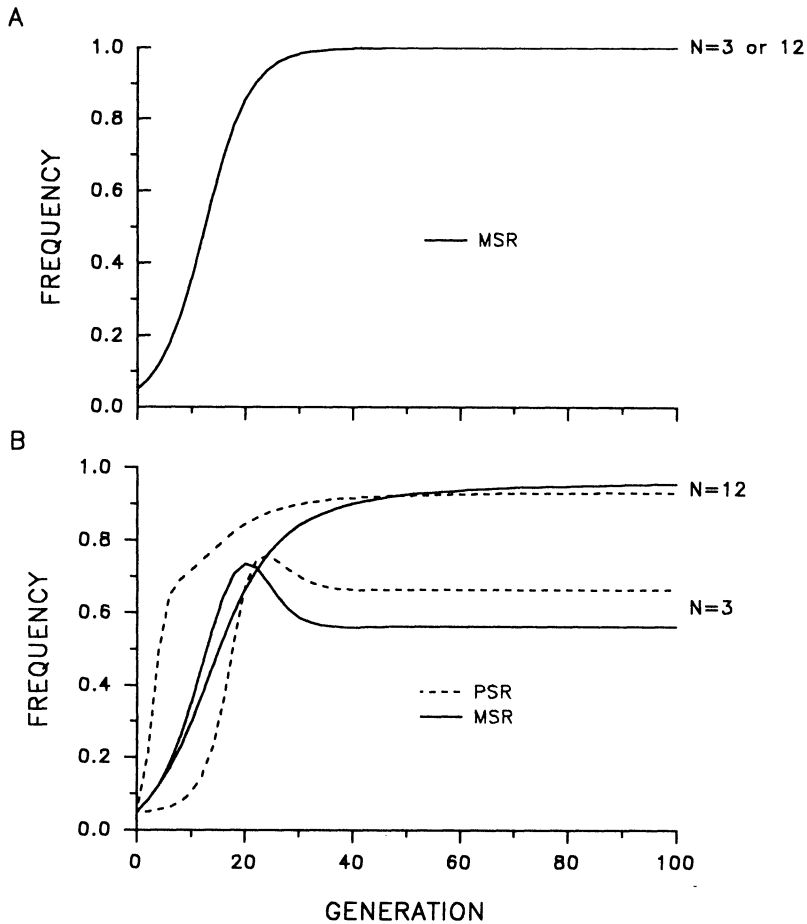


FIG. 4.—Change in frequency of (A) MSR in the absence of PSR, and (B) MSR and PSR in the presence of each other in two demic populations ($N = 3$ and $N = 12$). Fertilization proportions are 0.75 for the normal and 0.95 for the MSR cytotypic.

nearly the same as for panmixia). Unless otherwise stated, the proportion of eggs fertilized is 0.95 for MSR foundresses and 0.75 for normal foundresses.

First, the dynamics of MSR in the populations were determined in the absence of PSR. As expected (fig. 4A), MSR rapidly goes from a frequency of 5% to over 99% in the subdivided populations and would eventually go to fixation. Thus, in the absence of some counterbalancing frequency-dependent effect, MSR will go to fixation in subdivided populations.

Next, a series of simulations were conducted in which normal, MSR, and PSR foundress frequencies were tracked. It was found that equilibrium conditions were not influenced by starting conditions, and, therefore, the outcome of simulations with starting conditions $q = 0.05$ and $p_n = 0.05$ are shown. Results for the $N = 3$ deme population are particularly interesting. Maternal Sex Ratio rapidly increased in frequency in the population, followed by a rapid increase in PSR.

