1

Introduction

1.1 Synopsis

Death is part of life, and it can strike any time. The question is whether death necessarily becomes more likely as life proceeds. William D. Hamilton (1966), one of the leading biologists of the last century claimed that senescence is inevitable[1] because the force of selection declines with age, making later ages unimportant to evolution. Survival and reproduction are the key players in this game and they are the traits negatively affected when selection loosens its grip.

Since 1966 it has been dogma among gerontologists that a decline in physiological functioning with age, i.e. senescence, is an inherent, inescapable part of life. Humans inevitably grow old, which is probably why it seems so unlikely to us that other forms of life could escape senescence. Biologists, however, often observe that functioning improves as individuals develop. Therefore the idea of living beings that perform equally well or better over their life course until they eventually meet the Grim Reaper might not be so strange after all.

One major result of my article published in *PNAS* [11] is that no dogmatic statement can be made about the universality of senescence. By carefully studying Hamilton's work on the molding of senescence I show that Hamilton did not prove that senescence is unavoidable. He claimed that the force of selection must decrease with age for any

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[1] The word "aging" is often used instead of the narrower, more precise but less common word "senescence" to describe a decline in physiological functioning with age. Hence I chose to entitle this monograph "Inevitable aging?" instead of "Inevitable senescence?". Throughout the monograph, however, I make a clear distinction between aging and senescence: I use the term aging to refer to any kind of variation in functioning with age, for the better or worse, and reserve the term senescence for a deterioration in functioning.

conceivable organism. The weaker the force of selection, the more un-
favorable mutations might sneak in, constituting a mutational burden.
Contrary to his results, I point out that the force of selection can in-
crease with age and, in this case, will counteract mutational burden at
higher ages more strongly than at younger ages. The specific nature
of a mutational effect, i.e. whether a mutation affects mortality in an
additive or in a proportional way, determines the dynamics of the force
of selection with age.

Combining Hamilton's analysis with the concept of mutation– se-
lection balance and providing a critical analysis of theoretical issues
and empirical evidence, I strengthen the view that the age-patterns of
mortality and fertility are largely shaped by optimization rather than
by the accumulation of deleterious mutations. However, the question
of the impact of mutational burden vs. optimization is not yet closed.

Building on the insight that senescence is likely to be a byproduct of
an adaptive process, I developed simple state-dependent models, three
based on size and one on vitality.

The size-based models [200] show that negative senescence can be
an optimal life-history strategy. The trajectory of growth is a crucial
determinant in tipping the scale between senescence and sustenance. In-
determinate growers, i.e. species that exhibit a period of parallel growth
and reproduction as part of their life history, are likely candidates for
sustenant strategies, whereas senescence is expected for species that
stop growing at about the age of reproductive maturity.

A fundamental insight gained from the vitality-based optimization
approach, vitality being the size of an individual weighted by function-
ing, is the major importance of the costs of maintenance and growth for
the determination of senescence versus sustenance. The model shows
that a rich diversity of age-patterns of mortality can be optimal. Suste-
nance outperform senescence when maintenance costs are low. I show
that changes in intrinsic and extrinsic mortality can switch the life his-
tory between senescence and sustenance strategies if the level of costs
of reproduction and growth is not too high. The model is a step forward
in identifying the characteristics in a species that predict whether the
species follows a senescent or a non-senescent life history.

A further insight from the vitality model concerns a mortality para-
dox. Contrary to "Williams' Hypothesis" that species living under
more hazardous extrinsic conditions should exhibit faster senescence, I
show that an increasing extrinsic hazard could switch an optimal life
history from a senescent to a non-senescent one if maintenance costs
are low.

In all my models, optimal equilibrium is assumed, something that might never be reached in nature. The variability of the environment is neglected. Competition between individuals in a population and among populations as well as the resulting interdependent population dynamics are not taken into account. One might perhaps claim that I study evolution without evolution. I defend my approach with the argument that I wish to study whether and when senescence can be avoided by any conceivable organism. The idea is that if senescence is not inevitable and is only one of many options for the age-patterns of life in optimal equilibrium, then this is a hint that the real world may provide these options as well.

