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What does a fly's individual fecundity pattern look like? The dynamics of resource allocation in reproduction and ageing

V.N. Novoseltsev[a,b,1,2], J.A. Novoseltseva[a,3], A.I. Yashin[b,c,*]

[a] Institute of Control Sciences, 117997 Profsoyuznaya 65, Moscow, Russia
[b] Max-Planck Institute for Demographic Research, 114 Doberaner Str., D 18057 Rostock, Germany
[c] Sanford Institute of Public Policy, Duke University, Durham, NC 27708-466, USA

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Abstract

Reproduction is usually characterised by an average fecundity pattern having a maximum at earlier ages and a subsequent gradual decline later on. An individual fecundity trajectory does not follow such a pattern and has no maximum. A three-stage pattern, which includes maturation, maturity and reproductive senescence, is a more appropriate description. An analysis of the power balance of an adult female fly during its life course allows us to predict two critical periods in an individual life history. The first crisis occurs at early ages when the increasing power demand becomes greater than the power supply. It often results in premature death. The surviving flies enjoy maturity and lay eggs at a presumably constant rate. The second critical period at advanced ages ends up in a senescence-caused death. Our approach predicts that there will be a bimodal death time distribution for a population of flies.

Keywords: Fecundity pattern; Resource allocation; Premature death; Homeostenosis

1. Introduction

Strong correlations between fecundity, mortality and longevity have been found in various species, particularly, in flies (Williams, 1966; Rose, 1984, 1991; Reznick, 1985; Bell and Koufopanou, 1985; Partridge, 1986). Fecundity timing influences other life history traits and trade-offs and affects reproductive and mortality costs. It also plays an essential role in the optimality hypothesis of the evolutionary biology of ageing (Kirkwood, 1977, 1990, 2002; Rose, 1991; Partridge and Barton, 1993). However, in spite of a great interest in fecundity scheduling, 'surprisingly little detailed information exists on the patterns of reproduction over the lifetime of even a single insect species' (Carey et al., 1998a).

Despite the fact that in many laboratories the 'fecundity of mated females was measured individually' (Ackermann et al., 2001), usually only averaged fecundity patterns have been analysed in insects. For example, only population-averaged fecundity data were presented and studied in numerous experiments on artificial selection in *Drosophila* which were devoted to postponed senescence (Rose, 1984; Chippindale et al., 1993; Djawdan et al., 1996), late fecundity (Luckinbill et al., 1984; Arking, 1987; Arking et al., 2000), reproduction at a 'young' or an 'old' age (Partridge and Fowler, 1992; Roper et al., 1993 etc.). In many cases, researchers use even more simple indicators of age-related averaged fecundity. They evaluate 'early' or 'late' fecundity by counting up the averaged productivity during several first days after the onset of reproduction, and during some period at advanced ages. Such indicators proved to be adequate in the majority of insect fecundity studies. Only in the latest publications were some 'unpleasant' findings presented showing that the early

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* Corresponding author. Tel.: +49-381-2081-106; fax: +49-381-2081-406.

E-mail addresses: novoselc@ipu.rssi.ru, novoseltsev@demogr.mpg.de (V.N. Novoseltsev), novoselc@ipu.rssi.ru (J.A. Novoseltseva), yashin@demogr.mpg.de (A.I. Yashin).

[1] Tel.: +95-334-88-91.

[2] Tel.: +49-381-2081-106; fax: +49-381-2081-406.

[3] Tel.: +95-334-88-91.

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fecundity indicator is particularly sensitive to the assay conditions (Ackermann et al., 2001).

Although some experiments involving individual fecundity measurements were carried out about 20 years ago (Aigaki and Ohba, 1984; Whittier and Shelley, 1993), only the latest studies have paid special attention to individual fecundity (Carey et al., 1998a,b; Blay and Yuval, 1999; Shelley, 2000; Müller et al., 2001). Accordingly, little attention has been given to the study of genetic and physiological mechanisms, which underlie experimentally observed age-related fecundity trajectories. Pioneering studies of individual fecundity were performed by Carey et al. (1998a,b) with 1000 Mediterranean fruit flies. Müller et al. (2001) presented a thorough analysis of the associations of individual fecundity with longevity in these flies.

Natural deaths in laboratory populations are mostly senescence-caused. Fries (1980) and, independently, Hayflick (1998) described senescence-caused death in humans as resulting from a crisis in homeostatic ability and energy exhaustion. Senescence-caused death occurs because of homeostenosis, i.e. when a homeostatic resource of an organism runs out so that even a smallest internal or external violation of homeostasis results in death. However, reproduction-related deaths may also happen in populations of flies. Since reproduction is costly, it may demand an extremely high expenditure of energy at a period of maximal reproductive effort. In some flies these demands are impossible to satisfy. These flies die prematurely from reproduction overload.

The sporadic and vague evidence, which has now been accumulated, supports the notion that at least some of the early-aged deaths in fly populations are related to reproduction. Chapman et al. (1998) suggest that females flies ‘suffer a decrease in survival as a result of egg production and of mating, and these costs are independent of one another’ (Chapman et al., 1998). In a paper devoted to the delayed wave of deaths from reproduction, Sgró and Partridge (1999) observed statistically non-significant peaks of deaths in *Drosophila* females shortly after mating which were presumably reproduction-related. Carey et al. (1998a) report that many ‘short-live flies died before they were old enough to produce a high level of eggs’ (Carey et al., 1998a).

To date, the best-formalised description of individual fecundity in a fly was presented by Müller et al. (2001). These authors described patterns of individual reproductive activity using a simple heuristic approach. Namely, they considered only the latest stage of the fecundity pattern and used an exponentially declining function with a randomly located maximum for the description. However, such a method is not appropriate for our goals since it does not allow for a detailed investigation of the individual power allocation mechanism, which plays an important role in both fecundity and life span determination. In particular, energy considerations can help clarify the causes of death in animal populations.

In this paper we address the question of how individual fecundity patterns can be described and whether such a description might help in better understanding the connection between reproduction and life span.

2. Species-specific mechanisms forming individual fecundity

In Novoseltsev et al. (2002) we proposed a formalised approach to the description of a fecundity pattern. We hypothesised a mechanism by which reproductive capabilities of a female organism under given conditions manifest themselves in the form of an age-related fecundity pattern. The realised pattern of an individual fly was assumed to be determined by the following two processes: an endowed age-related reproductive program and a decline in the homeostatic capacity of a reproductive system that comes into play later in life.