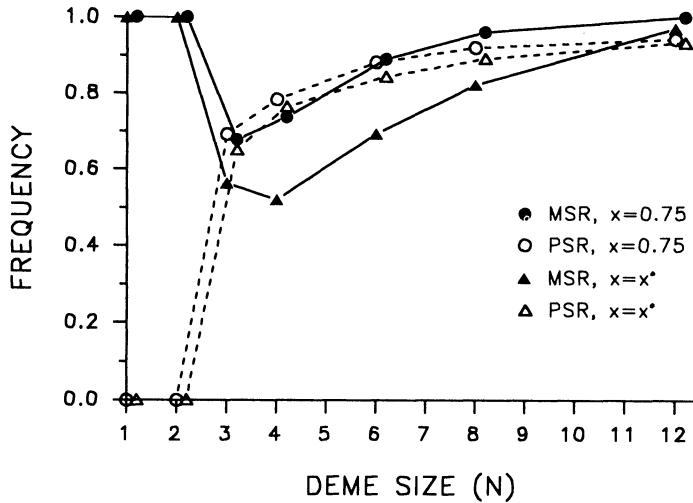


FIG. 5.—Effect of deme structure on equilibrium frequencies of MSR and PSR in the presence of each other. Results are for fertilization proportions of 0.75 or the Hamiltonian ESS (x^*) for the normal cytotype, with the MSR cytotype producing a proportion of 0.95 fertilized eggs.

High frequencies of PSR apparently create a negative fitness effect on MSR, because MSR subsequently decreased in frequency and achieved a polymorphic equilibrium relative to the normal cytotype (normal females) of around 57%, whereas PSR reached 67% (fig. 4B). The pattern in $N = 12$ populations is quite different. There, MSR rapidly increased in frequency, followed by PSR, but the frequency of MSR did not subsequently decline; it stayed near fixation, at 96%, as did PSR frequency. Results from experimental populations are qualitatively consistent with this model (Beukeboom and Werren 1992), although MSR and PSR are selected to much lower frequencies than indicated here in the $N = 3$ populations.

Why does PSR select for the normal cytotype under highly subdivided populations such as $N = 3$? The intuitive explanation is as follows: When PSR is common, nearly all mates available for females in a three-foundress deme are PSR males. Since normal cytotype females produce more unfertilized eggs than do MSR females, they produce a greater number of non-PSR males that can mate with their daughters, thus “protecting” the normal cytotype from mating with PSR males. The MSR cytotype, on the other hand, produces so few males that there are virtually only PSR males available in the deme to mate with their daughters. This is detrimental to transmission of the cytotype. Therefore, the normal cytotype has a selective advantage over MSR. The advantage to the normal cytotype is accrued most strongly in small demes, where brother-sister mating is likely.

According to the formulae above, the equilibrium conditions for MSR and PSR in the presence of each other can be determined for different deme structures by iteration until an equilibrium is achieved. Results are shown in figure 5 for 0.75 and Hamiltonian ESS sex ratios and foundress numbers ranging from one to 12

(note that for $N = 1$ an ESS sex ratio of 0.90 was used). For deme sizes of one and two, PSR cannot be maintained in the populations and MSR therefore goes to fixation. However, for deme sizes greater than three, PSR achieves appreciable frequencies, and this can create a selective advantage for the normal cytotype that results in a polymorphic equilibrium between MSR and normal cytotypes. Lowest frequencies of MSR occur in $N = 3$ or $N = 4$ populations, in which frequencies between 60% and 70% MSR are found. As deme size increases, equilibrium frequency of MSR also increases, and, in subdivided populations with large demes, MSR is expected to occur at or near fixation. Similarly, PSR increases with deme size, owing primarily to the increasing frequency of the MSR cytotype, and can reach frequencies of over 90% in populations of large demes. Indeed, the conditions converge on the panmictic solution (Werren 1987a). Under these conditions the population would likely go extinct owing to the high frequency of PSR.

Paternal Sex Ratio and the "Fitness" of Populations

It was proposed above that PSR can negatively affect populations. It has been shown that, within demes of a subdivided metapopulation, increasing frequency of PSR does reduce deme productivity. Paternal Sex Ratio also potentially reduces the fitness of metapopulations. In order to pursue this concept further, it is necessary to more precisely define what the fitness of a population is. Population fitness may be measured by the "persistence" of a population over time—that is, its probability of not going extinct. An alternative measure of a population's fitness may be the number of new populations produced by emigration over its "lifetime." Yet another measure may be the intrinsic rate of increase (λ) of a population. These measures may correlate with each other and clearly would be influenced by ecological circumstances.

