**Beetle stuff**

**Arc et al. 2013. Antimicrobial secretions and social immunity in larval burying beetles, Nicrophorus vespilloides. *Animal Behaviour***

it is increasingly recognized that nonimmunological responses that reduce or mitigate host exposure to pathogens are key components of antimicrobial defences (Parker et al. 2011).

Social immunity forms an important part of the defence against pathogenic microorganisms in animal societies, and ranges from the collective efforts of several individuals in a social group to costly responses of individuals that are mounted to benefit others (Cotter & Kilner 2010).

parents maintain the carcass by depositing antimicrobial secretions on the carcass surface (Arce et al. 2012).

This parental form of social immunity peaks during brood rearing, is costly to parents and increases larval survival (Cotter & Kilner 2009; Hall et al. 2011; Steiger et al. 2011; Arce et al. 2012).

The lytic activity in larval secretions from whole broods declined over time

Larvae exposed to wild-type S. aureus cells had significantly higher mortality than larvae exposed to the PBS control, the S. aureus mutant or heat-killed bacterial cells

Our results provide the first evidence that larvae of the burying beetle N. vespilloides are active participants in their own defence against microbes

The highest antimicrobial activity in secretions was seen in the youngest larvae shortly after their arrival at the carcass

Parental investment in social immunity is known to be costly and to peak during brood rearing (Cotter et al. 2010; Arce et al. 2012). Thus, the parent’s optimal level of investment in social immunity might be lower than the optimal level from the offspring’s perspective.

**Bartlett, J. 1987. Filial cannibalism in burying beetles *Behavioural Ecology and Sociobiology* 21: 179-183**

In the case of *N. vespilloides,* brood reduction is shown here to be causedby adults killing and eating their own young duringthe normal raising of a brood

It is suggested that the consequent brood reduction can be interpreted as a means of optimising the eventual ratio of larvae to available carrion food.

*N. vespilloides,* the species used here, creates a burialchamber or crypt around the buried corpse andscatters its eggs up to several centimetres away

Both adults are normally present throughout larval development, feeding the young, repairing any damage to the chamber, and driving off insects which trespass on the crypt.

The number of *Nicrophorus* larvae a corpse can support increases with corpse size (Easton 1979; Wilson and Fudge 1984). However, the North American species *N. orbicollis* was found not to adjust its clutch size according to corpse size and to lay more eggs on a 15 g corpse than the corpse could support

Fifteen broods with a mean of thirty first stage larvae (to match the brood size found in the previous experiment) were created on 15 g mice by pooling the hatchlings of several families and dividing them between the mice.

experience suggested that adult *N. vespilloides* cannot recognise their own larvae and will raise a foster-brood,

Clutch size on 30 g mice is not significantly different from clutch size on 15 g mice, but subsequent survival of the brood is very different

On 15 g mice there is no significant difference between the mean number of eggs laid and the mean number of first stage larvae reaching the mouse but the difference between the mean number of first stage larvae and the mean number of larvae at dispersal shows that only about half of the larvae which reach a 15 g corpse are likely to complete development

significant fall in larval numbers between first and second instars but no significant mortality between second and third instars and up to dispersal

There was no mortality between first and second instars if the brood size was below about 15, but for broods larger than this numbers dropped sharply in the first 24 h on the mouse

In all the broods set up for observation the parents were seen to kill and eat first stage larvae

The main period of larval mortality on 10 g and 15 g corpses is at the first instar, during the first 24 h after the larvae have reached the corpse.

It is most unlikely that food is limiting at this time since only a small hole has been eaten in the skin of the mouse and the larvae have not begun to penetrate the

body.

Variable mortality of eggs or of hatchlings making their way to the corpse may explain why *Nicrophorus* lays many more eggs than are raised around a small corpse

or are bound by a physiological constraint such that they must lay a minimum clutch which is greater than the capacity of a small corpse.

In the laboratory N. *vespilloides* will lay 46.83\_+5.86 eggs on a 75 g corpse (n=18) and 18.44\_\_2.05eggs on a 5g corpse (n = 27), showing that some adjustment of egg number with clutch size is possible and that it is physiologically possible to lay a clutch smaller than the capacity of a 15 g corpse.

The strong relationship between brood size and mean larval weight at dispersal (Fig. 3) is found

even over a range of brood sizes less than that at which culling would be expected to occur

Intraspecific competition over corpses, the result of which is largely determined by body size (Wilson and Fudge 1984), means that small beetles have a greatly reduced chance of breeding

Small size also restricts the number of eggs a female can lay, both in a single episode on a large corpse and over several breeding attempts on a sequence of corpses

The adults cannot afford to let the members of an excessively large brood compete amongst themselves for the corpse and they therefore reduce the number by culling rather than by allowing some to starve

If filial cannibalism is to benefit *Nicrophorus* parents, then their total number of grandchildren must be greater, through the increased reproductive success of their surviving offspring, than it would have been through a larger brood of individually smaller young.

**Bartlett, J. 1988. Male mating success and paternal care in *Nicrophorus vespilloides* (Coleoptera: Silphidae). *Behavioural Ecology and Sociobiology* 23:297 303**

Burying beetles bury the corpses of vertebrates and use the carrion to feed their young.

If more than a single pair find the corpse, numbers are reduced by fighting, females with females, males with males (Pukowski 1933)

what is the benefit to those who help and are then driven away

Their larvae are fed with regurgitated carrion, they are defended from invertebrate predators, and any damage to the underground 'crypt' in which the corpse is buried is quickly repaired (Pukowski 1933).

In a fight the larger male could easily displace the smaller (unpublished observation).

A further sign was that males which were considered to have left were covered by a swarm of mites (carried by all burying beetles [Neumann 1943]) which had bred on the corpse and were now dispersing with the male. Males still in the crypt carry far fewer mites; most are still feeding on the corpse.

Small males, with little chance of winning another corpse, might stay more readily than larger males.

males tolerated one another on the corpse, signalled together in the evening and buried the corpse together overnight (if a female was then introduced, only the larger male and the female would later be found on the corpse).

often saw the smaller male mate with the female, although the larger male was the resident in the crypt. Once driven off, the loser stayed not far from the corpse and returned several times

The day on which males left the brood was not correlated with male pronotum width

nearly 80% of the males on the 5 g corpses had abandoned their broods by the fourth day and the rest were gone on the following day

The males from three of the 5 g broods were found dead. They had lost their antennae and one or more legs and had punctures along the abdomen. They had clearly been killed by the female with which they had been paired. Males only gradually left the 25 g broods, following the pattern usually seen for male care in broods used in other experiments. None of these males was found dead.

There was no significant difference in median lifespan between caring and non-caring males:

a single female seems to be able to feed a brood as efficiently as an adult pair.

males of any size seem always to stay until almost the end of larval development

**Bartlett and Ashworth, C.M. 1988. Brood size and fitness in Nicrophorus vespilloides (Coleoptera: Silphidae). *Behavioural Ecology and Sociobiology* 22:429-434**

Adult size usually affects fitness

The larvae of animals which lay their eggs on or around a discrete, limited resource compete with one an-other for the available food.

Eventual size is a product of this competition and so of larval numbers

Parents can therefore influence the size and eventual success of their offspring by adjusting the number of young they attempt to raise on a given resource. This effect has become well-known in many insect parasites, where an inverse relation-ship between brood size and mean size of brood members has been found (Klomp and Teerink 1967; Mitchell 1975; Dantharayana et al. 1982).

The absence of field data on breeding success in Nicrophorus limits any discussion of the implications of laboratory data on fitness

Field studies on the North Amer-ican species N. orbicollis and N. defodiens have shown that size is important in winning corpses (Wilson and Fudge 1984).

The corpse is enclosed in an underground chamber (the crypt) and eggs are scattered in the soil around it. The larvae develop on the corpse through three instars. They feed on the corpse and are also fed regurgitated carrion by their parents. The third instar larvae disperse from the corpse and pupate in individual chambers in the sur-rounding soil.

clutch size increases with corpse size up to 75 g but not beyond

In all cases in this experiment parents were caring for larvae from a mixture of broods. This does not affect breeding success (Bartlett 1987).

To make broods larger than fifteen, which normally would be culled, a different technique was used. Pairs of adults buried 30 g mice on the day before another set of adults buried 10 g mice. Once a brood of the required number of first stage larvae (20, 25 or 30) had arrived on the 30 g corpse these larvae and their parents were transferred with one of the buried 10 g mice to a new crypt in another box of compost.

In almost all cases beetles from larger size classes defeated those from smaller classes.

On 75g corpses, the mean clutch size for the large females was greater then that for the small females

using a sequence of 25g corpses, there was a strong relationship between female pronotum width and the total number of eggs laid

no corrleattion between protum width and longevity

Brood size therefore has an effect on mean larval weight at dispersal even on the larger mice, but the effect is much less marked than on smaller corpses

the smallest adults at ecosion have a relatively high size:weight ratio

In spite of culling on the 10 g mice, which reduced brood size compared with that on 30 g mice, and of the ability of small larvae to become relatively large adults, broods from 10 g mice still produce lighter and smaller adults than those from 30 g mice.

The reproductive success of Nicro-phorus is therefore likely to be limited by the chance of successfully finding and winning possession of a corpse (Springett 1967).

Winning corpses in this way depends largely on size. We have shown that size sometimes also affects repro-ductive ability once a corpse has been secured.

On 30 g mice the average brood raised is about 30. On 10 g mice the average brood is about 15. These brood sizes are not random, but the product of'decisions' at two levels, the clutch laid (Easton 1979; pers. obs.) and the extent of culling at the first larval instar (Bartlett 1987)

The advantage of increased size is clear, but why then do heavy larvae not also divert their resources into adult structure so as to become larger still? Only the lightest larvae adopt this course. There is a potential cost to sacrificing reserves to external structure. If there is a shortage of food at eclosion, the 'hollow' adults will suffer most. The result is compatible with the idea that there is a threshold adult size below which adults have very little chance of breeding because of the importance of size in settling the possession of corpses (Wilson and Fudge 1984)

adults eclosing from broods raised on 10 g mice are still smaller than those from broods on 30 g mice.

As further evidence that a 30 g corpse is not more than can be dealt with, clutches of 40-50 eggs can be laid on 75 g corpses in the laboratory

Reducing competition from mould is an important aspect of Nicrophorus pa-rental care (Halffter et al. 1983; Wilson and Fudge 1984).

Culling is necessary when a high proportion of eggs survive and produce larvae which reach the corpse

**Eggert, A. et al. 1998. Parental care improves offspring survival and growth in burying beetles**

Among invertebrates, however, parental care isrelatively infrequent

for most care-giving invertebrates,such studies are lacking or incomplete, including

one of the better-studied examples, the genus *Nicrophorus* (burying beetles).

under laboratory conditions, a male whose mate disappears from the carcass can raise a brood as successfully as a single female or a pair

Improved offspring survival or quality, or, in the case of male parental care, improved mating or fertilization success must offset these costs to maintain the parental investment pattern

At this temperature, female *N. vespilloides* typically begin to oviposit 8–24 h after theirfirst contact with the carcass (A. K. Eggert, M.Reinking & J. K. Mu¨ ller, unpublished data), andeggs take a mean of 56 h to develop (Mu¨ ller &Eggert 1990).

Larvae from other broods could be used because the beetles do not discriminate between their own and unrelated offspring except on the basis of temporal cues (Mu¨ ller & Eggert 1990).

posthatching care, which encompasses the creation of an opening in the carcass

Survival rates were much lower in broods without care than in broods that received care (Fig. 2a). Survival rates were similar among the groups that received parental care for at least 12 h (12, 24, 48 or 120 h; Fig. 2a).

The mean body mass of dispersing larvae continued to increase, however, with increasing durations of parental care beyond the first 12 h.

At about the time the first larvae appear on the carcass, the parents chew a hole in the skin of the carcass.

Multiple comparisons of the number of larvae surviving in different groups (Fig. 3a) revealed that more larvae survived on unprepared and prepared carcasses if they had an opening

Parents manipulate the larval food source in a way that maximizes larval survival and growth, including direct regurgitation of pre-digested carrion to the larvae, and they defend both larvae and carcass.

The first 12 h have the most profound effects on larval survival and growth, presumably because parents at this time create an opening within which larvae assemble and feed.

The location of the opening may also affect larval survival; in experiment 3, unprepared opened carcasses had a hole in the thigh, and the number of surviving larvae was significantly greater than on unprepared carcasses in experiment 1, which had a hole in the abdomen

Successful ‘orphaned’ broods in our experiments seemed to be broods in which larvae jointly fed at one particular site on the carcass, suggesting that the joint production of digestive enzymes, or use of mandibles, may facilitate access to the carrion for such broods.

As Pukowski herself noted, larvae raised in the absence of an adult take no longer to leave the carcass than do larvae receiving parental care

the manufacturing of an opening in the carcass surface and regurgitation to young currently do have positive effects on breeding success.

**Lock et al. 2007. Co-adaptation of prenatal and postnatal maternal effects**

Among insects, younger mothers tend to produce offspring that have greater juvenile survivorship (Hercus and Hoffmann 2000; Kern et al. 2001), greater longevity (Priest et al. 2002), and higher preadult performance (Fox 1993).

mother’s age at first reproduction profoundly affects offspring fitness in species from insects (Mousseau and Dingle 1991)

prenatal and postnatal maternal effects can be confounded in species with prolonged parental care because the quality of parental care can also depend on the age of the mother (Cameron et al. 2000; Clark et al. 2002; Weldji et al. 2006).

Thus, where there are trade-offs, such as might occur with age-related changes in egg quality, selection should favor the combination of pre- and postnatal maternal effects that maximizes fitness.

We hypothesized that there could be adaptive postnatal compensation of maternal effects because timing of reproduction may be unpredictable in species where resources required for reproduction are scarce and ephemeral and competition for these resources is intense

reproduction may occur at different ages because there is unpredictability in resources required for reproduction

Begging and direct provisioning is greatest during the first 48h, after which the larvae obtain food primarily by selffeeding (Smiseth et al. 2003).

The carcass is the sole food resource for the developing larvae. Parental care involves keeping the carcass free of fungus and bacteria with anal secretions as well as partially digesting the carcass and feeding the offspring directly (Smiseth and Moore 2004*a*).

Eggs were removed from the soil around the prepared carcass, hatched in petri dishes,

Six weeks represents approximately half or two-thirds of a breeding season in a year and, therefore, sufficient time for females to discover the necessary resources and a period well before reproductive senescence.

we therefore expect negative correlations between early and late maternal effects

Age at first reproduction influenced allocation of resources to eggs. Offspring from different-aged mothers had significantly different birth weights - with newborn offspring produced by females with delayed reproduction being significantly heavier than offspring produced by early-reproducing females

Age at first reproduction influenced maternal behaviour (fig. 1). Caretakers with delayed reproduction spent significantly more time in the cavity without feeding the offspring than did caretakers with early reproduction

Females with delayed reproduction spent more time provisioning the larvae (

in an average 6.6 days of feeding. There was no significant main effect on weight gain from birth to dispersal from the carcass.

Age of first reproduction also influenced the number of days offspring took to develop from egg to adulthood in a similar pattern (fig. 3*B*).

Offspring that were heavier at birth had higher survivorship. Individuals that gained more weight as larvae were also more likely to survive to adulthood

Mothers also prepare and tend to the carcass, and the quality of this maintenance behaviour may also influence developing young

Aging of mothers also correlates with a decrease in offspring performance (Mousseau and Dingle 1991; Fox 1993; Hercus and Hoffmann 2000; Kern et al. 2001; Priest et al. 2002).

This neglect is perhaps not surprising given that maternal effects have only recently been considered in studies of aging (Kern et al. 2001; Priest et al. 2002).

However, incorporating maternal effects into life-history theories of reproduction may be difficult, because there are few generalizations for the relationship between maternal age and offspring fitness. While there is a general trend for older mothers to produce offspring with lower fitness it is also possible that age-related declines can be ameliorated by “targeted reproductive effort” (Cameron et al. 2000).

**Muller, J.K., Eggert, A. and Furlkroger, E. 1990. Clutch Size Regulation in the Burying Beetle *Necrophorus vespilloides* Herbst (Coleoptera: Silphidae). *Journal of Insect Behaviour,* Vol. 3(2): 265-270**

The buried carcass is the only food source for the larvae; it can be totally consumed by the larvae from a single clutch.

it would be selectively advantageous for them to adapt the number of eggs laid to the weight of the available carcass

Therefore we define clutch size as the total number of eggs laid before the female's first larva has hatched.

Clutch size was positively correlated with carcass weight

In contrast to Bartlett and Ashworth's (1988) study and Wilson and Fudge's (1984) study on *N. orbicollis,* our results indicate no correlation between female body size and clutch

Figure 1 – clutch size against weight of carcass buried – **useful**

Even on very small carcasses, some offspring could be raised. In all cases (n = 13) females on 2-g mice did raise some offspring that survived to pupation, the mean number being 4.1 (SD = 1.3). In nine undisturbed broods on 5-g mice, a mean number of 8.8 adults survived to the adult stage

When females cared for 50 larvae on 25-g mice, the survival rate was high (median, 96%; range, 88-100%). This result shows that females are able to care for 50 larvae on 25-g carrion, a number considerably larger than average clutch size on carcasses of this weight

Our data show that the number of eggs laid by *Necrophorus* females increases with the weight of the available carcass up to a carcass weight of 10g.

if the number of larvae is too small, females produce replacement clutches, either while feeding their larvae or after their larvae have left the carcass to pupate (Mfiller, 1987).

*N. vespilloides* lay all the eggs they mature only if the corpse is greater than 10 g and stated that some eggs are retained in the ovary on smaller corpses

Moreover, it is questionable whether *N. vespilloides* actually utilizes 75-g carcasses for reproduction in the field

On large carcasses females laid fewer eggs per gram carrion than on smaller carcasses, since there was no further increase in clutch size on mice heavier than 10 g.

Another explanation for the observed behavior may be that production of more than 35 eggs increases female mortality, or reduces their future productivity, so that their lifetime fitness is reduced

**Pukowski, E. 1933. Ökologische Untersuchungen an *Necrophorus* F. *Zeitschrift fur Morphologie und Oekologie. der Tiere* 27(3): 518-586**

The striking instinct of gravediggers (Necrophorus fabricuis) to bury small animals was first reported by Gleditsch (1752)

The habitat of N. vespillo is meadowland, while humator and vespilloides are indigenous to woodland.

N. humator, N. vespillo and N. vespilloides appear at approximately the same time and also disappear to hibernate at the same time.

but as a rule, all species begin their hibernation around the beginning to middle of October

The gravediggers are pronounced dusk and night animals

If the environmental conditions are unfavorable for the beetles, e.g. strong sunlight, high temperature, extreme drought, narrowness of cage and lack of food, they are driven to the surface during the daytime. They then undertake rapid running around and continual attempts to escape in which they fly round wildly. These are however clear reactions to abnormal conditions.

