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Cite this article: Hayward AD, Nenko I, Lummaa V. 2015 Early-life reproduction is associated with increased mortality risk but enhanced lifetime fitness in pre-industrial humans. *Proc. R. Soc. B* **282**: 20143053. <http://dx.doi.org/10.1098/rspb.2014.3053>

Received: 16 December 2014

Accepted: 28 January 2015

Subject Areas:

ecology, evolution, behaviour

Keywords:

ageing, human reproduction, trade-offs, senescence, life history, maternal effects

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Electronic supplementary material is available at <http://dx.doi.org/10.1098/rspb.2014.3053> or via <http://rspb.royalsocietypublishing.org>.

Early-life reproduction is associated with increased mortality risk but enhanced lifetime fitness in pre-industrial humans

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The physiology of reproductive senescence in women is well understood, but the drivers of variation in senescence rates are less so. Evolutionary theory predicts that early-life investment in reproduction should be favoured by selection at the cost of reduced survival and faster reproductive senescence. We tested this hypothesis using data collected from preindustrial Finnish church records. Reproductive success increased up to age 25 and was relatively stable until a decline from age 41. Women with higher early-life fecundity (ELF; producing more children before age 25) subsequently had higher mortality risk, but high ELF was not associated with accelerated senescence in annual breeding success. However, women with higher ELF experienced faster senescence in offspring survival. Despite these apparent costs, ELF was under positive selection: individuals with higher ELF had higher lifetime reproductive success. These results are consistent with previous observations in both humans and wild vertebrates that more births and earlier onset of reproduction are associated with reduced survival, and with evolutionary theory predicting trade-offs between early reproduction and later-life survival. The results are particularly significant given recent increases in maternal ages in many societies and the potential consequences for offspring health and fitness.

1. Introduction

Senescence is a decline in physiological function, survival and reproductive success with increasing age [1], and a large body of work has shown that senescence in survival and reproductive success is commonly detectable in wild animals [2]. Recent research has switched from establishing whether senescence occurs to quantifying variation between individuals in senescence rates and determining the drivers of such variation. Accelerated senescence has been associated with experience of adverse environmental conditions during early life in wild mammals [3,4] and birds [5]. In addition, individuals with higher reproductive success in early life may experience faster rates of reproductive senescence: red deer (*Cervus elaphus*) producing more calves in early adulthood showed more rapid senescence [6], and guillemots (*Uria aalge*) raising more chicks before the age of peak success had lower success once reproductive senescence began [5]. These results support the prediction of evolutionary theories of senescence that, since selection is stronger in early life than in later life, early reproduction should be favoured over later survival [7,8]. Despite these observations, this trade-off may not be apparent: instead, there may be positive covariance between reproduction and survival [9,10] since individuals with plentiful resources experience little constraint while those with fewer resources face more pressing resource allocation decisions [11]. Thus, variation in resources and reproductive investment may create variation in senescence rates.

Understanding reproductive senescence in humans is of increasing interest and importance because the age at which women desire children is increasing

in modernized society [12]. The physiological factors underpinning senescence in humans have been relatively well studied. These include endocrinological changes associated with reproductive senescence and the menopause [13,14], and the cessation of female fertility that occurs around the age of 50 across human populations [15]. Women experience a gradual decline in fertility with age similar to most other placental mammals, including our closest relatives, chimpanzees [16]. The physiology underpinning this is well studied: menstrual cycles gradually change in character, resulting in an increased frequency of anovulatory cycles and ultimately cessation of reproduction [17,18]. Large variation between women in age at menopause [15] suggests that there is likely to be variation between women in their rates of reproductive senescence, but the social and ecological factors which drive between-individual variation in ageing rates have not been well studied. Higher parity throughout reproductive life is associated with variation in susceptibility to different kinds of mortality in humans, particularly heart disease and cancer [19]. However, the consequences of high parity in early reproductive life in terms of a trade-off with later survival and reproductive success, as predicted by evolutionary theory, invoking genes with antagonistic effects on fitness in early and later life [7], selection on resource allocation strategies [8] and energetic costs of reproduction, is unknown. Testing this evolutionary hypothesis could offer fresh insight into the evolution of human life histories and provide information about the long-term consequences of early parity.

We used longitudinal data from a preindustrial human population exhibiting natural mortality and fertility rates, collected from church records during the eighteenth and nineteenth centuries in Finland, to examine age-related variation in reproductive success. We tested the hypothesis that high investment in reproduction in early life would be associated with reduced future survival and a more rapid rate of reproductive senescence, but be favoured by selection through enhanced lifetime reproductive success (LRS). We aimed to quantify: (i) changes in reproductive success with age; (ii) associations between reproductive investment in early life and reproductive success in later life; and (iii) the strength of natural selection on early-life fecundity (ELF).