On one hand, a fly’s genotype encodes an individual pattern of reproductive activity and egg production. Analysing published data and research findings on various flies (Alujaa and Liedo, 1993; Lawrence, 1993; Pitnick et al., 1995; Markow, 1996; Blay and Yuval, 1999; Harshman and Hoffmann, 2000; Shelley, 2000; Spencer and Miller, 2002), we came to the conclusion that the endowed reproductive machinery is likely to be designed to produce eggs at a constant rate. In this respect the reproductive system in flies does not differ from other functional systems, wherein functioning reaches homeostatic stability in the maturation period (e.g. systems responsible for flight capability; Bennett, 1991; Jones and Lindstedt, 1993; Suarez, 1996; Marden, 2000; or vision; Bui et al., 2000). Not too much is known about the genetic control of the development of different functional systems in flies (Salazar-Ciudad et al., 2001), and no genes are known to degenerate or stop the activity of any one functional system in an organism (Miller, 1999; Partridge and Gems, 2002). Functional capacity in a system deteriorates at advanced ages mostly due to resource inability. For example, at older ages flies cut off flying or demonstrate ‘supine’ behaviour (Sohal, 1986; Papadopoulos et al., 2002) presumably due to a power shortage and not because of genetic stoppage of the flying function.

A series of reproduction-related events that unfolds in an organism of a developing fly imposes a number of limitations at different ages on the power flux, which is needed to perform the prescribed activities. We will call ‘reproduction-related demand’ the power demand, which is necessary for successful execution of the corresponding biochemical and physiological processes.

Daily egg production is traditionally used as a measure of individual reproductive activity. The first publication that uses such an individual measure of reproductive efforts was the Aigaki and Ohba (1984) paper. These authors suggest that the ‘egg-laying activity is a parameter which changes regularly with female age and is appropriate for quantitative analysis of individual variations in female reproductive activity’ (Aigaki and Ohba, 1984). We will use this measure to estimate a reproductive-related power demand in mature female flies once the egg laying has started. We will use the number of eggs, which is processed in the ovaries at different ages, to estimate the power demand before the onset of reproduction.

Regulation of an ovipositional process is an issue of interest in various Diptera. For example, the difference in oviposition between virgin and mated flies was studied in *Musca domestica* (Riemann and Thorson, 1969), *Drosophila* (Aigaki and Ohba, 1984; Partridge, 1986), medflies (Carey et al., 1998a,b; Blay and Yuval, 1999), and onion flies (Spencer and Miller, 2002).

The process of egg maturation in the fly’s ovary is well studied (Lin and Spradling, 1993; Markow, 1996; Carlson et al., 1998; Carlson and Harshman, 1999). The follicle cells are produced in the germarium. It can be assumed that after the initial gap, the process of follicle production has a genetically endowed constant rate, which has been called ‘reproductive capacity’ (*RC*) (Novoseltsev et al., 2002). This rate is related to the number of ovarioles and is regulated by the nutrient income. The egg chambers produced enter the ovariole and move ahead. After a time lag, which is needed for ripening, the eggs arrive at the ovipositor and are laid. The number of egg chambers that are simultaneously processed inside the ovarioles increases from zero to a maximum value. This maximum is achieved, on average, at the ‘onset of reproduction’, i.e. at the age when the first mature egg leaves the ovariole. After this moment the number of eggs which input, $F_{inp}(x)$, and output the ovarioles, $F_{out}(x)$, are assumed to be equal. A steady state arises in this case (Fig. 1). In *Drosophila*, an ovariole has about six to seven progressively more mature egg chambers (Lin and Spradling, 1993). A fly’s ovaries can simultaneously process as many as 100 eggs (Markow, 1996).

Thus the most characteristic feature of the reproductive system is a genotype-specific maximal rate of egg production in the germarium, *RC*, which is attainable in a given environment (Novoseltsev et al., submitted for publication, J. Gerontol.). Then the individual time-pattern of fecundity can be represented as a step-wise function with a steady state level *RC*:

$$F_{out}(x) = \begin{cases} 0, & \text{if } x < X_{onset} \\ RC, & \text{if } x \geq X_{onset} \end{cases} \tag{1}$$

where X_{onset} is the age of the onset of reproduction.

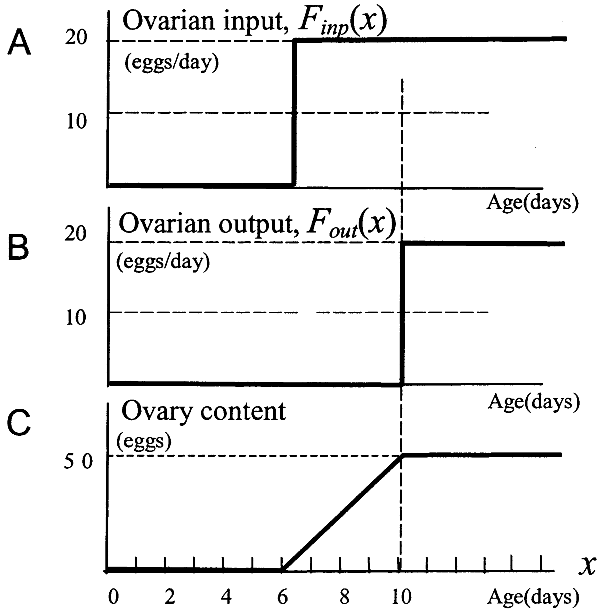

Fig. 1. Hypothetical individual age-related patterns of egg production in the gonads. From above: (A) follicles enter the ovaries of a fly from the germarium at a rate of 14 eggs per day, starting at day 6, (B) at day 10 the first ripened egg leaves the ovary to be laid by the fly, (C) eggs simultaneously processed in the ovaries have a steady state of 56 eggs achieved at day 10. The values widely correspond to experimental data on *A. suspensa* females (see Fig. 2).

Such a constant rate of egg-laying will proceed until the fly has enough power resources to sustain it.

When the averaging procedure is applied, it smoothes and widens the individual patterns. An experimental pattern for a population of Caribbean fruit flies is presented in Fig. 2 (Lawrence, 1993).

3. Decline of individual homeostatic capacity determines the tail of the individual fecundity pattern

To analyse how an individual age-related fecundity pattern is formed, we turn to the energy balance in the reproductive system of a female fly. The first observation is that the increase of the power demand begins earlier than the first egg is laid, thus reflecting the expenditures needed for egg maturation in the ovaries. We will assume that at any age the energy demand is proportional to the number of eggs being processed in the ovarioles at this age. This means that the power demand at early ages linearly increases until it reaches a maximum value, D_{max}, which is proportional to the *RC* in Eq. (1).

