Mortality change and lifespan inequality

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Paper presented at the Population Association of America meeting, New Orleans, 2013

<u>Please do not cite without author permission</u>

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Words: 4,012 (excluding references, tables and figures)

Figures: 6

Supporting Information: Supplementary derivations; Supplementary Figures 8; Supplementary Tables 1

Keywords. Disparity, health, longevity, retirement, social policy

Short title: Mortality change and lifespan inequality

In the past six decades, lifespan inequality has varied greatly within and among countries even while life expectancy has continued to increase. How and why does mortality change generate this diversity? We derive a precise link between changes in age-specific mortality and lifespan inequality, measured as the variance of age at death. Key to this relationship is a young–old threshold age, below and above which mortality decline respectively decreases and increases lifespan inequality. First, we show that the threshold's location modifies the correlation between changes in life expectancy and lifespan inequality, illustrating this over two centuries in Sweden. Second, we analyze the post Second World War trajectories of lifespan inequality in a set of developed countries, focusing on Japan, Canada and the United States (US). Here, the thresholds centered on retirement age. Our analysis shows that the focus of Japanese mortality decline shifted gradually from young to old, causing lifespan inequality to switch from decrease to modest increase ca. 1990. Early in the 1980s, mortality increases in young US males, led lifespan inequality to remain high in the US, while in Canada there were steady declines. In general, post Second World War mortality change varied most at young working ages, particularly in males. We conclude that if mortality decline continues to stagnate at young ages, but to progress steadily at old ages, lifespan inequality increases will become more common.

Introduction

Lifespan inequality is the defining measure of social and health disparity and, alongside life expectancy (the mean age at death), is a key indicator of population health (Tuljapurkar et al. 2000; Edwards and Tuljapurkar 2005). Changes in life expectancy are well understood in terms of the underlying changes in mortality: mortality reduction at any age increases life expectancy (Keyfitz 1977; Goldman and Lord 1986; Vaupel 1986; Vaupel and Canudas-Romo 2003). However, the precise link between lifespan inequality and age-specific mortality is less clear. First, only mortality decline at ages below a young–old threshold can decrease lifespan inequality (Zhang and Vaupel 2009; Vaupel et al. 2011; van Raalte and Caswell 2012). Second, there are several ways to quantify lifespan inequality and understand its change through time (Wilmoth and Horiuchi 1999; Cheung et al. 2005; Edwards and Tuljapurkar 2005; Horiuchi et al. 2008; Vaupel et al. 2011). Although highly correlated, these measures behave differently in response to change in the age structure of mortality (van Raalte and Caswell 2012). Here, we measure lifespan inequality by the variance of age at death, which measures the dispersion in age at death relative to life expectancy (Edwards and Tuljapurkar 2005). The variance of age at death is a central parameter in population and economic modeling (Tuljapurkar 2008; Caswell 2009; Tuljapurkar and Edwards 2011; Edwards 2012; Schindler et al. 2012) and it is therefore important to understand how it responds to mortality change. We present an exact relationship between age-specific mortality and the variance of age at death—a more transparent and demographically interpretable relationship than that derived by Caswell (Eq. 42 in Caswell (2009)). Our framework provides a powerful tool for quantifying how trajectories of age-specific mortality affect the variance, both within countries and in an international sample of countries.

Given period age-specific mortality, $\mu(x)$, and the corresponding probability of survival to each age $l(x)$, the age-distribution of death is $\varphi(x) = \mu(x)l(x)$. Figure 1 contrasts the age-distribution of death in Sweden in 1800 and 2000, illustrating the standard outcomes of development: (i) reduction of child death; (ii) increase of life expectancy; (iii) emergence and advance of a modal age at adult death; (iv) decrease of lifespan inequality (Lee and Carter 1992; Bongaarts 2005; Canudas-Romo 2008; Vaupel et al. 2011). These arise from an initial focus of mortality decline on children and young adults followed by a shift of mortality decline to older ages (Cutler et al. 2006).

Since about 1950 in the developed countries, life expectancy has increased consistently but change in lifespan inequality among countries has varied greatly (Edwards and Tuljapurkar 2005; Peltzman 2009; Smits and Monden 2009; Engelman et al. 2010). This is in striking contrast to the strong negative correlation between changes in life expectancy and lifespan inequality present during the first century of mortality decline (Vaupel et al. 2011). The recent variability of this relationship, we show, results from the very different responses of life expectancy and lifespan inequality to age-specific mortality change. First, we show that in Sweden, the threshold for the variance of age at death increased from childhood in the late 18^{th} century to around 65 years (y) in 1950. This movement of the threshold altered the relationship between changes in life expectancy and lifespan inequality. Second, we examine the pattern of post Second

World War lifespan inequality across many countries, and then focus on Japan, Canada and the United States (US). The application of our decomposition to these post war trajectories of lifespan inequality showed that fluctuations in lifespan inequality resulted primarily from mortality change at young working ages.

Results

The analysis of change

The variance of age at death after a specified index age A is

$$V(A)=\frac{1}{l(A)}\int_A^{\infty}\varphi(x)[x-e(A)]^2\,dx, \qquad (1)$$

where $e(A)$ is the life expectancy after age A. If we set A=0, life expectancy is $e(0)$ and the variance, $V(0)$, quantifies the dispersion among deaths at all ages. However, for developed countries it can be more informative to focus on adult ages, e.g. using $V(15)$[1].

[1] $V(0)$ is necessarily dominated by the (now usually small) fraction of infant deaths. If we set A=15, life expectancy $e(15)$ and the variance $V(15)$ describe the dispersion of adult deaths. The advantage of focusing on adult ages is that the effects of infant mortality change are removed. Infant mortality has fallen steadily, driving steady declines in $V(0)$ (Edwards and Tuljapurkar 2005; Tuljapurkar and Edwards 2011). Considering only mortality after particular index ages A can often reveal quite different trajectories of $V(A)$ (Engelman et al. 2010). Even with low infant mortality, the inclusion of the few youngest ages can obscure the lifespan inequality effects of adult mortality change. This makes $V(15)$ an ideal measure for investigating how the variability in age-specific mortality trajectories contributes to lifespan inequality change.

What is the change in $V(A)$ due to a proportional mortality reduction at an age x greater than A? Starting from Eq. 1, we find

$$\frac{dV(A)}{d\ln\mu(x)} = \frac{-2\mu(x)}{l(A)}\int_x^\infty l(z)[z-e(A)]dz, \qquad (2)$$

(for details, see Supplementary Information). The integral in Eq. 2 has a negative term: the contribution from ages between x and $e(A)$, and a positive term: the contribution from ages above $e(A)$. If mortality decreases at an age above $e(A)$, the variance $V(A)$ will increase. Now suppose that we reduce mortality at an age below $e(A)$. It is clear from Eq. 2 that reducing mortality at younger ages will gradually cause the negative contribution to dominate, thus decreasing $V(A)$. We therefore define a young–old threshold age, which we call $T(A)$, before which mortality decline decreases $V(A)$, and after which mortality decline increases $V(A)$.