2. Material and methods

(a) Study population and data collection

We examined age-related variation in reproductive success in women living in Finland during the eighteenth and nineteenth centuries, using data collected from Lutheran church records which has recorded all births, marriages and deaths across the country since 1750 [20]. We used data collected from five 'parishes': Hiittinen, Ikaalinen, Kustavi, Pulkkala and Rymättylä, in order to construct individual life histories for 2695 women born from 1702 to 1850.

We only analysed data from females who married at least once, since females who never married have an extremely low probability of reproducing. All women in the sample had a known fate up to the age of at least 50. Analysis was restricted to females born before 1851, so that their reproductive lifespan ended by 1900 when improved healthcare and contraception began to influence birth and survival rates [21]. One of the key correlates of fitness in this population is social class and so women were assigned a social class based on their husband's occupation: rich individuals included farm owners and craftsmen; poor individuals included labourers and crofters [22].

(b) Statistical analysis

(i) Age-related variation in annual breeding success across the whole reproductive lifespan

We began by exploring changes in reproductive success across the reproductive lifespan of all 2695 women in our sample. Our aim was to determine the age at which women were most likely to produce children, controlling for selective disappearance and appearance. Data were structured with a single year for each year of life of each female, giving a total of 86 776 female-years. We first analysed the probability of a female reproducing each year between the age of 16 and 50. We included all years for each individual, including years in which they were not married, in order to examine age-related variation in investment in reproduction rather than fertility *per se*. We used the 'glmer' function in the 'lme4' package in R v. 3.1.1 to perform generalized linear mixed-effects models (GLMMs) with annual breeding success (ABS) as the response variable (0, female did not give birth in a given year; 1, female gave birth), with a binomial error structure and logit link function. We constructed a base model, containing fixed effects of parish (five levels, as described above) and social class (as above) as categorical variables, and age at first reproduction (AFR) and last reproduction (ALR) as fixed covariates. These account for covariance between ABS and the timing of onset (selective appearance) and cessation (selective disappearance) of breeding [23]. We also included random effects of individual identity and year to account for repeated measures and variation in breeding success across individuals and years. Descriptive statistics associated with these data are shown in the electronic supplementary material, table S1.

To this model, we added functions describing the change in breeding success with age and tested which best described the ageing trajectory. We tested models with: (i) linear, (ii) quadratic, and (iii) cubic functions of age. We then fitted a series of one-threshold models [24], in which ABS varied as a function of age in two stages (e.g. an increase to the threshold age and a subsequent decline). We tested models varying the threshold between ages 18 and 47. We then fitted two-threshold models, in which ABS varied with age in three stages (e.g. an increase to the first threshold; a plateau to the second threshold; and a subsequent decline). The first threshold varied between 18 and 44, and the second between 21 and 47. We compared a total of 412 models using Akaike's information criterion (AIC) to describe ageing-related variation in female ABS. A model was deemed to be a statistically better fit to the data if the Δ AIC value was at least -2 relative to the next best model [25]. In all models, AFR, ALR and age were divided by 100 in order to aid model convergence.

(ii) Association between early-life fecundity and later-life fitness

Our analyses supported a three-stage ageing trajectory for ABS: an increase from age 16 to 25; a plateau between ages 25 and 41; and a decline from age 41 onwards. We therefore considered children born before age 25 to constitute a female's ELF, which was on average 0.76 ± 0.02 children per female. There were 1507 women who did not reproduce before the age of 25 (55.92% of our 2695 women); 583 (21.63%) produced one child; 409 (15.18%) produced two children; 146 (5.42%) produced three; 50 (1.86%) produced four or more. We then determined whether variation in ELF was associated with differences in survival, ABS and child survival in later life. Note that this is separate from AFR): ELF is the number of children a female produced before age 25, while AFR is the age at which a female produced her first child.