Although these gravediggers were enticed through the smell to decomposing fungi, they were still only hunting for the living diptera larvae in the fungus.

In spite of their preference for living prey Necrophorus show only a slight inclination for cannibalism

Still in nature, cannabalism can occasionally be observed, when sick or hadly injured individuals are attacked and consumed.

When a male and female of the same species meet on a suitable body for broodcare (or the body has been found by an already paired female (vgl. S 539) the carrion is buried and serves the larvae as food, till they are full grown and move further into the soil for the pupation

But what happens if the same quantity of food has to suffice for the brood of several females? Without doubt the development of all larvae would be greatly endangered through shortage of food.

when the carrion was found already in a subterranean hole, which Fabre called the crypt

the grave diggers dispute their right to possession of the carrion by fighting one another, and it is predominantly individuals of the same sex which fight

The strong female, having defeated the smaller, weaker one, now crept under the mole where meanwhile the male was pursuing his work.

last usually to a fight, from which the white male (largest) comes off victorious and turns back to this work, while the fugitives appear to keep away from the mole now.

I was never able to observe, under the same conditions, fighting between different sexes of individuals in N. vespilloides.

While one is allowed to accept that this stronger selection puts the reproduction of weaker or even genotypically retarded females in question.

The fighting of gravediggers is for possession of the carrion, not for possession of females, and males respectively

the weaker species usually hastily retreats before interacting with a larger species

The weapons of the gravediggers which are employed in the fight are above all the legs, in particular the last pair, the mandibles being of secondary importance.

As the gravediggers are not choosy concerning their own food, they are also satisfied with any carrion for the provision of the brood. Indeed the size sets the upper and lower limit. Beetles are not able to bury large pieces and small ones do not supply a sufficient quantity of food for the numerous hungry larvae

N. vespilloides is an apparent exception. This inhabitor of drier woods buries his finds only under mosslawns, leaf or needle litter which puts plenty of living room at his disposal. – states that moss or leaf litter is required for vespilloides to breed in the lab, not the case in modern experiments

The time which the burying of the carcass requires is dependent on the size of the object,

With its feet on the body and its back against the surrounding earth, he lifts the mass continuously through stretching of its strong bent legs away from itself. – measuring the size of the carcass?

all previous earth working of the gravedigger requires for success a certain moisture of the ground which the animals find in the wild at their living places and which is carefully supplied in the terrarium.

In the extraordinarily small time interval of 7 days for the development of beetle larvae, the necessary weight and size increase of Necrophorus larvae to form the adult occurs.

While the increase in length which normally is in no way exceeded (the N. vespillo larvae grow an average from 0.5 to 2.8 cm), the increase in weight is in proportion to developmental time

stage 1 larvae have an acute sense of smell and are drawn towards the carrion ball rapidly

As long as there is no lack of food during the 7 day development, instinct allows the larvae to leave the outside of the ball of carrion undamaged -indifferent to conditions - so that they finally rest in a nest with both shelter and food.

larvae of all stages lie in close proximity to each other within the crater – causes crowding and presumably competition for food

the habit of remaining bundled together of older burying-beetle larvae is an advantageous instinct, it is doubtful through which kinds of attraction they would intervene

it is extremely rare to observe a larva leaving the nest prematurely.

Without doubt, the brood is fed by the female.

The feeding can be observed during the first 48 hours of larval development, but is seldom repeated later when the brood gradually are made independent

Fowlers declaration (1912), which characterized the larvae of the grave digger as inactive maggots, is then in no way correct for the young larvae.

Newly hatched larvae are apparently completely dependent on the female for food. They beg extremely impatiently and follow the female for short distances over the carrion with great dexterity and ability.

At the age of 5-6 hours the larvae then begin to feed independently.

If the female is removed before the first larval feeding, and if the larvae are completely dependent on the female, death of the entire brood must result. It appears that such a radical result does not happen. Most of the larvae grow up as if fed by the female.

The other hand points to two facts that the absence of the female in any case operates disadvantageously.

the development time of Necrophorus larvae is strikingly short; a 7 day development with more than one year of each beetle larva subject to quality food material.

Above all the short duration of development is of use for any species, such as N. vespillo or N. vespilloides which rears two generations in a year.

The animal repairs the disturbed brood room.

The fact that male grave diggers are also equipped with a broodcare instinct, is not surprising as the participation of the male in the broodcare in beetles is a known occurrence.

Certain signs suggest that broodcare instinct of the male is less pronounced than that of the females

our of the mentioned Necrophorus species, namely N. germanicus, N. humator, N. vespillo and N. vespilloides pupate after a pause for rest of 12-17 days and complete their development still in the same years.

Under normal conditions, the animal remains in the protection of his subterranean room. until 4 days after the casting of the pupal skin when the complete coloring and hardening of the chitinous skeleton occurs

he species N. germanicus, N. humator, N. vespillo and N . vespilloides overwinter as adults, N. fossor and N. investigator in the prepual stage.

**Scott, M.P. 1998. THE ECOLOGY AND BEHAVIOR OF BURYING BEETLES**

although all species of burying beetles share the suite of behaviors for their unique reproductive biology, considerable variation exists among and sometimes within species.

Burying beetles use small vertebrate carcasses that they bury and prepare as food for their young. This resource is necessary for reproduction, is unpredictable in space and time, and is valuable to many other taxa.

burying beetles treat each reproductive event as if it were their only opportunity to breed, and they behave to maximize their lifetime fitness with their current brood alone (27, 66).

These species, *Nicrophorus vespilloides* in Germany and *Nicrophorus orbicollis* and *Nicrophorus defodiens* in the United States, are multivoltine.

The species within a community also exhibit different patterns of daily activity,

with main peaks in the afternoon, at sunset, or at night

*N. vespilloides*, which has a Palearctic distribution (3), reproduces in forests in Europe (43, 47, 52) but exclusively in bogs in southern Canada (1, 3, 10).

in Germany, *N. vespilloides* buries over 85% of the available carcasses (16, 33), even though two species of larger, competitively superior beetles are reproductively active at the same time

Burying beetles will bury any type of small vertebrate carcass (23, 73) and show no preference when given a choice of bird or mammal (37).

except for very large or very small sizes, different species use completely overlapping ranges of carcass sizes.

Although burying beetles have a suite of behavioral, physiological, and morphological characters that allow them to effectively use small carcasses, there are anecdotal reports that *Nicrophorus* spp. can rear broods on a large carcass, such as a rabbit, without burying it (49).

A carcass is a valuable resource to many organisms. The importance of competitors other than beetles varies with latitude, habitat, and season.

Microorganisms are more serious competitors on relatively large carcasses than on smaller ones.

Large carcasses are difficult to prepare, and mould often makes part or all of the carcass unusable by the beetles.

Extended maternal care is unusual in insects (14, 76, 77, 101, 103), and the substantial parental investment by males is even more surprising and raises questions concerning its evolution.

Carcasses, not mates or food, limit reproductive opportunities for both males and females, and both sexes are capable of breeding again as soon as they leave a brood (7, 42, 68).

Larvae of large species, *N. orbicollis* and *N. sayi*, are extremely dependent on parental regurgitation and die beforethey reach second instar if they receive no parental care

*N. vespilloides* surviveswithout parental feeding (55)

even when not required or when extended beyond the period that it is required, feeding often improves larval survival and growth

In all studies conducted either in the laboratory or in the field, the number of larvae reared and the total mass of the brood is strongly positively correlated with carcass mass and not with the number of parents present – density mediated affect?

Fungi, subterranean ants, and insect predators can also contribute to brood failure. Microbes and fungi can outstrip the beetles’ ability to preserve the carcass

*N. defodiens*, for instance, suffers significantly more brood failure on large carcasses than on small ones, which reflects the greater difficulty in preparing and preserving a large carcass (85). Male assistance may help keep fungi in check

At 20\_C, eggs hatch on average 56 h later (*N. vespilloides*; 45). – 20C very warm for across most of *N. vespilloides*  range, what about other temps?

*N. vespilloides* is much more likely to meet a conspecific than a member of another species in competition over a carcass.

The risk of takeover changes over time as the larvae grow and consume the carcass

Both males and females of some, perhaps most, species often bury a carcass and rear a single brood with others of their sex.

members of the smaller species, *N. defodiens*, *N. tomentosus*, and *N. vespilloides*, are all often found in cooperative associations

Multiple males and/or females of both *N. orbicollis* and *N. defodiens* are twice as commonly found on 50- to 90-g carcasses as on 20- to 30-g ones (84). – no examples form *N. vespilloides*

a smaller carcass can be fully utilized by a single female, whereas a larger one cannot

The largest female is almost always the one to provide the longest care (19, 46, 63, 70, 92), just as the largest male provides longer care than smaller males (63). Relative duration of care is positively correlated with relative reproductive success within each association,

**Schrader et al. 2015. Parental care masks a density-dependent shift from cooperation to competition among burying beetle larvae**

However, parents and offspring are usually not genetically identical to one another and this genetic asymmetry generates an evolutionary conflict of interest, with offspring selected to demand more resources from their parents than is optimal for parents to supply (Trivers 1974).

Interactions between dependent siblings may also represent a tension between cooperation and conflict (Roulin and Dreiss 2012). Conflict between dependent siblings (i.e. sibling rivalry) is an obvious and often brutal part of family life for many animals.

Cooperation between dependent siblings is much less obvious and has received scant attention compared to sibling competition.

Siblings may also engage in behaviors that may not have evolved as adaptations for cooperation *per se* but that still benefit one another. These behaviors have been referred to as mutually beneficial (West et al. 2007). Here the mere presence of nest or littermates enhances the thermal environment experienced by each sibling, which increases survival and offspring performance (Forbes 2007; Hudson and Trillmich 2007).

The precise position on this continuum of any given sibling interaction is likely to vary, with ecological factors tipping the balance towards competition in some environments and cooperation in others.

There is also evidence that stressful environments can induce cooperation between different individuals of the same species

*Nicrophorus vespilloides*, to uncover a density dependent shift between mutually beneficial and competitive interactions among sibling larvae that is masked by the presence of parental care

measured larval density (the number of larvae at dispersal divided by the mass of the breeding carcass)

In the absence of parental care, initial increases in larval density had beneficial effects on average larval mass but further increases in larval density reduced larval mass.

except we prevented parents from provisioning larvae by removing both parents from the breeding box after carcass preparation and egg laying but before the eggs had hatched

We next randomly assigned each pair of beetles a manipulated brood size between 2 and 9 larvae - not very many and may not see a difference, well within the distribution and not the extremes

Thus experimentally reducing brood size in the absence of post-hatching care was likely to result in high rates of complete brood loss. – used natural variation, correlational not manipulative for larval density

we removed the prepared carcasses, gently removed all of the larvae from each carcass, and placed all of the larvae on the surface of a moist paper towel (larvae from both broods were pooled).

Boxes assigned to the low-density treatment were given 10 larvae and boxes assigned to the high-density treatment were given 20 larvae – on 8-14g mice

We also compared the proportion of cases in which the breeding carcass began to mold between the low and high-density treatments using a chi-squared-test

In the Full Care treatment there was a negative relationship between average larval mass and larval density that was best described by a linear regression model

* larval mass was highest at the lowest larval density.

in contrast in the No Care treatment, larval mass was maximized at larval densities of approximately 0.77 larvae per gram of carcass.

Larval density had a large effect on the ability of larvae to penetrate the breeding carcass in the absence of parents. In the low-density treatment, larvae were unable to penetrate the breeding carcass. However in the high-density treatment, 35 % of the replicates (8/23) had larvae feeding within the carcass 90 hours after pairing.

There was no evidence that larval density influenced the growth of mold on the carcass. At 90 hours post-pairing, 38 % (8/21) of the low-density replicates had mold growing on the carcass compared with 61 % (14/23) of the high-density replicates. The difference between these two proportions is not significant

In the absence of parental care, initial increases in larval density had beneficial effects on average larval mass but further increases in larval density reduced larval mass.

First, Smiseth et al. (2007) manipulated broods to contain 5, 20, or 40 larvae. In contrast, we utilized continuous variation in brood size with broods containing 1 to 44 larvae

It is possible that the carcass sizes used by Smiseth et al. (2007) minimized sibling competition in the absence of parental care while the carcass sizes used in our study induced sibling competition in relatively large broods.

the benefits of having many mouths on the carcass may reach an asymptote beyond which increasing larval density results in exploitative competition between siblings for a fixed pool of resources.

A second possibility is that the benefits of social immunity (Cotter and Kilner 2010), mediated through the production of antimicrobial exudates, are density dependent.

However, beyond a certain larval density the nutritional impact of exploitative sibling competition might overwhelm the effects of social immunity.

**Smiseth, P.T., et al. 2007. INTERACTION BETWEEN PARENTAL CARE AND SIBLING COMPETITION: PARENTS ENHANCE OFFSPRING GROWTH AND EXACERBATE SIBLING COMPETITION. *Evolution***

Evolutionary biologists have noted for decades that species with elaborate forms of parental care often exhibit intense competition among offspring for access to resources (Trivers 1974; Clutton- Brock 1991).

something of a paradox because parental resource provisioning is predicted to evolve by increasing the offspring’s access to critical resources (Clutton-Brock 1991).

Begging reflects the nutritional needs of the larvae (Smiseth and Moore 2004a) in accordance with game-theoretic models for the evolution of offspring begging signals (Godfray 1991, 1995; Parker et al. 2002).

The level of sibling competition can vary considerably due to variation in both availability (i.e., size of carcass used for breeding) and demand (i.e., brood size) for resources

We expected that larvae would grow faster in smaller broods than in larger broods given that the amount of resources would be more limited in the latter than in the former and that resource limitation may increase the intensity of sibling competition (Mock and Parker 1997)

In both experiments, we provided each pair with a carcass of standardized size to control for potential effects of the size of the carcass (mean ± SD carcass size: 21.7 ± 3.2 g, *n*=185, range: 15.0–30.0 g).

male care is redundant under laboratory conditions

(M¨uller et al. 1998; Smiseth et al. 2005

We transferred all eggs from the old container to a moist filter paper placed in a petri dish. We checked petri dishes for the presence of newly hatched offspring four times each day.

In both experiments, the newly hatched larvae were used to establish experimental broods comprising 5, 20, or 40 offspring.

This manipulation is well within the natural variation with respect to brood size in *N. vespilloides* (mean ± SD brood size: 21 ± 10 offspring, range 2–47 offspring; Smiseth and Moore 2002)

Thus, the effects of the presence or absence of female parents and brood size on larval growth were not independent of each other

this interaction effect occurred because brood size had a much stronger negative effect on growth when female parents were present than when female parents were absent

In the absence of parents, by contrast, there was no significant effect of the interaction between age and brood size on larval body mass - therewas no evidence that brood size had an effect on growth when female parents were absent

brood size had a strong effect on growth when parents provided care, but no effect when parents were absent.

offspring in larger broods shifted from more begging toward self-feeding as they aged than did offspring in small broods

Intense forms of sibling competition, such as conspicuous begging scrambles, jockeying over favourable positions, or aggressive fights, are thought to evolve when parents provide their offspring with resources that are limited due to the costs of care incurred by parents (Mock and Parker 1997).

the interaction between the presence or absence of caring parents and brood size, suggests that parental resource provisioning increases the scope for interference among competing siblings

the finding that offspring were considerably less effective at begging for resources from the parents in larger broods than they were in smaller broods suggests that there was a considerable interference when parents provided care

suggests that sibling competition was more intense in larger broods

showing that parental resource provisioning enhances offspring growth yet exacerbates the level of sibling competition

**Trumbo, S.T. 1990. Reproductive benefits of infanticide in a biparental burying beetle *Nicrophorus orbicollis.* *Behavioural Ecology and Sociobiology* 27: 269-273**

A male-female pair of burying beetles *(Nicrophorus* Fabricius spp.) will bury a small vertebrate carcass whichis used as a resource for their brood

Body length was measured as the distance from the tip of the mandibles to the edge of the elytra. Beetles were marked by clipping off a small part of the posterior edge of one of the elytra

The body size of beetles established on a carcass was related to their ability to retain ownership. In a large proportion of cases a male intruder was larger than the male resident replaced. The proportion was similar for female intruders and residents Male intruders were not significantly longer than resident single females they joined.

indirect evidence that intruders kill larvae they find on the carcass and then initiate their own reproductive attempt

When the larger intruder was a female, the roles of attacker and the pursued reversed as the encounter proceeded

Once infanticide began, larvae were not killed all at once but opportunistically as the intruder inspected the carcass.

In 22 of 28 trials in which an intruder was introduced into a container with a resident female and her brood, all the larvae in the initial brood died

Intrusions and takeovers, therefore, appear to be a regular feature of the breeding system of *Nicrophorus* in the field.

Intruders of both sexes kill larvae they find on the carcass and attempt to use the resource for their own reproduction

**Trumbo, S.T. 1990. Regulation of Brood Size in a Burying Beetle, *Nicrophorus tomentosus* (Silphidae) *Journal of lnsect Behavior,* 3(4): 491-500**

Such adjustments of brood size should not maximize the number of offspring that will survive to reproductive age or the size of offspring but should maximize total fitness of the parents' offspring (Smith and Fretwell, 1974).

Burying beetles (Silphidae, *Nicrophorus* Fabricius) compete with rivals of the same sex for small vertebrate carcasses on which to reproduce.

*Nicrophorus* is known to regulate brood size by adjusting number of young to carcass size such that the mean mass of individual larvae at dispersal is similar on small and large carcasses (Wilson and Fudge, 1984; Kozol *et al.,* 1988; Scott and Traniello, 1990; Trumbo, 1989).

Bartlett (1987) has shown that parents can reduce brood size by cannibalizing firstinstar larvae.

*Nicrophorus* is an intriguing genus for a study of regulation of brood size and possible parental control of offspring size. Burying beetles use a wide range of carcass sizes (5-200 g), there is a 10-fold difference in body mass between the smallest and the largest species, body size is important in competitive interactions, and the mechanisms employed to assess resource size and brood size are poorly understood

The length of adult beetles was measured from the tip of the mandibles to the posterior edge of the elytra

The number of offspring was strongly related to carcass size but was not affected by the size of the female. Means mass of individual larvae, on the other hand, was not affected by carcass size nor by female size.

