Evolution of longevity through optimal resource allocation

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SUMMARY

Models of life-history evolution predict optimal traits of a simplified organism under various environmental conditions, but they at most acknowledge the existence of ageing. On the other hand, genetic models of ageing do not consider the effects of ageing on life-history traits other than fecundity and longevity. This paper reports the results of a dynamic programming model which optimizes resource allocation to growth, reproduction and somatic repair. A low extrinsic (environmentally caused) mortality rate and high repair efficiency promote allocation to repair, especially early in life, resulting in delayed ageing and low growth rates, delayed maturity, large body size and dramatic enhancement of survival and maximum lifespan. The results are generally consistent with field, comparative and experimental data. They also suggest that the relationships between maximum lifespan and age at maturity and body size observed in nature may be by-products of optimal allocation strategies.

1. INTRODUCTION

Ageing is a process of decline in physiological functioning which results in increasing mortality rates with age. Because it appears non-adaptive it puzzles evolutionary biologists. Medawar (1952), Willams (1957) and later Hamilton (1966) argued that ageing occurs because natural selection acts less strongly on traits expressed late in life than on those expressed early in life. There are two main evolutionary theories of ageing based on this assumption (see, for example, Rose 1991; Partridge & Barton 1993). One is known as the mutation accumulation theory (Medawar 1952), in which late-acting deleterious mutations accumulate in populations over many generations (the non-adaptive explanation). The other is known as the antagonistic pleiotropy theory (Williams 1957) because it requires genes that have opposite effects on fitness when expressed at early and late ages: ageing results from optimization of life history if a high reproduction rate or survival rate early in life decrease performance late in life (the adaptive explanation). There is a variant of the theory of antagonistic pleiotropy founded in physiology: the disposable soma theory, in which ageing results from a low level of repair of somatic damage, whose accumulation during life leads to deterioration of an organism's physiology (see, for example, Kirkwood 1981). The theory is formulated under the so-called allocation principle: acquired energy is limited and should be invested in a way that maximizes fitness (Perrin & Sibly 1993).

Studies of resource allocation to somatic growth, maintenance and reproduction are central to life-history analyses (Koztowski 1992). Energy invested in reproduction contributes directly to fitness, while the benefits from investment in soma are expected only in future. Under unavoidable mortality risk, investment in soma might never be paid back before the organism dies. Clearly, the organism should stop investing in soma when the costs exceed the expected benefits. Models of optimal resource allocation usually deal with two components of allocation: investment in growth and investment in reproduction (Koztowski 1992; Perrin & Sibly 1993). They usually confirm that it is optimal to grow early in life and at a particular age to stop growing and start reproducing at the maximum rate until the end of life. It is well known that the main determinant of life-history strategies is the ratio of the production rate to the mortality rate (Werner & Gilliam 1984; Perrin & Sibly 1993). Ageing might affect both components, decreasing the production rate or increasing the overall mortality rate. Mortality affects optimal age and size at maturity, longevity and fecundity-related traits (see Koztowski 1992; Perrin & Sibly 1993, for a review). Kirkwood (1990) also found that decreased mortality favours repair, low fecundity and long life. Abrams (1993) showed that mortality's effects on ageing depend on the assumed density dependence. Analysis of ageing requires a clear distinction between 'intrinsic mortality', associated with the accumulation of unrepaired defects, and age- and condition-independent mortality, caused by environmental factors such as non-selective predation ('extrinsic mortality', Abrams & Ludwig (1995)). Here I present a dynamic model based on the disposable soma theory and investigate life-history evolution under different levels of extrinsic mortality.