First, we assessed the association between ELF and survival in married women from age 25 onwards. We used the R package 'survival' to perform Cox proportional hazards models (function 'coxph') to determine the predictors of mortality risk in the 2660

women in our sample who lived to at least the age of 25 (35 women from our original sample died before this age). Thus, we analysed survival from the peak age of ABS as defined by our initial model. The models included parish and social class, plus ELF. We statistically compared models fitting ELF as a factor with two levels (ELF2; no children before age 25, versus at least one child); three levels (ELF3; zero, one or at least two children before 25); four levels (ELF4; zero, one, two, three+ children); or as a covariate (ELF, a linear function of the number of children born). We also investigated whether the impact of ELF varied across social classes by fitting interactions between social class and the different variables describing ELF, predicting that any effect would be strongest in poor individuals. We compared models using likelihood ratio tests (LRTs), where the χ^2 -test statistic is calculated as $-2(\text{LogLik}_{\text{model1}} - \text{LogLik}_{\text{model2}})$, and by comparing model AICs [25].

Second, we investigated the effects of ELF on ABS from the age of 41 onwards, the age at which our models suggested ABS began to decline. We restricted this analysis to years in which women were married: thus, we considered their actual fertility, given the strong effect of being married on probability of reproduction. We analysed 16 348 female-years in 1922 women. Once again, we used GLMMs with binomial errors and logit link, with ABS as the response variable, random effects of individual identity and year, and fixed effects of parish, social class, AFR and ALR. We fitted age as a linear covariate, to test for a significant decline in ABS, and ELF as a three-level variable (ELF3, comparing women who produced zero, versus one, versus at least two children before the age of 25). We predicted that high ELF would accelerate senescence in ABS, and that this would be most pronounced in poor individuals. To test this prediction, we fitted a three-way interaction between age, social class and ELF3 and all two-way interactions between these three variables. The model was simplified by removing non-significant terms in the order of least significance, assessed by LRTs as outlined above.

Third, we used binomial GLMMs to analyse the association between ELF and child survival to the age of 15, at which point individuals are considered independent. We treated offspring survival as a maternal trait, based on the fact that it reflects maternal ability to produce a robust offspring and successfully rear it. We analysed the survival of 1614 children born to 1162 women aged 41–50, to match the ABS analysis above. The unit analysed was the child, rather than the female-year (0, the child died before age 15; 1, the child survived to age 15). The fixed- and random-effect structures of the model were the same as the model for ABS, including the two- and three-way interactions. The model also included, as fixed effects, age as a quadratic covariate, to test the hypothesis that the late-life change in offspring survival was nonlinear, and the time since the birth of the focal child's elder sibling as a fixed factor (0, the child was firstborn; 1, less than 1 year since the birth of the last child, up to 7, more than 6 years since the birth of the last child). This allowed us to distinguish firstborn children from later-born children, and then the intervals which later-born children were born at, in the same explanatory variable. We also fitted the child's sex and whether or not the child was a twin as categorical fixed effects. Finally, we controlled for effects of maternal survival on child survival: maternal presence affects child survival in this population, but this effect diminishes after the first few years of life [26]. We fitted a two-level categorical fixed effect describing maternal survival in the first five years of a child's life (0, mother was alive until the child was aged 5; 1, mother died before the child was 5). Again we simplified the model by removing non-significant terms in the order of least significance using LRTs. Descriptive statistics associated with these data are shown in the electronic supplementary material, table S2.

Table 1. A comparison of generalized linear mixed-effects models (GLMMs) investigating age-related variation in annual breeding success in 2695 Finnish women born 1702–1850. (Only the best-fitting one- and two-threshold models are shown; all one- and two-threshold models are shown in the electronic supplementary material, tables S4 and S5, respectively. The best-fitting model is shown in italics.)

model	AIC	Δ AIC
null	78225.52	10079.65
linear	78219.96	10074.09
quadratic	68311.96	166.09
cubic	68299.40	153.53
one threshold (age 30)	69767.06	1621.19
<i>two threshold (ages 25 and 41)</i>	<i>68145.87</i>	<i>0.00</i>

(iii) Early-life fecundity and lifetime reproductive success

Finally, we determined whether ELF was under phenotypic selection through LRS, defined as the number of children born to a female across her lifetime that survived to age 15. We regressed LRS on life-history traits potentially associated with fitness to calculate selection gradients [27]. We fitted linear mixed-effects models (LMMs, using the 'lmer' function in 'lme4') with relative LRS, calculated by dividing individual LRS by its mean, as the response variable with Gaussian error structure. As explanatory variables, we included social class as described above, plus AFR and ALR, longevity and ELF as covariates, standardized to mean = 0 and standard deviation = 1, in order to account for selection on correlated traits [27]. We also fitted quadratic effects of all of these covariates in order to test for nonlinear selection. We tested the significance of each model term by sequentially removing them from the model and comparing models using LRTs.