We will use the intrinsic rate of increase as a measure of population fitness. The assumption is that the maximal growth rate potential of a population is positively correlated with the lifetime productivity of the population. We recognize that this assumption would be violated, for instance, if (1) populations with high growth rates were more subject to unstable population fluctuations leading to extinction or (2) populations were stable and under density-dependent regulation, in which case the potential rate of increase of the population is irrelevant.

The intrinsic rate of increase for a population with discrete nonoverlapping generations is given by $\lambda = Bg$, where B is the lifetime number of offspring produced per female zygote and g is the proportion of daughters produced. In a population with PSR present, $\lambda = Bg(1 - p)$. The ratio of these rates of increase (I) is simply $I = 1 - p$.

Populations in which PSR has achieved an appreciable frequency will have significant reductions in population growth rate. For example, suppose $\lambda = 1.20$ in the absence of PSR and PSR equilibrates at $p = 0.30$ in the population. Under these conditions, $\lambda = 0.84$; the population will be in decline. Allowing for coevolution of MSR and PSR often causes PSR to achieve frequencies over 90%. The result would be $\lambda < 0.12$. It is difficult to imagine that density dependence could compensate for such a severe reduction in the number of females in a population, and therefore extinction of the population would be expected.

DISCUSSION

There is a great deal of theoretical and empirical interest in the potential role of different levels of selection (e.g., gene, individual, group, and species) in evolution (Wade 1978; Wilson 1983; Sober 1984, 1987; Nunney 1985; Williams 1985; Maynard Smith 1987*a*, 1987*b*; Wilson and Sober 1989). Non-Mendelian sex ratio distorters promise to be particularly useful for studies of hierarchical selection, because they can have obvious consequences to the fitness of individuals and the survival and growth of populations. For example, because PSR produces all-male families, the growth potential of a population carrying it can be severely reduced if PSR achieves appreciable frequencies. Female-biasing sex ratio distorters are known in a wide range of organisms (Uyenoyama and Feldman 1978; Werren et al. 1988; Taylor 1990). These fall into two major categories. Cytoplasmically inherited microorganisms cause female-biased sex ratios by shifting the primary sex ratio or causing male lethality. Examples include microsporidia in mosquitoes (Kellen et al. 1965; Andreadis and Hall 1979), spiroplasms in *Drosophila* (Williamson and Poulson 1979) and the Son-Killer bacterium (Werren et al. 1986). The second major category is X chromosome drive systems. These result in a female bias because the X chromosome is overrepresented relative to the Y in gametes of males. Examples occur in *Drosophila* (Gershenson 1928; Sturtevant and Dobzhansky 1936; Stalker 1961; James and Jaenike 1990), the mosquito *Aedes aegypti* (Hickey and Craig 1966), the butterflies *Acraea encedon* (Chanter and Owen 1972) and *Danaus chrysippus* (Smith 1975), and the wood lemming *Myopus schisticolor* (Fredga et al. 1977). There is currently little evidence that frequencies of driving X chromosomes in these systems are regulated by interdemographic selection (Werren et al. 1988; Wu and Hammer 1991).

The consequences of female-biasing elements for populations are potentially complicated. At intermediate frequencies, they could actually increase the reproductive potential of populations. Thus, species carrying such elements could be at a competitive advantage relative to species that do not. James and Jaenike (1990) have found that *Drosophila testacea*, which harbors a driving X chromosome, has more female-biased sex ratios than do other mushroom-feeding drosophilids with which it co-occurs. They have argued that the presence of a Sex Ratio drive chromosome in that species could enhance its intrinsic rate of increase. On the other hand, driving X chromosomes that approach fixation can have serious negative consequences for populations, because of low mating frequencies among females (Gershenson 1928). For instance, Owen (1973) found extremely female-biased sex ratios in some natural populations of the tropical butterfly *A. encedon*, and often very few females were mated in such populations. Hamilton (1967) has pointed out that in haplodiploids (in which unmated females produce males) female-biasing distorters can cause severe destabilizing population fluctuations.