The other process involved in the formation of a fecundity pattern is the energy supply, that is, the capability of the energetic mechanisms, which maintains the reproduction, to produce the power consumed in the vitellogenesis and other related processes. The reproduction-related energy supply can be presented as the initial

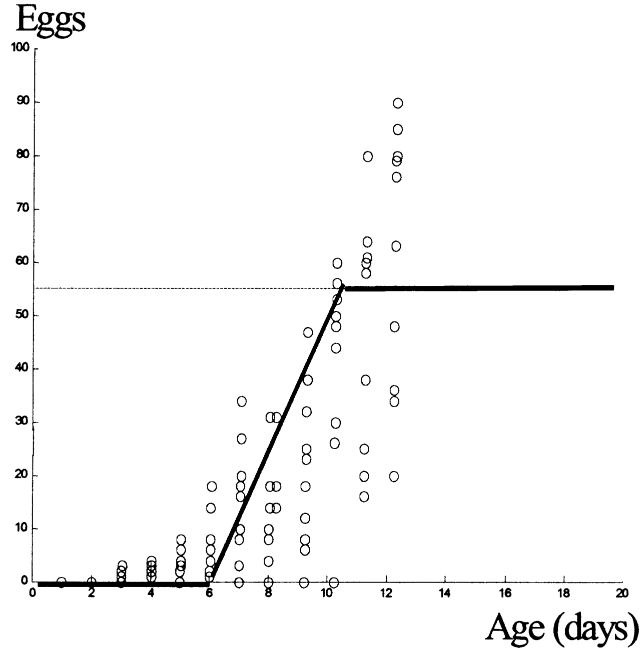

Fig. 2. Increase in the number of eggs simultaneously processed in the ovary of a female fly (averaged population data). Open circles are for *A. suspensa* females (Lawrence, 1993) while a solid line represents a hypothetical model for an assumed follicle production 14 eggs per day, starting at day 6 (see Fig. 1). A steady-state number of eggs simultaneously processed in the ovary is achieved at day 10 and is equal to 56.

power devoted to reproduction, which then slowly decreases due to reproductive senescence.

We describe this senescence-caused decrease as a result of the degradation of homeostatic mechanisms converting the external resources into ATP consumed by the organism's systems. The basic notion of a mathematical model, describing the process, is homeostatic capacity $S(x)$. It characterises the ability of the systemic mechanisms (at age x) to convert substances delivered from external sources into energy. It was shown (Novoseltsev et al., 2000, 2001) that the homeostatic capacity $S(x)$ is governed by a quasi-exponential function:

$$S(x) = S_0 \cdot \exp\left[-\int_0^x R(t)dt\right], \tag{2}$$

which describes the 'homeostenosis', that is the age-related decrease of the capacity. Here $R(t)$ is a relative rate of ageing. It is proportional to the oxygen consumption rate $W(x)$, which is modified by the defensive and reparative mechanisms, $R(x) = \beta(x) \cdot W(x)$. $\beta(x)$ describes the age-related oxidative vulnerability of a system.

The time course of this 'exponential-looking' function can be very far from the real exponent since both $\beta(x)$ and $W(x)$ may drastically alter with age. But it is true that $S(x)$ decreases with age at a decelerated rate. As hypothesised by Ukraintseva and Yashin (2001), the age-related deceleration of senescence described by Eq. (2) widely corresponds to the basal decrease in the rate of living during an individual life, which is common to all living things.

Based on experimental observations in flies (Carey et al., 1998a,b; Müller et al., 2001) it can be assumed that $S(x)$ converges to a 'pure' exponent at advanced ages:

$$S(x) = S_0 \cdot \exp[-x/\tau_{tail}], \tag{3}$$

that is, the rate of ageing $R(x)$ becomes approximately constant. As for a maximum power supply in the maintaining system, S_{max}, is proportional to the homeostatic capacity (Eq. (3)), the maximal power devoted to egg production also comes out exponentially at older ages. At some age this decrease results in an inability of the mechanisms supporting the reproductive system to fulfil the endowed reproductive program. The rate of egg production in the germarium decreases, thus diminishing the number of eggs in the ovarioles. Some days later the ovaries empty and egg-laying stops.

Thus an individual fecundity pattern can be viewed as a result of interplay of the two energetic processes, the genetically prescribed reproduction-related demand, D_{max}, and the age-wise diminishing power supply in the reproductive system. When the maximal reproductive-related supply at age x_{sen}, $S(x_{sen})$, lowers below the demand D_{max}, the onset of senescence is manifested. The arising insufficiency of the energetic capability of reproductive-related mechanisms:

$$S(x_{sen}) < D_{max}, \tag{4}$$

manifests the onset of reproductive senescence. Here S_{max} and D_{max} are expressed in relative units.

Experimental evidence exists that a resource available for metabolic support of reproduction affects the rate of egg production. For example, when one of the two primordial gonads was surgically removed from a female larvae, single-ovary *Drosophila* females increased their per ovary egg output by 50% (Markow, 1996).

Thus the individual age-related pattern of egg-laying has three parts (Fig. 3). The first one is a zero-egg period of reproductive maturation. The main part is a reproductive plateau kept at the ages of reproductive maturity. The last stage is reproductive senescence with an exponentially decreasing rate of egg-laying.

This finding apparently contradicts the well-known bell-shaped fecundity pattern observed in traditional experimental studies. Such a three-stage fecundity pattern was never used in analysis of the most studied species, *Drosophila* and medflies. Either at the population level or at an individual one, the fecundity pattern in these species is described heuristically as having two parts. It is assumed that fecundity reaches a maximum at some age and then slowly declines.