3. Results

(a) Age-related variation in annual breeding success across the reproductive lifespan

The best-supported model describing ageing-related variation in breeding success between ages 16 and 50 had thresholds at 25 and 41 years (table 1). This model was statistically supported over linear, quadratic, cubic and all one- and two-threshold models, with Δ AIC = -15.80 relative to the next best-fitting model (electronic supplementary material, table S5). The model predicted an increase in ABS from almost 0 at age 16 to around 0.3 at age 25; a relatively stable period followed until age 41 before a subsequent steep decline (figure 1). Parameter estimates from the final model (electronic supplementary material, table S3) suggested that poor females were less likely to reproduce at a given age than rich females; females with an earlier AFR were more likely to reproduce in any given year; females with a later ALR were more likely to reproduce at a given age. Thus, women who began reproduction early and continued childbearing until old age were more likely to reproduce at any given point in their lives than women who began later and finished earlier. Comparisons of one- and two-threshold models are shown in the electronic supplementary material, tables S4 and S5, respectively. These results led us to define ELF as the number of children born to a female before the peak age of 25 (i.e. reproduction up to and including age 24).

Table 2. A comparison of the Cox proportional hazard models estimating causes of variation in risk of mortality from the age of 25 onwards. (The model with highest statistical support, assessed by a comparison of AIC values and likelihood (LogLik) ratio tests is shown in italics. Abbreviations: ELF, ELF as a covariate; ELF2, zero versus at least one child born before age 25; ELF3, zero, one, or two or more children; ELF4, zero, one, two, or three or more children.)

model	structure	AIC	Δ AIC	LogLik	versus	d.f.	χ^2	<i>p</i> -value
0	social + parish	36585.35	2.36	−18287.67				
1	+ELF2	36586.76	3.77	−18287.38	0	1	0.58	0.446
2	+ <i>ELF3</i>	36582.99	0.00	−18284.50	0	2	6.34	0.042
3	+ELF4	36584.62	1.63	−18284.31	0	3	6.72	0.081
4	+ELFr	36583.50	0.51	−18285.75	0	1	3.84	0.050
5	+ELF2 × social	36587.97	4.98	−18286.99	1	1	0.78	0.377
6	+ELF3 × social	36585.23	2.24	−18283.62	2	2	1.76	0.415
7	+ELF4 × social	36588.38	5.39	−18283.19	3	3	2.24	0.524
8	+ELFr × social	36583.89	0.90	−18284.94	4	1	1.62	0.203

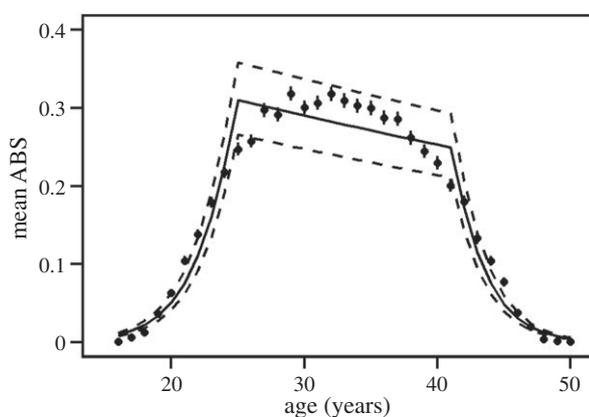


Figure 1. Annual breeding success (ABS) in Finnish women varied substantially across ages. The filled black symbols show mean ABS at each age \pm 1 s.e. The solid black line shows predictions of the two-threshold model chosen in table 1, the parameter estimates of which are given in the electronic supplementary material, table S3, while the dotted lines show \pm 1 s.e. This was the best-fitting generalized linear mixed-effects model (GLMM) of age-related change, fitting thresholds at ages 25 and 41.

(b) Associations between early-life fecundity and later-life fitness

First, high ELF was associated with an increased mortality risk from the age of 25 onwards: the statistically best-supported Cox proportional hazards model contained ELF as a three-level factor (table 2). Women who produced one child before age 25 had similar survival rates to those who did not produce any children (hazard = 0.96, 95% confidence interval (CI) = 0.87–1.06), but those who produced at least two children before age 25 had a significantly higher hazard of mortality (hazard = 1.11, 95% CI = 1.01–1.22). Poor women had a significantly higher hazard of mortality than rich women (hazard = 1.17, 95% CI = 1.05–1.32), but an interaction between social class and ELF3 did not improve model fit, indicating that the ELF effect on mortality did not differ between rich and poor individuals (table 2).