All eight pairs in Treatment 2 raised fewer offspring per gram of carcass in their second reproductive attempt

There was an inverse relationship between the number and the size of individual larvae. When the effect of total brood mass is removed, there is a strong partial correlation between number of larvae and mean mass of individual larvae on large carcasses

If parents are essential for regulation of brood size, larvae that develop on **a** limited resource without parental care are expected to be underweight. In the absence of parents, there was a trend for fewer larvae to mature on the small quantity of food

individual larvae produced on a smaller resource were of significantly lower mass than larvae produced on a larger resource

When food is abundant and accessible, larvae of *N. tomentosus* can develop to the final instar and disperse at the normal size without posthatching parental care. Because larvae do not grow to a normal size when food is limited and parents are removed, larvae do not appear to be able to regulate brood size on their own. This suggests scramble competition for the resource in the absence of parents.

Using both *N. defodiens* Mannerheim and *N. orbicollis* in field studies, I found that parents consistentlyproduced many more larvae on large than on small carcasses (Trumbo, 1987;Trumbo, 1989).

This study demonstrates a trade-off between number of larvae in the brood and mean mass of individual larvae at dispersal. When the number of offspring is too large for the resource in broods without parents, larvae are considerably underweight

By regulating brood size, parents affect the body size of larvae and thus the eventual adult size and reproductive success that their young will achieve

**Aging Theory**

**Bonsall, M.B. Longevity and ageing: appraising the evolutionary consequences of growing old. Philosophical Transactions of the Royal Society B 361: 119–135**

Senescence is a decline in physiological functioning that leads to a decrease in reproduction and an increase in mortality with age. Senescence appears maladaptive as it directly affects key life-history traits (such as the schedules of reproduction and survival) that influence fitness

Questions on the biology of ageing range from the molecular through to the whole organism- and population-level, and from the pathological through to evolution

Although, the general theory for the evolution of senescence is well established (Medawar 1952; Williams 1957; Hamilton 1966), the necessity for ‘improvement is long overdue’ (Williams 1992).

While no single gene can be credited as responsible for ageing, the mechanisms of ageing are clearly under genetic control

Harman (1956) hypothesized that endogenous oxygen radicals produced during aerobic respiration could cause cumulative oxidative damage resulting in senescence and eventual death (of cells, tissues and organs

It is important, at the outset, to distinguish between the causes and consequences of ageing

Reducing calorie intake, for example, has been shown to slow ageing in a variety of organisms spanning all the major phyla including mammals (e.g. rodents, McCay et al. 1935; primates, Lane et al. 2001), invertebrates (e.g. spiders, Austad 1989; Drosophila, Partridge et al. 2005) and fungi (e.g. yeasts, Lin et al. 2004).

Rate of living effects correlate with a range of abiotic variables. For instance, in the rockfishes, longevity increases with maximum depth (Cailliet et al. 2001)

assessment of the rate of living might also be confounded with body mass (Promislow & Haselkorn

2002) since size, metabolic rate and longevity may be tightly linked (West et al. 2001

The function of one gene, in particular, appears to have wide effects. Sir2 is a gene in yeast that regulates lifespan: in its absence the lifespan of Saccharomyces cerevisiae is shortened. This gene is highly conserved and is known to affect ageing across a broad range of organisms

Antioxidants such as SOD are widespread across all taxa and their role in reducing oxygen toxicity is undoubted. However, their role in reducing mortality rates and extending lifespan is more questionable

It is now well established that normal cells have a limited capacity to divide. This phenomenon is known as the ‘Hayflick limit’ (Hayflick 1965; Shay & Wright 2000

The importance of the Hayflick limit for understanding the mechanisms of ageing was discovered by

Olovnikov (1973, 1996). Olovnikov understood that the properties of DNA replication prevent cells from fully transcribing the ends (telomeres) of nuclear DNA

Telomeres are highly conserved regions of DNA (Ridley 1999) and the effects of telomere shortening have been shown to be correlated with lifespan in birds and mammals

First, is it appropriate to define lifespan or rate of ageing as a measure of longevity? Second, is it sufficient knowing the mechanisms of ageing to argue that the process of growing old is inevitable?

It has been known for almost two centuries that agerelated mortality trajectories follow an exponential increase (Gompertz 1825

Many organisms show determinate patterns of growth: i.e. organisms reach a fixed size at sexual maturity

In contrast, some organisms show indeterminate patterns of growth, where growth continues after reaching sexual maturity. These organisms tend to show no patterns of age-related dysfunction and age-dependent mortalities that are constant following sexual maturity.

suggests that even though, the mechanisms of ageing are under genetic control, the manifestations of senescence are as different as the difference between species

Medawar (1952) argued that the force of natural selection that maintains individual survival and fertility declines with increasing age. Medawar suggested that mutations acting early in life would be eliminated by natural selection. However, mutations that appeared at or around reproductive maturity would not be purged by natural selection (Partridge & Barton 1993), could accumulate and lead to a decline in survival and/or fertility

An alternative theory for the evolution of longevity, antagonistic pleiotropy, proposed by Williams (1957) suggests that there is a trade-off between early fecundity or survival and late mortality

The disposable soma theory proposes that resources are required to maintain cell integrity and, as such, there is a trade-off in reproductive capacity and physiological integrity.

More rigorously, in support of the mutation accumulation theory, Hughes & Charlesworth (1994) have shown that genetic variance in mortality rate increases with age in male D. melanogaster

As predicted by the mutation accumulation theory these late-onset genes with deleterious effects are not purged by natural selection (Hughes et al. 2002) and provide strong support for the mutation accumulation theory

Tests of the antagonistic pleiotropy theory have used artificial selection experiments on Drosophila. By selecting lines for late reproductive output, it has been shown, in general, that there is a trade-off: longevity and late fertility increase from lines initiated from ‘old’ adults (Rose & Charlesworth 1980) and there is a correlated decline in survival and fertility of ‘young’ adults (Rose 1984; Partridge & Fowler 1992).

It is postulated that the rate of ageing should increase, reproduction should start early and average lifespan decline as the rate of extrinsic mortality increases.

Using guppies, Poecilia reticulata, Reznick and colleagues showed that fish derived from different (high and low) mortality environments and reared at two different levels of resource availability showed different patterns in lifespan. Guppies from high-mortality environments began reproducing earlier, suffered significant decline in neuromuscular function but tended to have longer total lifespans

Given the variability in the manifestations of the molecular mechanisms of ageing, it is, however, entirely plausible that different patterns in mortality trajectories might arise through an interaction between genetic and environmental processes

it has been shown thatmeasures of age-specific mortality in plantain (Plantago lanceolata) depend on both fixed genetic characteristics and variable ecological and life-history factors such as temperature, rainfall and body size (Roach & Gampe 2004).

If extrinsic mortality risk is high, less resource is allocated to repair (and more to growth), the greater the degree of intrinsic mortality (cellular damage) and the lower the probability of surviving to a given age

Individual mortality is the product of natural selection acting on behaviour, growth and reproduction, and of the physiological processes acting across the life of an organism

changes in the population dynamics of Drosophila subobscura (figure 3), are principally determined by changes in mortality rate. These changes in mortality operate in a density-dependent manner such that there is higher mortality at higher population sizes and lower mortality at lower population sizes.

intense competition for limiting resources, rapid development and sustained metabolic damage are more likely to be manifest when population sizes are large.

If there is parental investment in offspring, then significant and often lethal conflict can occur among siblings, despite the close degree of genetic relatedness.

the patterns of age- and stage-dependent food transfers are important in affecting caste function and ageing (Amdam & Page, 2005).

there might be a link between genome size and lifespan (Monaghan & Metcalfe 2000; Griffith et al. 2003) which, given our understanding of the molecular machinery of ageing, is entirely plausible. in birds, a significant positive relationship exists between genome size and longevity (when corrected for body size; Monaghan & Metcalfe 2000

Genes often have several functions each controlled by different regulatory mechanisms with multiple pleiotropic effects. Redundancy or specialization can take a number of distinct forms such that the expression of gene duplicates occurs in different tissues or in novel developmental stages (Force et al. 1999).

Ageing is a deleterious trait. In some respects this is a conventional evolutionary puzzle, in others it is not.

Understanding why and how fertility and survival decline through time should be a relatively straightforward problem. However, the multitude of mechanisms by which ageing and senescence occur leaves a bewildering array of potential explanations for the longevity problem

**Bourke, A.F.G. 2007. Kin Selection and the Evolutionary Theory of Aging. 38: 103-1028**

any gene increasing survival or fecundity is more strongly selected for when its phenotypic effects occur at younger ages, and conversely, any gene decreasing survival or fecundity is less strongly selected against when its phenotypic effects occur at greater ages

The first, antagonistic pleiotropy, proposes that aging stems from selection of pleiotropic genes having a positive effect on survival and fecundity early in life and a negative effect late in life. The second, mutation accumulation, proposes that aging stems from lack of selection against genes of purely negative effect, where these effects occur only late in life (e.g., Hughes & Reynolds 2005, Kirkwood & Austad 2000).

the age at first reproduction represents the critical period beyond which aging is predicted to occur (Charlesworth 1980, Rose 1997, Stearns 1992).

finite resources entail the occurrence of trade-offs between somatic maintenance and reproduction (Barnes&Partridge 2003, Kirkwood 1977),

Related studies have provided better support for antagonistic pleiotropy than for mutation accumulation as genetic routes to aging (e.g., Campisi 2005, Hughes & Reynolds 2005, Kirkwood & Austad 2000, Leroi et al. 2005, Partridge & Barton 1993, Partridge & Gems 2002a, Rose 1991), with some phenomena not readily reconcilable with either route (Mitteldorf 2004).

The evolutionary theory of aging, including its derived versions, has traditionally considered patterns of aging with reference to an individual’s fitness evaluated in the absence of social effects (e.g., Hughes & Reynolds 2005, Rose 1991).

If the interacting individuals are relatives, the focal individual’s inclusive fitness will be altered, and hence patterns of aging in the focal individual will, in principle, be subject to kin selection

older models, however, frequently proposed that organismal death either benefited nonrelatives or brought long-term evolutionary benefits, thus invoking an unsustainable, naive group selection

if individuals gain inclusive fitness from postreproductive life, the degree to which the force of natural selection is attenuated in later life would be reduced with respect to both late-acting effects of pleiotropic genes and the accumulation of late-acting deleterious mutations.

many researchers have argued that aging will be moderated in species in which care is provided by parents, grandparents, or helpers (reviewed in Arking 2006, Carey & Gruenfelder 1997, Lee 2003)

if older individuals enhance their inclusive fitness through care dispensed to relatives (e.g., offspring, grandoffspring, other relatives), selection should counteract aging later in life

When investments are transferred, Lee (2003) argued that selection would bring about an optimal allocation of resources between number of offspring produced (fecundity) and level of investment per offspring

the age-specific strength of selection on mortality would be influenced only by the transfer effect

because postreproductive adults may still make investments, the transfer effect remains positive after reproduction has ceased, so the model predicts the extension of postreproductive life span

Lee (2003) implicitly assumed asexual reproduction This precludes the possibility of parent-offspring conflict over the timing of intergenerational transfers of investment and hence does not capture the range of evolutionary possibilities inherent in a model with sexual reproduction

a shorter, deterministic life span, or an increased rate of aging, or both, can evolve when dispersal is limited

Mitteldorf’s (2006) model assumed asexual reproduction and limited dispersal and found that increasing dispersal led to reduced aging

local density dependence inhibits the evolution of altruism by kin selection because altruistic genotypes remain in competition with one another

existing patterns of aging can be modified by social effects as a function of population structure

**Increased Focal Individual’s Life Span, Increased Recipient’s Fitness**

Given that the duration of care affects the amount of care received, increasing the caregiver’s life span would, other things equal, raise the recipients’ fitness. If caregivers and recipients are related, it would also, by allowing more relatives to be reared, raise the caregiver’s inclusive fitness.

The most probable mechanism for such an increase in life span would be a delayed onset of aging, as merely decreasing the rate of aging might reduce the quality of care provided.

colonially breeding species in which no reproduction occurs below a threshold density (Allee effect, e.g., Stephens et al. 1999). Here, the presence of any given individual within the colony indirectly increases the fitness of others - to the extent that a focal individual’s longer life provides a mechanism for maintaining its presence in the colony, Allee effects could select for an extension to the focal individual’s life span

within-taxon comparisons provide suggestive evidence for kin selection (through the provision of care to offspring, grandoffspring, and perhaps other related young) leading to extensions in caregivers’ postreproductive life spans or overall life spans

a physiological disassociation between somatic and reproductive aging in female mammals leads to independent selection upon them.

At the ultimate (evolutionary) level, a postreproductive life span in females might be expected to be widespread in a taxon whose hallmark is maternal care of young.

Møller (2006) found no significant difference in life span between colonially breeding and solitarily breeding birds

**Increased Focal Individual’s Life Span, Decreased Recipient’s Fitness**

Merely existing deprives other individuals of the resources that a focal individual consumes. Hence, an increase in the life span of a focal individual will, other things equal, reduce the fitness of others.

When nonrelatives suffer reduced fitness, this has no evolutionary consequences for focal individuals, whose inclusive fitness is unaffected. However, when relatives lose fitness, kin selection acts as a brake on the level of cost that one individual inflicts on another

But the parent is related to its own progeny by 0.5 and to its offspring’s progeny (grandoffspring) by 0.25, and so values each of its own progeny twice as highly as it values each progeny of its offspring. Hence, by Hamilton’s rule, if parental fecundity (*c*) is declining, the offspring favors the handover of the territory when *c* falls below *b*, that is, when *c*/*b<*1. But the parent favors it when *c<*0.5*b*, that is, when *c*/*b <* 0.5.

From the parents’ standpoint, such harassment might, within the parental lifetime, lead to further fecundity declines and so create greater incentive to offspring to harass. Over evolutionary time, it might constitute a further source of extrinsic mortality, increasing the intrinsic rate of decline in parental fecundity

over both the timescale of one generation and over an evolutionary timescale, resource inheritance systems conceivably create positive feedback between offspring harassment of aging parents and the rate of fecundity decline in parents, leading to accelerated parental aging and death

Evidence exists that, in social systems with resource inheritance, resource holders and resource inheritors indeed differ over the timing of resource handover and hence over the timing of the death of resource holders – e.g. honey bees

**Decreased Focal Individual’s Life Span, Increased Recipient’s Fitness**

in systems of resource inheritance, the death of a resource-holding focal individual releases benefits to its successor

if the resource holder passes a threshold beyond which its cost-to-benefit ratio for dying is sufficiently low, then its inclusive fitness is enhanced by its death and selection should act upon it to commit adaptive suicide, possibly by accelerated aging.

the theory predicts that, other things being equal, within species the philopatric sex should show a greater rate of aging

Both obligate and facultative adaptive suicide benefiting relatives (particularly offspring) are known or suspected in a number of taxa

Facultative self-sacrificial defense by workers in favour of related nest mates is widespread in social Hymenoptera and termites(Wilson 1971).

**COEVOLUTION OF AGING PATTERNS WITH HELPING BEHAVIOR AND SOCIALITY**

greater offspring survival and reduced parental fecundity, followed by greater parental survival (through reduced costs of reproduction) and hence extended parental life span. In turn, this provides more opportunity for intergenerational transfers, including those to grandoffspring

evidence exists that insect species resembling those likely to have been ancestral to social species were already characterized by offspring with a long period of dependency, combined with short-lived adults (Field & Brace 2004).

reproductives in highly social species have relatively longer life spans than individuals in related, solitary species [insects

recent discoveries demonstrate that some of the molecular pathways affecting aging are influenced by single genes and are conserved across a very broad phylogenetic span (Arking 2006, Guarente&Kenyon 2000)

single genes might influence the molecular pathways underlying the trade-off between somatic maintenance (survival) and reproduction (Barnes&Partridge 2003). If so, conserved, single-gene effects on aging do not uniquely support a social theory of aging.

many authors have argued that, under the classic theory, aging is not a coordinated process under direct genetic control like development and hence is not programmed (e.g., Hayflick 2000, Kirkwood 2005, Kirkwood & Austad 2000, Partridge & Gems 2002a).

labeling aging via antagonistic pleiotropy as adaptive or nonadaptive depends upon whether one defines adaptation in terms of evolutionary fitness or individual welfare

**Carey, J.R. and Judge, D.S. 2001. Life Span Extension in Humans Is Self-Reinforcing: A General Theory of Longevity. *Population and Development Review* 27(3): 411-436**

if model species are so similar to humans in molecular makeup that they can serve as models, why do mice age as much in 2 years as humans do in 70 years?

Despite the arguments by Sacher and others (e.g., Hayflick 2000) in support of developing a longevity-oriented theory of the finitude of life, no such theory has ever been published

from environmental factors associated with the evolution of extended longevity in insects (Carey 2001a, 2001b

First, whereas senescence is a byproduct of evolution (Medawar 1955), life span is an evolved life-history trait that results from positive natural selection

Second, unlike the evolutionary theory of senescence, which is based solely on individual natural selection (Williams 1957), this theory includes processes of sexual selection and kin selection, bringing life-history theory more fully to bear on questions concerned with the latter portion of the life cycle

animals that possess armor (e.g., beetles; turtles) or capability of flight (e.g., birds; bats) are often long- lived (Austad 1997; Kirkwood 1992)

The evolutionary theory of senescence suggests that animals better able to escape sources of stochastic mortality such as predators (e.g., via armoured defences or effective escape mechanisms) live longer, and thus the force of natural selection at older ages is increased and the evolution of longer pre-senescent life span is possible

the observation that flight ability and extended longevity are correlated does not provide any insight into why within-group differences in life span exist (e.g., among birds), nor does it account for the variation in longevity in insects where adults of the majority of species can fly.

Across a wide taxonomic spectrum, many long-lived species appeared to cluster within one of two general ecological and/or life-history criteria: (1) species that live in either unpredictable environments (e.g., deserts) or where food resources are scarce (e.g., caves; deep water); or (2) species that exhibit extended parental care and/or live in groups with complex or advanced social behaviour

intensive parental care is linked to flight capability in birds and bats,7 which, in turn, is also linked to extended life span

Nesting behavior and sociality result in improved micro-environmental conditions, which foster greater survival; and greater survival improves conditions for increased provisioning and more-intensive social organization

Medawar ( 1957) proposed that if deleterious hereditary factors are expressed at some intermediate age of an individual, and if the age of this expression is both variable and heritable, then selection will weed out earlier expressions more effectively than later expressions, delaying the average age of expression and increasing longevity

longevity. As the force of selection is reduced by the declining reproductive value9 of increasingly older individuals, those deleterious traits will accumulate-resulting in a mosaic and variable pat- tern of age-specific infirmity and thus senescence (Kirkwood 1997

deterioration. As more individuals live longer, the force of selection increases at later ages, weeding out later-expressing deleterious alleles; selection for somatic maintenance is prolonged; and senescence is delayed

Increased per capita investment in offspring decreases juvenile mortality, increases the health and well-being of offspring, and thus improves adult health and survival

Selection for longevity also increases the return on higher levels or prolonged periods of investment

allocation of energy to reproduction removes its availability for somatic growth and repair and thus is reflected in increased mortality

increased survival from birth to sexual maturity improves energetic efficiency to the parent by decreasing reproductive waste and allows parents either to produce more young or to invest more per capita in existing young

forgone. Increased resources available for reproduction can have any of the following effects depending on which age classes can access them: (1) in- crease the number of young, (2) increase the survival of the young, (3) de- lay maturity of the young by allowing the parental generation to support overlapping sets of offspring, (4) reduce the cost of reproduction to moth- ers through "grandmothering" (Hawkes et al. 1998).

