Diagnosing Senescence: Inferring Evolutionary Causes from Phenotypic Patterns can be Misleading

Albert Blarer; Michael Doebeli; Stephen C. Stearns

Proceedings: Biological Sciences, Vol. 262, No. 1365 (Dec. 22, 1995), 305-312.

Stable URL:
http://links.jstor.org/sici?sici=0962-8452%2819951222%29262%3A1365%3C305%3ADSIECF%3E2.0.CO%3B2-E

Proceedings: Biological Sciences is currently published by The Royal Society.

Diagnosing senescence: inferring evolutionary causes from phenotypic patterns can be misleading

ALBERT BLARER, MICHAEL DOEBELI AND STEPHEN C. STEARNS

Institute of Zoology, University of Basel, Rheinsprung 9, CH-4051 Basel, Switzerland

SUMMARY

Based on the predictions of two theories for the evolution of senescence, the 'antagonistic pleiotropy' and the 'mutation accumulation' theory, an age-specific increase in mortality and a decrease in fecundity are widely used criteria to diagnose senescence in natural and laboratory populations. In this study we question the reliability of these criteria. Using a simple model we show that similar phenotypic patterns result from optimal life histories without senescence. With a tradeoff between reproduction and period survival, optimal life histories produce patterns of increasing mortality and decreasing fecundity as organisms age, even if the tradeoff does not deteriorate with age, so that we are not forced to invoke genetic effects such as antagonistic pleiotropy or accumulation of deleterious mutations to explain such patterns. Furthermore, if optimal life history theory is applied to senescent organisms, phenotypic patterns can result that are usually not associated with senescence. We conclude that the reliability of a diagnosis of senescence based on phenotypic patterns and the comprehension of the phenomenon senescence depends critically on understanding to what extent tradeoffs are determined by the effects of segregating genes.

1. INTRODUCTION

Senescence can be defined as the persistent decline of viability caused by physiological deterioration as organisms age. There are two accepted theories for the evolution of such deteriorations: 'antagonistic pleiotropy' and 'mutation accumulation' (Medawar 1952; Williams 1957). Both theories imply the evolution of characteristic patterns of phenotypic variation in fitness components, i.e. reproduction and survival, as organisms age. The predictions of the evolutionary theories are straightforward, and senescence appears to be a phenotypically obvious phenomenon (Rose 1991): the mortality rates of senescing organisms should increase, and their reproductive rates should decrease with age.

This clarity has led to the widespread belief that by logical conversion, patterns of phenotypic variation throughout the life of an organism can be used to infer that senescence has evolved. Thus patterns of age-specific mortality and fecundity, lifespan and various combinations of these traits are widely used to detect senescence in natural and laboratory populations (Comfort 1979; Rose & Charlesworth 1980, 1981*a*, *b*; Luckinbill *et al.* 1984; Rose 1984; Service *et al.* 1988; Promislow 1991; Austad 1992, 1993; Chippindale *et al.* 1994; Gaillard *et al.* 1994). In particular, antagonistic pleiotropy or accumulation of deleterious mutations are often inferred from an age-specific increase in instantaneous mortality, or from a decrease in instantaneous birth rates, or both. In this note we point out that this practice should be used with caution. We show that optimal life histories under fixed physiological constraints that do not change during the life of an organism can account for the same phenotypic patterns that are usually associated with senescence, and genetic effects such as antagonistic pleiotropy or the accumulation of mutations are not necessary for their explanation. Thus the problem with using phenotypic criteria to diagnose senescence lies in the equivocal relation between evolutionary outcomes, i.e. the phenotypic patterns, and their causes. Patterns of age-dependent birth and death rates may have evolved for several different reasons. They do not indicate unambiguously the selective forces responsible for their evolution.

For example, Medawar demonstrated such an ambiguity for lifespan, which at first sight seems to be a very obvious diagnostic criterion for senescence. Consider two species with different, but constant, age-independent mortality rates. Neither organism has senescent mortality, but the organism with the higher mortality has a lower expected lifespan: the expected lifespan is the inverse of the (constant) mortality rate (Hirsch 1980). This simple example shows that a decrease in lifespan is not necessarily associated with senescent mortality, and that inferring causes from phenotypic patterns can be tricky. For example, the shorter lifespan of mammals when compared with birds has often been ascribed to senescent effects (Comfort 1979; Prothero & Jürgens 1987; Hoekstra 1993; Partridge & Barton 1993). However, that birds live longer than mammals of the same size might just be because flying is a less risky life style than living on the ground, and it does not necessarily imply stronger senescence in mammals.

In the following we focus only on phenotypic patterns of mortality and fecundity. We build a simple model for optimal life histories and use a few examples

Proc. R. Soc. Lond. B (1995) **262**, 305–312
Printed in Great Britain

to make the following point: patterns of phenotypic variation that are usually thought to be caused by antagonistic pleiotropy or mutation accumulation can simply arise from optimal life histories in a physiological environment that does not change with age.