1.2 Background

1.2.1 Senescence – Paradox? – Inevitable?

Life is shaped by evolution as described by Darwin [48, p. 5]:

> "As many more individuals of each species are born than can possibly survive; and as, consequently, there is a frequently recurring struggle for existence, it follows that any being, if it vary however slightly in any manner profitable to itself, under the complex and sometimes varying conditions of life, will have a better chance of surviving, and thus be *naturally selected*. From the strong principle of inheritance, any selected variety will tend to propagate its new and modified form".

The key players in evolution are survival and reproduction. To reproduce you have to be alive, to be selected you need to reproduce more successfully than your competitors, and finally you have to transmit this ability to your offspring. Senescence is a process of decline in physiological functioning that results in a decrease in survival and/or reproduction with age. Therefore, senescence is an unfavorable process in the struggle for existence. The question arises: Why, then, could it evolve at all? Clearly, senescence did evolve – but did it evolve in all forms of life? This is the burning question I wish to answer from a theoretical perspective. Is senescence an inherent part of life or could it be that some species have escaped senescence?

William D. Hamilton wrote a very influential article in 1966 on "The moulding of senescence by natural selection," in which he claimed that senescence is inevitable. Hamilton states that "no life schedule, even under the most benign ecology imaginable, could escape my spectrum

of forces of senescence ... in the farthest reaches of almost any bizarre universe" [76, p. 90]. "[F]or organisms that reproduce repeatedly, senescence is to be expected as an inevitable consequence of the working of natural selection" [76, p. 109]. Did Hamilton really prove that senescence is inevitable? I will treat this question in Chaps. 2 and 3, and the answer is: No, he did not.

1.2.2 Evolutionary Theories of Senescence

Two main approaches have been developed to explain the evolution of senescence: The first approach assumes that senescence is due to a burden of deleterious mutations at later ages, whereas the second approach assumes that senescence is a negative byproduct of an adaptive process constrained by trade-offs. Both approaches hinge on the assumption that the force of selection declines with age. The force of selection is determined by differences in reproductive success. The larger the difference in reproductive success between two alternative variants of a trait, the stronger the force of selection on that trait. Reproductive success is determined by survival and reproduction. Consequently, the force of selection is determined by survival and reproduction.

Since death is certain, the number of survivors of a birth cohort declines with age. Medawar [126] conjectured that, because fewer and fewer individuals survive up to higher and higher ages, those ages matter less and less to life-time reproductive success, leading to a decline in the force of selection with age. Hamilton [75] thought he had proved that the force of selection must decline with age, but I will show later that, under some circumstances, the force of selection can increase with age.

Medawar [126] proposed the theory of mutation accumulation. Mutations occur recurrently. To the extent that reproduction or survival are in any way negatively affected, an individual carrying such a mutation will be at an evolutionary disadvantage relative to non-carriers of that mutation. Clearly, the force of selection would tend to wipe out deleterious mutations. However, as the force of selection peters out, bad mutations manage to creep in, being less and less strongly opposed by evolutionary forces. Medawar argues that the smaller the force of selection, the more mutations would accumulate.

Williams [212] proposed the theory of antagonistic pleiotropy after the basic idea was initially formulated by Medawar [126, p. 64]. Like the theory of mutation accumulation, Williams's approach is based on the precondition that the force of selection decreases with age. Genes are considered that have fitness enhancing effects earlier in life and

fitness depressing effects later in life. Because the force of selection decreases with age, the advantage early in life receives a much stronger weighting than the disadvantage late in life. Unlike the passive process underlying mutation accumulation, mutations are actively selected that imply a deleterious effect at older ages, since the balance between costs and benefits favors younger ages.