Parents experiencing fewer births but unchanged levels of reproduction be- cause of higher rates of child survival remain healthier. Consequently par- ents themselves experience higher survival and can invest more of their resources in a smaller number of "high-quality" offspring-healthier, larger, more competitive (Clutton-Brock 1994

First, the life spans of nearly all primate species are greater than those predicted by body mass alone

a theory of longevity raises questions about the interpretation of studies on the biological mechanisms of aging that rely on model species such as fruit flies, laboratory rodents, and nematode worms, all of which are solitary (nonsocial) species

example, the aging re- sponse to caloric restriction (Sohal and Weindruch 1996; Weindruch 1996) in solitary species, which must survive independent of a social group, may be fundamentally different from the mechanisms in social species with evolved behaviors for helping, sharing, and food storage

Whereas the aging-oriented question assumes that age-specific improvements in survival exert their impact only at older ages, the self-reinforcing model argues that age-specific decrements in late-life mortality can also have a positive effect on early survival and productivity through selection, inter- generational transfers of resources and information, and increasing innovation from specialization

**Caswell, H. 2007. Extrinsic mortality and the evolution of senescence**

Williams [2] predicted that increased extrinsic mortality would do just this, causing the selection gradient to fall off more rapidly with age, thus favoringmore rapid senescence.

Unfortunately for its use as a predictive tool, this prediction is false. Additional mortality has no effect on the age pattern of selection gradients unless the additional mortality is itself age-dependent, in which case its effect on senescence may be either positive or negative

instead, the selection gradient at a given age depends on the age distribution and the reproductive value

Thus, increased mortality alone has no effect on the age pattern of selection gradients

If the additional mortality h(t) varies stochastically, the selection gradient is the derivative of the stochastic growth rate log ls [12,13], and this selection gradient is equally unaffected by the additional age-independent mortality

If neither the extrinsic mortality nor the density dependence are age specific, then the extra mortality has no effect on the pattern of selection gradients.

Extrinsic mortality affects senescence only if it affects different age classes differently. It is an interesting problem to figure out how the age specificity of mortality interacts with that of the selection gradients.

**Clare and Luckinbill 1985. The effects of gene-environment interaction on the expression of longevity.**

Natural selec-tion, therefore, is seen to act on life span by altering the action of modifier genes.

Selection favouring reproduction by individuals at an advanced age should increase life span, while reproduction by the young should hold life span low or reduce it.

In a comprehensive series of studies with Drosophila melanogaster, Lints and Hoste (1974; 1977) and Lints et al., (1979) applied selection for increased life span under different regimes of age-specific reproduc-tion with the expectation that longevity would increase in lines reproduced at a late age in life. - But their results were so unusual that no genetically based theory of aging could explain them

Other selection experiments by Rose (1984) and Rose and Charlesworth (1980; 1981) and Luckinbill et a!. (1984), however, are consistent with evolutionary theories based on genetic con-trol, and present evidence in support of Williams' (1957) notion of pleiotropic gene action.

crosses were also raised at a constant larval density of 10 per standard shell vial, as in Lints and Hoste (1974) and Lints et al. (1979) - Populations were raised at controlled densities of 10, 30 and 50 larvae per vial

Viability was not estimated in this study and percentage survivorship is measured from eclosion only.

As shown by the F1 populations in figs. 2 and 3, the control of larval density alters adult life span in both parental and F1 lines. All populations raised at a low controlled-density have a substan-tially lower longevity than when uncontrolled, and are very close to the short-lived parental line.

mean longevity is reduced in the long-lived parental line from 7853 days to 6356 days, which is less than the midparent value for the uncontrolled treatment

Increasing the density of F1 populations to a high level can restore additivity even though development occurs in vials and density is con-trolled.

Short-lived parental lines lay 22 or 24 per cent more eggs in the same period than do lines selected for late-reproduction and long life – higher density in short lived flies than long lived ones

When numbers of developing larvae are held low, populations show only a short adult life regardless of their genetic capability.

Our experi-ments, however, show that maternal effects are not the determinants of longevity, and confirm an alternative explanation

We suggest that genes con-trolling longevity are conventional in every sense, even showing near ideal additivity in the uncon-trolled-density treatment, and like other genes, their expression also includes an environmental component, significantly touched upon here by developmental conditions.

It is the expression of genes, and not the genes themselves which differ in the density-treatments of this study.

First, development at low density may limit the permissible adult life span in some unknown physiological manner.

A second possibility, with similar predictions, is that the repression of long adult life by develop-mental density is genetic in origin. That is, in what appears to be nearly optimal conditions of con-trolled-density, variations in life span are sup-pressed in favour of the short-lived phenotype.

Genes ser'isitive to population density during develop-ment could have a threshold, expressing domi-nance at first, and finally additivity at higher density as development becomes more stressful.

Early-fecundity varies here between replicates, yet within a replicate, early-reproducing lines lay a consistent 22—24 per cent more eggs in early life than late-reproducing lines. Thus, life span has been improved in these strains at considerable cost to early-fecundity.

**Charlesworth, B. 2000. Fisher, Medawar, Hamilton and the Evolution of Aging. *Genetics* 156: 927–931**

THE idea that senescent decline in the performance ofmbiological systems must have an evolutionary basis traces back almost to the beginnings of evolutionary biology

At first sight, the nearly universal existence of senescence in species of multicellular organisms is paradoxical, given that natural selection supposedly causes the evolution of increased, not decreased, fitness.

But unicellular organisms, such as bacteria, which propagate simply by binary fission, and the germ lines of multicellular organisms, have been able to propagate themselves with- out senescence over billions of years, showing that biological systems are capable of ongoing repair and maintenance and so can avoid senescence at the cellular level

The large amount of variation among different species in their rates of senescence also clearly indicates that aging is subject to variation and selection (Comfort 1979; Finch 1990; Rose 1991; Wachter and Finch 1997).

Modern evolutionary theory has demonstrated that, in species with a clearcut distinction between parent and offspring, senescence is a virtually inevitable result of the fact that genes that affect survival or fecundity) only early in life have a greater selective impact than genes whose effects are manifest only late in life

It is probably not without significance in this connexion that the death rate in Man takes a course generally inverse s, to the curve of the reproductive value. The minimum of death rate curve is at twelve, certainly not far from the primitive maximum of the reproductive value; it rises more steeply for infants, and less steeply for the elderly than the curve of reproductive value falls, points which qualitatively we should anticipate, if the incidence of natural death had been to a large extent moulded by the at a given age, of differential survival. Fisher (1930) page 29

a hypothetical mutant gene that increases survival over a small time interval at an age when reproductive value is high would thus have a higher net effect on fitness than a gene acting at an age when reproductive value is low.

expectation that selection will be more effective in improving performance early in adult life than late in life

alleles with positive effects on performance early in life, but with negative effects because of physiological trade-offs later on, are more likely to be established by selection than alleles with the opposite pattern. This idea was more fully developed by Williams (1957) and is now known as the “antagonistic pleiotropy” theory of aging

if fecundity increases exponentially with age during adulthood, reproductive value also increases exponentially, so that its use would lead to the conclusion that selection opposes senescence

In contrast, Equation 6 implies that there is always a selective premium on early survival, although the rate of decline of the intensity of selection with age is greatly slowed if fecundity increases with age

Our understanding of the evolution of senescence is, at one level, very complete; we know that senescence is an evolutionary response to the diminishing effectiveness, of selection with age and that this explains many

aspects of the comparative biology of senescence (Williams 1957; Rose 1991; Charlesworth 1994; Ricklefs 1998).

On the other hand, it is at present hard to be sure which of the two most likely important mechanisms by which this property of selection influences senescence (accumulation of late-acting deleterious mutations or fixation of mutations with favourable early effects and deleterious late effects) plays the more important role, especially as these are not mutually exclusive possibilities

**Lee, R.D. 2003. Rethinking the evolutionary theory of aging: Transfers, not births, shape senescence in social species. *PNAS* 100(16): 9637–9642**

In classical aging theory, as individuals age, their continued survival contributes less and less to reproductive fitness, because less of their lifetime fertility remains. Consequently, natural selection acts more weakly to reduce mortality at older ages

An alternative theory considers both fertility and transfers, including parental care and help from others such as older siblings or grandparents. It is shown that selective pressure to reduce mortality also depends on the cumulated investment needed to produce a survivor to a given age, including costs wasted on offspring who died earlier.

Fisher (11), noted that there would also be indirect effects on reproduction as when ‘‘a mother past bearing may greatly promote the reproduction of her children

In some species, postreproductive females make substantial contributions to their descendants, either through direct parental care or through grandparental care

the sex that mainly provides care to offspring tends to have

the higher life expectancy (18).

if there is continuing parental investment, then the force of selection against mortality should rise with juvenile age, and mortality should fall.

If higher fertility and less investment per offspring would improve fitness, then selection on mortality at a given age will be a weighted average of the classic and transfer effects, with positive weights on both. Lower mortality at younger ages would raise the growth rate, and lower mortality at younger and at older ages would economize on resources for investment, also raising the growth rate.

In the opposite case, where lower fertility and increased investments per birth would raise fitness, then lower juvenile mortality could actually reduce reproductive fitness by increasing competition for investments per surviving offspring. There would be strong selection for adult survival, but there might also be selection for increased juvenile mortality at early ages.

Most species that invest heavily per offspring, such as mammals, birds, and many insects, will have evolved an optimal allocation of resources between level of fertility and level of investment per offspring.

More rapidly growing populations are younger, with more juveniles per adult. At a given growth rate *r*, populations with lower mortality (higher survival) will be older with fewer juveniles per adult

Mutations affecting fertility and mortality are assumed to occur relatively frequently, mostly with adverse effects on fitness, which selection constantly tends to remove. A mutation–selection balance will be reached at each age, with stronger selection leading to lower mortality (31).

Lower mortality even at a postreproductive age reduces the ratio ofjuveniles to adults at any given growth rate, permitting higher consumption

Higher consumption raises survival, particularly of juveniles, so wastage of resources is avoided, and the adult\_juvenile ratio rises for a given population growth rate. (*ii*)Higher consumption raises productivity through larger body size and increased energy. (*iii*) Higher consumption may be associated with greater and longer investments in juveniles, which might have a high payoff for later production

The intuition is that higher mortality near age 0, for example at an early juvenile age, will thin out the number of surviving juveniles, permitting greater parental investment in each, which has a big payoff and raises the growth rate. Higher mortality is a poor substitute for lower fertility, and a more flexible model might instead imply situational infanticide as observed for birds in nature (32).

consider a mortality decrease at an intermediate age, between 0 and the cessation of fertility. Selection will be negative near age 0 and positive near the last age of fertility, with a crossover someplace between

Selection leads to a more efficient life history, permitting the species to equilibrate at a higher density by investing more in each offspring (higher \_), and in this way crowds out the original population even though the original population can replace itself (*r* \_ 0) at a lower level of consumption

For empirical work, measures of transfers would ideally include not just food but also such activities as warming, fanning, guarding, carrying, leading, and teaching, and would also reflect incremental mortality risks incurred in making these transfers.

Among the various approaches to the evolutionary theory of aging, including the classic theory, the disposable-soma theory, formal life-history optimizations based on it, and other recent variations on these themes, none incorporates the flow of resources transferred to offspring.

But for many others, continuing transfers to offspring are centrally important for survival, growth, and eventual reproductive success, and such organisms have evolved lower fertility, and plausibly optimize the quantity–quality tradeoff. The theory offered here shows how evolution shapes the life histories of such organisms for efficient use of parental and other resources and most strikingly shows that, in this case, only the transfer effect shapes mortality, explaining both postreproductive survival and why juvenile mortality declines with age

**Leroi, A.M., Bartke, A., Benedictis, G.D., Franceschi, C., Gartner, A., Gonos, E., Feder, M.E., Kivisild, T., Lee, S., Kartal-O¨ zer, N., Schumacher, M., Sikora, E., Slagboom, E., Tatar, M., Yashin, A.I., Vijg, J. and Zwaan, B. 2005. What evidence is there for the existence of individual genes with antagonistic pleiotropic effects? *Mechanisms of Ageing and Development* 126: 421–429**

estimates place the heritability of longevity in western populations around 25% (Skytthe et al., 2003)

In 1957, George Williams proposed the ‘‘antagonistic pleiotropy’’ theory of senescence (Williams, 1957). Briefly, this theory held that ageing was due to the decline of the force of natural selection late in life, and that the fixation of alleles with positive effects upon fitness early in life also had deleterious effects late in life

lines of fruit-flies selected for late-life reproductive success became long-lived while also experiencing a decline in early-life fitness (fecundity, mating success) relative to lines selected for early-life reproductive success (Rose, 1984; Sgro` and Partridge, 1999)

human studies are association studies and so are always subject to the caveat that apparent pleiotropies (or even the main effect) may be due to linked loci

While it is certainly possible to measure fitness in laboratory populations of model organisms, such studies, if done at all, suffer from two objections: the alleles studied are often not natural polymorphisms but severe loss of function or even null mutants; and plush laboratory environments may obscure allelic effects that would be apparent in the wild (Zwaan, 2003)

five possible sources of antagonistic pleiotropy: gonadal signals, insulin-like growth factor signals, the control of free-radical production, heat-shock proteins and the control of apoptosis.

Among the many mutations that affect the fecundity of C. elegans, some of the most interesting are those that cripple glp-1, required for stem-cell proliferation in the germ. Such mutations produce few or no sperm and eggs and so are ~sterile. Interestingly, recently it has also been found that they are long-lived (Arantes-Oliveira et al., 2002).

Somatic maintenance (longevity) and gametes (fecundity) both require common, limiting, resources, proteins, lipids and the like

the gonads of the nematode worm, C. elegans, are the source of several molecular signals that regulate longevity (Hsin and Kenyon, 1999). Surprisingly, while the somatic gonad is the source of a signal that promotes longevity, the worm’s germ line is the source of a signal that represses it.

The evolutionary function of the germ-line signal, and whether or not it can explain the traditional ‘trade-offs’ detected by ecological experiments is a matter of debate (Leroi, 2001; Lessells and Colegrave, 2001; Barnes and Partridge, 2003)

loss-of-function mutations in the C. elegans insulin-like growth factor receptor homologue, daf-2 spectacularly increase longevity (Kenyon et al., 1993), a great deal of effort has gone into studying the effects of IGF signalling on longevity and health in a variety of organisms.

In C. elegans, insulin signalling appears to act at two stages in the life of the worm. First, during larval development it controls the formation of the stress-resistant dauer stage. Second, in adulthood it appears to regulate life-history as well, albeit in a more subtle way (Dillin et al., 2002).

A study of 16 independent daf-2 alleles shows a striking negative correlation between life time fecundity and longevity (Gems et al., 1998; Leroi, 2001) - as fine a demonstration of antagonistic pleiotropic effects between longevity and fecundity as one could hope to find

dwarfing mutations in drosophila leads to increases longevity and decreases fecundity

Perhaps the greatest surprise of recent years, has been the finding that insulin signalling also controls ageing in mammals

mutations (e.g., in the genes encoding pituitary specific transcription factors (Prop-1, Pit- 1) and growth-hormone-releasing hormone receptor (Ghrhr), cause mice to be dwarfed, long-lived with reduced fertility (Brown-Borg et al., 1996; Bartke et al., 2001a,b)

Why is antagonistic pleiotropy so pervasive in the IGF pathway? Many workers argue that IGF signalling is an ancient device to control alternate life-history strategies in the face of environmental vicissitudes

Under experimental conditions designed to mimic the natural environment, age-1 (phosphatidylinositol 3-OH kinase catalytic subunit) mutants suffered a 23% reduction in fitness relative to wild type worms (Walker et al., 2000); this had remained unnoticed under ‘‘standard’’ laboratory conditions

the Indy (I’m not dead yet, a membrane protein involved in the transport of Krebs cycle intermediates) mutation doubles the life time, but shows decreased fecundity only under caloric restricted adult food conditions (Marden et al., 2003).

The free-radical theory of ageing proposes that ageing is caused by the accumulated damage that reactive oxidative species inflict upon cells over the course of years

centenarians more commonly have the mitochondrial J haplotype than expected (De Benedictis et al., 1999; Ross et al., 2001; Niemi et al., 2003). Similarly, in the Japanese population the C5178A missense mutation (characterizing the Asian haplogroup D) has been reported to be associated with longevity (Tanaka et al., 1998). Do these longevity-associated haplogroups have any effect on early-life fitness?

it is hard to demonstrate the causal role of any given substitution on longevity, much less fitness. This is not the case for nuclear genes encoding mitochondrial proteins—and mutations in these genes frequently reveal antagonistic pleiotropic effects.

worms fed bacteria lacking coenzyme Q show an increase in late-life survivorship, but a decrease in early-life survivorship (Larsen and Clarke, 2002).

heat shock proteins seem to exhibit the sort of physiological relations that we might expect to give rise to alleles with antagonistic pleiotropic effects. Genetic experiments suggest that this is so.

Any system that regulates apoptosis might be expected to have antagonistic pleiotropic effects. Early in life, apoptosis is an anti-cancer mechanism; late in life, as stem cells no longer exist in sufficient quantity to maintain cell populations, it is supposed to contribute to the failure of tissue integrity. Any genotype, therefore, that increases late-life tissue integrity by repressing apoptosis does so at the expense of an increased risk of cancer

If, however, we consider the evidence for the existence of natural polymorphisms with antagonistic pleiotropic effects in the wild—the kind of polymorphisms most relevant to evolutionary theory and human health—the evidence becomes much thinner

**Metcalf, C.J.E and Pavard, S. 2006. Why evolutionary biologists should be demographers. *TRENDS in Ecology and Evolution* 22(4): 205-212**

Demography, the study of survival, fertility and population dynamics, is a crucial tool for evolutionary biologists. In particular, survival and fertility at each age or life-history stage determine offspring production, which defines fitness.

if the mutation acts at a specific age, the degree to which it alters fitness depends on the survival and fertility of the affected individual at all other ages. For example, if mortality is such that few individuals are alive beyond a certain age, and the contribution of these individuals to lifetime reproduction is negligible, mutations acting after this age are effectively neutral

late-acting deleterious mutations are subject to less selection and their resulting accumulation is one possible explanation for the evolution of senescence

Using a single fitness component as a proxy for fitness can, consequently, be problematic

timing effects: if a population is growing, mutations for earlier reproduction are successful because the earlier offspring are produced, the more descendants they leave

Life span varies from a few hours (mayflies) to hundreds of years (trees)

mammals can be categorized along a continuum from species with late maturity, few offspring per reproductive event and a long generation time, to species that reproduce early, have large litters and a short generation time), are relatively well understood. Some however deviate from this trend.