2. MODEL AND RESULTS

We assume that an organism lives in a population of constant size and use its lifetime reproductive success R_0 to measure its fitness. R_0 is defined as the sum of reproductive success, measured once each year by the quantity $l_x \cdot m_x$, from birth to death at age ω:

$$R_0 = \sum_{x=1}^{\omega} l_x \cdot m_x. \quad (1)$$

Here m_x denotes the organism's fecundity in age class x, and l_x is the probability that the organism survives from birth to obtain reproductive success m_x in year x. The survival probability l_x is defined recursively by

$$l_x = l_{x-1} \cdot p_x, x = 2, \ldots, \omega \quad \text{and} \quad l_1 = J \cdot p_1. \quad (2)$$

Here J is the juvenile survival, i.e. the survival probability from birth to the beginning of the year in which maturity is reached. In our model J is a parameter, and because it occurs in all summands of the right hand side of equation (1), we can set $J = 1$ without loss of generality when studying optimality problems. The $p_x, x = 1, \ldots, \omega$, are the probabilities to survive year x and to receive the reproductive success m_x of that year, provided the organism has survived to the beginning of that year x. In general, the survival probability l_x and the fecundity m_x do not evolve independently of each other but are connected by tradeoffs. Tradeoffs can be defined as the linkages between two or more traits that constrain their simultaneous evolution (Stearns 1992). Here we assume that the reproductive effort of an organism has costs in form of reduced period survival. We denote by e_x the reproductive effort in year x and scale it so that $0 \leqslant e_x \leqslant 1$. The relation between reproductive effort e_x and fecundity m_x is

$$m_x = c_x \cdot e_x, \quad (3)$$

where the proportionality factor c_x may or may not vary with age (see below). We assume that the tradeoff between reproductive effort e_x and period survival p_x is linear (figure 1*a*):

$$p_x = a_x - b_x \cdot e_x. \quad (4)$$

The parameters a_x and b_x are constants that may change with age and define the form of the tradeoff. Because $0 \leqslant e_x \leqslant 1$, and because p_x is a probability, we must have $0 \leqslant a_x \leqslant 1$. The parameter a_x determines the period survival in the absence of reproductive effort, which can be smaller than 1 because of extrinsic sources of mortality such as predator pressure or because of intrinsic costs incurred from previous life history decisions. The slope b_x determines the strength of the tradeoff. b_x is positive, but to avoid negative values of p_x for large reproductive efforts we assume $b_x \leqslant a_x$.

In general, the optimality problem can be formulated as follows. A reproductive strategy is a set of numbers $\{e_1, \ldots, e_\omega\}$ that determine reproductive effort in each year. Given a strategy, equation (3) is used to calculate the fecundities $m_x, x = 1, \ldots, \omega$, and formulas (4) and (2) are used to calculate the survival probabilities $l_x, x = 1, \ldots, \omega$. Then the fitness of the given strategy can be calculated using equation (1). The task is to find the reproductive strategy with maximal fitness.

One feature of this model deserves a closer description. The definition of the survival probabilities l_x we use in equation (2) differs from the standard definition used in life history theory (Charlesworth 1994). In our definition (2), the period survival p_x of the year x is included in the corresponding l_x. In terms of reproductive costs, this means that the fitness payoff in a particular year is only received after the costs of the reproductive effort in that year have been paid. By contrast, according to the standard definition reproductive costs are paid in the subsequent year, and the reproductive effort e_x in year x trades off with the period survival p_{x+1}. The difference between these two alternatives is discussed more fully in Doebeli & Blarer, unpublished data. Here it suffices to note that both models can be biologically plausible. For example, in species with extended parental care, e.g. many birds, the model used here is probably more realistic, because the payoff in form of fledged offspring is only received after having been exposed to higher mortality risk from parental care. The alternative model may be more realistic in species without parental care, in which the costs of reproduction are paid in form of having to recuperate after the payoff has been received. All the results discussed below can be obtained with the alternative model, but this requires a more complicated form of the tradeoff curve. We used the model that would yield these results with the simplest possible tradeoff, a straight line.

This tradeoff is the essential feature in our optimality approach. The reproductive tradeoff measures the costs of reproductive investments in the form of reduced survival probabilities. Critical to our argument is the assumption that a tradeoff contains effects other than those caused by antagonistic pleiotropy, i.e. that reproduction and survival trade off within a clone because of mechanisms common to all members of the clone. What causes the tradeoff is important for a reliable diagnosis of senescence. There are at least two ways of interpreting why a tradeoff arises. First, there may be extrinsic causes. Consider an organism that suffers a greater probability of dying because of a larger predation risk during its reproductive period. If this extrinsic mortality increases with larger investments to reproduction, for example, if mobility changes during pregnancy, then the extrinsic source of mortality alone may explain the tradeoff in figure 1*a*. Second, there may be intrinsic, physiological causes for a tradeoff: an organism's physiology may deteriorate because of increasing reproductive investments, leading to higher mortality.

However, this deterioration need not be thought of as senescent. To see this, consider an organism with a constant tradeoff throughout its life. In our model, this means that the parameters a_x and b_x in equation (4) do

not change with age: in every breeding season, the organism faces the same costs of reproduction for the same amount of reproductive effort. The physiology of the organism as described by the tradeoff does not change with age, and there is no senescence. The organism may choose a reproductive strategy of 'increased reproductive efforts e_x with increasing age' simply because such a strategy implies a higher total fitness R_0. With such a strategy, the organism will have a higher mortality late in life, and its physiological state deteriorates, because the higher reproductive investments imply higher physiological costs. However this physiological deterioration is not caused by senescent effects such as antagonistic pleiotropy or mutation accumulation. It is simply a consequence of the life history strategy chosen. The organisms could restrain their reproductive investment early in life to have a higher survival probability to late stages, or they could choose to keep reproductive effort constant throughout life and so prevent a physiological deterioration. If this is not the best strategy because increasing effort with age also increases fitness, the organism is not senescent but has a phenotypic pattern of mortality that resembles the pattern of an organism in which antagonistic pleiotropy or mutation accumulation are acting.