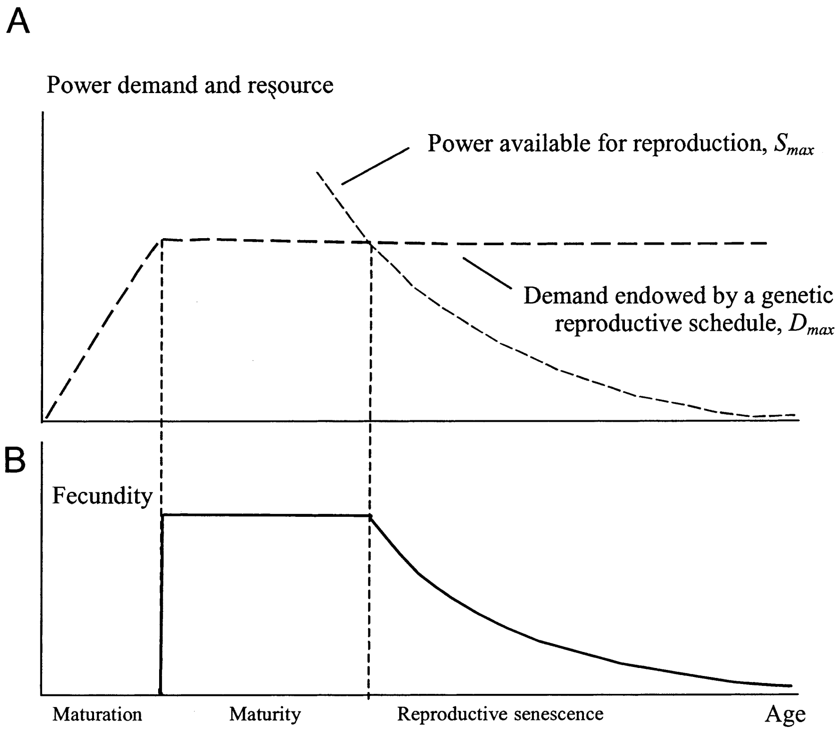

Fig. 3. The three-stage fecundity pattern of an individual female fly. (A) Mechanism underlying fecundity scheduling in an individual female fly. Two age-related processes involved in giving form to a fecundity pattern are presented: an age trajectory of the energy demand endowed by the genetic reproductive program, and a time function representing the power resource available for reproduction. At maturation stage, the energy demand is governed by the needs of vitellogenesis and other processes preceding egg laying. The first ripened egg is laid at age X_{onset} thus giving the manifestation of the onset of reproduction. Then the rate of egg-laying rapidly achieves a steady-state level. The power resource, initially enough to sustain all the reproduction-related processes, decreases as time passes. At some point, the attainable power falls below the level needed for the full-strength functioning of the reproductive machinery. Maintenance of the genetically prescribed rate of egg production becomes impossible. (B) The resultant three-stage pattern of egg-laying in an individual female fly. The rate of egg-laying is zero at maturation stage, and at each age of maturity and senescence it is a minimum of the two above curves.

Such a description is very common in *Drosophila* at a population level, starting from Lints and Lints (1968). In medflies, the same description was also used at an individual level. ‘Individual egg-laying trajectories rose sharply after egg-laying began 5–17 days after emergence, reached a peak and then slowly declined’ (Müller et al., 2001). Exponential approximation for a reproductive decline was found both in *Drosophila* (Pretzlaff and Arking, 1989) and medflies (Müller et al., 2001). Various mathematical approaches were used to describe reproductive patterns in different species, but to the best of our knowledge, there were only a few attempts to confront the results of mathematical modelling to the experimentally measured fecundity pattern (Stearns et al., 2000; Shanley and Kirkwood, 2000; Cichon, 2001).

Nonetheless, flat reproductive patterns were observed in some Diptera species such as onion flies *D. antiqua* and oriental fruit flies *Bactrocera dorsalis*. These flies are characterised by a stable and prolonged reproductive period, so that a usual way to describe fecundity is ‘cumulative egg production’ (Figs. 4 and 5). A linear increase in a cumulative pattern is equivalent to a stepwise individual daily fecundity. For example, in onion flies ‘after mating, the egg-laying rate shifted abruptly upward from near 0 to about 15 eggs per day and was maintained for about 3 weeks’ (Spencer and Miller, 2002).

4. Parametric descriptions of individual reproductive patterns

4.1. Three stages in the adult life history

Parameterisation is an inevitable stage in quantitative analysis of any experimental data. The simplest technique to parameterise age-related reproduction at a population level is a usage of simple heuristic indicators like early or late fecundity. Müller et al. (2001) made the only parameterised description of individual age-related fecundity known to the authors.

As for individual fecundity, the obvious obstacle for parameterisation is an extremely high degree of individual variability in daily egg scores. Our three-stage

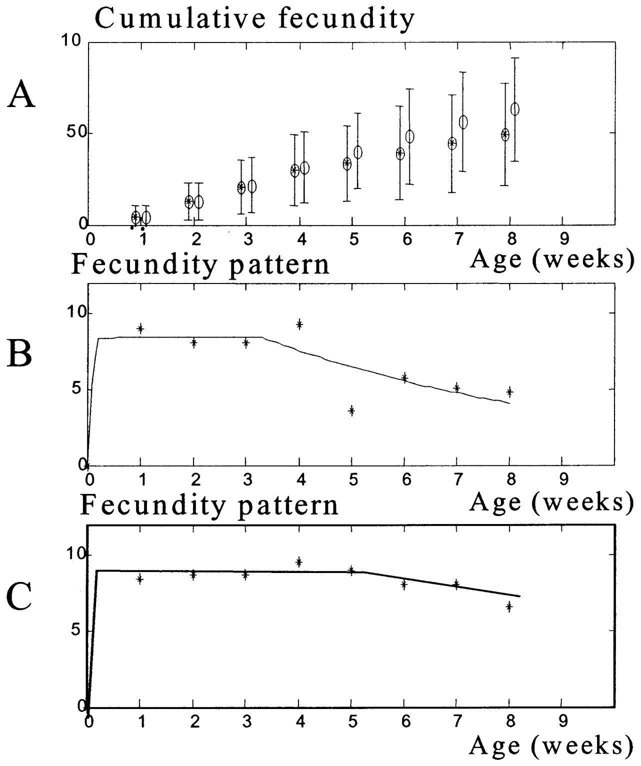

Fig. 4. Fecundity patterns in oriental fruit flies. (A) Cumulative egg production of females mated singly (closed circles, $N = 61$) and multiply (open circles, $N = 67$). Weakly mean±S.D. are given (Shelley, 2000). Weekly fecundity for singly mated (B) and multiply mated females (C) calculated from this data. Solid lines are for the least-mean-squared approximations of three-stage patterns.

presentation allows a stadial parameterisation of individual fecundity. A maturation stage may be characterised quantitatively by the two indicators, a duration (or the age when maturity is achieved) and an egg delivery rate to the ovaries. A maturity stage can also be described by a duration (i.e. the difference between the ages of the ‘onset of reproduction’ and the ‘onset of senescence’) and a value of reproductive capacity. To characterise mathematically a ‘tail’ stage, one may use an age of ‘onset of senescence’ and a time constant of the exponent of a reproductive decay. At this stage, an additional indicator may be used, a duration of a post-reproductive period.

These indicators are not independent. For example, knowing the maturation stage duration and the rate of follicle delivery to the ovaries allows us to calculate the steady-state rate of egg production. That is why we have analysed various combinations of indicators to develop a shortlist of only five parameters for a fly. The list includes four parameters for reproductive life history (the onset of reproduction X_{onset}, RC, duration of maturity stage T, and the senescence time constant τ_{tail}), and the fifth one for an individual life span, LS. A typical life history pattern parameterised with the proposed technique is presented in Fig. 6.