Hereafter, we refer to the rate of change in Eq. 2 as the sensitivity of $V(A)$. Figure 2a shows the sensitivity of the variance for A=15, for Sweden in 1950 and 2011. Three features of the plot are typical of mortality in developed countries: (i) mortality decline at ages from 15 to about 65 y decreases V; (ii) mortality decline after about 65 y increases V; (iii) there is a threshold, $T(15)+15$, at approximately age 65 y, which separates 'young' ages, where mortality decline decreases V, from 'old' ages, where mortality decline increases V. The sensitivity of life expectancy $e(15)$ to a proportional mortality decline at age x (Goldman and Lord 1986; Vaupel 1986; Vaupel and Canudas-Romo 2003) is shown for comparison in Figure 2b. The obvious distinctions are that mortality decline at any age increases life expectancy; and that mortality decline close to the threshold has least effect on V. The great difference in the shape of these sensitivities of life expectancy and lifespan inequality, especially below the threshold age, is the critical factor driving their divergent responses to the same age structure of mortality change.

Long-term mortality change

Sweden was the first country to record ages at death systematically, with records from 1751 to the present (Human Mortality Database 2012). These data provide the best opportunity to understand the long-term association of the young–old threshold with changes in lifespan inequality. Figure 3 displays the annual change in the thresholds $T(A)+A$, for index ages A=0, 15, and 65 y. Figure 4 shows the concurrent changes in $e(A)$ and $V(A)$.

To provide some basic intuition on how the threshold depends on the age structure of mortality, we note that a lower bound on the threshold for A=0 (derived from Eq. 2 in the Supplementary Information) is

$$T(0) \geq 2e(0) - \omega, \qquad (3)$$

where ω is the longest lifespan. In the early years of transition to low mortality, before the late 19th century, the lower bound defined by Eq. 3 was below or close to zero. In the first half of the 20th century, life expectancy increased rapidly, which substantially increased the threshold age—e.g. with $e(0)$=65 and ω=100 we have a lower bound at 30 y. More recently, life expectancy has begun to converge on ω. This convergence is commonly known as 'rectangularization' of the age structure (Wilmoth and Horiuchi

1999), and it causes the lower bound on the threshold to advance. We now turn to exact values of the young–old threshold.

Before about 1875, the threshold $T(0)$ followed a fluctuating increase to about 20 y (Fig. 3), so only mortality decline in children and very young adults could decrease V. However, $V(0)$ changed little (Fig. 4a), indicating an even distribution of mortality decline below and above the threshold age. From 1875 to about 1950, the threshold advanced to near 60 y, so mortality decline at a greater range of young ages could now decrease V. This reinforced the strong negative correlation between changes to life expectancy and lifespan inequality. In this period, V decreased rapidly and life expectancy increase accelerated, indicating much faster mortality declines below the threshold age. After 1950, the threshold continued advancing to 70–75 y. In this recent period, decreases in V slowed, despite continued increases in life expectancy, indicating the switch to more even mortality decline below and above the threshold age.

Increasing the index age after which we measure lifespan inequality advances the young-old threshold. To investigate changes in lifespan inequality among adults, we use an index of 15 y. $V(15)$ did not begin to decrease rapidly until ca. 1925 (Fig. 4b), when the threshold $T(15)+15$ was 57 y (Fig. 3). That this decrease began around 50 y later than the decrease in $V(0)$ indicates the much later spread of rapid mortality decline from below 15 y to 15–57 y. By 1950, mortality reduction below 15 y had converged the thresholds $T(0)$ and $T(15)+15$ to 60–65 y. This initiated a period when the distribution of mortality change between working and retired ages was critical in shaping the trajectory of lifespan inequality.

Consider now an index age of 65 y: the obvious feature of mortality change is the consistent positive relationship of changes in life expectancy and lifespan inequality (Fig. 4c). The threshold $T(65)+65$ was always near 70 y, so only mortality decline at a few young ages could decrease $V(65)$. Therefore, even with mortality reduction by an equal proportion at each age, there was a strong bias for variance increase. The only deviation occurred after 1980, when the trajectory of $V(65)$ flattened while $e(65)$ increased; the threshold was 75 y in 1980. Comparison of mortality change at ages 65–75 y, and >75 y showed an abrupt increase in mortality decline among males, which was greatest at 65–75 y (Fig. S1). This was large enough to overwhelm the bias for variance increase and, for the first time since 1751, disrupted the positive correlation between increases in life expectancy and lifespan inequality. We now return to lifespan inequality across the full range of adult ages.

The young–old threshold for mortality in developed countries

In developed countries the age-distribution of death has a well-defined modal age in adulthood (Fig. 1). This makes it a reasonable fit to the Gompertz model in which mortality increases with age as

$$\mu(x) = Be^{kx}, \qquad (4)$$

where B is the initial level of mortality and k is the exponential rate of mortality increase. From Eq. 4 (see Supplementary Information and Pollard (1991)) the mode (m) and standard deviation (σ) of age at death are

$$m = \frac{1}{k}\ln\frac{k}{B}, \qquad (5)$$

and

$$\sigma = \frac{1}{k}. \qquad (6)$$

Life expectancy is given to a good approximation by

$$e(0) \cong m - \frac{\sigma}{2}, \qquad (7)$$

and our threshold is approximated by

$$T(0) \cong m - \frac{3\sigma}{2}. \qquad (8)$$

This places the threshold at 1.5 standard deviations of the age at death below the modal age, and (using Eq. 7) 1 standard deviation below life expectancy. The threshold's advance is therefore driven by increases in both adult life expectancy and modal age at death.

Age-specific drivers of lifespan inequality change in developed countries post-1947

We now focus on the post war changes to $V(15)$, for which the young–old threshold was largely at ages 60–70 y. Our analysis shows that changes in lifespan inequality were shaped by striking differences in mortality change for young versus old adults. Figure 5 (solid lines) shows the average sex-specific trajectories of $V(15)$ across 40 regional data series in the Human Mortality Database (Vaupel et al. 2011). The average variance trajectory fluctuated more for males, and the annual direction of variance change was less consistent among regions for males (Fig. S2). In Figure 5, we also show (dashed lines) the variance effects of mortality change at young ages (below the threshold) and at old ages (above the threshold), with each component again averaged across regions. Fluctuations in the trajectories of variance change were clearly driven by mortality change at young ages, particularly in males. This conclusion is supported by the pattern (grey shading) of the annual 95% range among regions of the young and old components of variance change.