Second, we investigated associations between ELF and ABS in married women after the age of 40. Parameter estimates and test statistics for these models are shown in the electronic supplementary material, table S6. The decline in ABS after the age of 40 was strong and significant ($\chi^2 = 1549.50$, $p < 0.001$).

Social class, parish and AFR were not significantly associated with ABS after age 40, but women who finished reproducing later were more likely to reproduce during this period (electronic supplementary material, table S6). However, compared with women who produced no children before age 25, the decline in breeding success with age was no steeper in women who produced one or more children before age 25 ($\chi^2 = 0.32$, $p = 0.854$). In addition, women who reproduced before age 25 had statistically similar probabilities of reproducing in a given year after age 40 compared with women who did not reproduce before the age of 25, whether they had one or two children before age 25 ($\chi^2 = 0.11$, $p = 0.948$). A modifying effect of social class on the ageing trajectory was not statistically supported: the effect of ELF on the ageing trajectory did not differ statistically between rich and poor women ($\chi^2 = 2.66$, $p = 0.264$), and there was no statistical support for different age trajectories between rich and poor ($\chi^2 = 0.17$, $p = 0.681$).

Third, we analysed the association between ELF and the probability of child survival to 15 years in women aged over 40 to test whether ELF hastened senescence in ability to successfully rear offspring to independence. Parameter estimates and test statistics for these models are shown in the electronic supplementary material, table S7. There was marginally non-significant evidence that the decline in child survival to age 15 with maternal age was intensified by high ELF ($\chi^2 = 5.64$, $p = 0.060$; figure 2). Compared with women who did not reproduce before age 25, there was no statistical support for a steeper decline in child survival with age in women who produced one child (age \times ELF = 1 estimate = -8.15 ± 9.00), but there was some evidence for a steeper ageing slope in women who produced at least two children before age 25 (age \times ELF = 2 estimate = -18.09 ± 7.91). There was no statistical support for the three-way interaction between age, social class and ELF ($\chi^2 = 0.03$, $p = 0.985$), providing no support for our prediction that the effect of ELF on senescence was greatest in poor women. There was no evidence that poor women experienced a different pattern of child survival with age compared to rich women (age \times poor $\chi^2 = 0.16$, $p = 0.686$). Finally, there was no statistical support to suggest that child survival varied as a nonlinear function of maternal age (age² $\chi^2 = 0.48$, $p = 0.488$). The final model controlled for lower survival to age 15 among twins compared with

Table 3. Parameter estimates and significance tests from linear mixed-effects models of the association between standardized life-history traits (AFR, age at first reproduction; ALR, age at last reproduction; longevity; ELF, early-life fecundity) and LRS (relative lifetime reproductive success). (Predictions from this model were used to draw figure 3.)

variable	estimate	s.e.	χ^2	d.f.	p-value
fixed effects removed from the final model:					
ELF ²	0.0020	0.0077	0.07	1	0.792
ALR ²	0.0105	0.0067	2.40	1	0.122
fixed effects in the final model:					
Intercept	1.0644	0.0156			
social (rich)	0.0000	0.0000			
social (poor)	-0.1699	0.0227	55.93	1	<0.001
sdAFR	-0.2527	0.0203			
sdAFR ²	-0.0259	0.0080	8.99	1	0.003
sdALR	0.3620	0.0110	1111.60	1	<0.001
sdLongevity	0.0364	0.0087			
sdLongevity ²	-0.0221	0.0081	5.93	1	0.015
sdELF	0.0623	0.0167	12.98	1	<0.001
random effects in the final model:					
birth year	0.0035	0.0050			
residual	0.1598	0.0077			

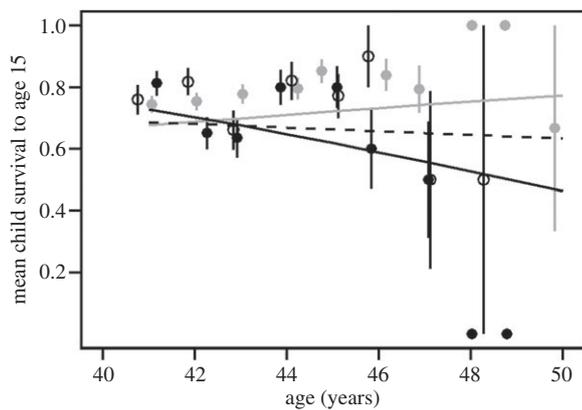


Figure 2. The change in child survival with maternal age after the age of 40 was associated with the number of children born before the age of 25. Women who did not give birth before the age of 25 (grey line and points) showed no decline in child survival with age; women who gave birth to one child before the age of 25 (broken black line and open black points) showed a non-significant decline in child survival with age; women who gave birth to two or more children before the age of 25 (black line and filled black points) showed a significant decline in child survival with age. Lines show model predictions from the best-fitting GLMM; points show mean child survival calculated from the raw data ± 1 s.e.

singletons, and among children whose mother died before they reached age 5 compared with those whose mother was still alive when they reached age 5.