The disposable soma theory assumes that organisms adjust their investment of resources in repair and reproduction. Kirkwood (e.g. 1990) suggested

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that the optimal level of investment in repair, constant in his model, is lower than that required to repair all damage. Thus, ageing is inevitable. Recently a dynamic model of the disposable soma theory was developed (Abrams & Ludwig 1995). Both models focused mainly on adult life, with a trade-off assumed between reproduction and repair. My model considers the whole lifetime of an organism and three resource-demanding activities: growth, reproduction and repair. The rate of ageing as well as the rates of growth and reproduction result from the allocation strategy. The effect of repair on ageing has already been established (see, for example, Kirkwood 1990; Abrams & Ludwig 1995). Here I concentrate rather on the effects of variation in resource allocation and thus variation in ageing on life-history traits such as age and body size at maturity, the growth rate, survival rate and maximum longevity.

2. THE MODEL

An organism living in a constant environment (no seasons, non-growing population) acquires resources at size-dependent rate, P, being the difference between assimilation and respiration,

$$P(W) = aW^{\mathrm{b}} - cW^{\mathrm{d}}, \tag{1}$$

where W is body size in energy units and a, b, c and d are constants ($a = 2$, $b = 0.5$, $c = 0.21$, $d = 0.83$ throughout the paper). The constants are not derived from any specific biological situation and their values do not matter for the general pattern of results as long as the shape of the acquisition function remains concave. At each moment of life the organism allocates excess energy P in age-varying proportions to growth (u), reproduction (v) and repair ($z = 1 - u - v$) in a way that maximizes the expected lifetime allocation of energy to reproduction. Allocation to reproduction at each time is $v \cdot P$, and reproductive output is released at the end of each time unit. The lifetime allocation converted to offspring number is a proper measure of fitness for populations at equilibrium regulated by density dependence early in life (Mylius & Diekmann 1995). Under constant offspring size, the expected present and future reproductive allocation at any age is equivalent to the reproductive value, which is indeed maximized in the model. The trajectory analysed in maximizing the reproductive value involves only segments of the life history from a given age until the death of the cohort (Taylor *et al.* 1974; Goodman 1982). It is advantageous to search out optimal short segments of the life history, starting from the oldest age and working backward toward the youngest, using a dynamic programming method (Bellman 1957; McNamara & Houston 1996).

According to dynamic programming, expected reproductive output (F) satisfies the recursive relation

$$F(W,S,t,T) = \max_{A} \varepsilon(S,A,t) \times \{R(W,A,t) + F(W,S,t+1,T)\}, \tag{2}$$

where ε denotes the probability of survival from t to $t+1$, T the final age, A the allocation strategy at t, R the current reproduction and S the intrinsic mortality caused by accumulation of unrepaired defects. Survivability over one time unit is given by $\varepsilon = \mathrm{e}^{-(S(t)+m)}$, where m denotes the extrinsic mortality rate. The reproductive value at final age $F(W,S,T,T)$ is equal to zero. According to the backward procedure, future survival and reproduction $F(W,S,t+1,T)$ is already known at current time unit t.

Body size increases by the amount of energy allocated to growth in every time unit according to the formula

$$\frac{\mathrm{d}W}{\mathrm{d}x} = u(t)P(W(x)), \tag{3}$$

solved numerically for time x from the interval $t-1$ to t by the Runge–Kutta method.

Ageing affects the mortality rate (intrinsic mortality here), and for the sake of simplicity it is assumed that it does not directly affect reproduction (relaxing this assumption does not qualitatively alter the patterns found). The organism is subject to damage from the beginning of life; damage appears at constant rate μ per time unit ($\mu = 0.001$ throughout the paper), and is potentially repairable at some cost. Damage can include any repairable defects appearing in somatic tissues at any level, from a change in a single molecule to the loss of whole organs and structures: DNA damage, protein turn-over, oxidative damage caused by free radicals, cell turn-over, heavy metal detoxication, etc. (see Kirkwood 1981, for a review). Damage is expressed in mortality units in the model. The intrinsic mortality rate at time t is described by the formula

$$S(t) = S(t-1) + \mu(1-z)^n, \tag{4}$$

where z denotes the proportion of production directed to repair. Parameter n, called 'efficiency of repair' here, maps the amount of resources invested in repair into an intrinsic mortality rate. If the effect of defects on mortality is multiplicative rather than cumulative, we can expect $n > 1$. Because a reasonable value of n and its variation among different organisms is not established, results for four different ns are presented. N.B. This model assumes that all damage is repaired only when $z = 1$ (equation (4)), assuming lower boundary z values (like $z > 0.8$) did not qualitatively alter the results (data not shown).