The PSR chromosome is the most extreme example of a selfish genetic element so far described. However, both panmictic and subdivided population models show that this element will increase in frequency in populations only under certain special circumstances. In panmictic populations, more than 50% of the eggs must be fertilized in order for the PSR chromosome to exist (Werren 1987*a*).

In the theoretical analysis presented here it was found that, as deme size decreases in subdivided populations, an increasing bias in the proportion of fertilized eggs (the proportion of females) is necessary for PSR to exist in a population. However, local mate competition theory (Hamilton 1967) predicts just that trend—that is, selection for autosomal genes that cause an increasing female-biased sex ratio with decreasing deme size. Whether PSR can evolve in subdivided populations of a given deme size could depend on the resolution of these two counterbalancing forces, (1) decreasing deme size selecting against PSR and (2) increasing fertilization proportion (with decreasing deme size) selecting for PSR. The analysis indicates that PSR can exist in populations with intermediate deme size, but only at low frequency.

There are several caveats with the scenario above. First, the presence of other non-Mendelian sex ratio elements, such as MSR, can dramatically alter the situation. Our analysis indicates that MSR greatly facilitates the evolution of PSR in subdivided populations, and that PSR can achieve very high frequencies when MSR is common. Thus, we have the very interesting scenario that the spread of MSR in a population could set up the conditions for PSR to spread to near fixation, thus driving the population to extinction.

A second consideration is that the presence of PSR in a population could select for a shift in the ESS autosomal sex ratio to a greater female bias; that is, the autosomal sex ratio may coevolve with PSR. A previous analysis for panmictic populations has shown that the equilibrium autosomal sex ratio is not altered from one-half males, even in the presence of PSR or MSR (so long as t is close to 1.0) (Werren 1987a). However, it is not certain that this result holds for subdivided populations. Although we have not explicitly modeled this, we believe that the presence of PSR will reduce the effective number of foundresses and therefore select for more female-biased sex ratios.

An unresolved question is, What is regulating the MSR element in natural populations? Results presented here suggest that PSR under highly demic situations selects against the MSR cytotype, which leads to sex ratio cytotype polymorphisms in the population. This is unlikely to be an important regulating mechanism in nature, however, because PSR has so far been found only in Utah, Idaho, and Wyoming populations, and there at low frequencies (Skinner 1983; J. H. Werren, unpublished data). Maternal Sex Ratio may itself be regulated in subdivided populations by local scarcity of males in these demes with MSR, which would result in a greater frequency of MSR females remaining virgins or poorly mated.

A final difficulty relating the current results to natural populations is that a single deme size was assumed for all demes within the metapopulation. Deme sizes in natural populations of *Nasonia* are highly variable, ranging from apparent sib-mating situations ($N = 1$) to large demes containing over 10,000 progeny (Werren 1983). Temporal and spatial variation in deme size could have a major impact on the frequencies of PSR and MSR. Similarly, in some cases multiple generations within a deme may occur, altering the expected dynamics.

In an earlier study (Beukeboom and Werren 1992) we used experimental populations of *Nasonia* to test some basic predictions and assumptions of the deme-

structured models presented here. It was found that highly demic populations (three founding females per deme) select against PSR, whereas moderate deme sizes result in polymorphic equilibria. Population experiments revealed that the MSR cytotype is selected against in the presence of PSR in highly demic situations, as "predicted" by the model presented here. However, it should be noted that it was the experimental observation that led to the theoretical discovery that PSR selects against MSR in these situations. Furthermore, although the model predicts a polymorphic equilibrium of MSR and normal cytotypes, MSR was apparently being eliminated from the $N = 3$ experimental population (Beukeboom and Werren 1992). Clearly, more experimental work on the codynamics of MSR and PSR is needed to elucidate the dynamics between these elements. Although some general predictions of the models are met in experimental populations, results indicate that additional factors are involved in PSR dynamics that have not been incorporated into these models.

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