(c) Early-life fecundity and lifetime reproductive success

Our selection analyses revealed that ELF was significantly positively associated with relative LRS, suggesting that it was under positive selection. We tested for a nonlinear association between ELF and LRS, but this was not statistically

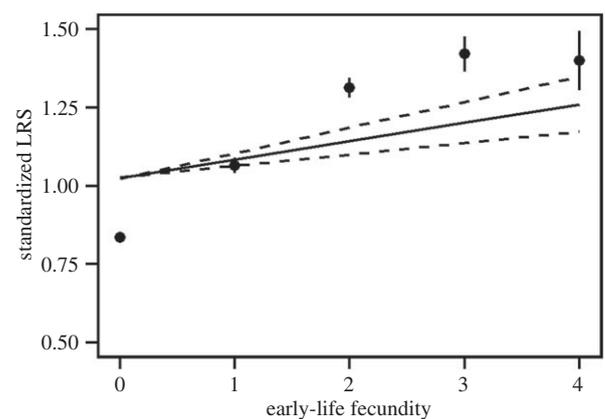


Figure 3. Women who produced more children before the age of 25 had higher lifetime reproductive success (LRS), defined as the number of children that survived to age 15, suggesting that early-life fecundity (ELF) was under positive selection. Points show mean relative LRS for individuals within each ELF class ± 1 s.e.; minimum n within a group is 50; solid lines show model predictions of the ELF–LRS association from the model shown in table 3, with dashed lines denoting predicted standard errors.

supported (table 3); instead, the model predicted a linear increase in LRS with increasing ELF (figure 3). Women who did not reproduce before the age of 25 had a mean LRS of 3.00 ± 0.05 s.e. children, while women at the top end of the scale, who produced more than three children before the age of 25, produced 5.02 ± 0.34 surviving children on average. This analysis accounted for higher relative LRS in rich individuals; a nonlinear effect of AFR which suggested that starting reproduction earlier enhanced lifetime fitness; and positive selection on ALR, suggesting that individuals who ceased reproduction later also have higher lifetime fitness. There was also a nonlinear effect of longevity, which supported a decelerating increase in LRS with increasing lifespan.

4. Discussion

In this study, we investigated age-related variation in female reproductive success in a pre-industrial population experiencing natural rates of mortality and fertility. ABS increased from age 16 to age 25, followed by a relatively stable phase until age 41 and a subsequent decline. ELF, defined as the number of children born before age 25, was not significantly associated with fecundity after the age of 40 or the rate of senescence in ABS: females with high ELF were no less fecund in later life than females with low ELF. However, higher ELF was associated with increased mortality risk from age 25 onwards and a (statistically marginal) more rapid decline in child survival rate with maternal age. Ultimately, ELF was under positive phenotypic selection: women who produced more children before the age of 25 had overall higher LRS despite apparent survival costs.

The annual probability of giving birth increased from age 16 to age 25. The main driver of this was almost certainly the increase in the proportion of women who were married: in our sample, less than 1% of women were married at age 16; this rose to approximately 51% by the age of 24. We did not include marriage status in these initial models as: (i) all women in the sample married at some point; (ii) we were interested in determining the peak age of breeding success, rather than peak fertility; including marriage status in the model would have predicted probability of reproduction when married, rather than probability of reproduction overall; and (iii) we included AFR to control for selective appearance in the models, which is highly correlated with marriage age (electronic supplementary material, table S1). The predicted probability of giving birth was relatively stable from age 25 until age 40, from which point the probability of giving birth declined.