Optimal life history strategies can produce such patterns in the absence of senescence. To show that, we start with the simplest possible model, in which we assume that the tradeoff does not change with age, i.e. that the parameters a_x and b_x in equation (4) are the same for all x (figure 1*a*), and that the proportionality factor $c_x = 1$ for all x in equation (3), hence that reproductive effort e_x and fecundity m_x are identical. We also assume that the organism lives for a fixed number of years, say $\omega = 10$. Using simulated annealing (see below), the optimal reproductive strategy can be obtained (figure 1*b*). An organism with this strategy increases its reproductive effort with age, and consequently incurs a higher risk of mortality with age.

This increase in age-specific mortality is not senescent because the tradeoff does not change during life. But if physiology does not change with age, then the future of the organism looks always the same. Shouldn't we expect a constant reproductive strategy in this case? In fact, the increase in mortality with age here is caused by a particular detail. The assumption of a finite lifespan ω constrains the organism's life history, and from the viewpoint of the organism the future must change at age ω. As a consequence its reproductive effort and instantaneous mortality increase towards the end of the life to optimize its fitness. Thus the increase in mortality is caused by the additional assumption that the organism dies after ten years.

Such assumptions of finite lifespans that interfere with the patterns of mortality and fecundity are inconvenient in the context of senescence. To get around this difficulty, we relaxed the strong assumption of a finite lifespan in the following way. The organism may potentially live for an infinite number of years. However, we assume that from a particular year onwards, which we call ω, the reproductive effort e_x is constant, and so is the reproductive tradeoff given in equation (4). This leads to a constant period survival p_x for all age classes x larger than ω. The rationale behind this assumption is that the period survival p_x can be expected to decrease with age, but it is bounded from below by the value 0. Therefore, it must become approximately constant at some point. With this assumption we can rewrite the fitness equation (1) in the following form (see Appendix):

$$R_0 = \left[\sum_{x=1}^{\omega-1} l_x \cdot m_x\right] + \frac{l_\omega \cdot m_\omega}{1 - p_\omega(e_\omega)}. \qquad (5)$$

This simply means that the last summand in equation (1), $l_\omega m_\omega$, is replaced by $l_\omega m_\omega/[1 - p_\omega(e_\omega)]$ to account for residual reproductive success during the period in the organism's life in which all the life history parameters have become constant.

If we apply this new fitness definition (5) to the simple model described previously, the optimal reproductive strategy is constant, as it should be (figure 1*c*). Thus, what we expected intuitively and what is biologically plausible is obtained with the new model (5). Using the fitness definition (5), an optimal reprodutive strategy still consists of a set of numbers $\{e_x, \ldots, e_\omega\}$, but ω does not denote lifespan anymore, but the moment when reproductive efforts become constant. This is the correct model for our purposes, and we will now use it to investigate what the optimal reproductive strategies are under various conditions. Before we address these questions, however, we describe briefly the optimization technique used in this study.

(*a*) *The optimization technique*

Optimal strategies can be found by using various methods; however analytical solutions become unwieldy if ω becomes large (say $\omega > 4$), and numerical methods are then easier to use. The classical numerical technique for evolutionary optimization problems is dynamic programming (Bellmann 1957). We used a different approach that is based on simulated annealing (Kirkpatrick *et al.* 1983). Annealing techniques consist of a clever search for maxima in the landscape defined by the fitness function R_0 on the space of all possible strategies. One generally walks uphill in this landscape, but to avoid getting trapped at local optima, downward movements of a certain size are also allowed. The allowed size of these downhill moves diminishes in the course of the simulation, so that the algorithm converges to the simple hill climbing rule. The idea is that this only happens after one has reached the vicinity of the global maximum, which can then be reached by just walking uphill. A simple version of this algorithm was invented by Dueck & Scheuer (1990), who showed that it works well for difficult optimization problems easy to implement.

In the present context, one starts with a randomly chosen strategy $\{e_1, \ldots, e_\omega\}$ and calculates its fitness R_0^{old}. One then creates a new strategy by changing slightly one of the efforts e_x of the old strategy. We used uniformly distributed random numbers to decide which component of the old strategy should change and by what amount. One then compares the fitness of the new strategy, R_0^{new}, with the fitness of the old one,