For example, mortality in many species increases with age (senescence), although it can also remain constant (e.g. hydra [32]) or decrease (e.g. a monocarpic plant [1]).

the force of selection does not necessarily decrease with age if fertility and survival increase sufficiently with age. This might explain why some species do not senesce.

Humans (and many other animals – Mortality is high for infants and is then low until maturity, corresponding to the initial drop in survival. In late adulthood, mortality increases gradually (senescence) and survival continues to falls away. Maximum recorded age is 122. Fertility peaks at \_30 and then falls to zero at \_50 (the age of menopause

Hydra – Over a period of four years, mortality was low and showed no sign of increase with age; consequently, survival diminished gradually. Fertility (both asexual and sexual reproduction) remained approximately constant

In Drosophila [37] and other species, lifespan can respond plastically to caloric restriction: if resources become scarce, individuals reduce metabolism, allocating resources preferentially to survival

Average population survival curves flatten off at advanced ages. However, this flattening might not accurately reflect the survival trajectory of an individual, but might be observed only because ‘frail’ individuals die early, so that only individuals with overall lower mortality are present at late ages [38,39].

it is still not clear, even for humans, what fraction of variation in age trajectories of survival is heritable, what fraction is environmentally imposed and what fraction is due to plasticity.

**Moorad and Promislow. Evolution: Aging Up a Tree?**

A new study [2] compares maximum lifespan in nearly 800 species of arboreal and terrestrial mammals. In support of Williams’ prediction, the authors find that arboreal mammals outlive their terrestrial counterparts. However, recent theoretical studies suggest that the explanation for such patterns may be more complex than previously thought.

This (extrinsic mortality) leads to the prediction that senescence should evolve to be more pronounced in environments with high risks of death.

Stearns et al. [4] found that flies evolved shorter lifespans when adults were exposed to high extrinsic mortality.

In a series of comparative studies, researchers have found that, in general, taxa that are protected from predators also appear to be long lived.

Among eusocial species, in which colonial life provides protection from both biotic and

abiotic hazards, queens have evolved lifespans an average of 100 times that of less protected solitary species [8].

Arboreal or semi-arboreal groups always lived longer than terrestrial ones (Figure 1), with the exception of primates and marsupials

While Shattuck and Williams’ [2] results are robust, G.C. Williams’ prediction regarding extrinsic mortality may turn out to be, well, up a tree.

models have shown us that selection can, indeed, actually favour reduced lifespan in the face of increased mortality if young individuals suffer more from the negative effects of high population density [11], or if the effect of extrinsic stresses depends on an individual’s intrinsic condition [12].

if density dependence acts primarily at late age, the effects of extrinsic mortality are reversed. Perhaps more importantly, mathematical models of extrinsic mortality [11,13] show that, if survival is density-independent, extrinsic mortality might have no effect whatsoever on selection.

if increased mortality in terrestrial habitats is density- or condition-dependent, slower aging could evolve.

**Partridge, L. and Barton, N.H. 1993. Optimality, Mutation and the Evolution of Aging. *Nature* 362: 305-311**

death is often proceeding by imitations of mortality, in the form of a decline in fertility and most aspects of biological performance, a characteristic of senescence or aging

aging is an evolutionary paradox if organism ca function well in youth why not when older?

aging reduces the contribution of older individuals to future generations

the rate of aging is highly variable

mechanistic accounts of aging invoke various forms of damage, to DNA, cells, tissues and organs. From this perspective the rate of aging could be determined solely by the level of exposure to damaging influences: the process would be inevitable and in no need of evolutionary explanation. not seen as even captive populations senesce.

Organisms vary in the extent to which they avoid or combat damage if it is a major factor – comparisons of birds and mammals of same size; turtles and other reptiles etc

because aging reduces the genetic contribution of individuals to the next generation it is opposed by natural selection.

but the selection that that maintains fertility and survival becomes weaker throughout life – even without aging organisms are at risk of death and impaired fertility from disease, predation and accidents

gnes that influence later life will be under weaker selection because by the time they take affect more of the original carriers will already have died or become infertile

problem of senescence one general question: to what extent does the degree of adaptation reflect the strength of selection?

aging could evolve as part of an optimal life history. On this view, senescence arises from the deleterious side-effects late in life of processes that are favourable early on (antagonistic pleiotrophy)

early reproduction may impair survival or future fertility by consuming resources causing somatic dmage or exposing the organism to environmental injury. The disposable soma theory is an optimal account of aging in which allocation of resources to reproduction jeopardizes somatic repair mechanisms and hence longevity

The optimisation theory of aging has become known as the ‘plieotropy theory of senescence’ because it is often developed in terms of genes with effects on more than one aspect of the phenotype, in this caseon the survival and fertility at different ages.

mutation pressure could lead to aging because the intensity of selection on later-acting mutants declines with age, alleles with deleterious effects will reach a higher frequency in a mutation selection balance the later the age at which they reduce fitness.

surprisingly, minor mutations reduce fitness just as much as those with larger effects, because they rise to higher frequency in a mutation slection balance

because a given change in performance has less effect later in life, we expect deleterious mutations to cause a greater frop in fertility and survival probability later in life assuming the same mutation rate for each age

the same argument can explain why different functions often decline with similar age: synchronous collapse does not imply a single mechanism of senescence

for empirical tests we must distinguish between predictions that are common to all evolutionary theories and those that can distinguish between optimality and mutation-accumulation.

because we know that there is a substantial input of deleterious mutations to populations and that it is impossible for individuals to combine indefinably high survival and fertility both the optimality and the mutation –accumulation theories of senescence must apply.

the two theories are difficult to separate as can both be tied to the same patterns – both e presence and absence of genetic variation could mean either theory is at work

if senescence is primarily due to late-acting deleterious mutations then one would expect the additive genetic variance to for survival and fertility to increase with age – not found in studies of drosophila

inbred lines of drosophila which are liable to give different colorations that actually occurring and are unsuitable for the evolution of aging

selection of breeding amoung older adults would be expected to reduce aging because of selection for higher longevity and fertility at older ages

misleading gene-environment interactions can occur in an environment other than in which the life history evolved. may apply to most published studies and a genral problem with experiments

environmental manipulations have the considerable advantage that they can be used in wild populations and they are also relatively quick

evidence for the mutation acculamaltion theory in drosophila – selected for early breeding for 120 generation s led to increased aging

affects of aging must have evolved – primordial soup replicators could ot have evolved if not immortal (genes are immortal) and senesce could be prevented with contious binary fission.

senescence of clones is probably cuased by the accumulation of deleterious mutations

**Partridge, L and Gems, D. 2002. Mechanisms of Aging: Public or Private? *Nature Reviews* 3: 165-175**

Ageing is a process of intrinsic deterioration that is reflected at the population level as an increase in the likelihood of death and a decline in the production of offspring1–3.

During ageing,macromolecules accumulate damage, including the PEROXIDATION of lipids, PROTEIN CARBONYLS and various forms of damage to DNA4,5

for work on these organisms (yeast, C. elegans and Drosophila) to be relevant to research in humans, their mechanisms of ageing need to be in common with those in mammals

We therefore need to know which mechanisms of ageing are ‘public’— those shared across distantly related evolutionary lineages — and which are ‘private’— those peculiar to particular evolutionary lineages13

ageing often occurs at different rates in different tissues and in different individuals, and seems to have a stochastic element16

Furthermore, no genes seem to have evolved specifically because they cause damage and, therefore, ageing. Ageing, and changes in its rate by genes and the environment, can be understood only as a side effect of something else

Calorific restriction, in which nutrient intake is restricted to 60–70% that of voluntary levels, slows ageing in many organisms,

21.A lower rate of reproduction also slows down ageing21,22; this so-called ‘cost of reproduction’ also occurs across a range of organisms

despite ageing’s deleterious nature, it occurs throughout the animal kingdom and is seen in natural populations in the wild25,26

Interestingly, among mammals, bats are long lived for their size27, which indicates that something about flight might lead to the evolution of a slower rate of ageing.

The key to the evolution of ageing lies in an observation by J. B. S.Haldane in the 1940s (REF. 29).Haldane was puzzled by Huntington disease — a genetic disease that causes severe mental illness and death

dominant lethal mutations can be maintained in a population by mutation if their effects are delayed until after reproduction

Is it possible that ageing itself is the result of mutations that strike very late in life, at ages beyond the control of natural selection

Two key theories had emerged: the mutationaccumulation theory and the PLEIOTROPY or trade-off theory (PLEIOTROPY

The capacity of different alleles of a gene to affect more than one aspect of a phenotype)

The evolutionary theories of ageing give us a clear, but stark, picture of the biological function of ageing: there is none. It is merely a nonadaptive epiphenomenon.

Species that lead a hazardous lifestyle or live in environments with high levels of external hazard from predators or disease will have high death rates, even in the absence of any intrinsic ageing process.

Late-acting deleterious mutations will therefore reach a higher frequency under the mutation–selection balance, and the latelife deleterious effects of pleiotropic mutations will weigh less heavily against their early benefits

Mutation accumulation might be expected to lead to lineage-specific, private mechanisms, because there is no reason for new mutations or their phenotypic effects to be shared across different evolutionary lineages

Under the theory of mutation accumulation, the heritable (additive) genetic contribution to death rates should increase in magnitude with age35

This theory also predicts that new mutations with late ages of onset should occur at a measurable frequency

the balance of experimental evidence is not strongly in support of mutation accumulation as a significant mechanism for the evolution of ageing. By contrast, pleiotropy/trade-offs and, in particular, a timelagged cost of reproduction, is implicated as an important general mechanism for the kind of delayed genetic effect that will lead to the evolution of ageing – (all experiments with drosophila which may not be a good species to use)

The evolutionary theories of ageing and the empirical tests of them indicate that differences in the rate of ageing between animal species might be partly due to a re-balancing of the trade-off between early reproductive rate and the subsequent rate of ageing in response to differing levels of extrinsic hazard

The key to understanding how the length of an organism’s life is specified is therefore to understand the mechanisms that generate latent damage and that determine the length of time between its occurrence and its expression as later mortality

findings from these model organisms, although somewhat different, hint at a possible mechanistic link between ageing and reproductive rates, through the response of both to variations in nutrient supply

The first-identified, long-lived *C. elegans*mutant carried a mutation in *age-1* (REF. 54). This gene encodes part of a lipid kinase enzyme (phosphatidylinositol-3 kinase)57 that transmits signals from DAF-2 (dauer formation constitutive) — a receptor that is thought to respond to insulin-like ligands — into the cell5

Mutant worms with defects in the chemosensory neurons that innervate the AMPHIDS show increases in mean lifespan of up to 121% (REF. 63). Studies of compound mutants have shown that these increases in lifespan result from reduced insulin/IGF signalling6

in wild-type *C. elegans*, ageing is accelerated by insulin/IGF signalling

The evolutionary theory predicts that the accelerated ageing is likely to be the downside of a trade-off with a fitness-enhancing trait, such as increased early reproductive output

The trade-off model is also particularly implausible in this instance because in *C. elegans*, unlike in *Drosophila*, egg-production levels have no discernible effect on lifespan54,55,72

if the germ line in C, elegans is removed by laser microsurgery, there are increases in lifespan68 and body size74 - a worm with a doubled lifespan might potentially be around for twice as long to reproduce

Strikingly, a mild reduction of *Inr* function increases mean female lifespan by up to 85% (REF. 78) and loss of function of *chico* by up to 52%

In contrast to studies in *C. elegans*, evidence from *Drosophila* studies provides some support for the hypothesis that the insulin/IGF pathway has a role in modulating a trade-off between fertility and longevity in response to changes in nutrition.

the hypothesis that trade-offs between fertility and lifespan are modulated by insulin/IGF signalling in response to nutrition, although more research is needed to confirm this hypothesis.

So, insulin/IGF signalling modulates the rate of ageing in two very distantly related animal species, and therefore represents a public rather than a private mechanism of ageing

There are many potential explanations for the increased lifespan of these dwarf mice: they are deficient in thyroid-stimulating hormone, growth hormone and prolactin, and have reduced fertility

in mammals, as in nematodes and probably insects, there exist powerful neuroendocrine modulators of ageing which shorten lifespan in wild-type animals

**Priest, N.K., Mackowiak, B. and Promislow, D.E.L. 2002. The Role of Parental Age Effects on the Evolution of Aging. *Evolution* 56(5): 927-935**

The phenotype of an individual can be influenced not only by its genotype and the environment in which it is raised, but also by the genotype and condition of its parents

From the genealogical records of 8797 descendants of a colonial American family, Bell found that children from older mothers had 45% shorter lives than children from younger mothers repeated in: rotifers, duckweed, house flies, stink bugs, fruit flies, flour beetles, mealworms, nematodes, and yeast. This pattern is referred to as the "Lansing effect," after Albert Lansing's (1947, 1948, 1954)

Evolutionary theories of aging, which assume that parental age effects do not influence life span, predict that cultivating old females should produce offspring that are longer-lived, not shorter-lived (Hamilton 1966; Williams 1966; Edney and Gill 1968; Charlesworth 1994).

Still, the role of parental age in the response to selection on aging is unknown.

If the effect of parental age on offspring longevity varies among genotypes, then selection on the quality of offspring produced by parents of different ages can influence the evolution of aging

quantitative genetic studies have established Drosophila as an ideal model system in which to test evolutionary theories of aging

the strains were cultured in plastic half-pint bottles at a density of approximately 250 eggs/bottle for two generations.

Egg density can affect patterns of mortality (Clare and Luckinbill 1985).

for the wild-caught strain UGA98, daughters of older mothers were significantly shorter-lived than daughters from younger mothers, with a 12% decrease in longevity overall. In contrast, for the laboratory strain, Canton-S, daughters of older mothers were significantly longer-lived than daughters of younger mothers, with a 10% increase in longevity.

Maternal age effects on sons were in the same direction as the effects on daughters, but in this case, only Canton-S showed a significant correlation

For experiment II, older mothers produced daughters with shorter lives (longevity declined by 5% for 79L, 26% for 67L, 15% for 58S, and 18% for 35S; Table 1, Fig. 1). Maternal age was only weakly correlated with life expectancy of sons. The effect of maternal age on daughters was significantly greater than on sons

In experiment I, maternal age did not significantly alter mortality slope or the intercept for any particular sex in the two genotypes. In experiment II, maternal age significantly influenced the mortality intercept and slope of daughters in many of the inbred strains

The sex-specific maternal age effects on longevity resulted from changes in intercept (maternal age X sex, and not slope

This study shows that both maternal age and paternal age can influence offspring aging. Older mothers produced shorter-lived daughters in five of the six strains we examined. The effects on longevity were largely consistent with the Lansing effect studies conducted over the past 50 years

Overall, we found that paternal age had a much weaker affect on offspring longevity than maternal age, although both maternal and paternal age influenced offspring mortality trajectories

It is not surprising that maternal age has a greater effect than paternal age on offspring longevity because the mother contributes most of the mRNA, lipid, carbohydrate, and protein molecules in the zygote cytoplasm.

we would have expected older mothers to produce longer-lived offspring regardless of the age of the mate

Our findings of genetic variation in maternal age effects on adult mortality, together with Kern et al.'s (2001) finding of genetic variation for maternal age effects on juvenile mortality, suggest that parental effects may play a fundamental role in the evolution of aging

Both of these models (mutation accumulation and antagonistic pleiotrophy) have implications for the influence of maternal age on the evolution of aging. First, parental age effects can alter the rate of mutation accumulation by changing the age-specific decline in the force of selection. Second, parental age effects can influence the na-ture of life-history trade-offs. The life history of an individual may involve balancing resources not only for early-age and late-age fitness traits, but also for fitness traits of offspring (Trivers 1974).

inclusive fitness and parent-offspring conflict theories, as developed by Hamilton (1964) and Trivers (1974), respectively, may turn out to play a critical role in the evolution of aging

**Williams, G.C. 1957. Pleiotrophy, Natural Selection and the Evolution of Senescence. *Evolution* 11: 398-411**

Senescence is a widespread phenomenon

an organism is an open system in a state of material flux

It is indeed remarkable that after the seemingly miraculous feat of morphogenesis a complex metazoan should be unable to perform the much simpler task of merely maintaining what is already formed

Weismann (1891) proposed a ‘specific death mechanism’ for aging

Aging fallacy: identifying senescence with mechanical wear and tear

other things being equal, a long lived individual will leave more offspring than a shirt lived one

Natural selection should ordinarily proceed towards lengthening life, not shortening it

there has been increasing awareness of the decline in selection pressures with increasing age

Comfort (1956) argues that senescence is outside the developmental program that concerns natural selection

no one would consider a man in his 30s senile, yet, according to athletic records and life tables, senescence is rampant during this decade

assume initially that senescence is an unfavourable character, and that its development is opposed by selection

an indirect effect of selection and results from the selection of genes that have different effects on fitness at different ages

Medawar (1953) expressed this concept in genetic terms by suggesting that linkage and pleiotrophy may be involved

**The Theory**

3) Pleiotrophic genes of a special sort. It is nessesary to postulate genes that have opposite effects on fitness at different ages, or, more accurately, in different somatic environments

Convincing examples are hard to find – more in modern times

best example (in 1950s) are black and speck mutants of Drosophila who increase longevity but are also rare in the wild

The wild alleles of these genes must confer some earlier advantage that offsets the later disadvantage

4) Decreasing probability of reproduction with increasing age

even in the complete absence of senescence there would be always be a cumulative probability of death with age

probability of reproduction at any age is a function of the probability of surviving to that age

No matter how low the mortality rate there is always a greater chance of surviving to age A than to age A+1

seasonal breeder would have not one but a series of modes, one for each breeding season

the key to understanding the evolution of senescence is any genic affect that arises late in life will have a low p-value

Natural selection could be said to be biased in favour of youth over age whenever a conflict of interests arises

An influence on the likelihood of coming through the birth process would alter the probability of survival to any age subsequent to birth

An effect of survival coming during the adult period, however, would alter only the part of the reproductive probability that follows the age of onset

since p starts to decline at the age of reproductive maturity, this point should theoretically mark the onset of senescence

each new gene effect is judged on the current reproductive probability distribution

any previously established genes that cause senescence will increase the rate of decline in p and make it easier for other genes to become established – self aggravating process

senescence might be regarded as a group of adaptively unfavourable morphogenetic changes that were brought in as side effects of otherwise favourable genes

the rate of senescence would depend on a balance between the favouring vigour of youth at the price of late life and direct selection that aims to reduce the ‘price’

**Testable decductions from theory**

1) no senescence of protozoan clones

asexuals should show senescence

there is a problem to what constitutes an individual in an asexual clone – confusion in plants also

2) low adult death rates should be associated with low rates of senescence and high adult death rates with high rates of senescence

in wild populations generally senescence has more than a slight influence on mortality

birds have a lower mortality rates than mammals of similar size and as expected greater potential longevity

the shells of turtles may account for greater longevity and lower senescence

according to theory death rates before maturation have no influence on the evolution of senescence

3) senescence should be more rapid in those organisms that do not increase markedly in fecundity after maturity than those that do show and increase

4) where there is a sex difference, the sex with the higher rate of mortality and lesser rate of increase should undergo more rapid senescence – males greater mortality, females longer lived

selection will always be greatest in the most senescence prone system

6) there should be little or no post reproductive period in the normal life cycle of any species

- not seen in humans often longer than reproductive period

sterility is the selective equivalent of death

not seen in humans often longer than reproductive period

no one is post reproductive until the youngest child is self sufficient

menopause a special and odd case – not part of the aging symdrome

multiple breeding leads to lower senescence

7) the time of reproductive maturation should mark the onset of senescence

8) rapid individual development should be correlated with rapid senescence

sexual maturity reached quicly in beetles – short life spans and high senescence

relationship between delayed reproduction and delayed senescence

9) successful selection for increased longevity should result in decreased vigour in youth

- it does not follow that long lived individuals were below average in youthful vigour

**Williams and Day.**

Senescence has been defined as a persistent decline in the somatic function of an organism with increasing chronological age, leading to decreased survival probability and/or fecundity (Abrams 1991; Rose 1991; Partridge and Barton 1993, 1996).