The recursive equation (2) allows construction of an algorithm in which the equation is solved iteratively from final age T backwards to $t = T-1$, $t = T-2, \ldots, t = 1$. The allocation strategy (the values of u, v and z) yielding maximal F is considered optimal. An array with optimal proportions of allocated energy for different state variables (W and S) is saved for every time unit. Using these arrays it is possible to reconstruct the optimal life history proceeding forward, starting from $W = 1$ and $S = 0$, and following the growth trajectory and the trajectory of accumulation of intrinsic mortality. With this known, survival curves can be constructed. The life horizon is not determined beforehand. The model assumes that the backward procedure is interrupted if survival counted from time unit t to T (proceeding forward) is less than 0.001. In other words, maximum lifespan is defined as the age at which the probability of survival under a given strategy is less than 0.001. Thus, maximum lifespan results from the adopted allocation strategy.

3. RESULTS

The optimal proportions of allocated resources change with an organism's age. They are shaped by the extrinsic mortality rate and repair efficiency (figure 1). First growth is favoured, and reproduction begins when growth stops. Repair, if any, competes for resources with growth and sometimes with reproduction. The share of resources allocated to re-

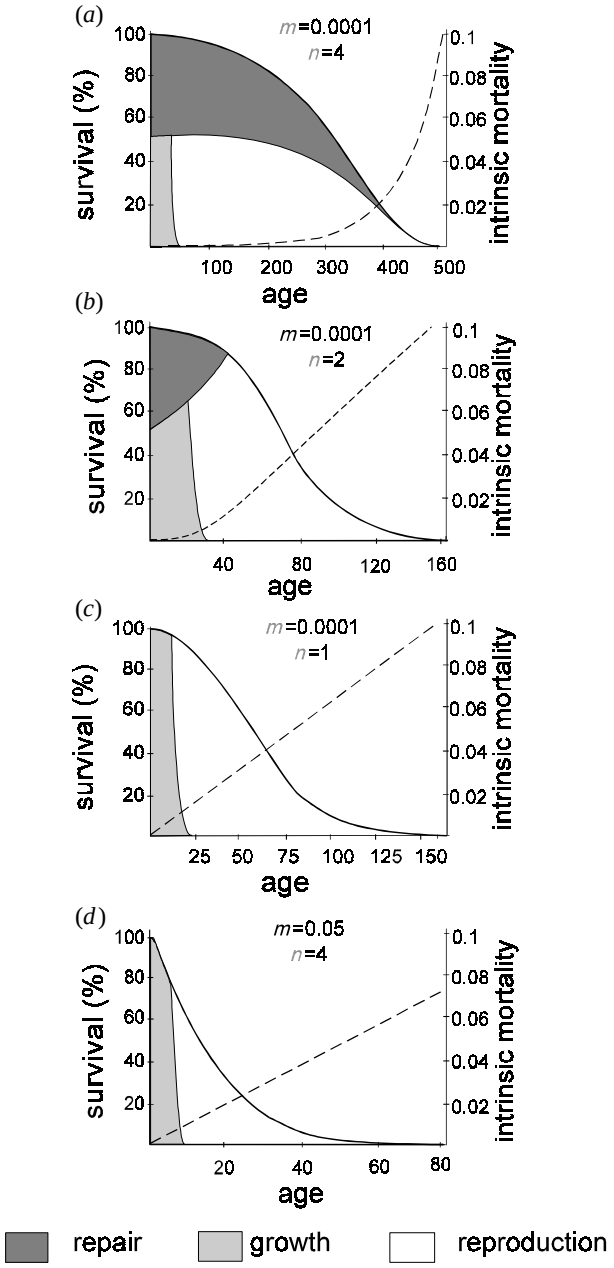

Figure 1. Optimal allocation strategies under different levels of extrinsic mortality rates (m) and repair efficiency (n), and resulting probabilities of survival. The proportions of resources allocated to growth, reproduction and repair are expressed as the relative heights of the differently shaded areas at each age. Note that in the subfigures with larger dark areas representing repair, survival early in life is enhanced and the lifespan prolonged. The intrinsic mortality rate is also presented (dashed line).