Note that the general idea underlying antagonistic pleiotropy is to actively balance linked traits that affect survival and reproduction in opposite ways. Genes with antagonistic and pleiotropic effects are a specific case of a trade-off affecting fitness. The general idea of trade-offs underlies the disposable soma theory proposed by Thomas Kirkwood [97, 98]. Kirkwood's approach is based on the observation that the critical part of an individual that must survive is the genetic code. The genetic code contains all information needed to ensure the persistence of a lineage. It is therefore economic to separate the germ cells from the rest of the body cells, the soma, and to protect only the germ line from the ubiquitous occurrence of damage. The soma merely serves as a vehicle for the genetic code to be transported over generations. Kirkwood conjectured that the costs required for the persistent repair of the soma is too high and evolution therefore trades off the protection of the germ line against senescence of the soma.

1.2.3 Measuring Senescence

Senescence can be defined as a decline in physiological functioning with age that negatively affects the ability to survive and/or to reproduce. There is, however, no generally agreed upon measure of senescence.

One approach to measure senescence is to look at the change in mortality with age. In this case, senescence corresponds to an increase in mortality with age. This is a simple and widely accepted working definition [56, p. 12].

Since mortality and fertility are closely linked, an ultimate measure of senescence should include both survival and reproduction. Partridge and Barton [149] suggest using reproductive value at age a to determine the state of senescence of an individual. Reproductive value captures the remaining reproductive contribution of an individual that is alive at age a. It was defined by Fisher [59] as

$$v(a) \; = \; \frac{e^{r\,a}}{l(a)} \; \int_a^\infty \; e^{-r\,x}\,l(x)\,m(x)\;dx \; . \qquad (1.1)$$

The survival function $l(x)$ indicates the probability of survival from birth (or conception) to age x and the maternity function $m(x)$ indi-

cates age-specific reproduction. Age-specific survival and reproduction are weighted by the population growth term e^{-rx}, which discounts future reproduction by the intrinsic rate of population increase r [94]. The integral sums up all reproductive contributions from age a onwards. Multiplication by $e^{ra}/l(a)$ accounts for the fact that the individual has already survived to age a.

Senescence in this framework corresponds to cases when reproductive value declines with age, i.e. the derivative of $v(a)$ given in (1.1) with respect to age is negative,

$$\frac{dv(a)}{da} < 0 \,. \tag{1.2}$$

Applying the product and chain rules from basic calculus yields

$$\frac{dv(a)}{da} = r \, \frac{e^{ra}}{l(a)} \int_a^\infty e^{-rx} \, l(x) \, m(x) \, dx \tag{1.3}$$

$$- \frac{e^{ra}}{l^2(a)} \frac{dl(a)}{da} \int_a^\infty e^{-rx} \, l(x) \, m(x) \, dx$$

$$- \frac{e^{ra}}{l(a)} e^{-ra} \, l(a) \, m(a) \; < \; 0 \,.$$

Note that the probability of survival to age a, $l(a)$, is determined by the age-trajectory of mortality $\mu(x)$ from age zero to age a through the relation

$$l(a) \; = \; e^{-\int_0^a \mu(x) \, dx} \,. \tag{1.4}$$

Thus, (1.3) can be simplified by substituting

$$\mu(a) \; = \; -\frac{\frac{dl(a)}{da}}{l(a)} \tag{1.5}$$

as well as substituting expression (1.1) for reproductive value, which leads to

$$\frac{dv(a)}{da} \; = \; r \, v(a) \, + \, \mu(a) \, v(a) \, - \, m(a) < 0 \,. \tag{1.6}$$

After rearranging it can be concluded that senescence occurs when

$$v(a) \; < \; \frac{m(a)}{\mu(a) + r} \,, \tag{1.7}$$

where $\mu(a) + r > 0$. Note that, if mortality and fertility do not change with age , i.e. $m(a) = m$ and $\mu(a) = \mu$, then – following from its definition in 1.1 – reproductive value is constant at the level

$$v(a) = \frac{m}{\mu + r} \qquad (1.8)$$

for all ages a. Conditions (1.7) and (1.8) imply that senescence occurs if reproductive value at age a is lower than it would be if both mortality and fertility remained constant from that age onwards. Clearly if mortality and fertility are constant, then the organism does not senesce. Condition (1.7) implies that at least one of the two fitness components is adversely affected, which is intuitively appealing.