By age 24, 44% of women had produced their first child and thus had reproduced in what we defined as 'early reproductive life' [6,28]. Women who produced two or more children before age 25 had an 11% higher mortality risk in each subsequent year of life than women who did not reproduce in early life, suggesting that investment in reproduction during early adulthood carried a survival cost. Support for the link between lifetime number of pregnancies (gravidity) or births (parity) and long-term health in women is mixed: some have reported the predicted positive association between parity and mortality risk [29], while others have found no association [30], and yet others have found a lower risk associated with very high gravidity [31]. In addition to these analyses of the consequences of total gravidity/parity, are studies of the association between AFR and later-life survival. Such studies have found that early AFR is associated with reduced longevity [32,33]. In United States cohorts born from 1931 to 1941, controlling for social status, education, marital status and parity, women who gave birth during their teens had a 42% greater hazard of mortality from the age of 50 onwards, largely due to increased cardiovascular disease, lung disease and cancer [34]. Similarly, a comparison of three modern populations in the UK, Norway and the USA found that mortality risk between ages 50 and 70 was increased 21–57% in women who had their first child as a teenager [35]. However, other studies have found the association only in certain subsets of the population [36] or that later-life survival or longevity is independent of AFR [37,38]. Nevertheless, a general pattern

emerges whereby more births and earlier onset of reproduction are associated with a later-life survival cost, which is consistent with our finding that high ELF was associated with increased mortality risk in later life. A potential evolutionary mechanism underpinning this trade-off could be selection for genes promoting early fecundity at the expense of late survival [7], while a likely physiological explanation could be that physiological 'wear and tear' leads to an increase in hazard of death from metabolic disease or cancer.

We found that fertility declined rapidly after age 40 in married women. The biological basis of the decline may have been accompanied to some extent by a reduced frequency of intercourse at these ages [39]. However, reduced frequency of intercourse does not significantly affect the likelihood of pregnancy, if intercourse occurs during the fertile window [40]. Despite this, the desire for more children may be lower at later ages, and there is, therefore, likely to be a cultural aspect to the age-related decline in ABS in addition to the biological basis of reduced fertility and eventual menopause. ABS declined significantly from age 41 to 50 in this group, with approximately 20% of women giving birth at age 41, approximately 10% at 45, and zero at age 50. This decline is consistent with the observation of complete cessation of female fertility, across human societies, by age 50 [15]. The gradual decline was probably due to changes in the hormonal profiles of menstrual cycles leading up to menopause: the final 30 cycles before menopause increasingly exhibit delayed ovulation or are anovulatory [18]. However, we did not find that this decline was affected by ELF, and thus found no support for the hypothesis that there would be an accelerated senescence cost of early reproduction [6]. Nor did we find any association between ELF and the annual probability of giving birth during this period. Such a lack of negative association between early reproductive output and later birth rate is not surprising, given that early AFR was associated with higher ABS across all ages, probably reflecting that those females with young age at the onset of reproduction were more fertile overall. This is in line with findings from another long-lived mammal, the Asian elephant (*Elephas maximus*), where individuals producing many offspring in early life were more likely to produce offspring in later life [28]. However, these results are to our knowledge the first indication of the association between ELF and later-life reproductive success in humans.

Contrary to the results for later-life ABS, we found that high ELF was associated with faster senescence in child survival in older mothers. The probability of child survival declined with maternal age, and this decline was most rapid in women with high ELF (figure 2), suggesting that high investment in early reproduction carried a cost in terms of ability to successfully rear children born in later life. This could reflect social factors: for instance, these children may have experienced competition with elder siblings [41], or their grandparents were less likely to still be alive, compared with their older siblings [42,43]. Our results do not reflect older mothers dying before their offspring and therefore not being present to care for them, since we controlled for this known effect [26] in our models. Physiological explanations could include wear and tear induced by earlier births, which may reduce maternal ability to produce and raise a robust offspring [14]. It is interesting to contrast this result with the finding that ELF did not affect

senescence in ABS. Potentially, 'wear and tear' may not apply to the same extent to annual breeding probability, which only reflects the ability to bring a pregnancy to term, which is potentially less costly than extremely energy-expensive lactation [44]. It is also not surprising that breeding success and offspring survival showed different senescence patterns, given that different aspects of reproductive success senesce at different rates in wild animals [45,46]. Our results are consistent with the results of a study of red deer which showed that higher ELF was associated with faster senescence in calf birth weight and date [6]. Conversely, a study of common lizards (*Zootoca vivipara*) showed that females investing heavily in reproduction in their first breeding attempt subsequently showed higher litter success and offspring corpulence than those making low investment, and no decline in these traits at older ages [47]. Finally, correlates of offspring fitness decline as a function of parental age in many vertebrates: for example, survival of blue-footed booby (*Sula nebouxi*) chicks [48,49] and red squirrel (*Sciurus vulgaris*) kittens [50] and birth weight and survival of Soay sheep (*Ovis aries*) lambs [45]. A previous study of the Finnish population found a 4% decline in the probability of offspring survival to 15 in mothers aged 44 compared with those aged 32, and an 18% decline in LRS for individuals born to a 43 year old mother compared with individuals born to a 21 year old mother [51]. However, in this study we show an additional effect of early-life reproduction on this decline, a finding which has not, to our knowledge, been investigated before in humans.