We now examine in more detail Japan, Canada and the United States (US), which illustrate the main features of post-1947 mortality change in developed countries: relatively steady increase in life expectancy (Fig. S3), but large fluctuation in V (Fig. S4). We focus on two features: the rapid decrease in variance immediately after 1947, which was especially pronounced in Japan; and the slowing of variance decrease or onset of variance increase in the 1980s. The US in particular showed a striking variance increase in the early 1980s. The average threshold age was close to the conventional age of retirement, although there was a steady increase in the thesholds over time—by a maximum of 28 y in Japanese females (Fig. S5). Figure 6 shows how mortality change at young ages (below the threshold) and at old ages (above the threshold) generated the contrasting variance trajectories of each country. We also computed the components of variance change from below and above the fixed age of 65 y (Fig. S6). These components were near identical to those either side of the shifting threshold, indicating that mortality change near the threshold had minimal influence. We now focus on Fig. 6, which presents the components of variance change from below and above the shifting threshold age.

Japan

Each sex in Japan followed the same basic trajectory of variance change: a rapid decrease from 1947 to about 1975, and then increase after about 1990 (Fig. 6a & b). The sexes differed in that V initially decreased faster for females, and the reversal from variance decrease to increase was earlier for females. Our decomposition (considering successive periods of ten-years) showed that variance decrease before 1977 was driven by the variance contracting effects of mortality decline at young ages, which dominated the effects of mortality decline at old ages (Fig. 6a & b). From 1977 to 1987, these opposing effects reached a rough equilibrium and so V changed little. After 1987, the negative effects of mortality decline at young ages weakened further, which led the positive effects of mortality decline at old ages to dominate. This shift in the focus of mortality decline to old ages led V to increase (Fig. S7). Females had an initially faster variance decrease because they had faster mortality declines at young-ages (Fig. S7). Females switched earlier from variance decrease to increase because, after 1987, male mortality decline slowed at old ages leaving females the larger positive component of variance change. After 1997, the continued slowing of mortality decline at young ages caused variance increase for both females and males.

Canada and the US

In Canada and the US the variance changes after 1947 were much smaller than in Japan (note the difference in *y*-axis scales in Fig. 6). Prior to 1983, Canada and the US followed similar trajectories, each with little net variance change. However, after 1983, V increased and continued to fluctuate in the US, but began a rapid and consistent decrease in Canada. The result was that, from 1983 to 2007, the Canadian variance (for females and males respectively) change from 8% and 9% lower than the US, to 20% and 15% lower.

We now focus on the period 1983–1994, which captures the major variance divergence between Canada and the US (Fig. 6 c–f). In Canada, mortality decline at young ages produced percentage variance changes of −10.8% for females and −10.1% for males (Fig. 6c & d). From old ages the changes were 1.0% in females and 2.9% in males. In the US, mortality change at young ages produced variance changes of −3.3% in females and 3.6% in males, and from old ages 1.5% and 4.8% respectively (Fig. 6e & f). Thus, due mainly to differences in male mortality change, the US produced a larger component of variance increase from old ages, and a much smaller component of variance decrease (and for males, variance increase) from young ages.

How did mortality change differ at young ages between Canada and the US? In the US, male mortality increased at ages 15–22 and 27–45 y, with increases greater than 30% at 34–37 y (Fig. S8). US females showed a similar pattern, but of smaller magnitude (a maximum increase of 20% at 35 y). By contrast, mortality increase for Canadian males was limited to ages 32–40 y, with a maximum increase of 17%; mortality generally declined for Canadian females. The age-specific changes in mortality therefore differed most between Canada and the US at young working ages, particularly in males. The resulting sharp variance divergence between Canada and the US is in stark contrast to their very similar trajectories of life expectancy during this period (Fig. S3).

Discussion

We have shown how change in lifespan inequality, as measured by V, depends strongly on the balance of mortality change around a young–old threshold. The threshold advances with increases in life expectancy, the modal age at death, and with the compression of mortality into a narrower range of ages. Before about 1950, changes to life expectancy and lifespan inequality had a strong negative correlation (Smits and Monden 2009; Vaupel et al. 2011). This arose because the emphasis of mortality decline was on ages below the threshold (Vaupel et al. 2011). Since 1950, lifespan inequality decrease has slowed, and occasionally even reversed. We show that the post Second World War fluctuations lifespan inequality were driven by fluctuations in mortality at young working ages, below the threshold age, while at old ages mortality decline was relatively consistent. The implication of these trends is clear: if mortality at young ages continues to fluctuate, and mortality at old ages continues its steady decline, lifespan inequality increases will become more common.

But what drives these trajectories of age-specific mortality, causing them to vary both within and among countries? Age-specific mortality is ultimately associated with education, income, social support (from family or public institutions, including the provision of healthcare), lifestyle, disease and living conditions. These interact with the proximate, health related, causes of death to generate lifespan inequality (Edwards and Tuljapurkar 2005; Shkolnikov et al. 2011; Nau and Firebaugh 2012). For example, Japanese development after 1947, including the start of universal healthcare in 1961, generated rapid mortality decline at mainly working ages. However, social gradients in age-specific health and mortality were also strengthening, characterized widening differences in age-specific mortality by education and income, particularly for young adult males (Fukuda et al. 2004; Kagamimori et al. 2009). At the same time, Japan's rapid progress against young-age mortality likely reduced the scope for further mortality decline at young ages, by leaving only the harder to prevent causes of death.

A great deal of research is aimed at understanding why young adult mortality remains high in the US compared to other high-income countries (Crimmins et al. 2011; IOM 2012). One source may be high geographic disparity in young adult mortality rates within the US. For example, Cullen et al. (2012) showed that mortality differences below age 70 among US counties resulted largely from differences in education and income, particularly for males (see also Backlund et al. 2007; Crimmins et al. 2009). Recent evidence also suggests that life expectancy differences between educational groups in the US have widened in recent decades (Olshansky et al. 2012). A part of this variation is likely due to differences in healthcare access among young adults (Crimmins et al. 2011). In the US, healthcare access at working ages depends largely on employer-provided health insurance; in 1994, 18.6% of non-elderly adults in the US had no insurance (Holahan and Kim 2000). Being without insurance limits care, particularly preventive care at young ages (Lasser et al. 2006), with evidence for consequently higher mortality

(Wilper et al. 2009). The 1980s lifespan inequality divergence between Canada and the US is likely explained by such social factors, that likely interact with the common causes of young adult death—drugs, violence and infectious disease (Nau and Firebaugh 2012). For example, HIV/AIDS became prevalent in the 1980s and early 1990s, particularly among US males aged 25–64 y (Armstrong et al. 1999; UNAIDS 2013).