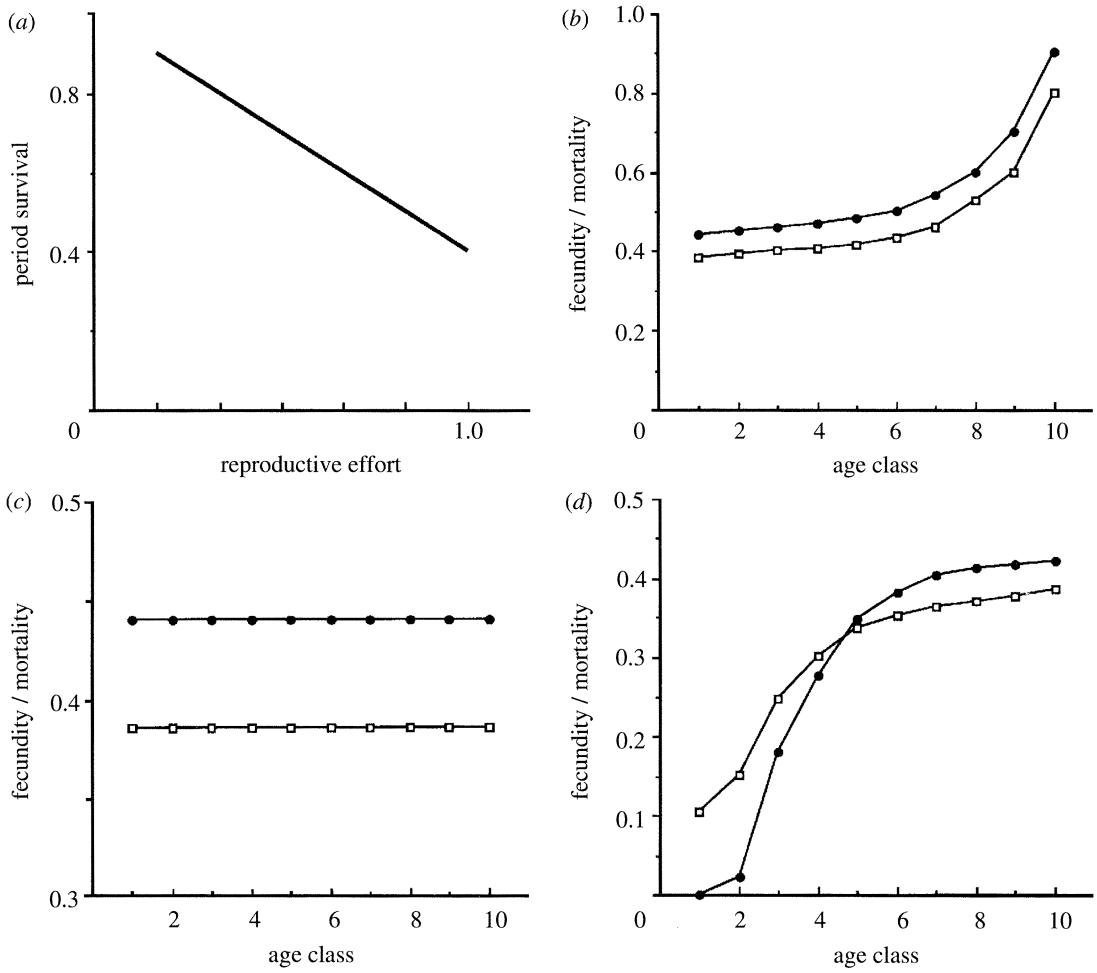

Figure 1. (*a*) Tradeoff between reproductive effort and period survival. Increased reproductive effort results in a lower period survival. For the figure we put $a = 0.9$ and $b = 0.5$ in equation (4). This tradeoff was used to obtain the results in figs 1 *b–d*. In the corresponding models, the tradeoff was the same in each year. Thus the tradeoff structure did not deteriorate with age, and there was no senescence. (*b*) The optimal life history of an organism living a fixed amount of $\omega = 10$ years. In each year, the reproductive tradeoff is that of figure 1 *a*, and the fitness definition (1) was used with $c_x = 1$ for all x in equation (3). The optimal life history consists of increasing reproductive efforts with age. However, this is an artefact of the assumption of certain death at age $\omega = 10$. The mortality shown in the figures is defined as the negative logarithm of period survival $-\ln p_x$. In all panels, filled circles indicate fecundity and hollow squares indicate mortality. (*c*) The optimal life history using the fitness definition (5) instead of (1). Because the tradeoff does not change with age, and because the organism's lifespan is potentially infinite, its future looks always the same, hence the optimal reproductive effort is the same throughout life. (*d*) Using the fitness function (5) and assuming size-dependent fecundity (equation 7), an optimal life history with increasing age-specific fecundity and mortality results. The growth rate $k = 0.9$ in equation (6) was chosen so that the organism has almost reached the limiting size s_∞ at age $\omega = 10$. After age $\omega = 10$ reproductive efforts, body size and hence fecundity and mortality become constant. There is no senescence, but mortality increases as the organism grows.

R_0^{old}. If $R_0^{\text{new}} \geqslant R_0^{\text{old}} - T$, where the threshold value $T \geqslant 0$ is the allowed size of downhill moves, then the new strategy replaces the old strategy. This procedure is repeated many times, but in the course of the simulation the threshold T becomes smaller and smaller and converges to zero. The algorithm stops if no new strategies have been accepted for a long time, which indicates that the fitness of the current strategy is optimal. For the sake of brevity we omit further technical details, which can be found in Dueck & Scheuer (1990), Dueck (1993) and Blarer & Doebeli (1995), where the technique was applied to life history theory. All results presented below were obtained by using this simple method.

To illustrate our main point that inferring senescence from phenotypic patterns can be tricky, we now use two models based on formula (5). In both models there is no senescence, yet common practice would infer senescence from the phenotypic patterns that are produced by the optimal life history strategies.

(*b*) *Model 1: size-dependent fecundity*

In this model we assume that fecundity m_x is size-dependent, and that the growth of an organism is determined by reproductive effort. Growth is slow if reproductive effort is high. More precisely, we assume that the time devoted to growth in year x *is*