The change in reproductive value with age accounts for both the change in mortality and fertility, which is a favorable argument for its use as a measure of senescence. However, reproductive value in general and condition (1.7) in particular take into account the whole remaining life history. It seems more reasonable that the state of senescence of an individual at a certain age interval should be determined by changes in mortality and fertility at that specific age interval alone without any knowledge about the future. Furthermore, note that the population growth rate r enters the measure of senescence if reproductive value is used to account for the senescent state of an individual. But why should the population growth rate influence the definition of senescence? This issue disappears under the optimal equilibrium assumption since $r = 0$.

An alternative definition of senescence can be derived that accounts only for changes in the state of an individual at the current age interval, determined by mortality and fertility. Senescence corresponds to cases where mortality increases while reproduction is constant or decreases with age. Senescence also occurs if mortality does not change with age but fertility decreases. On the other hand, no senescence is observed if mortality decreases or remains constant and fertility increases or remains constant.

If mortality and fertility both increase, or both decrease, one has to be careful. If, for instance, fertility increases but mortality increases even more, then the loss in survival outweighs the gain in reproduction. If, on the other hand, mortality decreases, say, at a rate of -2% but fertility decreases even more, say, at a rate of -4%, then the gain in survival is more than erased by the loss in reproduction, i.e. $-4\% < -2\%$. In sum, senescence depends on the change in mortality vs. the change in fertility.

Formally, this can be expressed by comparing the relative change in mortality with the relative change in fertility. Relative changes are used to produce comparable quantities with the same units; change per time. The relative change in mortality is given by

$$\frac{\frac{d\,\mu(a)}{da}}{\mu(a)} \equiv \acute{\mu}(a) \;, \tag{1.9}$$

where the change in mortality over age relative to the current level of mortality is denoted by the short hand notation $\acute{\mu}(a)$. The same holds analogously for fertility $m(a)$.

In general, senescence[2] pertains to cases when the relative change in mortality is greater than the relative change in fertility at age a, i.e.

$$\acute{\mu}(a) \;>\; \acute{m}(a) \;. \tag{1.10}$$

Table 1.1 summarizes the cases for senescence vs. non-senescence [3].

Table 1.1. Senescence or not

	$\acute{m}(a) > 0$	$\acute{m}(a) = 0$	$\acute{m}(a) < 0$
$\acute{\mu}(a) > 0$	sen if $\acute{\mu}(a) > \acute{m}(a)$ not if $\acute{\mu}(a) \leq \acute{m}(a)$	sen	sen
$\acute{\mu}(a) = 0$	not	not	sen
$\acute{\mu}(a) < 0$	not	not	sen if $\acute{\mu}(a) > \acute{m}(a)$ not if $\acute{\mu}(a) \leq \acute{m}(a)$

The burning question of my work is whether the lower "triangle" in Table 1.1 is filled with life. Are there life histories that lack senescence which have been evolutionarily more successful than life histories with senescence? The first step on the way to answering this question is to

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[2] Note that my definition of senescence is a demographic definition, i.e. on the level of changes in mortality and fertility. The definition of senescence as decline in physiological functioning (see [172]) pertains to the level of phenotypic traits. It is possible that some changes in physiology do not become apparent (at least not immediately) at the demographic level.