Alternate inequality metrics

There are several established metrics of lifespan inequality (van Raalte and Caswell 2012). For the same mortality data, the young–old threshold can differ widely among these metrics, e.g. by around 20 y between *V* and the metric known as lifespan disparity or $e^{\dagger}$ (Zhang and Vaupel 2009). Our results indicate that the major post Second World War mortality changes occurred outside the zone of threshold disagreement among metrics, indicating that our qualitative conclusions are robust to the choice of metric. We use *V* for several reasons: it is easily understood and interpreted as a measure of relative dispersion, easily decomposed (Edwards and Tuljapurkar 2005; Edwards 2011; Nau and Firebaugh 2012), and finds direct use in analyzing the demographic and economic consequences of mortality change (Tuljapurkar 2008; Edwards 2012; Schindler et al. 2012).

The future

The young–old threshold in developed countries is now approaching 75–80 y (Figure 2a), so only mortality decline at the oldest retired ages can increase lifespan inequality. Given the ongoing fluctuation of age-specific social gradients in health and mortality, and the importance of social mortality gradients for generating lifespan inequality (Cullen et al. 2012; Olshansky et al. 2012), we suggest that future work focus on the population-level effects of mortality change within specific subgroups (Edwards 2011; Shkolnikov et al. 2011; van Raalte et al. 2011; Nau and Firebaugh 2012; van Raalte et al. 2012). Our results highlight that without an increased consistency of young-adult mortality decline, we cannot assume that future mortality change will follow the historical pattern of increasing life expectancy and decreasing lifespan inequality.

Materials and Methods

We downloaded our data from the Human Mortality Database in January 2013 (Human Mortality Database 2012), see the Background Information for each country, www.mortality.org. For international comparisons, we used the same data series as Vaupel et al. (2011). Table S1 shows the range of years between 1947 and 2011 covered by these data. We conducted all calculations in the R environment (R Development Core Team 2012). The Supplementary Information gives the derivation of each formula presented. For our age-decomposition of change in $V(15)$, we adapted Eq. 2 to

$$\frac{dV(15)}{dt} = -2\int_{15}^{\infty}\frac{a(x)\mu(x)}{l(15)}\int_{x}^{\infty} l(z)[z-e(15)]dzdx, \qquad (9)$$

which gives the change in $V(15)$ over time interval dt. The observed proportional changes in age-specific mortality, $a(x)$, between years t and t+1 were computed as

$$a(x) = \frac{\mu(x,t+1)-\mu(x,t)}{\mu(x,t)}. \qquad (10)$$

To convert time in these formulae to discrete 1 y intervals, we discretized the probability density function of age at death, considered survivorship to the mid-point of each age-interval, and substituted instantaneous mortality for central death rates. We counted age in 1 y intervals starting from 0.5 y. Where we present mortality change over wider age intervals, we compute a weighted average of the 1 y central death rates in each interval, using the probability of survival to each age as weights (Ahmad et al. 2001).

Acknowledgements

This project is funded by the National Institutes of Health grants AG22500 and AG039345 to S.T. and by the Stanford Center for Population Research.

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Figures

Fig. 1 The period age-distributions of death for years 1800 and 2000 in Sweden. The vertical lines show life expectancy *e*(0). The modal age at death in adulthood became prominent only after the major process of mortality decline

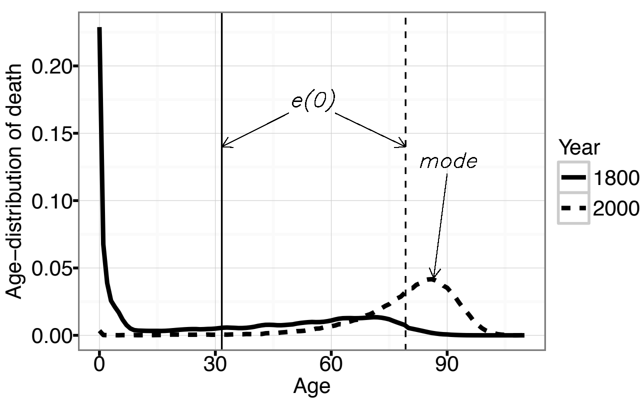

Fig. 2 The age-specific sensitivities to proportional mortality reduction in Sweden for 1950 (solid lines) and 2011 (dashed lines) of: (a) the variance of age at death after 15 y; and (b) the mean age at death, i.e. life expectancy, after this age. The vertical lines show the life expectancy after 15 y, *e*(15)+15

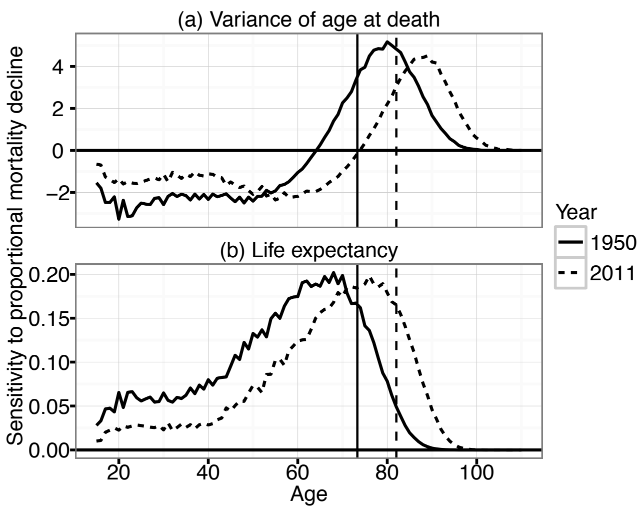

Fig. 3 The young–old thresholds, *T*(*A*)+*A* for *A*=0, 15 and 65 y from 1751 to 2011 in Sweden. Note that even in 2011, *T*(65) is only 14 years, much smaller than *T*(0) and *T*(15)