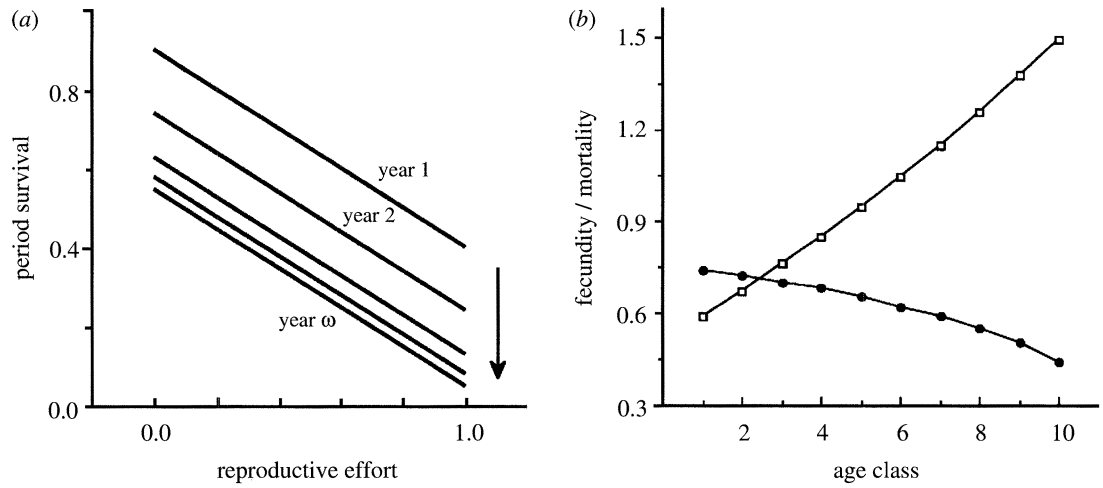

Figure 2. (*a*) Reproductive tradeoff that deteriorates with age. The deterioration is determined by the body size of the organism, for example, due to size-dependent predation. Each body size s_x corresponds to a particular intercept a_x of the tradeoff curve. The extremal body sizes $s_x = 0$ and $s_\infty = 1$, respectively, determine the boundary values $a_{\max} = 0.9$ and $a_{\min} = 0.5$ of the tradeoff structure. As the organism grows intermediate tradeoff curves occur (not all of them are shown), each with a constant slope $b = 0.5$ and with decreasing intercepts a_x given by $a_x = a_{\max} - (a_{\max} - a_{\min}) \cdot s_x$. (*b*) The optimal reproductive strategy under the tradeoff structure in (*a*). Reproductive efforts decrease with age (fecundity and reproductive effort are equal, i.e. $c_x = 1$ for all x in equation (3)). Because of the deterioration of the tradeoff the organism grows into risk. Despite decreasing reproductive efforts, its mortality increases with age. With a growth rate $k = 0.4$ in equation (6) the organism has almost reached the asymptotic size s_∞ at age $\omega = 10$. The mortality shown is the negative logarithm of period survival $-\ln p_x$. Filled circles represent fecundity and hollow squares represent mortality.

proportional to $1 - e_x$, where e_x is reproductive effort. We also assume that the growth dynamic is given by the Bertalanffy equation

$$s_x = s_\infty \cdot \left[1 - \exp\left(-k \cdot \sum_{i=1}^{x} (1 - e_i)\right)\right]. \quad (6)$$

Here s_x is size at reproduction in year x, and s_∞ is the asymptotic size (Roff 1992). The term $k \cdot \Sigma_{i=1}^{x}(1 - e_i)$ incorporates the growth rate of the organism and the time devoted to growth up to year x.

Growth within a particular year is always assumed to precede reproduction. To make fecundity size-dependent, we assume that the proportionality factor c_x in $m_x = c_x \cdot e_x$, equation (3), is an allometric measure of body size (we chose a fish-like allometric exponent of 3):

$$m_x = [s_x]^3 \cdot e_x. \quad (7)$$

Strictly speaking, the fitness equation (5) is an approximation in this scenario, because the fecundity m_x might still increase after age ω even with a constant reproductive effort, because the organism grows asymptotically towards the maximal body size s_∞. Nevertheless, we make use of the fitness measure (5) because in the scenarios considered, the constant asymptotic size s_∞ is almost reached at age ω, and the error is small. In the model, the reproductive tradeoff does not change with age. A reproductive effort e_x implies the same period survival $p_x = a - b \cdot e_x$ in each year. The corresponding fecundity m_x is given by (6) and (7), and these data are used to calculate the fitness of a given reproductive strategy $\{e_1, \ldots, e_\omega\}$.

Figure 1*d* shows the result of the optimization, representing the patterns of fecundity and mortality resulting from the optimal life history for two particular values a and b that define the reproductive tradeoff, equation (4). Both the instantaneous mortality and the fecundity increase with age. These increases are a consequence of the increasing reproductive efforts that represent the optimal reproductive strategy when fecundity is size-dependent.

(*c*) *Model 2: size-dependent mortality*

In the optimal life history in model 1, both mortality and fecundity increase with age. One might therefore argue that a reliable criterion for senescence would be an increase in mortality with a concomitant decrease in fecundity. The second model shows that this criterion is also in general not reliable. Here we again assume that organisms grow according to the Bertalanffy equation. However, size does not influence fecundity. Instead, we envisage a scenario in which size determines the intercept a_x of the tradeoff (4) by assuming that a greater size implies a lower a_x, i.e. that larger organisms experience higher extrinsic mortality rates. For example, this could occur with size-dependent predation pressures. On the other hand, the slope of the tradeoff (4), which expresses physiological constraints, does not change with age, so that there is no senescence. For simplicity, we assume that growth is independent of reproductive effort and occurs at a constant rate. To obtain the size s_x in year x we use equation (6) with the sum in the exponent replaced by the age x. We further assume that the parameter a_x in the tradeoff equation (4) is determined by body size s_x in year x according to

$$a_x = a_{\max} - (a_{\max} - a_{\min}) \cdot s_x. \quad (8)$$

Thus, assuming an asymptotic size $s_\infty = 1$, the intercepts of the reproductive tradeoff lie between $a_{\max}$ and $a_{\min}$. The slope b_x of the tradeoff is constant, $b_x = b$ for all x. Finally, we assume that fecundity is equal to reproductive effort, i.e. that $c_x = 1$ for all x in equation (3).