pair is highest early in life and decreases slowly or quickly, stopping completely before the end of life. Repair is high when extrinsic mortality is low and repair efficiency is high (repair is relatively cheap). Figure 1 also shows how dramatically allocation to repair can change the probability of survival and maximum lifespan. Note that in the subfigures with large dark areas representing repair, survival early in life is enhanced and the lifespan prolonged.

Given the same amount of available resources,

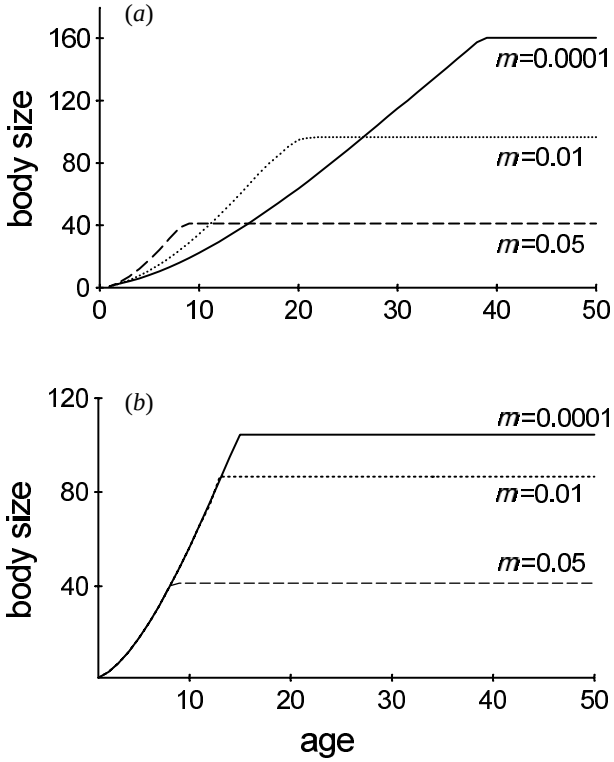

Figure 2. Optimal growth curves for different extrinsic mortality rates. In the top figure (a), repair efficiency is high ($n = 4$); the amount of repair varies, highest under low mortality rates and absent for the highest mortality. In the bottom figure (b), repair efficiency is low ($n = 1$); repair is not beneficial and is absent at all mortality rates.

growth is fast in risky environments and slow in safe ones because the drain on resources for repair varies (figure 2a). Note, however, that the slow-growth strategy leads to large body size, while small body size is achieved by the fast-growth strategy. This is because high investment in repair and consequently low investment in growth slows down ageing, enhances longevity and delays age at maturity. In contrast, the growth rate is the same for all mortality rates when repair is not optimal, and differences in body size reflect only undramatic differences in age at maturity (figure 2b).

Figure 3 shows the joint effect of mortality and repair efficiency on body size (a) and maximum lifespan (b). The right-hand and front edges of the surfaces in figure 3 show the dependence of body size and maximum lifespan expected from the model ignoring repair, because repair is never optimal, neither under the highest assumed mortality rate nor under the lowest repair efficiency. The elevation of the surfaces, especially pronounced for lifespan, results from increased allocation to repair.

There is a positive correlation between maximum lifespan and size at maturity ($r = 0.96$, $p < 0.0001$, figure 4a) and a similar correlation between maximum lifespan and age at maturity ($r = 0.93$, $p < 0.0001$, figure 4b) in the data set, which includes different allocation strategies obtained under different levels of extrinsic mortality and different repair efficiencies.