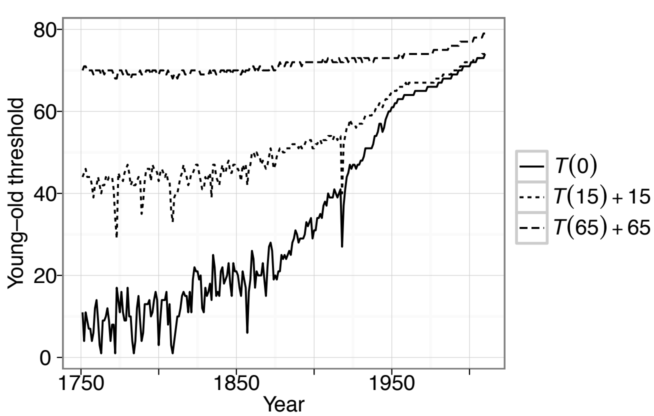

Fig. 4 The trajectories of the variance $V(A)$ for A=0, 15 and 65 y, in panels (a), (b) and (c) respectively, alongside the corresponding trajectories of life expectancy, $e(A)$. Each trajectory has been scaled so that it ranges between zero and one during the study period

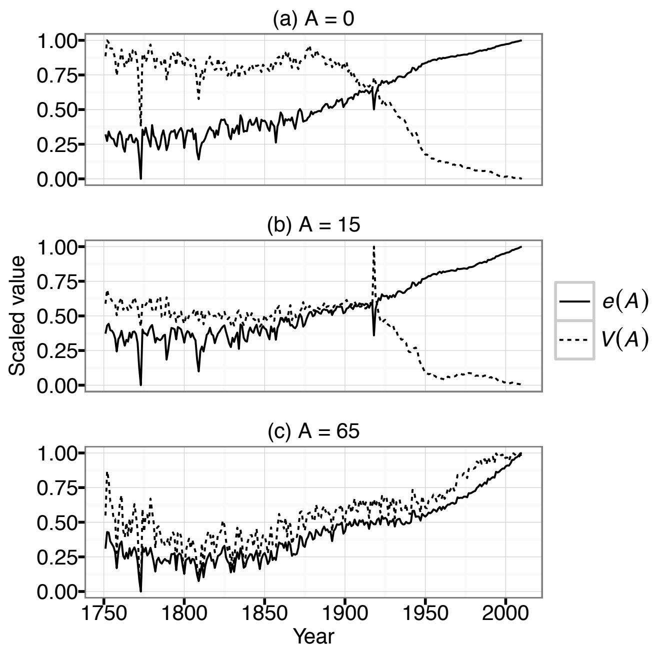

Fig. 5 For females (a) and males (b), solid lines show the average trajectory of the variance of age at death after 15 y, $V(15)$, across 40 regions in the Human Mortality Database (see Table S1 for details). The upper dotted lines show this average trajectory as it would have been with mortality change only above the threshold age, $T(15)+15$. The lower dashed lines show this for mortality change below the threshold. Note that the lines do not show the variance change at each time t ($1947 \leq t \leq 2011$), but show the cumulative effects of mortality change from 1947 to time t. Thus, if W is the annual change in V due to mortality change below or above the threshold in each year, the dotted

and dashed lines are given by $V(15,\ 1947)+\int_{1947}^{t} W(15,u)du$. The grey shading around the dotted and dashed lines shows the 95% range among regions of the annual components of change

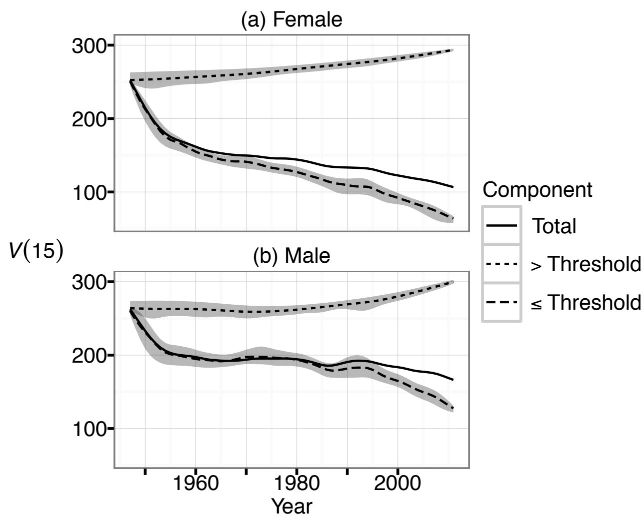

Fig. 6 Decomposition of the variance of age at death after 15 y, $V(15)$ into the effects of mortality change below and above the young–old threshold age, $T(15)+15$. Solid lines show the overall variance change, dashed lines the change produced from ages below the threshold, and dotted lines the change produced from ages above the threshold. We show separate decompositions for females and males in Japan (a & b), Canada (c & d) and the United States (e & f) from 1947 to 2007. Lines show the cumulative variance effects of mortality change plus $V(15, 1947)$, see details in the legend of Fig. 5

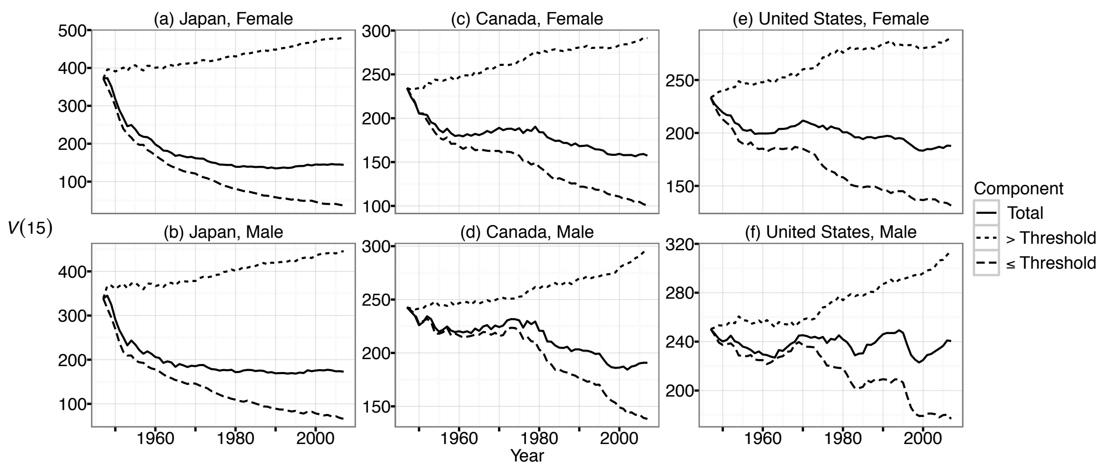

Fig. S1 Weighted average one-year central death rates between 65–75 years and above 75 years for each sex in Sweden from 1950 to 2010. The weights used in the calculation were proportional to the probability of survival to each age. The trajectories have been standardized so that each ranges between zero and one