[3] Carey and colleagues [21] point out that mortality patterns of medflies fluctuate up and down with age, which would correspond to "alternating periods of positive and negative senescence. It is questionable whether it is helpful to define the word senescence in this way." I agree that short-term fluctuations in mortality may not indicate positive vs. negative senescence. Consequently, in defining senescence as in (1.10), it is important to consider changes in mortality and fertility over reasonable age intervals, which should be determined relative to a species' lifespan.

determine how to measure "fitness", i.e. the evolutionary success of a strategy.

1.2.4 Measuring Fitness

The notion "fitness" captures the reproductive success of a genotype. Reproductive success results in population growth. Fitness is therefore often measured by the intrinsic rate of population increase, r, which is implicitly defined by the Lotka Equation [179],

$$1 = \int_0^\infty e^{-r\,a}\, l(a)\, m(a)\, da \;. \tag{1.11}$$

From the beginning of life until the end, this integral sums up age-specific reproduction $m(a)$, which can only be realized if an individual is alive at age a, captured by $l(a)$. Furthermore, later-born offspring are discounted by population growth ($e^{-r\,a}$) because earlier-born offspring contribute relatively more to future generations. The value of r that uniquely satisfies this equation for given schedules of $l(a)$ and $m(a)$ is the intrinsic rate of population increase.

Another frequently used measure of fitness is the net reproduction rate, R, given by

$$R = \int_0^\infty l(a)\, m(a)\, da \;. \tag{1.12}$$

Note that R counts the number of offspring produced per lifetime, accounting for survival. This measure of fitness is appropriate when the population size does not change. Otherwise, the intrinsic rate of population increase is more appropriate.

Both fitness measures hinge on the underlying assumptions of stable population theory. In his famous equation Lotka assumes a homogeneous population that is closed to migration. Either individuals are of one sex or individuals of only one sex determine r and R. Birth and death rates are constant over time and the environment is unchanging. There are no density effects. Intergenerational transfers such as parental care are neglected.

In the 1970s Charlesworth, building on Haldane [72] and Norton [141], justified the use of r as a fitness measure. The results of Charlesworth [24] show that in an age-structured, diploid, randomly mating population r can be associated with the fate of a rare, nonrecessive gene. In Charlesworth [25] he gives approximations that are otherwise necessary. A comprehensive treatment can be found in Charlesworth [27, Sect. 4.6.1].

The use of the intrinsic rate of population increase, r, is accepted as a reasonable working assumption [27, 28, 172] for cases of constant and density-independent environments, but one must be aware of its restrictions (see Chap. 6).

1.2.5 Optimal Life History

An optimal life history is captured by the age-trajectories of survival and reproduction that maximize fitness. Fitness can be measured by the intrinsic rate of population increase r and is determined by the schedules of survival and reproduction. In this context it is important to highlight that optimal life-history schedules depend on the level of r [69]. If a population grows quickly, later births are devalued heavily and therefore a short generation time are favored. This strategy might differ substantially from a strategy that maximizes fitness in a non-growing, stationary population.

In my work, I will assume a population that is in long-term optimal equilibrium. I will not consider the evolutionary process of getting there and I will exclude the possibility that an equilibrium might never be reached. This is a simplified but reasonable assumption because, on an evolutionary time scale, any small deviation from $r = 0$ will have strong consequences: *"...any being, if it vary however slightly in any manner profitable to itself, under the complex and sometimes varying conditions of life, will have a better chance of surviving, and thus be naturally selected."* [48, p. 5]. Many species have survived in essentially unchanged form for many generations: their life histories may be close to optimal. In any case, it is possible that some species are close to optimal equilibrium and it is of interest to study whether for such species senescence is inevitable. If it is, then this strengthens Hamilton's case. If it is not, this disproves Hamilton's claim that senescence is inevitable for any conceivable organism.