Empirical studies have generated evidence for both theories (pleiotropy: Rose and Charlesworth 1980, 1981; Walker et al. 2000; mutation accumulation: Mueller 1987; Charlesworth and Hughes 1996; Pletcher et al. 1998), although pleiotropy appears to be more strongly supported at present (Partridge 2001).

higher extrinsic (environmentally imposed) mortality rates are predicted to result in the evolution of higher rates of intrinsic, or senescent, mortality (Williams 1957; Edney and Gill 1968; Promislow 1991; Rose 1991; Stearns 1992) - Most of these studies report results that conform to this prediction, although a recent investigation with field crickets (Gray and Cade 2000) failed to generate any supportive data

One potential difficulty with many such tests, however, arises from an ambiguity in what is meant by ‘‘extrinsic’’ mortality.

That is, most of these sources are likely modified by a condition-dependent component, where individuals of poorer condition experience enhanced susceptibility relative to those in better condition.

Given the ubiquity of parasitism in natural populations, immune senescence is likely an important component of condition-dependent mortality risk

Finch (1990) pointed out that even relatively mild joint and/or bone deterioration might greatly increase a bird’s probability of succumbing to environmental hazards and might help to explain the slow rate of senescence in many avian lineages

the potential importance of interactions between organismal condition and environmental hazard appears generally to have been underappreciated in most experimental studies of senescence evolution

Evidence for such a trade-off has appeared in numerous works with *Drosophila melanogaster* (Luckinbill et al. 1984; Rose 1984; Zwaan et al. 1995; Partridge et al. 1999) and other taxa (Rose 1991).

Despite this apparently broad range of possible evolutionary outcomes, our analyses of the way that fitness sensitivity expressions change in response to increases in conditiondependent hazard levels indicates that timing effects can have important general consequences for the predicted direction of evolution in senescent deterioration

if both benefits and costs occur early in the life history, selection will often favour decreased senescent deterioration, whereas large time lags between receiving fecundity benefits and paying senescent costs can favor increased senescent deterioration

we predict that, in response to increased condition dependent hazard, optimal senescence schedules should often show a pattern of decreased age-specific deterioration early in life, but a steeper rate of change in age-specific deterioration, and possibly greater age-specific deterioration, at late ages.

In other words, fish from high-predation areas might display a more abrupt pattern of senescence in the ability to escape predation than fish from low-predation areas, a pattern that has recently been found using populations of guppies

Our results also suggest that, given the ubiquity of condition- dependent mortality sources, Williams’s hypothesis should often not be correct

Stearns et al. (2000) found evidence for greater intrinsic mortality in flies from high extrinsic mortality treatments.

Such experimental conditions are the most conducive to obtaining support for the hypothesis (issues of population regulation aside; see Abrams 1993), but their relevance to evolutionary responses in natural populations, where much extrinsic mortality is condition-dependent, is unclear.

the mortality rate at any given age, and therefore the pattern of mortality throughout an individual’s life, will depend on the environment in which it is measured

Suppose, however, that extrinsic mortality is mediated through condition-dependent hazards and that physiological senescence has actually evolved to be lower (see Fig. 2) in response to higher hazard (i.e., organisms in the high-hazard environment have evolved decreased levels of age-specific physiological deterioration when compared to those of the low-hazard population).

**Experiments**

* **DENSITY**

**Baldal, E.A., van der Linde, K., van Alphen, J.J.M., Brakefield, P.M. and Zwaan, B.J. 2005. The effects of larval density on adult life-history traits in three species of Drosophila. Mechanisms *of Ageing and Development* 126: 407–416**

The importance of longevity and starvation resistance to the mechanisms of ageing in part explains the interest in these traits.

Several authors working with D. melanogaster have found that longevity and starvation resistance are correlated

(e.g. Chippindale et al., 1993; Zwaan et al., 1991). Others found that selection on starvation resistance can increase longevity (Harshman et al., 1999; Rose et al., 1992) and vice versa (Zwaan et al., 1995)

environmental factors that affect life span and ageing (Tu and Tatar, 2003; Zwaan, 2003), including larval density (Miller and Thomas, 1958).

Longevity, starvation resistance and fat-content all show positive responses to higher larval density (Lints and Lints, 1969; Luckinbill and Clare, 1986; Miller and Thomas, 1958;Robinson et al., 2000; Sorensen and Loeschcke, 2001; Zwaan et al., 1991)

D. melanogaster lines reared at high densities showed higher starvation resistance than the same lines when reared at low densities

Selection lines for higher longevity in D. melanogaster showed elevated lipid content later in life (Djawdan et al.,

1996), and in general starvation resistance positively correlates with fat content (Djawdan et al., 1998; Graves et al., 1992; Zwaan et al., 1991).

starvation resistance and longevity are clearly related characters, and this relationship is modulated by larval density.

Longevity is the time between eclosion of the adult from the pupa and death of the adult under standard food conditions

The overall analysis shows a significant negative effect of increasing density on starvation resistance. The analysis of SR showed significant effects of species and density.

sexes behave differently among species. This is largely explained by the differences between males and females in D. melanogaster.

SR decreased significantly with increasing larval density in D. melanogaster, D. willistoni and D. ananassae

For longevity, both species and density were significant factors. However, sex differences were not found for this trait. The species–sex–density interaction showed a significant effect

Density was not important for D. melanogaster and D. ananassae longevity but was for D. willistoni

Larval density was important for SR2 in D. melanogaster and D. willistoni, but not for D. ananassae. In addition, D. melanogaster and D. willistoni showed significant sex–density interactions. D. willistoni males showed their highest starvation resistance at medium density whereas females showed their lowest starvation resistance at that density

The size of D. melanogaster and D. willistoni females declined with increasing larval density, whereas males showed no significant affect

In general, females of each species showed a stronger reduction in dry weight with increasing density than males. This effect on body size suggests that the animals were mildly stressed by higher larval density.

D. melanogaster and D. ananassae males showed effects of increasing larval density on adult fat content, whereas females did not

D. ananassae, D. melanogaster and D. willistoni showed significant effects of larval density on adult starvation resistance directly after eclosion and after 2 days of food

D. melanogaster is likely to allocate resources to reproduction rather than to somatic maintenance under laboratory circumstances

Female dry weight and fat-free dry weight declined in response to larval density. Males had a more uniform dry weight over different larval densities. Generally, fat content increased for all species and sexes with increasing larval density

animals from high larval densities showed the shortest starvation resistance.

We found that exposure to higher larval density reduces body size. This is in line with Santos et al. (1994), who found a decreased fitness and thorax length, and thus body size, at increasing densities

The effects of larval density in the present study tend to be small but are likely to reflect important responses to developmental conditions. Thus, we conclude that higher larval densities lead to smaller flies with a high relative fat content and reduced starvation resistance.

Starvation resistance is associated with longevity, suggesting that these traits share molecular pathways.

In the present study, relative fat content increases, and starvation resistance decreases with increasing larval density and vice versa

Responses of SR and longevity to larval density seem to follow a similar trend of reduced life span with increasing larval density in our experiments (Fig. 2) suggesting that these life-history characters share physiological

**A. N. Clements, A.N. and G. D. Paterson, G.D. 1981. The Analysis of Mortality and Survival Rates in Wild Populations of Mosquitoes. *Journal of Applied Ecology* 18: 373-399**

It is generally accepted that in nature few organisms die of senescence, most being killed by predators, disease, and other hazards long before they reach old age (Krebs 1972), and as a corollary of that belief it is sometimes deduced that mortality rates are independent of age (Macdonald 1952)

field, Macdonald (1952) concluded that the full life span of females is measurable in months but that in nature few females survive to die of old age, most dying of one or other hazards of wild life

Two patterns of survival can be shown to be appropriate for adult mosquitoes. In one, the mortality rate does not vary with the age of the individuals, and the points of the log survivorship curve fall approximately on a downward-sloping straight line. In the other the mortality rate increases with age, and here the points fall on a curve which is concave below

The Gompertz survival function has the form of a curve that is concave below, and a plot of the logarithm of the instantaneous mortality rates against age yields a straight line that slopes upwards

This section presents techniques for analysing survival data, in particular for establishing whether mortality rates are constant or increase with age and, in the latter case, for establishing whether or not they accord with the Gompertz mortality function

The first step is to plot the numbers N. on a logarithmic scale against age on a linear scale, producing a survivorship curve for the population. If the points fall approximately on a straight line then the simple exponential model may be appropriate, implying that the mortality rate does not vary with age

Mortality rates in laboratory cohorts will be considered first. Such data are relevant to the present study because they provide patterns of mortality and survival under conditions in which many individuals may survive to die of old age; they therefore represent the base line state which is modified on exposure to natural condition

In an early experiment, Gillies (1961) estimated the survival of Anopheles gambiae from a mark-recapture experiment carried out near Muheza. Regression of numbers recaptured against age showed that the males had a constant loss rate, due to mortality and possibly to emigration, for 30 days after release (P > 0.9), with a daily 'survival rate' of 0.862. The females showed a constant loss rate for the period 4 to 23 days after release (P = 0.1), with a daily 'survival rate' of 0.853

There was a tendency for the female mortality rate to increase with age over the adult life-span as a whole, and the Gompertz model gave a satisfactory fit to the survivorship data

It can be seen that the longevity factor is a term compounded of probability of survival to a later age (x + n) and the life expectancy of survivors at that age

It is certainly widely believed, or at least assumed, that in wild populations of mosquitoes the adult female mortality rates are independent of age (Garrett-Jones & Shidrawi 1969; Weidhaas et al. 1974; Dietz, Molineaux & Thomas 1974; Molineaux 1978), although some workers have recognized that mortality rates are higher among the small percentage of older female

Survival records are available for adult females, of a number of mosquito species, when held captive and fed more or less normally with both sugar and blood. In all cases the mortality rates increased with age, and in the cases where they had been analysed appropriately it was found that the Gompertz mortality function provided an accurate description of the mortality rate

In species for which the mortality rates of both captive and wild populations are known, i.e. Aedes aegypti (Putnam & Shannon 1934; McDonald 1977a) and Culex quinquefasciatus (Briegel & Kaiser 1973; Samarawickrema 1967), it is clear that mortality rates are much higher in the wild than in captivity, confirming that predators and other hazards of the wild take a toll of mosquito life.

Gillies & Wilkes (1965) observed, with three species of Anopheles, that female mortality rates increased during the later gonotrophic cycles, but they stated that in An. gambiae and An. funestus the mortality rates remained constant

**Graves, J.L. and Mueller, L.D. 1993. Population density affects on aging. *Genetica* 91: 99-109**

The study of the consequences of population density on the longevity of organisms was in fact first explored by scientists interested in problems in evolutionary ecology

Iteroparity, which is the pattern displayed by humans, fruit flies and many other organisms, is characterized by repeated episodes of reproduction after sexual maturity and thus a prolonged adult life stage.

MacArthur and Wilson suggest that natural selection will act in qualitatively different ways for populations kept at very high densities as opposed to those kept at very low densities.

low density conditions rapid reproduction and thus early maturity and semelparity would be favored, while at high population density repeated reproduction and thus iteroparity should be advantageous.

Many of the logical underpinnings of these verbal theories have been found to be faulty (see Mueller, 1991,

if density dependent natural selection acted only on pre-adult survival or fecundity, then it is possible that selec tion would favor increased longevity and delayed reproduction

An important aspect of drosophila experimental protocol is that population density decreases over

time since dead individuals are never replaced.

the patterns of mortality from these types of experiments show a response which reflects both the aging process (which presumably increases rates of mortality) and declining density (which will presumably decrease rates of mortality).

At later ages the variance in mortality rates between lines becomes so large that accurate assessment of mortality rate is not possible;

These data show that the patterns of mortality may also vary between males and females but larger samples would be required to establish this definitively.

populations of medflies were also experiencing declining population density, which would be expected to cause rates of mortality to rise and then decline in a manner similar to what has been observed for the numerous *Drosophila* populations.

In this light the Carey *et al.* results are more relevant to density dependent mortality than they are to the process of senescence (Nusbaum *et al.,* 1993).

if populations faced an early density crisis, and survivors might expect lower overall densities and a renewal of resources, then selection for delayed reproduction might result sult

First, if all individuals at high density are reproducing early, than larval competition would be fierce. Any individual who could withhold reproduction and lay eggs after the population has crashed may actually reproduce more offspring over their life time.

One of the most obvious mechanisms by which population density may affect Darwinian fitness and hence longevity is by food limitation

Numerous examples exist in which both invertebrate and vertebrate animal populations have been shown to have their fertility lowered or mortality increased by food scarcity - The competition for food generally has greater fitness effects on juveniles

Dietary restriction (DR) has a somewhat broad phylogenetic occurrence and is particularly powerful in its extension of mammalian longevity

Experimental evidence exists to support the assertion that dietary restriction operates by fostering analogous trade-offs between growth, survival, and reproduction in a wide variety of organisms:

High population density may also affect the ability of individuals to withstand stress of various sorts. These effects may then make individuals more susceptible to background causes of mortality, thus reducing longevity

Of course from the control populations it is also clear that high density alone dramatically increases the chances of mortality, especially at young ages when these density differences were most profound. – see paper for strudy example

The effects of density may act in specific ways thatare peculiar to certain groups of organisms.

Is it possible that the density at which larvae are raised could have an effect on the ability to select for adult longevity?

Miller and Thomas (1958). They showed that larval crowding, which generally reduced the size of the resulting adults, had the effect of increasing adult longevity.

Miller and Thomas showed that larval densities of 5-20 larvae/vial showed no appreciable change in final adult size but at densities of 40, 60, 80 and 100 larvae/vial adult size showed a continuous decline - thus larval densities used by other studies may not be on a scale to measure variation in larval densities

In general there was little evidence that age-specific selection affected the traits that responded to density-dependent selection or vice versa.

**Hawley 1985. THE EFFECT OF LARVAL DENSITY ON ADULT LONGEVITY OF A MOSQUITO, AEDES SIERRENSIS: EPIDEMIOLOGICAL CONSEQUENCES**

In no case, however, has it been shown that intraspecific variation in adult longevity may be related in a simple fashion to larval density – in 1985 at least

The present study shows that for a wild mosquito population (i) pupal size is inversely related to larval density and (ii) adult longevity is positively correlated with adult size.

Pupation success of A. sierrensis did not depend on larval density (Fig. l a), but mean pupal weight of females was inversely density dependen

in general, groups of larger females had higher parous rates than smaller ones

For A. sierrensis, adult longevity depended upon pupal size (Fig. 2), which depended upon larval density

For some species, mortality rate increases with age (Clements & Paterson 1981); for A. sierrensis, the nature of the relationship between age and mortality rate in nature is unknown

The total expectation of infective life calculated from equations in Table 2 differs greatly from that predicted on the assumption of size-independent adult survivorship only when larval densities are in excess of about 1000 larvae 1-1

Density-dependent adult survivorship is therefore of real epidemiological significance, and should be considered when designing control measures for this species.

Negative results from laboratory studies should not, however, be extrapolated to nature: survival of A. sierrensis adults is not size dependent in the laboratory

Density-dependent size variation occurs in mosquito populations in nature (Mogi 1984) and is repeatedly observed in the laboratory

survivorship. I know of no case of failure to find density-dependent size at metamorphosis in a mosquito population where the study has been designed to look for such an effect.

The ubiquity of size-dependent survivorship of adult female mosquitoes is less certain. The phenomenon has been reported for wild populations of Aedus triseriatus (Haramis 1983) and overwintering Culex pipiens pallens (Makiya & Taguchi 1981), but results for laboratory populations are mixed

**Leips, J. and Mackay, T.F.C. 2000. Quantitative Trait Loci for Life Span in *Drosophila melanogaster*: Interactions With Genetic Background and Larval Density. *Genetics* 155: 1773–1788**

Despite this near universal property, the potential life span of individuals varies a great deal among species (Finch 1990; Austad 1997; Gagny *et al.* 1997; Lass *et al.* 1997; Martı´nez 1998; Vaupel *et al.* 1998) and populations (Austad 1996; Ricklefs 1998).

Understanding the genetic basis of life span variation that and how the genetic components interact with environmental influences to limit life span is not only of practical importance to the medical community, it is fundamental for understanding how the process of aging itself has evolved

Both theories of aging are based on the assumption that the strength of selection declines with increasing age following the onset of reproduction (Hamilton 1966; Charlesworth 1994).

Evaluation of these hypotheses requires identifying the genes that contribute to variation in aging, determining their age- and environment-specific effects, and the pleiotropic effects of these genes on traits directly related to fitness (*e.g.*, age-specific fecundity, age at maturity)

the effects of specific genes on aging and life span limitation are mediated by environmental variation (Kenyon *et al.* 1993; Gems *al.* 1998). Second, there is increasing evidence that many genes that contribute to variation in life span have pleiotropic effects on other traits and interact epistatically with other genes to influence life span (Gems *et al*1998; Tissenbaum and Ruvkun 1998).