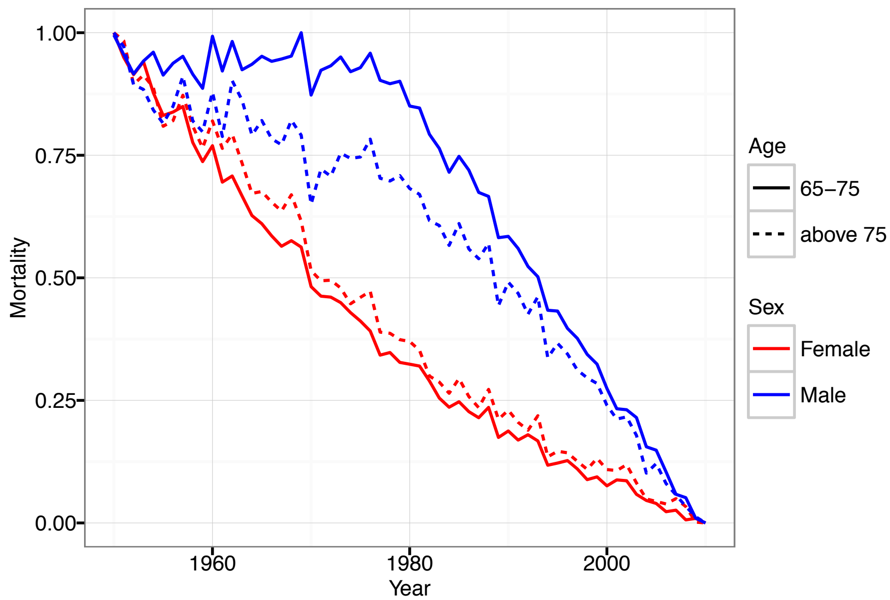

Fig. S2 The average trajectories of the variance of age at death after 15 years, $V(15)$, in 40 regions from the Human Mortality Database for females (solid lines) and males (dashed lines). The grey shading shows the 95% range among regions of the direction of variance change in each year. The maximum extent of years is 1947–2011, but not all regions have data for each year; see details in Table S1

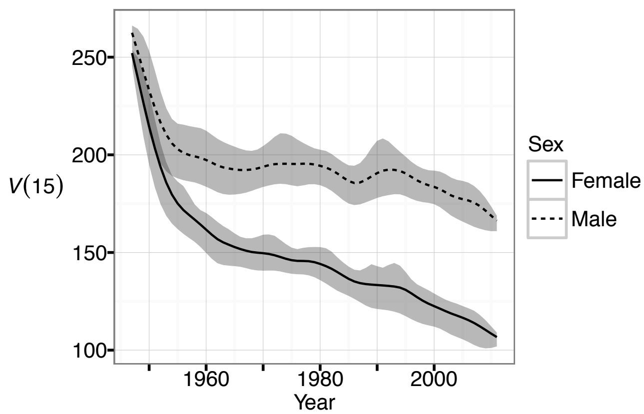

Fig. S3 Life expectancy after zero years i.e. at birth, *e*(0) and 15 years, *e*(15) respectively in (a) & (b) Japan, (c) & (d) Canada and (e) & (f) the United States from 1947 to 2007. Separate lines show the total population, females only and males only

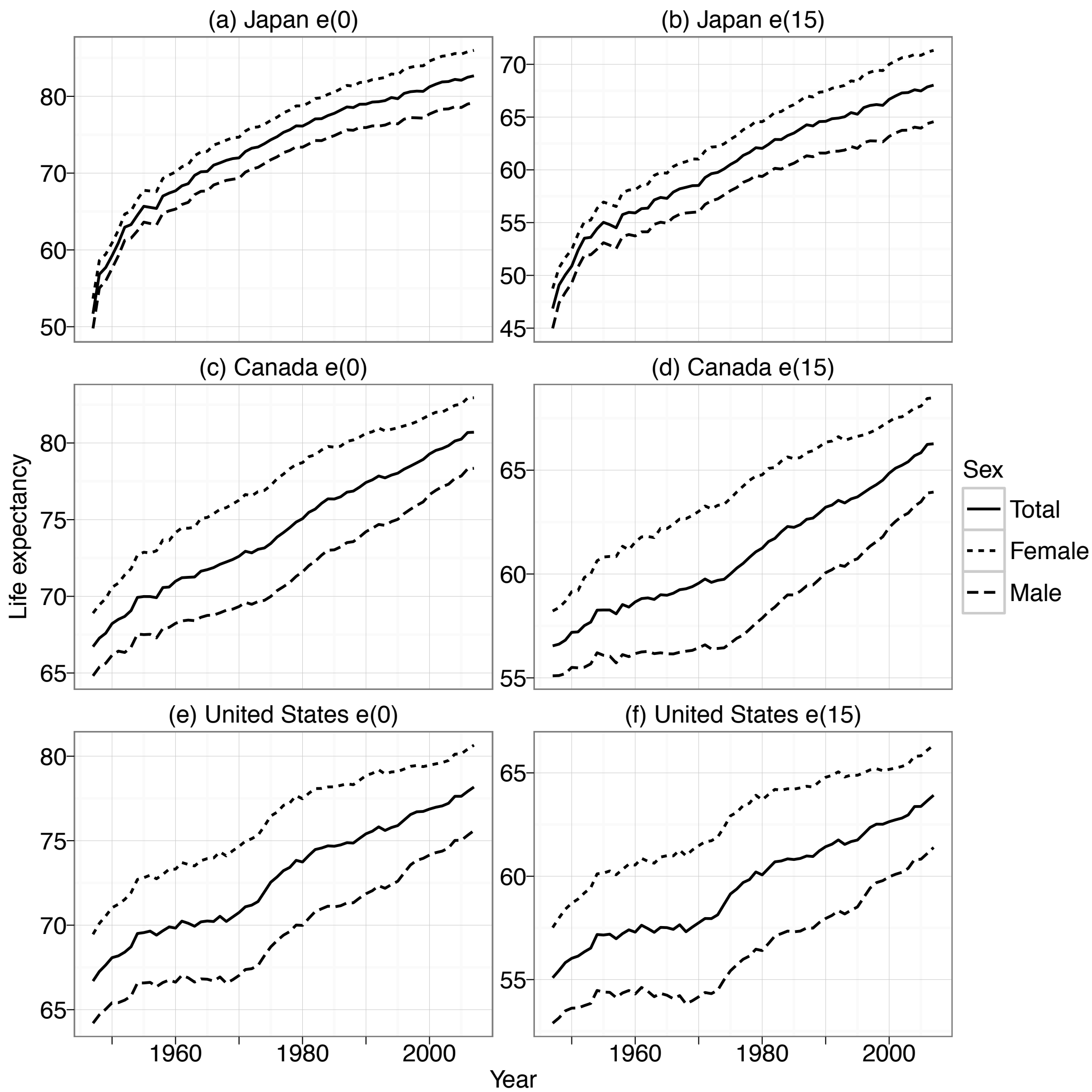

Fig. S4 The variance of age at death after 15 years, $V(15)$ in (a) Japan, (b) Canada and (c) the United States from 1947 to 2007. Separate lines show the total population, females only and males only