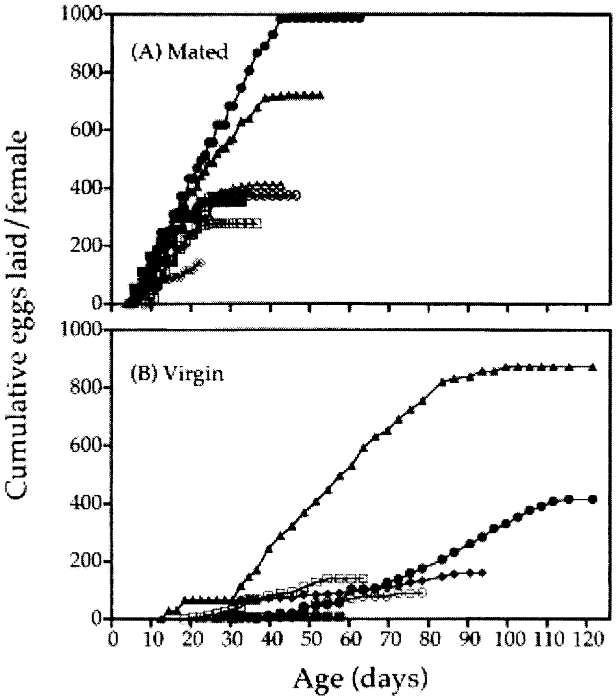

Fig. 5. Cumulative eggs laid over a lifetime by eight individual female mated (A) or virgin (B) onion flies *D. antiqua* (Spencer and Miller, 2002). A linear increase indicates that the individual fecundity patterns at these ages are step-wise ones with a constant rate of egg production, which differs in individual flies.

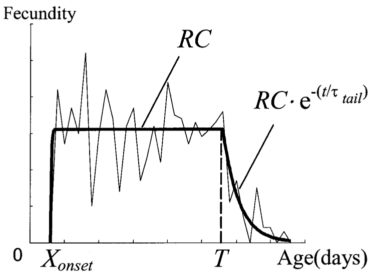

Fig. 6. Parameterisation of a typical individual life history in a female medfly. Fly #17 is presented from the study by courtesy of Blay and Yuval (1999). We associate this fly with a standard fecundity pattern shown in the figure with a thick solid line. The pattern has the following parameters: $RC = 31.1$, $X_{onset} = 3.0$, $T = 25.0$, and $\tau_{tail} =$ 2.35. In the exponent, $t = x - T - X_{onset}$. Death occurs at day 38. The onset of reproduction follows the last day without egg-laying.

4.2. *Averaging masks and deforms individual fecundity patterns*

It can be shown that the averaging usually used in experimental studies masks individual egg-laying scores in the flies. A schematic example is presented in Fig. 7. In this figure we take a three-stage pattern of fecundity and randomly scatter its parameters. Then we average the scattered curves to produce a ‘mean-population’ pattern of fecundity with a distinct maximum. The reason why the maximum arose is that the population

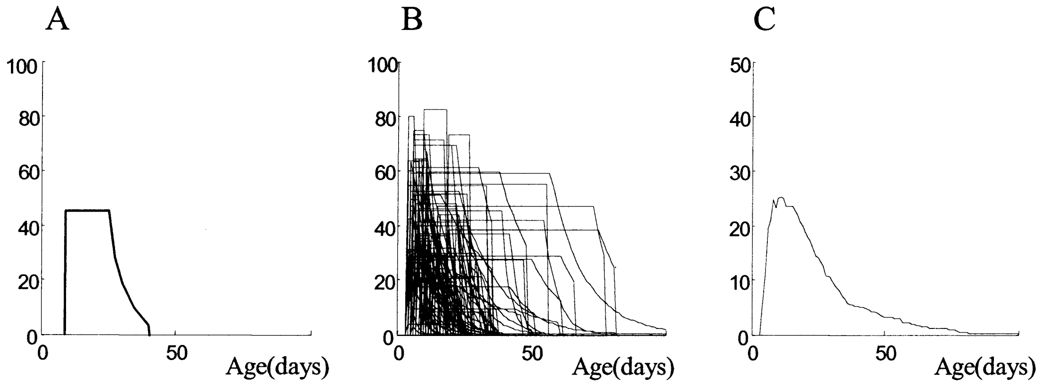

Fig. 7. Mean-population averaging deforms an individual fecundity pattern. (A) A typical individual fecundity pattern in a fruit fly. Life span = 37.0, $X_{onset} = 6.0$, plateau length $T = 14.0$, $\tau_{tail} = 8.0$, and a duration of senescence period $(LS - T - X_{onset}) = 17$ days. Reproductive capacity, $RC = 45.0$ eggs per day. (B) Individual fecundity patterns of flies in a population ($N = 100$) depicted together. To represent individual variability, a plateau level RC is assumed to be a Gaussian random variable with parameters 45.0 and 18.0. The values X_{onset}, T, τ_{tail} and a senescence period $SP = (LS - T - X_{onset})$ all are the random variables distributed exponentially with the corresponding parameters 5.0, 13.0, 7.0 and 16.0. A constant time delay *in* X_{onset} is 3.0. (C) The averaged daily fecundity for the population. A maximum in daily egg production (26.1 egg per day) is achieved at day 10.

has the essential variance of the onset of reproduction and the maturity stage.

Thus we predict that the averaging of experimental individual fecundity patterns, each having a flat summit, may yield a deformed and widened mean-population pattern with a distinct maximum egg-laying figure. This means that the maximum of fecundity usually observed in experimental studies is an artefact caused by averaging. A typical example of such a deformation is presented in Fig. 8. Only few exceptions from the rule, i.e. a flat plateau is seen in an averaged pattern of fecundity, can be found in the published data. These cases are mostly related to 'very stable' populations (as presented in Figs. 4 and 5 above). The other example is a population of *D. subobscura* ($N = 41$) where mean fecundity data were essentially greater than the S.E. values (Aigaki and Ohba, 1984; data of table 2).

Our observation—that a degree of distortion of the individual fecundity pattern in commonly used averaged presentations strongly depends on the ratio mean value/variance—is of special interest. Such analysis, however, is outside the scope of this paper.