Larval density varies a great deal in natural populations and is known to affect life span (Miller and Thomas 1958; see review of Graves and Mueller 1993) as well as a number of traits directly related to fitness (*e.g.*, age and size at eclosion; Miller and Thomas 1958; Barker and Podger 1970; Prout and McChesney 1985). Differences in larval density also affect the amount of heritable variation in life span that is expressed (*e.g.*, Clare and Luckinbill 1985; Buck *et al.* 1993a). Thus, larval density is an important ecological variable with potentially important effects on the evolution of life span.

On average newly eclosed male and female flies fromthe low density density vials were 15 and 16% heavier, respectively, than those that emerged from the high density vials

No other main effects (sex and density) or their interactions significantly affected life span.

the main effect of sex was significant, and females lived z20% longer than males in both densities.

For males, the only significant effect on life span was due to the cross-by-line interaction, which occurred in both density treatments. This interaction explained 9 and 11% of the total variation in life span in the low and high density treatments

6 QTL contributed to the variation in life span among lines, but different QTL were identified as important in each sex and larval density

Five QTL affected the sensitivity of life span to variation in larval density, but none were common to both sexes

In general, genetic differences among RI lines were evident for both males and females after exposure to high larval densities;

our finding that genetic variation for life span is more prevalent in high than in low density is consistent with the observation that selection for increased life span is more effective when flies are reared in high larval densities (*e.g.*, Clare and Luckinbill 1985;

genetic differentiation among lines in their general stress response may be reflected by differences in life span

Higher larval density generally leads to longer life span in *D. melanogaster* (Miller and Thomas 1958; Zwaan *et al.* 1991; Buck *et al.* 1993a), although in our experiment the response to density depended on sex and genotype

Oxidative damage from ROS is thought to be a major factor in aging (Harman 1956) and life span and several studies support this hypothesis (*e.g.*, Orr and Sohal 1994; Dudas and Arking 1995; Deckert-Cruz *et al.* 1997; Hari *et al.* 1998; Parkes *et al.* 1998).

Our finding that the effects of QTL genotypes on life span depend on genetic background, sex, and larvalenvironment is surprising

Life-history theory predicts that little, if any, genetic variation should persist for these traits because natural selection should fix the genes that produce the optimal phenotype in a given environment.

**Scott, D.E. 1994. The Effect of Larval Density on Adult Demographic Traits in *Ambystoma Opacum. Ecology* 75(5): 1383-1396**

Conditions in the larval environment may exert effects that extend beyond the larval stage

experimental studies have shown that larval density and food availability affect adult body size, fecundity, survival, and age at first reproduction – see paper for various examples

Adults from a pond of high tadpole density were small-er and averaged lower clutch sizes than frogs from a pond of low tadpole density (Berven 1988).

Frogs that were small at metamorphosis exhibited reduced adult survival and later age at first reproduction than those that were large

Few experimental studies have been conducted to determine the influence of larval conditions on adult traits in amphibians.

Collectively, these studies suggest that larval envi-ronment influences age and size at metamorphosis. These variables in turn influence species population dynamics and components of adult fitness,

At high initial hatchling densities, larvae grew more slowly and exhibited reduced larval survival, longer larval periods, and smaller body size at metamorphosis than larvae from low-density treatments (Scott 1990).

just used low and high density – no mention of what normal density is or any control of what this might be

Individuals from low larval densities metamor-phosed at significantly larger body size

Larval density also tended to affect the proportion of lipids in the carcass dry mass ofjuveniles (Table 1). Means for the low-density treatment groups were higher than for high-density treatment groups,

The effect of larval density on body size extended beyond the larval environment to the adults. First-breeding adults that were reared at low larval densities were larger than those from high densities

Low density promoted larger body size at metamorphosis (Table 1), which in turn trans-lated to larger SVL at first reproduction.

Larval density exerted a strong influence on age at first reproduction (DENSITY x REPRO). Averaged across sexes and years, 50% of the returning adults from low-density treatments matured in <2 yr, com-pared to 32% from high-density treatments.

Larval density effects on clutch size were evident in the 5-yr-old females

Differences in larval density caused variation in body size at metamorphosis (Scott 1990).

animals rely on energy reserves ac-cumulated during their larval period, which allow them to subsist for some time without feeding.

Within each cohort, low density and large size at metamorphosis appeared to enhance postmetamorphic survival, per-haps by reducing mortality directly in the 1st yr (Ber-ven 1990) and by reducing the time to maturation, thereby raising the probability that an individual will survive to reproductive age.

For species with com-plex life cycles, dispersal from crowded larval condi-tions may be important in population regulation (Crowley et al. 1987),

flexibility in traits such as age and size at maturity is indicative of potentially adaptive plasticity in life history traits (Rez-nick 1990)

a phenotype that results from en-vironmental modulation may exist simply because the individual passively responds to its environment (Smith-Gill 1983).

Given the strong link between metamorphic size and adult fitness observed in this study, one might expect greater plas-ticity in date of metamorphosis than is observed; small larvae might be expected to delay metamorphosis un-der favorable conditions to attain a larger size. – not seen is this study and also concurrent with beetles

larval density affects body size at metamorphosis and thereby a suite of adult traits presumably related to fitness.

In this study, low larval density was associated with higher survival to first re-production, larger body size at first reproduction, and earlier reproduction.

**Zwaan, B.J., Bijlsma, R. and Hoekstra, R.F. 1991. On the developmental theory of ageing. I. Starvation resistance and longevity in *Drosophila melanogaster* in relation to pre-adult breeding conditions. *Heredity* 66: 29-39**

The developmental theory of ageing predicts a positive correlation between developmental time and adult longevity

Current theories of ageing can be roughly divided into two groups: evolutionary and non-evolutionary theories

According to evolutionary theories senescence evolved as a non-adaptive trait for which no direct selection in nature occurs (Kirkland, 1989).

The developmental theory is the major non-evolutionary theory of ageing (Lints, 1978, 1988).

The theory considers life-span as an epigenetically controlled trait, i.e. whose expression is linked to the regulation of gene function and differentiation

It has been shown that increasing larval density results in an increased adult lifespan (Miller & Thomas, 1958; Lints & Lints, 1969).

The positive correlation found between developmental time and adult longevity (Lints & Lints, 1969) is caused by the increase in developmental time with larval density (Bakker, 1961; Barker & Podger, 1970). However, this relation is not necessarily a causal one

Because of the decrease in viability and adult body weight with increasing larval crowding (Bakker, 1961; Barker & Podger, 1970; Prout & McChesney, 1985), viability selection during the pre-adult stage and/or a change in adult physiology induced during the pre-adult stage might be involved.

Viability (egg-to-adult survival) was measured as the ratio of the total number of emerged flies to initial egg density of vials. Mean viability could be calculated over vials in each experimental group. For statistical analysis, angular transformation was applied to viability data.

Longevity (in days) of an individual fly was taken as the midpoint between two successive scorings. In this way mean longevity could be calculated over all individuals for each group and sex

The relative amount of fat is a determinant parameter for survival time without food (David et al., 1975a,b; Service 1987). – Something possible to look at in the future if results support some sort of starvation is occurring

Adult longevity (Table 2) increased significantly with increasing larval crowding for both females and males

Moreover, as commonly found for crowding, it also significantly affected developmental time, adult body weight and viability

Adult body weight decreased for females and for males with increasing crowding levels

In general, female and male longevities were not seriously altered by decreasing food levels.

Interestingly, even when the amount of yeast/egg was kept constant, increasing larval density was accompanied by an increase in longevity

Assuming that almost all mortality occurs during these first 60 h, - replicated across species? - beetles could die very quickly if out competed, maybe not if mould is a factor in low density treatments

There was no suggestion of an interaction between larval density and the 'time of eclosing' (F4249 = 1.33, P< 0.30), which implied that the effects of larval crowding on starvation resistance remained the same for all emerging groups

Apparently, different developmental conditions do not change the physiological dependence of starvation resistance on the relative fat content

From these results it becomes apparent that there was no unequivocal relationship between pre-adult developmental time and adult longevity

Both Miller & Thomas (1958) and Lints & Lints (1969) have shown that larval crowding increases adult longevity

However, Economos & Lints (1984b) showed that adult longevity in fact depended in a biphasic (parabolic) way on growth rate, and that duration of development was not a causative factor of life-span

when the growth rate is calculated from our data, using the same methods as Economos & Lints (1984a,b), no consistent relation at all was found between adult longevity and growth rate for either experiment

It can be concluded, therefore, from both our and previous results, that developmental time and growth rate are not related to ageing in D. melanogaster

If viability is decreased, only the fittest individuals survive to adults (viability selection) and this increase in mean fitness becomes evident in increased adult longevity and starvation resistance (fat content).

it is well known that female flies grown under crowded conditions have a lower total lifetime fecundity than uncrowded females (Lints & Lints, 1969; Prout & McChesney, 1985), probably because of their smaller body size.

In ageing individuals many normal body functions, such as food intake, are impaired and, consequently, relative fat content will determine the total duration of adult life, because it principally detennines survival time without food (David et al., 1975a,b; this study

Little is known about the precise physiological changes during ageing and the exact causes of death in Drosophila

The selected long-living phenotype is only expressed at higher larval densities, and it has been suggested that the physiological mechanism for this density-threshold is rooted 'in the complex of physical effects and feeding relationships

It has been suggested that this gene-environment interaction during the larval period is responsible for programming the eventual beginning of the senescent period (Arking, 1987)

It is possible that the density-threshold for the expression of longevity in selected lines could be the result of an increased fat content in high density groups, as in our experiments.

* **AGEING**

**Fox, C.W., Czesak, M.E. and Wallin, W.G. 2004. Complex genetic architecture of population differences in adult lifespan of a beetle: nonadditive inheritance, gender differences, body size and a large maternal effect. Journal of Evolutionary Biology 17: 1007–1017**

nonadditivity can cause the additive effects of alleles to change as the genetic composition of the population changes (i.e. the genetic variance–covariance matrices change in response to selection) and, as a result, the alleles that are favoured by selection, and the genetic relationships between traits, can change as the genetic background evolves

The evolution of lifespan, mortality rates and patterns of senescence is of substantial interest both because there is tremendous variation in these traits at all taxonomic levels (e.g. Promislow, 1991; Tatar, 2001) and because of the medical implications of genetic analyses of these traits.

studies of lifespan in D. melanogaster indicate that both dominance and epistasis may have significant effects on variation in lifespan

little is known about the genetic architecture of lifespan and senescence for organisms other than D. melanogaster and C. elegans

previous QTL studies with D. melanogaster have shown that the loci affecting lifespan differ between males and females and vary among rearing environments (Nuzhdin et al., 1997; Vieira et al., 2000; Harshman, 2002; Mackay, 2002;

Larval development and pupation are completed entirely within a single seed of their host species

adults have no access to food or water in a storage environment (they cannot feed externally on seeds) and there is little evidence that they feed as adults outside of a storage environment.

Life span and mortality rates of C. maculatus have been examined in numerous previous studies (Møller et al., 1989; Tatar et al., 1993; Tatar & Carey, 1994a, b, 1995; Fox et al., 2003a, b, 2004a).

The SI beetles lived longer than BF beetles by over 4 days in all sex–host combinations (Figs 1 and 2a,b; analysis of variance, F > 201, P < 0.001; for both sexes) and females outlived males by over 5 days in all population–host combinations

The SI beetles were significantly larger than BF beetles regardless of sex or rearing host (F > 741, P < 0.001) and in all population–host–sex combinations adult lifespan was positively correlated with adult body mass – larger beetles living longer

The mortality curves (hazard functions) for males and females were nonproportional within both populations, indicating that the mortality curves were not simply shifted between the sexes but that they actually differ in shape

For the SI population, males had both a faster rate of increase in mortality (b) and greater deceleration (s), but the baseline mortality rate (a) did not differ between the sexes – For the BF population, all three parameters of the logistic mortality curve differed between the sexes; males had a lower baseline mortality rate (a), but had a higher rate of increase in the mortality rate (b) and more rapid deceleration (s) than did female

For all sex–host combinations except females reared on cowpea, the slope of the mortality curve (b) was significantly greater for BF beetles than for SI beetles

In females, long lifespan alleles were generally dominant over short lifespan alleles – lifespan of hybrid female offspring resembled the lifespan of SI females. However, dominance was detected in only one of the two analyses for male lifespan and the composite genetic effect for dominance was smaller in both groups of males than in either group of females

the lifespan of male C. maculatus was influenced by a large maternal effect. In contrast, male lifespan was affected by a large and highly significant maternal effect that was not observed for female lifespan

some of the variation in lifespan among lines was explainable by differences in body size and, after correcting for body size variation, epistasis was detectable for the lifespan of females

In C. maculatus, the genetic correlation between the lifespan of males and lifespan of females is much less than 1.0 (e.g. Fox et al., 2004a) indicating that either different genes affect the lifespan of males and females or that these genes have different effects in the two sexes

offspring of older mothers lived longer than did offspring of younger mothers (Fox et al., 2003a) opposite the pattern commonly observed in other organisms (Priest et al., 2002).

Previous studies have found that patterns of mortality (e.g. Tatar et al., 1993; Messina & Fry, 2003) and the genetic architecture of lifespan (e.g. Leips & Mackay, 2002) both change when individuals are mated,

**Hämäläinen, A., Dammhahn, M., Aujard, A., Eberle, M., Hardy, I., Kappeler, P.M., Perret, M., Schliehe-Diecks, S. and Kraus, C. 2014. Senescence or selective disappearance? Age trajectories of body mass in wild and captive populations of a small-bodied primate. *Proceedings of the Royal Society B* 281: 20140830**

The increase in mortality probably results from functional senescence (FS, within-individual deterioration of physical or physiological functioning with advancing age), which, along with terminal disease or investment in reproduction at the expense of maintenance [5–8], can expose individuals to extrinsic hazards in a condition-dependent manner

Classic theories on life-history evolution [14] posit that populations with high extrinsic mortality (EM) rates (random mortality from environmental causes) should have a reduced lifespan and age rapidly, and support for this pattern has been found with experimental and comparative work [3,15–18].

In spite of the supposed significance of extrinsic factors in shaping life histories, ageing research is still largely biased towards captive animals living under standard, benign conditions (e.g. [16,19,20]).

the study of wild populations with high EM risk is essential for testing hypotheses on the evolution of lifespan and FS

The sexes often differ in their life histories, EM hazard and ageing processes [24–27], and female mammals typically enjoy longer lifespans than males [28

Therefore, a direct comparison of the sexes is essential for deciphering the evolutionary mechanisms behind senescence and lifespan determination.

BM broadly reflects resources available for allocation to physiological processes, making it a meaningful indicator of FS.

Given the high EM of M. murinus in the natural environment, we predicted average lifespan to be shorter in the wild than in captivity

however, extrinsic hazard selectively removes individuals in poor condition, evolutionary processes might instead lead to delayed FS or the survival of only the highest quality individuals (showing little senescent decline) to an old age.

As the same physiological processes presumably drive FS, senescent within-individual declines might nevertheless occur in both the wild and captivity.

Excluding juvenile mortality, captive males lived on average one season longer than females. By contrast, average minimum lifespan of wild females was on average seven months longer than that of males

An energy imbalance can quickly render an individual susceptible o disease [59] and predation [60] or lower their success in resource competition

However, our models indicated no support for sex differences in ageing in either captive or wild animals. It is possible that sex biases in mortality may lead to sex differences in FS, but these differences are masked by the strong seasonal effects and rapid terminal changes

As expected, the estimated lifespans of wild and captive M. murinus differ substantially: captive males live on average twice as long and females 50% longer than their wild counterparts

if lifetime fitness is sufficiently enhanced by living longer, selection may favour somatic maintenance and counteract the accumulation of damage [2,29,65]

**Maklakov, A.A., Fricke, C. and Arnqvist, G. 2007. Sexual selection affects lifespan and aging in the seed beetle. *Aging Cell* 6: 739–744**

Theory suggests that senescence evolves because the intensity of natural selection declines with age (Medawar, 1952; Williams, 1957; Partridge & Barton, 1993; Charlesworth, 1994; Hughes & Reynolds, 2005).

Increased rates of extrinsic mortality should lead to accelerated rates of intrinsic mortality (i.e. senescence) under both of these scenarios (Partridge & Barton, 1993; Hughes & Reynolds, 2005), and this prediction has been supported experimentally (Stearns *et al*., 2000

However, it has also been suggested that a high extrinsic mortality rate can select for increased investment in somatic maintenance, which can in turn result in decelerated senescence (Abrams, 1993; Williams & Day, 2003; Williams *et al* ., 2006)

In theory, increased levels of sexual selection may either elevate or depress adult survival rates

the sexual conflict theory of aging predicts that higher rates of sexual conflict lead to the evolution of higher rates of senescence. However, it is theoretically plausible that increased level of conflict will reduce age-related deterioration as a byproduct of increased investment in somatic maintenance

However, the effect of selection interacted with sex, such that females from monogamous populations lived longer than females from polygamous populations while there was no difference in lifespan between males from the two selection regimes.

The analysis of the rate of senescence showed that males generally senesce faster than females, while we found no effect of selection

Our experimental removal of reproductive competition among males and conflicts of interest between males and females triggered the evolution of decreased rates of mortality and elevated lifespan in monogamous females, presumably as a direct response to a release from a sexual selection load

This finding is consistent with the general trend that differences in lifespan between populations are often attributable to differences in baseline mortality rather than to differences in the rate of senescence (Promislow *et al* ., 1996; Pletcher *et al* ., 2000; Bronikowski *et al* ., 2002; Maklakov *et al* ., 2006b; but see Fox *et al* ., 2004a).

The sex differences in lifespan and mortality rates are generally consistent with previous studies in *C. maculatus*: males lived shorter and senesced faster than females (e.g. Fox *et al* ., 2003, 2004a),

**Reznick, D.N., Bryant, M.J., Roff, D., Ghalambor, C.K. and Ghalambor, D.E. 2004. Effect of extrinsic mortality on the evolution of senescence in guppies. *Nature* 431: 1095-1099**

Medawar’s1 ‘mutation accumulation’ theory predicts that populations with high mortality rates should accumulate deleterious mutations that reduce fitness late in life

Williams’2 ‘antagonistic pleiotropy’ theory predicts that high mortality rates will select for earlier maturity and a higher rate of investment in reproduction early in life, which incurs a cost in the form of reduced investment in maintenance and reproduction late in life

Increases in extrinsic mortality rate may be accompanied by decreases in population density and increases in resource availability to survivors5. When such complexities are included, increased extrinsic mortality may cause the evolution of earlier senescence, later senescence, or no change in patterns of senescence, depending on these additional factors

There is a striking discrepancy between the diversity of theory on the evolution of senescence and its treatment in the literature. Empirical evaluations of the evolution of senescence focus almost exclusively on the classical theory7–16, as do recent reviews17,18

Two generations of lab rearing removes confounding environmental effects

Low predation localities tend to have lower levels of food availability23, reflected in the lower growth rates and smaller asymptotic body sizes of guppies from those sites

Whereas theory is clear in making predictions about how senescence should evolve, it is less clear about how one should quantify senescence. We have taken literally the definition of senescence as any age-specific decline in variables associated with individual fitness, specifically mortality, reproduction and physiological performance.