The apparent effect of female ageing on offspring survival is potentially important, since in modern society an increasing proportion of births are taking place once women are into their forties [12]. Although it is possible that improved nutrition and medical care have attenuated the costs of reproduction in modern society, costs may still be apparent. For example, even though most babies now survive to adulthood in industrialized countries, maternal age may still affect development, leading to more subtle or longer-term effects on offspring health [52]. This effect could be exacerbated by earlier investment in reproduction and ultimately, in modern societies, delaying the onset of reproduction to later ages is associated with increased likelihood of pregnancy failure [53]. While our results are difficult to interpret in the context of modern human societies, they do suggest that human life histories have been subject to similar life-history trade-offs as are apparent in many wild vertebrate populations which show a cost of ELF in terms of reduced later-life survival [54,55] and reproductive success [5,6].

ELF therefore appeared to impose a survival cost, to both the female and her offspring produced later in life. However, despite these costs, ELF was under positive selection through LRS. This may be a result of variation between individuals in their acquisition or allocation of resources: women with the resources to reproduce in early life also have the resources to reproduce in later life [11,56]. Selection for earlier AFR has been demonstrated in human populations before [22,57], but this is, to our knowledge, the first study investigating selection on early-life reproductive investment in humans and a rare example in any species, especially those with a long lifespan. However, a previous study on guillemots found that higher ELF was associated with higher lifetime breeding success [5] and Asian elephant females

investing heavily in reproduction before the age of peak fertility had higher lifetime breeding success, despite a negative association between early-life fertility and later maternal survival as found in our study [28].

In this study, we found evidence for contrasting associations between early-life reproductive success and later-life survival and reproduction. Women who produced more children before the age of 25 had a higher risk of mortality after this age, but overall had higher LRS. A caveat to these results is that phenotypic associations may not reflect underlying genetic correlations, and therefore cannot be used to predict past and future trajectories of evolution. For example, non-genetic variation in exposure to disease or ability to access and use resources, and resulting effects on health and physiology, may create positive phenotypic associations where negative genetic associations exist [11,56]. We attempted to counter such effects by controlling for factors consistently associated with variation in resource acquisition, fitness traits and health in our population, chiefly birth year [58–60] and social class [22]. We also note that there is evidence for a genetic correlation between early reproduction and late survival in both human and non-human primates. Previous work on this population observed a positive genetic correlation between AFR and longevity, suggesting that genes for early reproduction are also associated with reduced lifespan [61]. Similarly, a study of Rhesus macaques (*Macaca mulatta*) found a positive genetic correlation between AFR and survival to various stages of adulthood [62]. While AFR and ELF are different traits, these results do suggest that to some extent the trade-off between reproduction at early ages and survival in later life may have a genetic basis, though we do not suggest that our results here provide evidence for such a trade-off at the genetic level. This could be explored further by determining the genetic association between ELF and later-life performance, including senescence rates and longevity: a study of red deer revealed a genetic trade-off between ELF and the rate of senescence in birth weight [63], but similar studies on humans are lacking. Other opportunities for further research include determining changes in the strength of the reproduction-survival trade-off with age [64], which may enable a test of the hypothesis that the menopause evolved as an early cessation of reproduction due to the survival costs of reproduction increasingly outweighing the benefits with increasing age [65]. In short, while the proximate mechanisms of human reproductive maturity and senescence are already relatively well understood, tests of evolutionary theory will enable us to determine the ultimate mechanisms underpinning the unusual human life history.

Data accessibility. The data used for this study are available on request by contacting Dr V. Lummaa (v.lummaa@sheffield.ac.uk).

Acknowledgements. We thank Lasse Iso-livari, Kimmo Pokkinen and Aino Siitonen for data collection, as well as Bobbi Low and two referees for comments on an earlier draft which improved the manuscript.

Author contributions. A.D.H. participated in the design of the study, performed the statistical analysis and drafted the manuscript; I.N. helped to draft the manuscript; V.L. participated in the design of the study, conceived the long-term project on the Finnish dataset and helped to draft the manuscript.

Funding statement. We are grateful to the European Research Council (A.D.H., V.L.), Polish Ministry of Science and Higher Education (I.N.) and Foundation for Polish Science (I.N.) for funding.

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