Taylor and colleagues [192] analytically proved that *"[m]aximizing the reproductive value at age zero is mathematically equivalent to maximizing the ultimate rate of increase"*. Here r is referred to as the ultimate rate of increase in order to emphasize that this is the rate to which a population's growth rate will ultimately converge [94]. Discussion of the theorem was raised by Caswell [22], who claimed that this would hold only under some very specific conditions. Yodzis [219] clarified the issue and showed that Taylor and colleagues [192] were generally right. However, he also pointed out the critical restrictions. First, maximizing the reproductive value gives only a local maximum of r. Second, the use of r as a fitness measure is an issue in itself. And third, the

consequences of population regulation mechanisms, such as predation and density effects, are not taken into account.

For $r = 0$ the reproductive value given in (1.1) at age $a = 0$ equals the net reproduction rate R given in (1.12), which is an alternative measure of fitness to r (see Sect. 1.2.4). Following the result of Taylor et al. [192] maximizing R is equivalent to maximizing r such that $r_{max} = 0$.

Maximizing life-time reproduction R with respect to any trait X can be formally expressed by the condition

$$\frac{d R}{d X} = 0 . \tag{1.13}$$

If trait X is independent of age and affects both survival, $l(a, X)$, and reproduction, $m(a, X)$, at various ages, then together with (1.12) this condition yields

$$\int_0^\infty \left(\frac{\partial l(a, X)}{\partial X} m(a, X) + \frac{\partial m(a, X)}{\partial X} l(a, X) \right) da = 0 . \tag{1.14}$$

Extracting the product $l(a, X) \, m(a, X)$ and using the shorthand notation

$$\frac{\frac{\partial l(a,X)}{\partial X}}{l(a, X)} \equiv \acute{l}_X(a, X) \tag{1.15}$$

for the relative change in survival with respect to trait X and an analogous notation for the relative change in reproduction, the condition can be expressed as

$$\int_0^\infty \left(\acute{l}_X(a, X) + \acute{m}_X(a, X) \right) l(a, X) \, m(a, X) \, da = 0 . \tag{1.16}$$

Finally, note that dividing by the life-time reproduction given in (1.12) yields the average value (indicated by the bar) of the relative change (indicated by the acute accent) in survival,

$$\frac{\int_0^\infty \acute{l}_X(a, X) \, l(a, X) \, m(a, X) \, da}{\int_0^\infty l(a, X) \, m(a, X) \, da} \equiv \bar{\acute{l}}(a, X) , \tag{1.17}$$

and analogously for reproduction. Consequently, Condition (1.13) is equivalent to

$$\bar{\acute{l}}_X(a, X) + \bar{\acute{m}}_X(a, X) = 0 . \tag{1.18}$$

The value of X that maximizes fitness corresponds to the point where the average relative change in survival plus the average relative change in reproduction with respect to trait X equals zero.

If trait $X(a)$ only affects survival and reproduction at a specific age a, i.e. $l(x, X(a))$ and $m(x, X(a))$, then (1.14) reduces to

$$\frac{d\,\mu(a,\,X(a))}{dX(a)}\,v(a) \;=\; \frac{d\,m(a,\,X(a))}{dX(a)} \;. \tag{1.19}$$

The value of $X(a)$ that maximizes fitness corresponds to the value where the change in mortality $\mu(a, X(a))$ with respect to trait $X(a)$ at age a times the reproductive value $v(a)$ at age a equals the change in reproduction $m(a, X(a))$ with respect to the trait at age a.

There are alternative ways to find the optimal schedule for a trait. Being optimal implies achieving the best life history strategy over the entire lifespan, which is equivalent to doing this at every age. Since the future does not influence the past, the optimal strategy at every age is to maximize

$$current\ reproduction\ + \tag{1.20}$$
$$survival\ to\ next\ age\ \cdot\ remaining\ reproduction$$

assuming the individual is alive at that age. Maximizing this quantity is equivalent to maximizing the current reproductive value given by (1.1), which can be seen using the discrete-time formulation

$$v_a \;=\; \frac{e^{r\,a}}{l_a}\sum_{i=a}^{\infty} e^{-r\,i}\,l_i\,m_i \;. \tag{1.21}$$