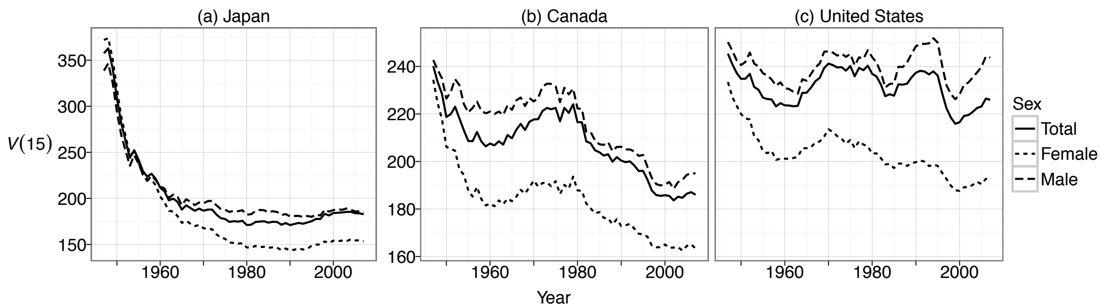

Fig. S5 The young–old threshold for individuals alive at 15 years, $T(15)+15$, for (a) Japan, (b) Canada and (c) the United States from 1947 to 2007. Separate lines show the total population, females only and males only. The blue lines show the fit of a loess smooth to the integer values that arise from our use of mortality data in discrete one-year age and period form

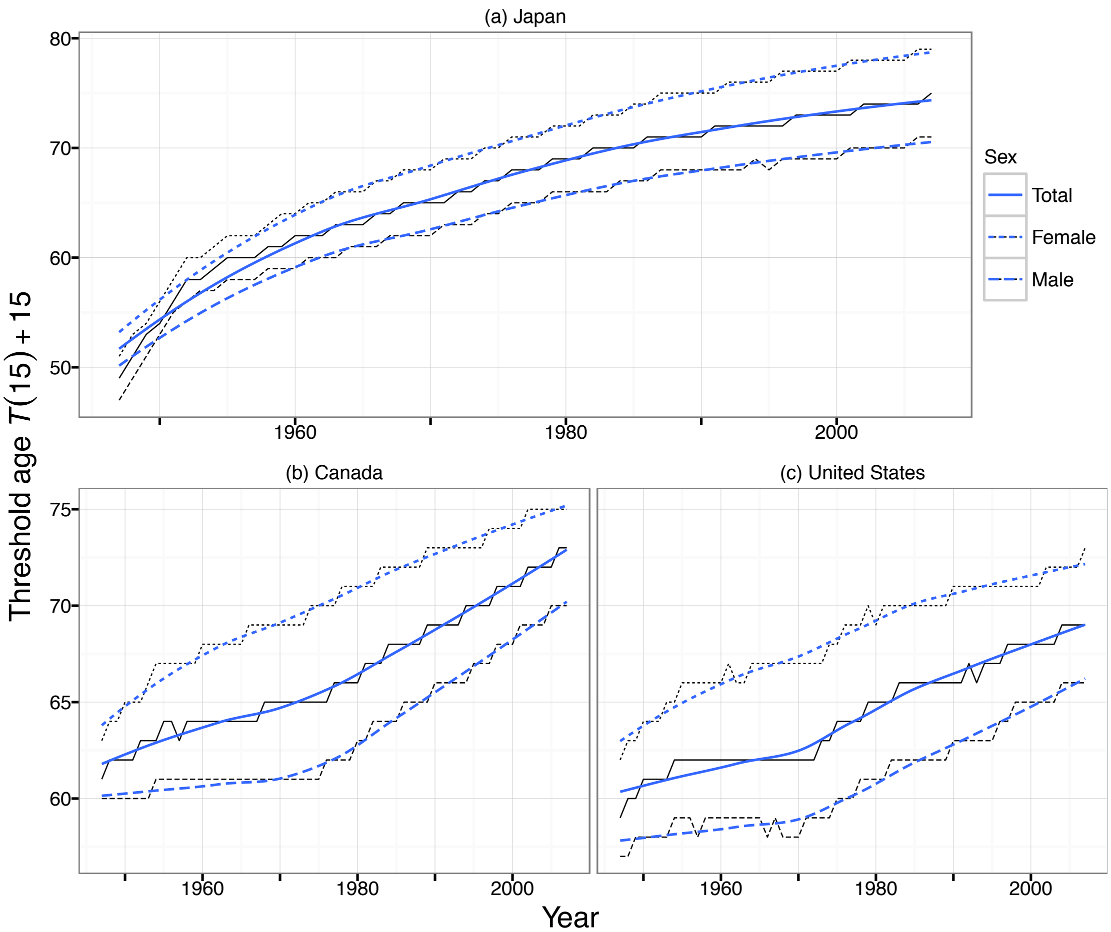

Fig. S6 Decomposition of the variance of age at death after 15 years, $V(15)$ into the effects of mortality change at working ages (15–65 years) and retired ages (>65 years). Solid lines show the total cumulative change, dashed lines the cumulative change produced by working ages only, and dotted lines the cumulative change produced by retired ages only. We computed separate decompositions for females and males in Japan (a & b), Canada (c & d) and the United States (e & f) from 1947 to 2007