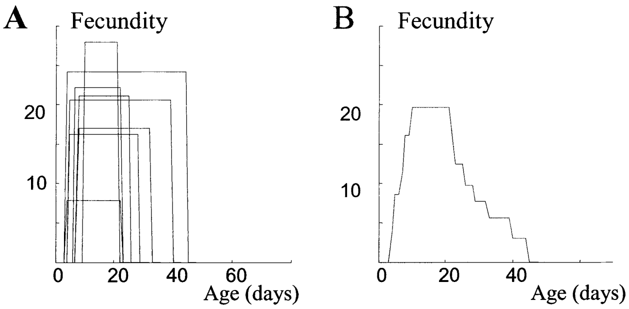

Fig. 8. Individual and averaged fecundity in a population of onion flies *D. antiqua* ($N = 8$; Spencer and Miller, 2002). (A) Individual patterns experimentally observed in eight flies shown in Fig. 4A. (B) Mean-cohort fecundity data calculated for the same cohort by averaging the results from (A).

5. Individual life history in a female fly

5.1. The tree of energy allocation forms life history

In terms of energy, the life history of an adult fly depends on which resource is acquitted at the developmental stage and how it is allocated between reproduction and maintenance (Gadgil and Bossert, 1970; Reznick, 1985; Reznick et al., 2000).

Essential traits related to reproduction and maintenance may be analysed in different forms. We used terms of power requirements, which were effectively applied to analyse fitness and trade-offs in different species. Brown and colleagues defined fitness in terms of reproductive power, i.e. the rate of conversion of energy into offspring, as follows.

> "An energetic definition of fitness has the potential to unify areas of ecology and evolutionary biology that have previously used models based on different currencies."

(Brown et al., 1993).

Each physiological function in an organism may be regarded as a two-faced issue having material and energetic ingredients. For example, Marden (2000) studied this property in respect to flight muscles and stressed that the flight system "is energetically and materially expensive to build and maintain". During the past decade a number of optimisation models were presented, which describe energy allocation and trade-offs. It was hypothesised that the N variables describing the energy investments into various functions are genetically determined at various nodes in the decision tree (van Noordwijk and de Jong, 1986; de Jong, 1993). Different versions of the standard 'Y allocation tree' were used in this analysis (de Jong and van Noordwijk, 1992; de Jong, 1993). This approach was applied in the analysis of positive versus negative correlations between traits that comprise functional trade-offs (for a review see Zera and Harshman, 2001). We hypothesise that the life history of a female fly is genetically formed using a multilevel decision tree as shown schematically in Fig. 9.

The basal partition of energy is made in the root node N0. One energy flux is invested in the whole-organism basal homeostatic branch and the other is channelled to the other parts of the tree. It is in this second part that functional organs are created. At the next level (N1 node) this energy is divided between soma and gonads. Each of these branches is then twinned into the structural and maintaining parts (in N2 nodes). This representation distinguishes soma and ovaries as independent systems in relation to reproduction (Markow, 1996). For example, male-derived products in *Drosophila* females 'exhibit uptake into soma than into ovaries';—she writes (Markow, 1996).

The N0 node is the most enigmatic. It seems as though resource partition at such a deep level was discussed only in plant physiology where resource allocation between 'organs' and 'maintaining respiration' was studied (Kiniry, 1993). Kiniry has found that in shaded wheat plants 15–68% of the total non-structural carbohydrates were consumed by maintenance respiration. An attempt was made to simulate 'the loss of resources' by maintenance respiration in relation to a wider range of organisms, but no relation to experimental studies was made (Sakai and Harada, 2001).

Each functional system (flight, reproduction, vision etc.) in accordance with the scheme in Fig. 9 has its own functional machinery supported with the function-specified energetics. Thus the events in each physiological system have their own 'life history'. A steady state is kept in each system until its maintaining resource is sufficient to sustain its functional activity at an endowed rate. Functional senescence arises when the energy balance is destroyed and the ability to maintain the steady state fails.

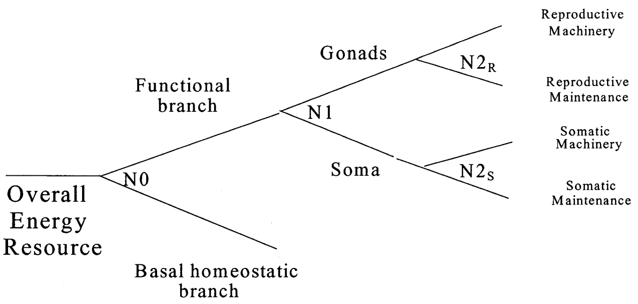

Fig. 9. Y-allocation tree forms a life history of a female fly. At the first step (N0 node) the overall resource is allocated between an organism's functional organisation and basal homeostatic mechanisms. The functional branch then divided (N1 node) for Gonads (reproduction system) and Soma (other functional systems including the flight muscles and the eye system). At the following step ($N2_R$ node) the gonadic resource is allocated between egg-production machinery and its metabolic support, whereas the somatic resources are parted in node $N2_S$ for creating and supporting different somatic structures. Each structure is supported with its own maintaining resources.

The scheme in Fig. 9 indicates that the energetic balances in an organism are dual. The lower-level balance is an inner property of each functional system. It controls when specific functioning starts, at what level it proceeds and when it decays. In particular, when the flight capacity is emptied, the fly stops flying. When the resource in the reproduction system is exhausted, the reproductive machinery becomes suppressed.

Energetically, the functional systems of an organism jointly form a whole-organism demand. This demand is age-related, as different activities vary during a lifetime. The demand must be met by the whole-organism homeostatic energy resource, which has been created at the N0 root. Generally speaking,

> "Design of metabolic flux capacities at the biochemical level can only be meaningfully considered in the context of… maximum physiological requirements at the level of the whole organism"

(Suarez, 1996).

The root-level balance compares the overall power demand and the basal maintaining resource. Death occurs when the demand becomes greater than the maintaining resource and when the balance is destroyed. In this case, the whole-organism maintaining resource is exhausted.

A number of experimental findings may be seen as widely supporting this Y-allocation scheme, especially in relation to gonadic properties.

Tight linear scaling of ovary volume to body size was found by Bonduriansky and Brooks (1999), suggesting the existence of 'common physiological constraints on relative ovary mass'. This means that the node N1 may represent an independent level of branching with a constant partition coefficient. Egg size was nearly constant within each of the seven Diptera species, whereas the egg number increased with body size, presumably by a manifest species-specific stabilising mechanism on egg size.

When body size was manipulated by nutritional deprivation of larvae, a proportional reduction in the ovariole number and egg production was observed (Robertson, 1957). This early result reveals the N0–N1–$N2_R$ path in the decision tree. However, a lowered energy flux forwarded to the reproduction branch N1 had no influence on the number of eggs produced per ovariole, thus demonstrating the independence of energy branching in the $N2_R$ node.