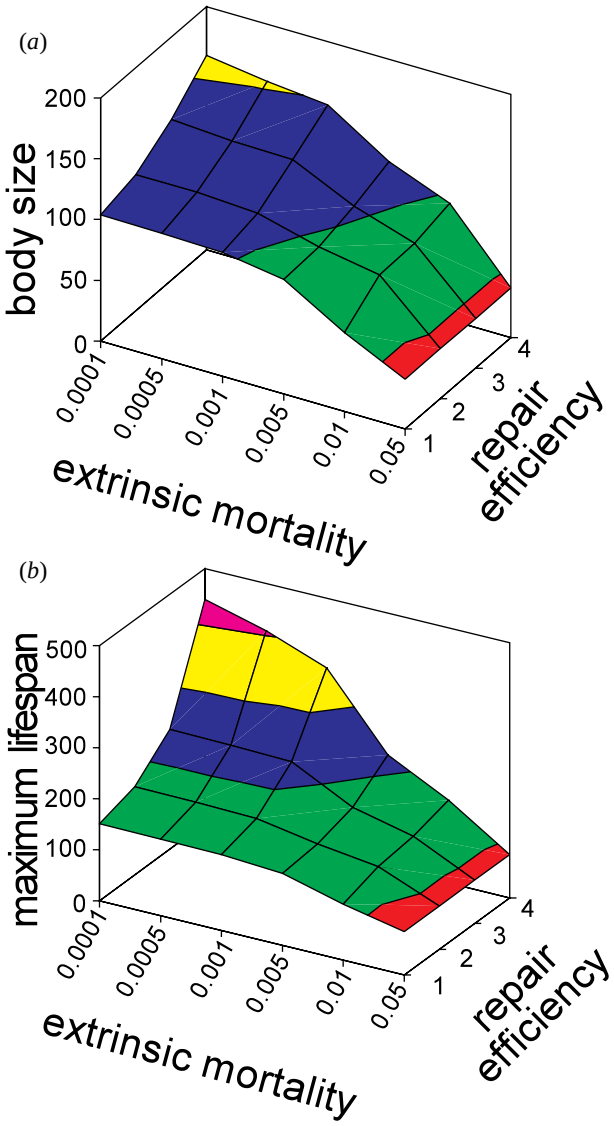

Figure 3. Body size at maturity (a) and maximum lifespan (b) under different extrinsic mortality rates, m, and different repair efficiencies, n. Note that it is never optimal to invest in repair when $m = 0.05$ or $n = 1$ (front and right edges of the surfaces).

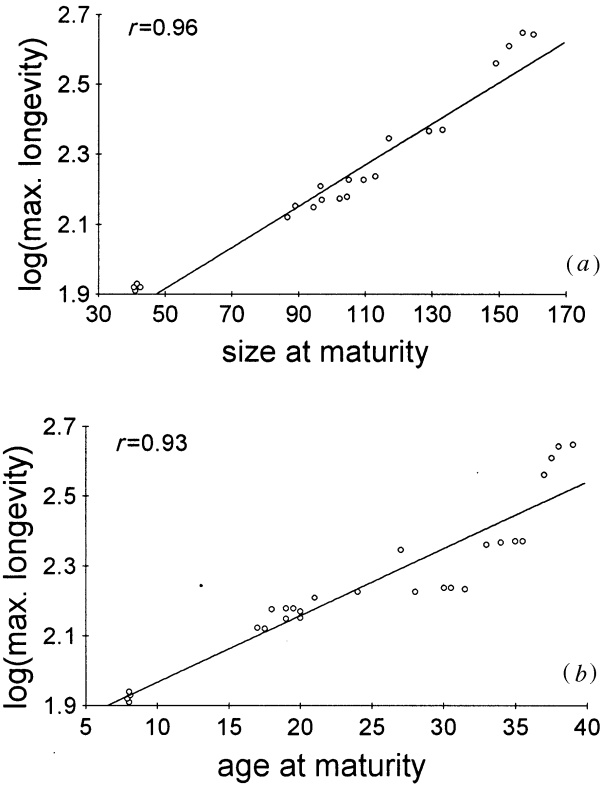

Figure 4. Size at maturity versus maximum lifespan (a) and age at maturity versus maximum lifespan (b). The points represent data obtained from numerical solutions for different extrinsic mortality rates and different repair efficiencies.