The growth dynamics result in a set of parallel tradeoff curves that move closer and closer as the limiting size s_∞ is approached (figure 2*a*). Given this deteriorating tradeoff structure, the optimal reproductive strategy consists of a reproductive effort, or equivalently fecundity, that decreases with age. Nevertheless, mortality increases with age. Figure 2*b* shows the age-specific pattern of fecundity and mortality that results from this scenario. As in the first model, there is no need to invoke genetic effects from antagonistic pleiotropy or mutation accumulation to interpret the changing tradeoff structure or the resulting phenotypic patterns. Here size-dependent mortality, which may be the result of extrinsic causes such as predation, is responsible for a pattern usually thought to be caused by senescence.

3. DISCUSSION

Many researchers use an age-specific increase in mortality and/or an age-specific decrease in fecundity as a criterion to diagnose senescence. The Gompertz analysis, which measures the exponential increase in age-specific mortality rates, and measures such as the 'mean rate to double the mortality' are widespread in the literature and represent the state of the art for diagnosing senescence (for example, see Finch *et al.* 1990; Johnson 1990; Promislow 1991). However, inferring senescence from age-specific patterns of mortality and fecundity is a risky business. We have shown that optimal life histories which are constrained by tradeoffs result in phenotypic patterns of mortality and fecundity that are usually thought to diagnose senescent effects such as antagonistic pleiotropy or mutation accumulation.

The interpretation of such patterns in the context of senescence depends critically on the causes of a particular tradeoff. Here, we proposed two common and biologically plausible interpretations of tradeoff structures that do not involve any senescent effects. In the first model we used a tradeoff curve that may represent a physiological constraint on the reproductive performance of an organism (figure 1*a*). If this tradeoff does not change as the organism gets older, the physiology does not deteriorate with age, which means that there is no senescence. Nevertheless, optimal life history predicts an age-specific increase in mortality caused by increasing reproductive effort with age (figure 1*d*). On the other hand, there may be purely extrinsic reasons for tradeoffs and their age-specific changes, for example size-specific predation risks. In the second model we assumed a size-dependent mortality independent of the yearly reproductive efforts. As the organism grows from year to year, its mortality rate increases, and the tradeoff deteriorates (figure 2*a*). Here, the optimality approach predicts an increase in age-specific mortality and a simultaneous decrease in fecundity because of diminishing reproductive efforts as the organism ages (figure 2*b*). Thus, even the phenotypic pattern usually believed to diagnose senescence more stringently can be the result of optimal life history strategies and need not involve senescent effects. In none of the cases we discussed it was necessary to invoke the theories of mutation accumulation or antagonistic pleiotropy to explain the tradeoff structure and the resulting phenotypic patterns.

One might wonder what a tradeoff structure might look like if mutations accumulate with increasing age and if genes exhibit antagonistic pleiotropy effects. Given senescence we expect that a tradeoff describing physiological constraints will deteriorate with age. Assuming a linear tradeoff curve as defined in equation (4), both genetic effects could induce such a deterioration by progressively steepening the slopes of the curve, i.e. increasing b_x in equation (4), with increasing age of the organism. Such deteriorating tradeoff structures can be analysed as above, and typically the result is indeed a decrease in fecundity with age. However, this decrease may overcompensate the deterioration in the tradeoff, so that even with senescence the optimal life history can lead to a decrease in mortality with age (figure 3). Not only need organisms whose mortality increases with age be non-senescent, but senescent organisms may have a decreasing mortality as they grow old. This clearly shows that to infer senescence reliably from phenotypic patterns, these patterns have to be viewed through the filter of optimal life history theory.

Recently, Partridge & Barton (1994) proposed the use of reproductive success, i.e. the product of age-specific survival and fecundity $l_x \cdot m_x$, to measure senescence. They suggest that the comparison of two life histories with respect to their age-specific reproductive success would reveal more rapid senescence in one life history if the difference in $l_x \cdot m_x$ is positive up to some age and then becomes negative for the rest of life. Unfortunately, even this pattern does not reflect senescence unambiguously. To see this, consider the first model where the tradeoff structure is constant throughout life (figure 1*a*). We compare the $l_x \cdot m_x$-curves resulting from two optimized life histories that differ only in their rate of growth k and the intercept a of the tradeoff curve that may change for extrinsic reasons only (cf. model 2). The curves resulting from the optimization model intersect once (figure 4), but as in model 1 neither of the two life histories contains any senescent effects.

A reliable diagnosis of senescence requires detailed knowledge of the different mechanisms that affect age-specific mortality and fecundity, and of possible tradeoffs, their causes and dynamics. Data on age-specific mortality and fecundity in laboratory or natural population do not in general allow us to distinguish between the different causes moulding them, and tradeoffs are notoriously difficult to measure (Stearns 1989). This suggests that it will be hard to find a reliable diagnosis of senescence based on phenotypic patterns. Implicit in our assumptions was that tradeoffs are produced by a mixture of causes, some resulting