The postponed senescence lines of *D. melanogaster* (O-flies) were studied with respect to oocyte maturation and ovariole number (Carlson et al., 1998). It was found that in these flies, early fecundity was reduced and oocyte maturation delayed, suggesting a lowering of the resource allocated to reproduction in the N1 node. Simultaneously, the number of ovarioles did not decrease, showing that there is no correlation between the responses in the N1 and $N2_R$ nodes. Thus, these nodes may be thought of as independent.

The essence of the above analysis is that the reproductive-related traits are formed in the nodes located downward the root energy allocation node N0. This suggests that no direct correlations must be expected between longevity and the reproduction-related traits of an individual life history. This finding is widely supported by a number of observations in different species of flies. An analysis of correlations between longevity and reproduction in *Drosophila virilis* shows that 'reproductive activity does not correlate simply with lifespan in individual flies' (Aigaki and Ohba, 1984). In their study on medflies, Blay and Yuval (1999) concluded that size (and the overall energy resource) 'determines the reproductive potential of the female, but when females attempt to realise this potential, other factors override the effect of size'. And thus at last, it was suggested that 'longevity and egg-laying can be decoupled' (Carey et al., 1998a).

5.2. Premature deaths in female flies and bimodal death time distribution

A novel understanding of the interplay between the age-related power demand and supply allows hypothesising about a mechanism, which would determine the causes of death in an individual fly. In any case, death occurs at the critical point when the whole-organism power demand can not be met by the power supply. Generally speaking, such a crisis arises in an organism twice. The first crisis arises at early ages, when flies with the smallest inherited power resources may die at the maturation stage. When at these ages the power demand drastically increases due to initiated egg production in germarium, the available homeostatic resource can turn out to be smaller than the demand. Premature death will occur in this case. If the crisis is over, the fly enjoys a steady state period of reproduction until the second critical period arises, which ends with a senescence-caused death. Some flies may have both an insufficient supply and an insufficient demand. These flies die from senescence at advanced ages. Thus death time distribution for 'weak' flies is predicted to be bimodal (Fig. 10).

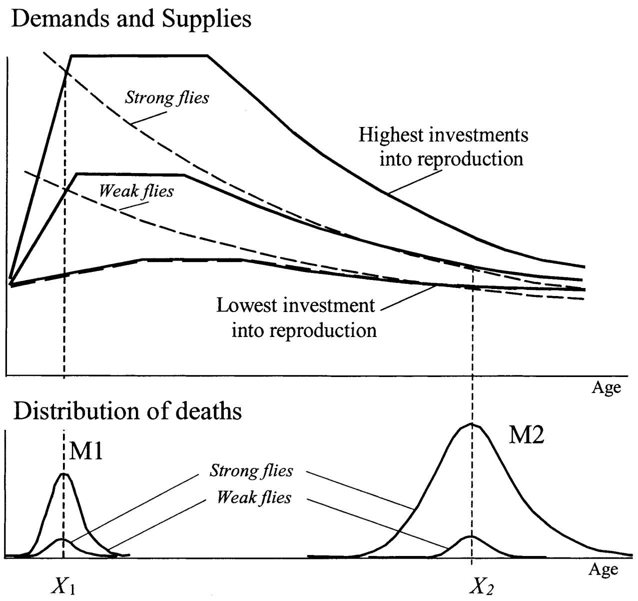

Fig. 10. Predicted premature deaths in female flies. Two groups of flies-strong and weak- are shown with age-related trajectories of the power supply represented with thin dashed lines. The solid-line patterns represent age-related individual power demands endowed for the highest-to-lowest levels of egg production. The demand/supply intersection points define the ages of death. Weak flies mostly die early, thus forming the M1 mode of the death distribution curve around age X_1, whereas the strong flies die around age X_2, at the M2 mode. Normally, the flies suffer senescence-caused death, but in the case of overly endowed rates of egg production, death may occur prematurely. A bimodal distribution of deaths arises, with M1 mode corresponding to premature deaths, and M2, to senescence-caused ones.

A similar bimodal death time distribution may be predicted for 'strong' flies. Normally, they die from senescence, but in cases of extremely high rates of egg production, death can occur prematurely. Individual variability scatters individual deaths over these critical periods, predicting two 'waves of mortality' in a female fly population.

Novoseltsev et al. (2002) show that evolutionary optimality yields a life history in which a fecundity pattern nearly entirely corresponds to the senescence stage in our classification. This means that under optimal resource allocation, death of individual females usually occurs at some age located along the final part of the fecundity tail. Experimental data mainly supports this finding. In *D. virilis*, for example, the reproductive period occupied about 60% of the total life span (Aigaki and Ohba, 1984). In medflies, this figure can be evaluated as a percentage of eggs laid by a fly during senescence, which is as high as 88.9% (Carey et al., 1998a). Thus, in laboratory populations a majority of flies die from senescence.

However, a small proportion of deaths might be accounted for reproduction-caused ones. Indeed, about 3–6% of flies in various species are non-egg layers. In onion flies, one female out of 70 mated flies and 6 out of 70 virgin ones never produced eggs (Spencer and Miller, 2002). In oriental fruit flies, 3–6% of flies failed to lay any eggs (Shelley, 2000). These observations may be conferred with 64 non-egg layers in a 1000-fly population of female medflies (Carey et al., 1998a). Most all of these flies die at early ages and probably do not suffer senescence, thus reproductive-related events may be thought of as a cause of their death.

As a result, ‘death due to ageing and age-associated changes in reproductive activity can be considered as under the control of different physiological processes’ (Aigaki and Ohba, 1984).

The flies, which lay no eggs during their lifetime, are usually excluded from a fecundity analysis. Carey et al. (1998a) were the first to analyse age-specific mortality rates in such females (Fig. 11). A bimodal death time distribution exists only for non-egg-layers, which are obviously the weakest group in the population. However, one can assume that a ‘premature death’ group was also present in the egg-laying part of the population, but was too small to produce a noticeable peak of mortality at early ages.

6. Discussion and perspectives

Age-related fecundity is one of the important components of an individual life history. To analyse it, averages of population egg-laying patterns were traditionally used. Such a pattern has a distinct maximum located some days after the onset of reproduction followed by the exponential decrease in egg-laying. This form of description was also used in the cases in which fecundity was studied individually (Carey et al., 1998a, Carey et al., 1998b; Blay and Yuval, 1999; Müller et al., 2001).