The rate of ageing13 is lower in the high predation localities in all four paired comparisons (drainage by food) between guppies from high and low predation localities

Guppies from high predation localities begin reproduction at an earlier age20, cease reproduction at a later age (Fig. 1) and hence have a longer reproductive lifespan. They also have longer total life spans (Table 1) but there are no differences among treatment groups in post-reproductive lifespan (data not shown).

A second way of evaluating senescence is through changes in the

rate of production of offspring with age

Whereas these analyses do not provide statistical support for differences among predator communities in reproductive senescence, they also do not comply with the prediction for delayed senescence in guppies from low predation communities.

guppies from high predation environments experience a more rapid deterioration in physiological performance with age than do their counterparts from low predation environments

Our results do not comply with the classical Medawar–Williams theory when senescence is evaluated in terms of survival, fecundity or reproductive value. Guppies from high predation localities have lower rates of ageing and do not differ in reproductive senescence relative to those from low predation localities

If older age classes benefit more than younger age classes from higher resource availability, then higher mortality can cause the evolution of delayed senescence, even though increased mortality without an indirect effect of density predicts the evolution of earlier senescence

Luckinbill and Clare30 showed that selection on late-life reproductive success causes the evolution of later senescence if larval density is high, but has no effect on the evolution of senescence if larval density is low

Stearns et al15. successfully selected for later senescence and the evolution of other life history traits by decreasing adult mortality rates, but only after increasing larval density and decreasing food supply

**OTHER**

**Campisi, J. 2005. Senescent Cells, Tumor Suppression, and Organismal Aging: Good Citizens, Bad Neighbors. *Cell* 120: 513–522**

Multicellular organisms contain two fundamentally different cell types: postmitotic cells, which cannot divide, and mitotic (or mitotically competent) cells, which can divide.

In many simple organisms—for example, the nematode *Caenorhabditis elegans* and fruit fly *Drosophila melanogaster*—postmitotic cells are the predominant, if not exclusive, cell type in the somatic tissues of adults

The evolution of renewable somatic tissues very likely afforded organisms increased longevity. In spite of this, renewable tissues—unlike postmitotic tissues are susceptible to hyperproliferative disease, the most deadly of which is cancer

gate keeper tumor suppressors promote longevity by preventing the development of cancer. The apoptotic and senescence responses they implement can have cumulative deleterious effects, and thus may also limit longevity by contributing to aging and late-life pathology

senescent cells are dysfunctional and may actively disrupt normal tissues as they accumulate gatekeeper tumor suppressor mechanisms may be an example of evolutionary antagonistic pleiotropy (reviewed in Kirkwood and Austad [2000]; Campisi, 2003b).

Hayflick and colleagues first formally described cellular senescence as the finite replicative life span of human fibroblasts in culture

Telomeres are the DNA sequence and proteins that cap the ends of linear chromosomes damage and prevent their fusion by cellular DNA repair processes.

Because functional telomeres maintain the integrity and stability of the genome, they suppress the development of cancer.

Although diverse stimuli can induce a senescence response, they appear to converge on either or both of two pathways that establish and maintain the senescence growth arrest. These pathways are governed by the gatekeeper tumor suppressor proteins p53 and pRB (Bringold and Serrano, 2000; Lundberg et al., rest (Figure 1A). Consequently, although the senes2000;

Campisi, 2001).

p53 is a crucial mediator of cellular responses to DNA damage, including the senescence response (Wahl and Carr, 2001).

Many murine cells undergo only a few doublings in culture, despite long telomeres and expression of telomerase. These cells most likely arrest because standard culture conditions cause oxidative stress, which human cells resist much more effectively than mouse cells (Parrinello et al., 2003).

Recent findings suggests that p53, despite being a crucial tumor suppressor, also contributes to aging and does so at least in part by enhancing the senescence response

How might constitutively hyperactive p53 accelerate aging? Cells from these modified mice were more susceptible to both p53-mediated apoptosis (Tyner et al., 2002) and p53-mediated senescence (Maier et al., 2004)

There is no evidence yet that enhanced pRB function, analogous to the enhanced p53 function conferred by truncated p53 proteins, accelerates aging

The combined results from use of both p16 and SA-β-gal indicate that cells with characteristics of senescence accumulate with age in multiple tissues from both humans and rodents

The antagonistically pleiotropic effects of senescent cells suggest that aging is, at least in part, a consequence of gatekeeper tumor suppressor mechanisms

**Fox, C.W. and Czesak, M.E. 2000. Evolutionary Ecology of Progeny Size in Arthropods. *Annual Review of Entomology* 45: 341–369**

progeny size is subject to selection in both the parental and progeny generations. This selection often varies in direction and/or magnitude among generations (parental versus offspring), among environments, and even among siblings within

a family, such that understanding the factors that influence the evolution of progeny size can become quite a challenge

The number of grandprogeny a female will produce depends on both the number of progeny she produces and the fitness of those progeny

there is a trade-off between the number of progeny a female can make and the amount of resources allocated to each of those progeny. If a female makes larger progeny, IYoung increases and N decreases.

If an individual has a fixed amount of resources available, those resources can be divided into three basic functions—growth, somatic maintenance, or reproduction.

For a trade-off between egg size and number to be evident, we must assume that the quantity of resources allocated to reproduction (ITotal) is constant. Yet ITotal is often not constant

larger individuals generally lay both more and larger eggs, leading to a positive correlation between egg size and number. In this case, the relationship between egg size and number will be negative only when body size is controlled

Smaller-than-average young have three developmental options: *(a)* mature at a smaller-than-average size, *(b)* extend development to fully or partially compensate for their small starting size, or *(c)* increase their rate of growth to mature at a normal size.

Most arthropods exhibit some degree of developmental plasticity by which progeny partially compensate for their small hatchling/birth size by extending development time

Progeny hatching from larger eggs can often better withstand environmental stresses such as larval competition (7), starvation (38, 89, 145, 199, 212), desiccation (201), oxygen stress (97), cold stress (36, 105), nutritional stress (27, 74, 78, 219), and environmental toxins (62).

shifts in the abundance of hosts may result in a change in optimal egg size, even without changes in the relationship between egg size and progeny fitness (183).

for organisms that exhibit parental care, large clutches may be less easily tended/defended than smaller clutches, such that progeny survivorship decreases with increasing maternal fecundity even if progeny size is constant.

For terrestrial insects size-selective egg predators and parasites impose selection on egg size that will vary with predation intensity.

The commonness of these latitudinal clines is often interpreted as evidence that large eggs are selectively favored at low temperatures. However, environmental effects of temperature on egg size often mimic the geographic clines observed in nature (larger eggs at lower temperatures; see below).

Within populations, larger females tend to lay larger eggs (Table 2), suggesting some morphological constraints on egg size.

Theoretical models generally predict that, as food availability decreases, and thus progeny mortality increases, females should shift to laying larger eggs (46, 189).

In some crustaceans females produce larger progeny at low food concentrations (Daphnia: 23, 24, 34, 58, 87–89, 92, 153, 173, 179; *Euterpina:* 93; and one isopod: 32), although progeny size may decrease at very low food levels (22, 213, 215). This increased progeny size often results in higher survivorship under food stress (89; references in 22

Females reared at high densities often lay eggs that are smaller than those of females reared at low density (73, 76, 79, 154; but see 65, 185), likely due to effects of competition on female size or nutritional status

Many studies show that females lay larger eggs when reared (104) or ovipositing (4, 5, 63, 101) at lower temperatures (232), although some arthropods lay larger eggs when reared at intermediate temperatures (10), lay larger eggs at high temperatures (110), exhibit variable responses to temperature depending on other environmental conditions

In many arthropods, progeny size varies throughout the year

In most arthropods, however, progeny size decreases with maternal age (Table 3), although an increase is commonly observed in orthopterans and heteropterans

**Jang, Y.C. and Remmen, H.V. 2009. The mitochondrial theory of aging: Insight from transgenic and knockout mouse models. *Experimental Gerontology* 44: 256–260**

The free radical or oxidative stress theory of aging proposed by Denham Harman in 1956 states that the age-related loss of physiological function is due to the progressive accumulation of oxidative damage and that this ultimately determines the lifespan of an organism (Harman, 1956).

In subsequent years, the mitochondrial theory of aging was further refined suggested that the accumulation of somatic mutations in the mtDNA induced by oxidative stress is the major contributor of aging and age-related degenerative diseases.

reactive oxygen species (ROS) emanating from the mitochondrial respiratory chain damages macromolecules, especially

mtDNA. As a result, an accumulation of mtDNA mutations leads to production of defective mitochondrial respiration, further increasing ROS generation and oxidative damage

The core principle of the mitochondrial theory of aging is based on the fact that mitochondrial respiratory chain, mainly through complex I and complex III, is the major source of superoxide anion (O2\_\_)

oxidative damage to mtDNA has been the major focus of the mitochondrial theory of aging

Oxidative damage to DNA is to known to cause modification to purine and pyrimidine bases, single and double-stranded breaks, and cross-linking to other molecules

studies using long-lived mice and experimental manipulations that extend lifespan, such as calorie restriction, have provided a strong correlation between oxidative damage to the mitochondria and lifespan (Barja and Herrero, 2000; Trinei et al., 2002; Barja, 2004).

in Saccharomyces cerevisiae, deletion of the key antioxidant enzyme, manganese superoxide dismutase (MnSOD,Sod2), which, dramatically accelerates chronological aging and overexpression unambiguously increases the organism’s lifespan (Longo et al., 1996)

mammalian transgenic/knockout models with alterations in key mitochondrial antioxidant enzymes have produced mixed results and do not fully support the mitochondrial theory of aging.

Although reducing MnSOD activity in Sod2 knockout mice tests whether superoxide toxicity in mitochondria is limiting to lifespan, the alternative approach is to test the whether an increase in mitochondrial MnSOD activity can extend lifespan.

overexpression of MnSOD in Drosophila was shown to have a beneficial effect, extending lifespan, and supporting the mitochondrial theory of aging (Sun et al., 2002).

an Sod2 transgenic mouse line that overexpresses MnSOD in all tissues failed to show increased lifespan even when the transgenic mice generated less superoxide

Although peroxisome and nuclear overexpression showed a trend toward increased lifespan, only the mitochondrial targeted construct provided the maximal benefit, increasing both median and maximal lifespan by 20%

Data from the mCAT mice undoubtedly support the mitochondrial theory of aging

Interestingly, overexpression of thioredoxin 1 (the cytosolic form) has been shown to increase lifespan in mice (Mitsui et al., 2002)

mouse models of mtDNA instability have provided direct evidence of mitochondrial ROS role in the aging process

Recent studies using the transgenic/knockout strategies have challenged the core principles of the mitochondria theory of aging as well as its parent theory, the free radical or oxidative stress theory of aging

most studies do not support or remain inconclusive on whether mitochondrial dysfunction and oxidative stress determine lifespan

Interestingly, in S. cerevisiae and P. anserina, the deletion of a protein that promotes mitochondrial fission (dynamin related protein 1- dnm1p) extended lifespan without lowering fitness or reproduction (Scheckhuber et al., 2007).

**Mair, W., Piper, M.D.W. and Partridge, L. 2005. Calories do not explain extension of life span by dietary restriction in Drosophila. PLoS *Biol* 3(7): e223**

Dietary restriction (DR), the extension of life span by reduction of nutrient intake without malnutrition, is often used as a benchmark comparison for interventions that extend life span [1–3].

some form of food restriction hasbeen shown to increase life span in commonly used model organisms such as yeast [5,6], nematodes [7], fruit flies [8,9], and mice [10], along with many species less often used for laboratory research such as water fleas, spiders, fish (see [3] for review), and dogs [11].

DR is often termed ‘calorie restriction’ because, in rodents, daily calorie intake per se has been implicated as the key determinant of life span, with the source of these calories (i.e., carbohydrate, protein, or fat) being considered irrelevant

Life span of female Drosophila was extended much more by reduction of yeast from control to DR concentration than by the equivalent reduction in sugar

In two independent experiments, reducing yeast concentration from control to DR levels whilst keeping sugar levels constant significantly increased life span

Flies fed food media with very similar caloric content showed marked differences in their life spans

This finding is in direct contrast to what would be predicted if ingested calories were the key mediator of life span in D. melanogaster and demonstrates that the nutritional composition of the diet affects life-span extension by DR in this species.

DR acts acutely to extend life span in Drosophila; it does not slow the accumulation of irreversible damage with age

The response of Drosophila life span to nutrition is not governed by calories, but rather by specific nutritional components of the food

Despite some reports in the literature that DR did not extend life span [38,41,42], the overwhelming majority of data support the idea that DR in some form extends life span across diverse taxa

The selective advantage of shifting resources from reproduction to maintenance when food is restricted could be the ‘‘public’’ factor shared between diverse organisms. However, the mechanisms by which extension of life span is achieved could be an example of convergent evolution, producing the same plasticity of life span in response to food shortage through mechanisms at least to some extent specific to different organisms, dependent upon their diet, experience of food shortages, and life history

**Pérez, V.I., Bokov, A., Remmen, H.V., Mele, M., Ran, Q., Ikeno, Y. and Richardson, A. 2009. Is the oxidative stress theory of aging dead? *Biochimica et Biophysica Acta* 1790: 1005–1014**

The free radical theory of aging proposed in the 1950s by Denham Harman [1], postulates that oxygen free radicals formed endogenously from normal metabolic processes play a role in the aging process because of an increase in oxidative damage to macromolecules

The imbalance between prooxidants and antioxidants leads to an accumulation of oxidative damage in a variety of macromolecules with age resulting in a progressive loss in functional cellular processes, leading to the aging phenotype [2].

longer-lived animals show reduced oxidative damage and/ or increased resistance to oxidative stress

the observation that the experimental manipulations that increase lifespan in invertebrates and rodents correlate to increased resistance to oxidative stress or reduced oxidative damage provides strong evidence in support of the oxidative stress theory of aging. However, all of the experimental manipulations that increase lifespan also alter processes other than oxidative stress/damage; therefore, the increase in longevity in these animal models could arise through another mechanism.

Longevity or lifespan is the most acceptable parameter that has been used for several years to study aging

we do know that it is possible to retard aging in multiple animal models and simultaneously lengthen lifespan; for example, when mice and rats are fed restricted amounts of food, aging mechanisms appear to be delayed and the animals live longer

Longevity or lifespan is the most acceptable parameter that has been used for several years to study aging. Ideally, it would be better to determine other parameters involved in changes in the basic mechanisms of aging or healthspan. However, nowadays there is no consensus about how to define healthspan and how to measure this parameter in all of these model systems

we do know that it is possible to retard aging in multiple animal models and simultaneously lengthen lifespan; for example, when mice and rats are fed restricted amounts of food, aging mechanisms appear to be delayed and the animals live longer.

it is critical that lifespan be determined under optimal husbandry conditions to eliminate/minimize deaths from non-aging causes, e.g., infectious disease, inflammation, stress, etc

studies with invertebrates have given mixed results with respect to the effect of reducing antioxidant gene expression on lifespan

One of the problems in determining whether oxidative stress plays a role in aging using knockout mice to accelerate aging is that many manipulations can shorten lifespan that would not have any effect on aging.

Therefore, most gerontologists agree that a manipulation that increases lifespan gives the greatest insight in to the mechanism of aging. In other words, determining whether an increase in the antioxidant defense system would increase lifespan would be more powerful evidence for oxidative stress/free radicals playing a role in aging than showing that a reduction in the antioxidant system decreases lifespan.

In summary, our research with 18 different genetic manipulations in the antioxidant defense system show that only the mouse model null for Sod1 had an effect on lifespan that would be predicted from the oxidative stress theory of aging. One could argue that we failed to observe an effect on lifespan

we believe that the fact that the lifespan was not altered in almost all of the knockout/transgenic mice is strong evidence against oxidative stress/damage playing a major role in the molecular mechanism of aging in mice.

**Vaupel and Yashin Heterogeneity's Ruses: Some Surprising Effects of Selection on Population Dynamics**

In a homogeneous population, all individuals of age x in year y face the same hazard rate ,u(x, y). A heterogeneous population consists of various homogeneous subpopulations

necessarily. As illustrated in Figure 1 there might be two groups of individuals, the reformed and the incorrigible. For individuals in each group, the hazard of recidivism might be constant. The observed decline would be an artifact of heterogeneity, a ruse

curves. Does this cohort curve imply that the fail- ure rate for a specific device decreases during the infant mortality phase, is roughly constant during the useful life phase, and increases during the wear-out phase? Not necessarily

Observations indicate that the average weight of 3-year-olds is about the same as that of 4-year-olds. Does that mean that individual members of the species do not gain any weight between the age of 3 and 4'? Not necessarily-each individual may be gaining weight, but selection of the fatter individuals may hold the average weight of the surviving individuals approximately constant

Cancer, for example, is more common than heart failure at younger ages but less common at older ages. Does this imply that any particular individual is more likely to die from cancer in youth and from heart disease in old age'? Not necessary

Essentially, the incidence of cancer declines relative to the incidence of heart failure because the individuals most susceptible to cancer have died

Some models of human disease processes are based on the hypothesis that the body has several lines of defense and that some diseases occur only after all of these lines of defense have failed. Thus the formula might also be applied to the study of human mortality and morbidity.

Health progress reduces mortality rates, at youn- ger ages, from the solid lines to the dotted lines. At later ages, however, the observed cohort death rate is higher than it would have been. The frail individuals saved in childhood are dying at older ages. Every individual's life chances are improved at youn- ger ages and are as good as ever at later ages, but observed cohort mortality makes it look as if pediatricians are making progress, whereas gerontologists are losing ground

follows. Reductions in mortality rates at younger ages permit more individuals from the frailer sub- population to survive to older ages. This influx of frailer individuals serves as a brake or counter-current on reduc- tions in mortality rates at older ages

Regardless of how many different attributes are consid- ered, individuals who are grouped together will differ along various neglected dimensions. Some of these differences will almost certainly affect the individuals' chances of death, marriage, unemployment, or other transition

The observed dynamics at the population level will deviate from the underlying dynamics at the individual level.

Sometimes, however, selection is important; and when it is, the patterns observed may be surprisingly different from the underlying patterns on the individual level