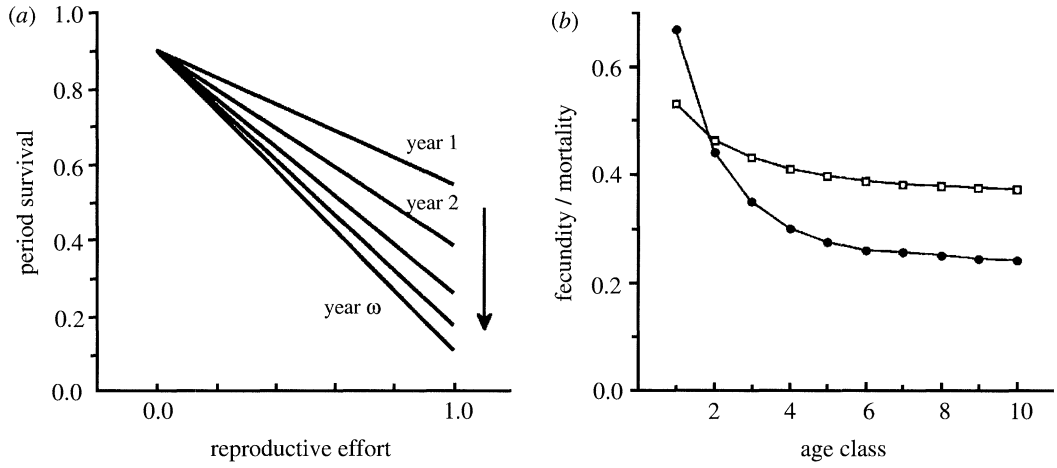

Figure 3. (*a*) Possible tradeoff structure of a senescent organism. In contrast to figure 2*a*, body size is now assumed to affect the physiology of the organisms by determining the slopes b_x of the tradeoff curve, i.e. the strength of the tradeoff. Larger sizes lead to larger slopes. For example, one can imagine that antagonistic pleiotropy has favoured a good physiology at small sizes early in life at the cost of a deterioration of the physiological constraints late in life. The result is a senescent deterioration of the tradeoff, where older and hence larger organisms pay more for equal amounts of reproductive effort. The slopes of the tradeoff range from $b_{\min} = 0.2$ to $b_{\max} = 0.9$ and are given by $b_x = b_{\min} + (b_{\max} - b_{\min}) \cdot s_x$. As in the previous model, the size s_x in year x is given by replacing the sum in the exponent of equation (6) by the age x. The intercept of the tradeoff remains constant at $a_x = 0.9$ for all x. (*b*) The optimal life history for the senescent tradeoff structure shown in figure 3*a*. As expected, reproductive effort, which is equal to fecundity (i.e. $c_x = 1$ for all x in equation (3)) decreases with age. However, at the same time mortality also decreases with age. This shows that senescent organisms need not necessarily exhibit phenotypic patterns that are typically associated with senescence. The growth rate k is set equal to 0.45 so that the organism has almost reached its limiting size s_∞ at age $\omega = 10$ years. The mortality is the negative logarithm of period survival $-\ln p_x$. Filled circles represent fecundity and hollow squares represent mortality.

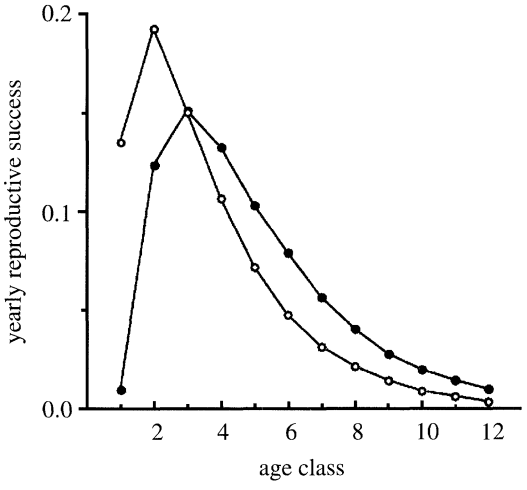

Figure 4. The reproductive success $l_x \cdot m_x$ of two optimized life histories based on model 1. The life histories only differ in their rate of bodily growth k and the intercept a of the constant tradeoff shown in figure 1*a*. For life history 1 the growth rate k equals 0.85, and the intercept of the tradeoff is set to $a = 0.91$. In life history 2 the organism grows faster with $k = 2.0$ and the intercept $a = 0.881$ was adjusted to get nearly the same fitness values R_0 in both life histories (they differ by an order of 10^{-3}). Both life histories are non-senescent. However, the lines connecting the yearly reproductive success intersect exactly once. This questions the generality of the view of Partridge & Barton (1994) that a single intercept of the $l_x \cdot m_x$ – curves indicates senescence in one of the two life histories. Filled circles represent life history 1 and hollow circles represent life history 2.

from antagonistically pleiotropic genes currently segregating in the population, others caused by physiological linkages fixed in the population and common to all its members. We think that only genetic studies can reliably uncover the genetic effects that cause senescence. The issue raised by this analysis is then as follows: can a method be found to partition tradeoffs into fixed, physiological effects and segregating genetic effects? At this point we do not know for any tradeoff whether it is properly defined as 1 % physiologically fixed and 99 % genetically variable or 99 % physiologically fixed and 1 % genetically variable. If we knew the answer, we would think more clearly about what we broadly label 'senescence'.

We thank Rolf Hoekstra, Jan Kozlowski and Anatoly Teriokhin for many helpful discussions. This work was supported in part by a grant of the Swiss National Science Foundation to S.C.S.