Extracting the first term from the sum yields

$$v_a \;=\; m_a \;+\; \frac{e^{r\,a}}{l_a}\sum_{i=a+1}^{\infty} e^{-r\,i}\,l_i\,m_i \;.$$

Multiplying the sum by a factor of $1 = l_{a+1}e^r\,/\,l_{a+1}\,e^r$ and letting $p(a)$ be the probability of surviving from age a to $a+1$, $p(a) = l(a+1)\,/\,l(a)$, the nature of the general life history trade-off becomes apparent:

$$v_a \;=\; m_a \;+\; p(a)\,e^{-r}\,v_{a+1} \;. \tag{1.22}$$

The first term captures the profits obtained from current reproduction, m_a. The second term captures the future prospects. The future prospects depend on the chance of getting there, i.e. surviving the age interval ($p(a)$, discounted by population growth e^{-r}) and future reproductive potential, which is reproductive value v_{a+1} at the next age (see [27, Chap. 5] for review).

Current reproduction trades off with future survival and reproduction. On the one hand, this trade-off could be due to a direct negative effect of reproduction on survival. Mating activities, for instance, could be risky. Also, reproduction could cause damage that negatively affects future breeding attempts. Whereas this direct negative effect is not necessarily observed in all species, a negative indirect link becomes apparent if survival and reproduction are understood as distinct processes that compete for limited resources.

Schaffer [176] stated that the *general life-history problem* is to allocate restricted resources between survival and reproduction in a way that maximizes an individual's fitness. To approach this problem Williams [213] introduced the reproductive effort model, where reproductive effort is defined as the fraction of energy devoted to reproduction. Williams [213] conjectured that, at every age, resources are allocated to maximize the remaining reproductive contribution of an individual that already survived to that age, i.e. the reproductive value. From Bellman's principle (see [12] and Sect. 4.3 of this manuscript) we know that maximizing reproductive value at every age is equivalent to maximizing reproductive value at age zero. In that way Williams [213] anticipated Taylor et al.'s [192] result that "*[m]aximizing the reproductive value at age zero is mathematically equivalent to maximizing the ultimate rate of increase*". Extensive treatments of the evolution of optimal life histories can be found in [186] and [169].

I want to emphasize how reproductive value emerges again and again as an important quantity. Not only was it proposed as a measure of senescence [149] – it was also proved to be a measure of fitness [192] and a central quantity for solving the general life-history problem [213].

1.2.6 Interesting Recent Developments

In Chaps. 4 and 5, I will develop models to explain the evolution of senescence that focus on the age-patterns of mortality, fertility and growth using the concepts outlined above. Reproductive-effort models were developed in the 1970s to understand when iteroparity (repeated breeding) is favored over semelparity (single breeding event, in which reproduction is fatal) (see [62], [175] and [31]). The shape of the age-trajectory of mortality itself attracted little interest. Instead, mortality was assumed to follow a particular pattern, for example to be constant, to be stepwise constant (distinguishing only between a juvenile and an adult period) or to follow an exponential pattern.

Some recent models of the evolution of senescence, however, do focus on the age-trajectory of mortality in conjunction with age-trajectories

of growth, reproduction and transfers. These models draw heavily on the concept of allocation of restricted resources and on dynamic optimization techniques (see [12] and Sect. 4.3).

Abrams and Ludwig [5] develop a theoretical model based on the disposable soma theory [97] and find that many different mortality trajectories can be optimal, an exponential increase being only one possible outcome. The model, however, does not allow for a decline in mortality with age.

Mangel and Bonsall [120] also show that a diversity of optimal mortality trajectories is possible when mortality is viewed as a result of multiple physiological processes as well as when mortality is the consequence of growth and metabolism and associated damage. In their model, mortality can decrease over some ages before it ultimately increases. Another recent model by Mangel and Munch [121] that focuses on compensatory growth derives mortality as result of growth and damage. The approach taken by Mangel and colleagues shows that optimal age-patterns of mortality can decrease if mortality is, at least in part, determined by physiological state. They point out the importance of "reunifying the connections between the biology of aging and demography" [120, p. 357]. Munch and Mangel [131] recently showed that mortality can follow various patterns at juvenile ages.