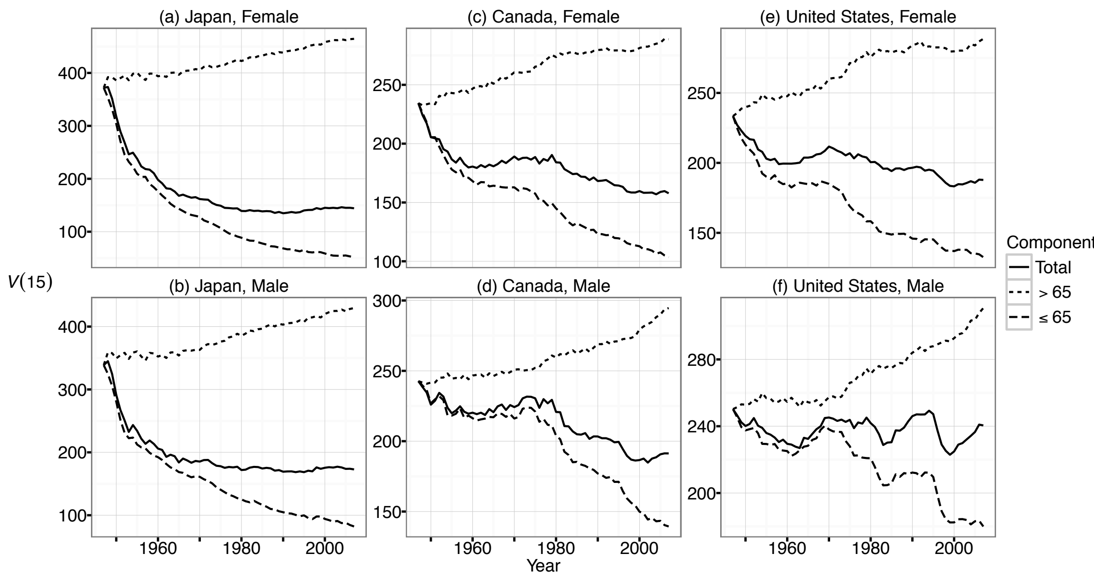

Fig. S7 Weighted average one-year central death rates between 15–65 years and above 65 years for each sex in Japan from 1947 to 2007. The weights used in the calculation were proportional to the probability of survival to each age. The trajectories have been standardized so that each ranges between zero and one

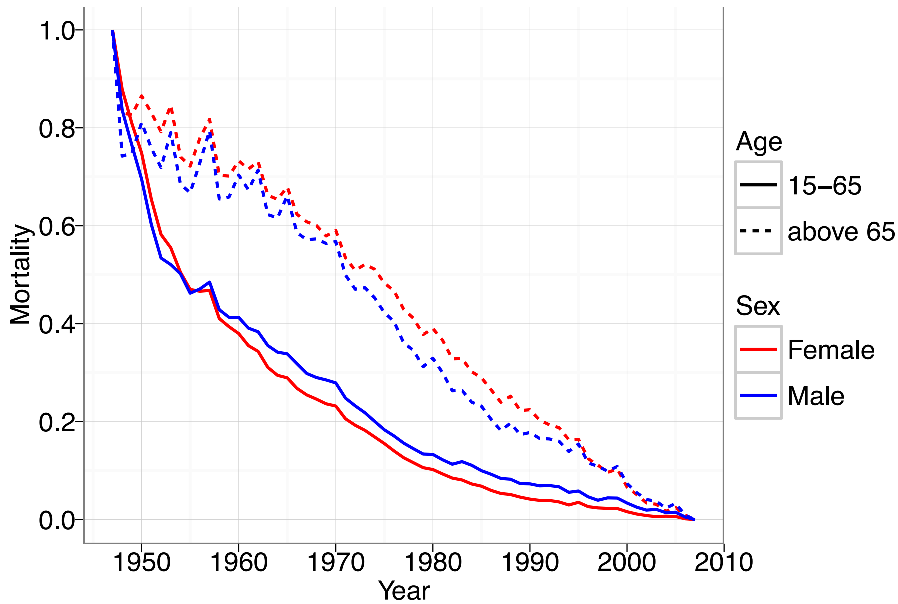

Fig. S8 The percentage changes to the central one-year death rates at ages from 15 years to the average young–old threshold for females (71 years) and males (64 years) between 1983 and 1994 in (a) Canada and (b) the United States. Separate lines show the change in females and males

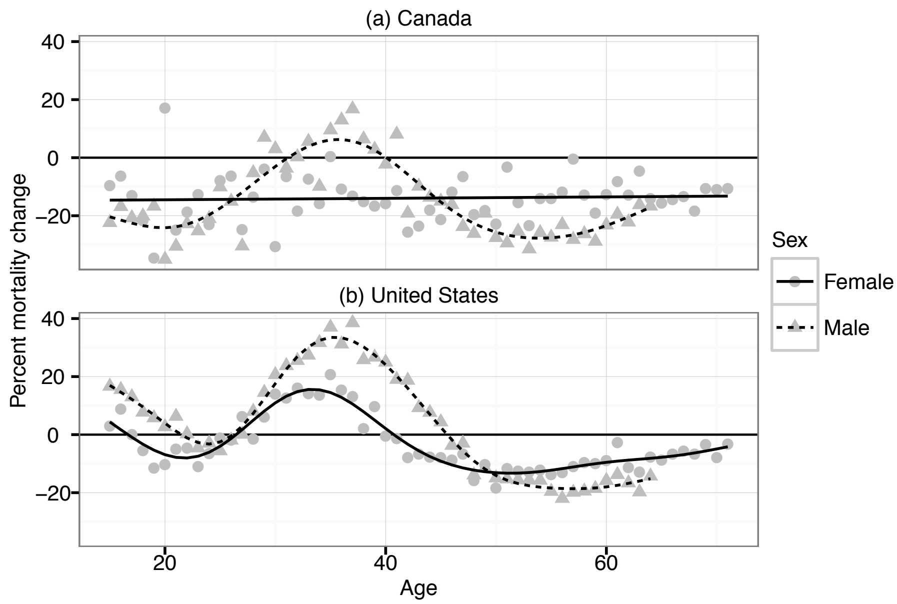

Table S1 Regional data series in the Human Mortality Database used in our international comparisons. The earliest and latest years show the data availability for each series in the period 1947–2011

Country or region	Earliest year	Latest year
Australia	1947	2009
Austria	1947	2010
Belgium	1947	2009
Bulgaria	1970	2010
Belarus	1970	2010

Canada	1947	2007
Switzerland	1947	2011
Chile	1992	2005
Czech Republic	1950	2011
West Germany	1956	2010
East Germany	1956	2010
Denmark	1947	2011
Spain	1947	2009
Estonia	1959	2010
Finland	1947	2009
France	1947	2010
England & Wales	1947	2009
Northern Ireland	1947	2009
Scotland	1947	2009
Hungary	1950	2009
Ireland	1950	2009
Iceland	1947	2010
Israel	1983	2009
Italy	1947	2009
Japan	1947	2009
Latvia	1970	2010
Luxembourg	1960	2009
Lithuania	1959	2010
Netherlands	1947	2009
Norway	1947	2009
New Zealand non-Maori	1947	2008
Poland	1958	2009
Portugal	1947	2009

Russia	1959	2010
Slovakia	1950	2009
Slovenia	1983	2009
Sweden	1947	2011
Taiwan	1970	2010
Ukraine	1970	2009
USA	1947	2010