APPENDIX

Consider an organism with a potentially infinite lifespan. Its lifetime reproductive success R_0 is an infinite sum:

$$R_0 = \sum_{x=1}^{\infty} l_x \cdot m_x.$$

If we assume that after a particular age ω its fecundity is constant and equal to m_ω, R_0 can be split into two sums:

$$R_0 = \sum_{x=1}^{\omega-1} l_x \cdot m_x + m_\omega \cdot l_\omega \cdot \sum_{x=\omega}^{\infty} \frac{l_y}{l_\omega}.$$

If we further assume that the tradeoff given in equation (4) and the reproductive effort do not change after age ω, then the period survivals also become constant after age ω, i.e. $p_x = p_\omega$, for $x \geqslant \omega$. Using the definition of survival probabilities given in equation (2) we can then express l_x/l_ω as:

$$\frac{l_x}{l_\omega} = p_\omega^{x-\omega}.$$

Thus the fitness R_0 is:

$$R_0 = \sum_{x=1}^{\omega-1} l_x \cdot m_x + m_\omega \cdot l_\omega \cdot \sum_{x=\omega}^{\infty} p_\omega^{x-\omega}.$$

The geometric series $\Sigma_{x=\omega}^{\infty} p_\omega^{x-\omega}$ is equal to $1/1-p_\omega$, so that the equation for the fitness becomes equation (5):

$$R_0 = \sum_{x=1}^{\omega-1} l_x \cdot m_x + \frac{m_\omega \cdot l_\omega}{1-p_\omega}.$$

REFERENCES

Austad, S. N. 1992 Primate longevity: its place in the mammalian scheme. *Am. J. Primatol.* **28**, 251–261.

Austad, S. N. 1993 Retarded senescence in an insular population of Virginia opossums (*Didelphis virginia*). *J. Zool.* **229**, 695–708.

Bellman, R. 1957 *Dynamic programming*. Princeton University Press.

Blarer, A. & Doebeli, M. 1995 Heuristic optimization of the general life history problem: a novel approach. *Evol. Ecol.* (In the press.)

Charlesworth, B. 1994 *Evolution in age-structured populations*, 2nd edn. Cambridge University Press.

Chippindale, A. K., Dat, T. H., Service, P. M. & Rose, M. R. 1994 The evolution of development in *Drosophila melanogaster* selected for postponed senescence. *Evolution* **48**, 1880–1899.

Comfort, A. 1979 *The biology of senescence*, 3rd edn. Edinburgh: Churchill Livingstone.

Dueck, G. 1993 New optimization heuristics. The great deluge algorithm and the record-to-record-travel. *J. Comput. Phys.* **104**, 86–92.

Dueck, G. & Scheuer, T. 1990 Threshold accepting: A general purpose optimization appearing superior to simulated annealing. *J. Comput. Phys.* **90**, 161–175.

Finch, C. E., Malcolm, C. P. & Witten, M. 1990 Slow mortality rate acceleration during aging in some animals approximate that of humans. *Science, Wash.* **249**, 902–905.

Gaillard, J. M., Allaine, D., Pontier, D., Yoccoz, N. G. & Promislow, D. E. L. 1994 Senescence in natural populations of mammals: a reanalysis. *Evolution* **48**, 509–516.

Hirsch, H. R. 1980 Evolution of senescence: influence of age-dependent death rates on the natural increase of a hypothetical population. *J. theor. Biol.* **86**, 149–168.

Hoekstra, R. F. 1993 Senescence and evolution. *Neth. J. Zool.* **43**, 352–358.

Johnson, T. E. 1990 Increased life-span of age-1 mutants in *Caenorhabditis elegans* and lower Gompertz rate of ageing. *Sciene, Wash.* **249**, 908–912.

Kirkpatrick, S., Gelatt, C. D. & Vecchi, M. P. 1983 Optimization by simulated annealing. *Science, Wash.* **220**, 671–680.

Luckinbill, L. S., Arking, R., Clare, M. J., Cirocco, W. C. & Buck, S. A. 1984 Selection for delayed senescence in *Drosophila melanogaster*. *Evolution* **38**, 996–1003.

Medawar, P. B. 1952 *An unsolved problem of biology*. London: H. K. Lewis.

Partridge, L. & Barton, N. H. 1993 Optimality, mutation and the evolution of ageing. *Nature, Lond.* **362**, 305–311.

Partridge, L. & Barton, N. H. 1994 Evolution of ageing: testing the theory using *Drosophila*. In *Genetics and evolution of ageing* (ed. M. R. Rose & C. E. Finch), pp. 109–118. Dordrecht: Kluwer Academic Publishers.

Promislow, D. E. L. 1991 Senescence in natural populations of mammals: a comparative study. *Evolution* **45**, 1869–1887.

Prothero, J. & Jürgens, K. D. 1987 Scaling of maximal life span in mammals: a review. *Basic Life Sci.* **42**, 49–74.

Roff, D. A. 1992 *The evolution of life histories*. New York: Chapman & Hall.

Rose, M. R. 1984 Artificial selection on a fitness component in *Drosophila melanogaster*. *Evolution* **38**, 516–526.

Rose, M. R. 1991 *Evolutionary biology of aging*. Oxford University Press.

Rose, M. R. & Charlesworth, B. 1980 A test of evolutionary theories of senescence. *Nature, Lond.* **287**, 141–142.

Rose, M. R. & Charlesworth, B. 1981*a* Genetics of life history in *Drosophila melanogaster*. I. Sib analysis of adult females. *Genetics* **97**, 173–186.

Rose, M. R. & Charlesworth, B. 1981*b* Genetics of life history in *Drosophila melanogaster*. II. Exploratory selection experiments *Genetics* **97**, 187–196.

Service, P. M., Hutchinson, E. W. & Rose, M. R. 1988 Multiple genetic mechanisms of senescence in *Drosophila melanogaster*. *Evolution* **42**, 708–716.

Stearns, S. C. 1989 Tradeoffs in life-history evolution. *Funct. Ecol.* **3**, 259–268.

Stearns, S. C. 1992 *The evolution of life histories*. Oxford University Press.

Williams, G. C. 1957 Pleiotropy, natural selection and the evolution of senescence. *Evolution* **11**, 398–411.

Received 14 August 1995; accepted 7 September 1995