4. DISCUSSION

Extrinsic mortality and repair efficiency appeared to be the main determinants of allocation strategies. That mortality affects the life history is well known (Koztowski 1992; Perrin & Sibly 1993). It has also been shown that extrinsic mortality determines the repair level and then the ageing rate: in a safe environment it is advantageous to invest in a potentially long-lived soma (Kirkwood 1990; Abrams 1993; Abrams & Ludwig 1995). The results of the present model confirm that the optimal allocation strategy depends on the level of environmental mortality. Moreover, the results show that investments in growth, reproduction and repair of defects change dynamically during an individual life. It appears optimal to grow first and then to cease growth and start reproduction. Kirkwood's (e.g. 1990) model of the disposable soma theory assumed for simplicity that the resource allocation to repair was constant. The present model does not assume constant allocation and shows that the optimal allocation to repair varies with age. If it is optimal to invest in repair at all, this allocation is highest early in life and decreases later, stopping completely before the end of life. Therefore the growth rate is particularly affected by repair. That investment in maintenance (which includes repair) should decrease with age has already been suggested by Calow (1979). Perrin & Sibly (1993) said that investment in maintenance should increase with reproductive value because more should be spent to preserve a more valuable soma. Recently, Abrams & Ludwig (1995) developed a dynamic model of the disposable soma theory in which age-specific mortality patterns were found to result from specific functions for the assumed trade-off between repair and reproduction. They did not, however, investigate allocation patterns and their consequences for life-history traits other than ageing. It is worth noting here that the present paper confirms Abrams & Ludwig (1995) finding that increase in age-specific mortality should not necessarily be exponential (figure 1) under the disposable soma theory.

The present results show that the growth rate may differ under different allocation strategies even though the same dependence of resource acquisition on body size is assumed in all cases. This is because the drain on resources for repair varies. Thus the growth rate might not be maximal, and it should be

negatively correlated with repair and positively with the level of extrinsic mortality. Low extrinsic mortality favours high investment in repair and in consequence low but long-lasting investment in growth. High investment in repair enhances longevity: thus growth can last longer and lead to large body size despite a slow growth rate. Against our intuition, the present model reveals a negative relationship between the growth rate and body size: fast growth leads to small body size and slow growth leads to large body size under the same trophic conditions. In previous allocation models, considering growth and reproduction only, under the same resources availability and different mortality levels the growth rate was the same but the age and size at maturity were different (see Koztowski 1992; Perrin & Sibly 1993, for a review). This accords with the case presented in figure 2*b*, in which repair is not optimal and growth and reproduction are always maximal. Previous models also showed that optimal life-history strategies maximize the ratio of the production rate to the mortality rate (see, for example, Perrin & Sibly 1993). Werner & Gilliam (1984) pointed out that the life history might be affected by optimization of the foraging strategy: it might be optimal under high external mortality stress to adopt less risky foraging, leading to lowered acquisition and impaired growth. Kirkwood's model (1990) also gives some predictions on age of first reproduction: elevation of the repair level results in delayed maturity and implies deterioration of growth.

Predicting the maximum lifespan from the extrinsic mortality rate, as the age to which survival is very unlikely, often yields estimations which are by orders of magnitude too large. This means that other factors must be involved. The disposable soma theory suggests that a negative correlation between the level of environmental mortality and longevity results from selection to vary the investment in repair (see, for example, Kirkwood 1990). The present results, although derived from quite a different model, accord with this prediction and show a negative relation between maximum longevity and extrinsic mortality. However, it is important to remember that investment in repair, not the maximum life span, is the target for selection.