We show that it is possible to represent the individual trajectory of egg-laying in the life history of adult females by the following three stages: maturation, maturity, and senescence. At maturation, a fly laid no eggs. Then the egg-laying activity abruptly comes up to its steady state until the onset of reproductive senescence arises with the exponentially decreasing fecundity tail. Thus, an individual fecundity pattern of a fly has no maximum, demonstrating a presumably constant rate of egg-laying during a relatively long period of time.

Fig. 11. Distributions of deaths in a 1000-fly population of medfly females observed for egg-layers and non-egg layers (modified from Carey et al., 1998a). The dashed line is for a bimodal distribution with two maximums of adult age, one of about 10 days, and the other of about 30 days (non-egg layers, $N = 64$). The solid line represents a unimodal distribution of deaths for egg laying flies with the same location of the maximum as the second one in non-egg layers ($N = 936$).

Such a pattern is seldom found in experimental studies and was never observed in *Drosophila* and Medfly. In these flies, egg-laying scores are random and very different in their form. Physiologically they are organised into ‘salvos’, which is clearly seen, e.g. in Fig. 6 in the paper. Insufficiency in reproductive resources may often result in false starts, i.e. short blow-outs of egg-laying that precede the main body of eggs, and in numerous zero-egg days during a fly’s life time. The arbitrary character of the individual patterns arises due to many factors, which may influence the inconstancy of a fecundity pattern. In particular, the number of matings and the level of sperm storage seem to be important. Ages at which flies reach reproductive maturity vary drastically for different individual flies. For example, *Drosophila* females reach maturity at anytime from 1 to 21 days (Markow, 1996).

The egg maturation process is also affected by dietary factors, which yield instability in the resultant fecundity patterns. ‘The supply of nutrients places an important constraint on the output of eggs’ (Markow, 1996). In particular, nutrition strongly affects the parameters of the individual patterns in the Medfly experiments (Carey et al., 1998b). A flat averaged pattern of fecundity was developed when the flies were fed with sugar until day 60 or 90 and thereafter fed protein additionally. The probable cause of the phenomenon is that these long-living flies are ‘slow’ in egg-laying and thus in providing ‘long’ individual fecundity patterns. A small variance in the duration of a constant fecundity phase in individuals in respect to the mean value may result in a ‘flat’ mean-population pattern.

The individual form of a pattern proved to be useful in analysing the causes of death in flies. In particular, early reproduction-related deaths persist in evolution because they may represent the minimum noise level in the organism’s signal transduction system, which underlies the organism’s energy allocation into different components. This may come via the mechanisms described by Elowitz et al. (2002) and Swain et al. (2002). These authors suppose that ‘intrinsic’ and ‘extrinsic’ noises are responsible for the phenotypic variation. The heterogeneity in individual fecundity in this study is treated analogously, due to the Gaussian noise in a plateau level and the exponentially distributed noise in the other parameters (see Fig. 7).

What other results may be awaited when the individual pattern is applied?

The parametric description itself is a powerful tool of investigation. We anticipate that individual fecundity patterns will find a field of application in analysing different life history traits and trade-offs, including reproductive and mortality costs. For example, the trade-off may be described in terms of reproductive effort (Williams, 1966). It represents the resources that are allocated to the current reproductive events, whereas residual reproductive value describes what is saved for the future. Thus our reproductive capacity may serve as a measure of the reproductive effort whereas the duration of the maturity phase and the time constant of the tail may be used to measure residual reproductive value. Trade-offs may be evaluated by the comparison of these values. As no trade-offs between reproduction and fecundity were found in Medflies by Müller et al. (2001), the problem arises: is it possible to find them out by using the parameterisation as suggested in this paper? To answer this question, one needs to apply the three-stage description to large populations of flies, for example, to a 1000-fly population of Medflies (Carey et al., 1998a).

Experimental studies on artificial selection devoted to postponed senescence, reproduction at a 'young' or an 'old' age, and high or low adult mortality present the other field of application. In particular, the researchers use 'early' or 'late' fecundity indices to describe the changes in the fecundity of the experimental population. In our view, it would be cleverer to use individual indicators in these cases. Indeed, early fecundity could be associated with the onset of reproduction and reproductive capacity, whereas late fecundity could be associated with the duration of the maturity stage and especially with the tail time constant.

In the paper, the individual fecundity patterns are parameterised with five parameters. In principle, more complicated descriptions are also possible, but the five parameters are enough to grasp the three main stages, thus, admitting the usage of the description in different studies. Of special interest is the exponential tail of the pattern, which allows us to view ageing in flies as related to the classical problem of vitality decline (Strehler and Mildwan, 1960; Rose, 1991; Novoseltsev et al., submitted for publication, J. Gerontol.).

This approach opens a new avenue in the studies of genetic aspects of fecundity. Each parameter involved in a description of the individual fecundity pattern may be genetically endowed. To test this, hypothesis-specific genetic analysis is needed. This analysis can be performed in a similar way to that utilised in genetic studies of life span (Curtsinger et al., 1995; Mylnikov and Smirnova, 1997).

The specificity of this approach is that we describe the accumulation of oxidative damage as a factor directly affecting the homeostatic capacity of an individual. Thus the approach can be called a homeostenotic modelling of ageing. This emphasises its close relation to homeostenosis, a fundamental notion of the biogerontology and physiology of ageing: a progressive decline in the capacity to maintain homeostasis in the face of challenges in each system of an organism (Troncale, 1996).

This model can be applied to the data on different regimes of diet and reproduction (Carey et al., 1998b). Although this work was not possible to perform in the framework of this study one may speculate which model parameters may respond to changes in these factors. We expect that changes in both dietary conditions and reproductive output will modulate the rate of decline in homeostatic capacity (relative rate of individual aging) described by index $R(t)$ in Eq. (2). Dietary conditions are likely to influence the rate of decline in fecundity with age. The host deprivation in medflies (which prevents egg-laying) in case of ad lib food is likely to decrease $R(t)$ and hence increase the mean and maximum life span in respective population of medflies. Analysis of such changes in model parameters may help to better understand the mechanism of trade-off connecting aging and reproduction in fruit flies.

Trade-offs play an essential role in evolutionary approach to ageing (Sgró and Partridge, 1999; Kirkwood, 2002). In general, the relative importance of an energetic mechanism is 'a central unresolved issue in trade-off physiology' (Zera and Harshman, 2001). The individual pattern of fecundity in a fly has a close relationship to the power allocation and trade-offs. The detailed analysis of how this pattern is formed and how it is linked to longevity will help researchers to better understand the insects' life history and shed light on the mechanisms of reproductive senescence and the occurrence of death.

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