Dynamic programming models that optimize resource allocation to growth, reproduction and repair of somatic damage based on the disposable soma theory of aging have been studied intensively by Kozlowski and Cichon [37, 38, 39, 102, 103]. Their models do not allow mortality to decline with age. Drenos and Kirkwood [52] also describe a mathematical model based on the disposable soma theory. In their model the optimal level of investment in repair is always less than that required for non-senescence.

An approach that explicitly questions when senescence can be escaped is given by Gardner and Mangel [64]. They develop a stage-based model and find that the strength of selection can, under some circumstances, increase with age for clonal organisms.

Travis [196] claims that, in a spatially structured population, a determinate lifespan can evolve with an optimal specific age of death, but in a freely mixing population with global dispersal evolution selects for individuals with ever-increasing lifespan. In a working paper, Doncaster and Seymour [50] demonstrate that ever-extending reproductive life can be optimal in populations with density regulated recruitment, e.g., in the case of Bristlecone Pines. If seeds can be established only on a

patch freed by the death of an adult, it pays to outlive your neighbors to ensure that your offspring can occupy the newly opened space.

Sozou and Seymour [183] show that mortality does not necessarily have to increase, i.e. that non-senescence can be locally optimal, if the potential onset of deterioration is sufficiently rapid or early. Interestingly, they find that "for all forms of profile considered, conditions can be found for which a strategy involving no ageing is locally optimal".

In a recent paper, Chu and Lee [36] study the conditions under which transfers from adult to offspring can be optimal. Applying dynamic optimization techniques and the idea of optimal resource allocation, they model the co-evolution of survival and transfers. A recent working paper by Robson and Kaplan [168] derive a dynamic optimization model for the evolution of the human mortality pattern incorporating investment in quantity and quality of somatic capital and a budget constraint that reflects intergenerational transfers. These models can explain why mortality declines during development and why evolution licences a substantial period of post-reproductive life in humans.

With the models I am going to develop, I will not be focusing on a single species such as humans. I wish to understand more generally under what conditions what pattern of mortality can be expected. In particular, I want to study if and when non-senescence can be optimal. My work is the first systematic attempt to find the characteristics that determine when senescence is optimal and when it is not. I will not focus on lifespan. A species with a short lifespan can still have a non-senescent life history. The length of life only reflects different time scales that different species live on. This would be a different question: When is it optimal to live on what time scale? Instead I ask: When is it optimal to live under what qualitative mortality pattern?

My modeling strategy is to exploit the power of focused simplicity. The models will be kept as simple as possible, including only necessary ingredients that are chosen based on my particular question.

1.3 Orientation

In the following two chapters I discuss Hamilton's paper on the molding of senescence [75], disproving his dogmatic claim that senescence is inevitable and pointing out deficiencies of Hamilton's framework. Given the theoretical issues and empirical evidence, I come to the conclusion that life histories are likely to be shaped largely by optimization rather than by a burden of deleterious mutations, at least over ages where the bulk of life-time reproduction is realized.

In the subsequent two chapters, I develop optimization models to determine the optimal pattern of survival and reproduction over the life course of a species. The models in Chap. 4 are based on the state-variable size. The Chapter makes the case for negative senescence, i.e. the models show that, theoretically, senescence is not an inherent part of life. The model in Chap. 5 is built around the state-variable "vitality" and takes into account and addresses some of the deficiencies of the size-based models. The vitality model demonstrates that the space of optimal life histories is wide and covers a broad range of senescent and non-senescent strategies.

The final chapter, Chap. 6, emphasizes the need to connect the world of mutation accumulation and the world of optimization. I also suggest directions for future research on the evolution of senescence.