The hypothesis that the repair rate shapes longevity has been studied comparatively. In different groups of vertebrates (fish, reptiles, birds and mammals) a positive relation between longevity and the rate of DNA repair usually has been observed (Bernstein & Berstein 1991; but see Promislow 1994), supporting the present model. Single-gene age mutations which extend the lifespan of the *Caenorhabditis elegans* worm also showed resistance to oxidative stress, thermal stress and UV radiation (see, for example, Lithgow & Kirkwood 1996). This indicates that those mutations extend the lifespan by a common mechanism, which could be related to repair of somatic damage.

Of course, the measure of ageing is central to this discussion. Recently some studies questioned the use of the mortality rate and fecundity as a measure of ageing (see Partridge & Barton 1996). Blarer *et al.* (1995) suggested that ageing can occur without any deterioration in the organism's physiology, and McNamara & Houston (1996) argued that it can occur even when an organism's state improves with age. Partridge & Barton (1996) pointed out that these anomalies result partly from an inappropriate measure of ageing. Namely, anomalies may arise when ageing is measured separately as an increase in mortality or a decrease in fecundity. They noted that selection acts on the product of survival and fecundity, and suggested the use of Fisher's reproductive value as a reliable measure of ageing; it includes the prospects for both survival and fecundity. Declining reproductive value indicates that the options for trade-offs open to an organism diminish with age. This is exactly the case in the present study: selection acts directly to maximize the reproductive value during the whole life.

Interspecific allometries of physiological and life-history parameters were recently suggested to be by-products of optimal allocation strategies (Koztowski & Weiner 1997). Contrary to previous analyses (summarized in Charnov 1993) in which selection was assumed to act on age at maturity, this approach considers body size as one of the dependent variables and resource allocation as the selection target. Adding allocation to repair, I extend Koztowski & Weiner's (1997) results to the correlations between maximum longevity and age and size at maturity (figure 4). These correlations are clearly the effect of optimizing allocation strategies under a variable mortality rate and variable repair efficiency. Optimal allocation determines both longevity and body size, and the observed correlations are by-products and not cause–effect relationships.

It is very difficult to test predictions that mortality and adopted allocation strategy shape ageing and life-history traits, because extrinsic and intrinsic sources of mortality are not usually distinguished. Comparative studies on mammals so far have not shown a significant negative correlation between overall mortality and maximum longevity (Promislow & Harvey 1991). In studies of Virginia opossums, females living under low mortality on an island had slower growth, reduced litter size and slower ageing than those in a mainland population under high mortality (Austad 1993).

Selection experiments designed to test genetic theories of ageing (see, for example, Rose 1991) may provide the data needed to test the model's predictions. Selection for early or late reproduction may modify the allocation strategy. Early reproduction may result from early cessation of repair, producing fast growth, fast ageing and a short lifespan. Selection for late reproduction may favour investment in repair, delayed ageing, lengthened lifespan, delayed maturity and increased body size. For example, in *Drosophila* stocks selected for late reproduction, slower development and larger body size were observed in addition to longer lifespan (Partridge & Fowler 1992). Similarly, under direct selection for longevity in *Drosophila*, its increase possibly arose

from decreased allocation to reproduction at all ages (Zwaan *et al.* 1995). Bean weevils (*Acanthoscelides obtectus*) selected for late reproduction lived longer, developed longer and were heavier than beetles selected for early reproduction (Tucić *et al.* 1996). If the allocation strategy shapes life-history traits, selection experiments may alter the allocation strategy and thereby the whole life history of the organisms. The present results may provide a physiological explanation for the pleiotropy observed in such experiments. Recent work on *Callosobruchus maculatus* by Tatar & Carey (1995) studied allocation patterns more directly. By manipulating both egg production and nutrient availability they found that nutrient allocation was directly responsible for mortality versus reproduction trade-offs.

The present results seem consistent with field and experimental data. However, studies are still needed to distinguish extrinsic and intrinsic sources of mortality. The correlation between the growth rate and maximum lifespan should be investigated for the case in which the growth rate varies despite similar trophic conditions. The results can also explain some data derived from selection experiments. The model predicts that the correlation between age or size at maturity and maximum lifespan is a by-product of optimal allocation strategies which needs experimental confirmation.

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