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Decomposing longevity: How life expectancy changes around the world ☆

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ABSTRACT

In economics, most empirical studies of the consequences of changes in longevity focus on life expectancy, without considering other moments of the survival probability distribution. Here, we apply a novel parsimonious parametric and easily implementable decomposition method of variation in longevity based on life table information. We document several empirical facts of longevity changes around the world and their associations with aggregate population dynamics and economic development, and demonstrate that a parametric decomposition of changes in longevity beyond life expectancy can be very useful for various applications.

Introduction

Life expectancy is an important determinant for individual decisions over the life cycle. For instance, life expectancy determines individual savings patterns (Bloom et al., 2003; DiNardi et al., 2009), education and fertility choices (Soares, 2005; Hansen and Strulik, 2017), and lifetime labor supply and retirement decisions (see, e.g. Bloom et al., 2014; Cervellati and Sunde, 2013). Similarly, at the aggregate level, life expectancy is an important factor for long-run growth dynamics and comparative development (see, e.g. Cervellati and Sunde, 2005, 2011, 2015).

Life expectancy is not always a sufficient statistic for mortality and changes in mortality in economic applications, however. For instance, it is well known that the increase in life expectancy in many countries over the past decades is, to varying degrees, due to changes in the shape of the mortality distribution at all ages – the process known as "rectangularization" – and due to extensions of the length of life – the maximum life span (Rossi et al., 2013; Strulik and Vollmer, 2013; Bergeron-Boucher et al., 2015). The strength and shape of these dynamics of the different moments of the mortality distribution has important consequences for economic decisions and outcomes. This is illustrated, for example, by the distinct effects of changes in the life horizon and uncertainty for savings and retirement (Kalemli-Ozcan and Weil, 2010), or reflected in the debate about the distinct roles of the length of life and of the rectangularization of the mortality distribution for the effect of life expectancy on education and lifetime labor supply (Hazan, 2009; Cervellati and Sunde, 2013).

Nevertheless, most theoretical and empirical studies of the consequences of variation in mortality and longevity in economics focus either on life expectancy without considering other moments of the survival probability distribution, or consider a fully non-parametric representation of age-specific survival rates that makes it difficult to compare the results across specific settings or studies. The reason for this focus on life expectancy is the lack of a parametric representation of the mortality distribution that extends the notion of life expectancy while retaining parsimony (and comparability) in terms of the number of parameters. As a consequence, comparable analyses of the dynamic patterns of longevity beyond life expectancy are scarce, and a systematic analysis of the dynamics of higher moments of the mortality distribution is lacking.

Here, we make progress in this direction by documenting how the application of a novel decomposition method based on life table information can provide a richer yet easily operationalized representation of changes in longevity and mortality. The methodology relies on applying a parametric survival model, such as the well-known Gompertz–Makeham Model (Gompertz, 1825; Makeham, 1860), reformulated as a location–scale model (Basellini et al., 2019), and decomposing changes in life expectancy into changes of the sufficient statistics of the different moments of the mortality distribution. Specifically, we decompose changes in life expectancy into changes of

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age-independent mortality (the Makeham constant) as well as changes in the location of the modal age at death (reflecting the life horizon), and the spread around this mode (reflecting uncertainty or inequality). This decomposition has the advantage of delivering a parsimonious yet much richer picture of the changes in mortality than merely considering life expectancy.

We document several empirical facts of longevity changes around the world and their associations with aggregate population dynamics and economic development. We begin by presenting some stylized facts of life expectancy and aging dynamics around the world over the past centuries. We also document cross-sectional correlations of the different dimensions of mortality with income, extending the existing evidence for the conventional version of the Preston Curve (Preston, 1975). We then illustrate how the decomposition can be used to shed new light on issues related to social inequality, using a select sample of countries and focusing on the USA in particular. We end by considering the implications of the Covid-19 pandemic in Africa. The results of our analysis suggest that the methodology has a wide range of possible applications.

Our paper relates to an extensive literature of estimates of parametric models of mortality that extend the traditional Gompertz–Makeham model (see, e.g., Siler, 1979; Heligman and Pollard, 1980; McNown and Rogers, 1989; Congdon, 1993; Cairns et al., 2006; Dellaportas et al., 2001; Tang et al., 2023). In particular, our analysis of changes in longevity patterns over time relates to recent and more sophisticated attempts to estimate parametric models of mortality with time-varying parameters (see, e.g., Alexopoulos et al., 2019; Ashwin and Scott, 2024).

Our paper also contributes to a large literature in demography about the dynamics of life expectancy and life span inequality across countries. This literature has found a steady decline in life span inequality over time along with an increase in life expectancy (see, e.g., Vaupel et al., 2011; Edwards, 2011; Seaman et al., 2016; Aburto et al., 2020; Clark and Snawder, 2020; Liou et al., 2020; Permanyer and Shi, 2022, among others). In contrast to this literature, which mostly focuses on measures of life expectancy and some global measures of inequality in mortality, such as Gini coefficients or entropy measures, our approach allows disentangling variation in the modal age at death and in the spread around the modal age, as well as variation in age-independent mortality as reflected in a constant death rate for all ages (the "Makeham" component). Our findings document that the increase in life expectancy is not necessarily associated with a monotonic decline in the spread of mortality. Instead, we find evidence for a hump-shaped relationship. This also contributes a different aspect to studies considering life span inequality across different age groups, which reported a decline in life span inequality mostly among younger ages, and less for older ages (Permanyer and Scholl, 2019) and a weakening of the relationship between life expectancy and life span inequality at high levels of life expectancy (Permanyer and Shi, 2022).

Complementary to this cross-country evidence is work on the distinct mortality patterns of women and men, which shows that males have lower life expectancy and greater life span inequality than females, with the differences being associated with behavioral differences (Zazueta-Borboa et al., 2023). Several studies have explored the heterogeneity in the link between length of life and life span inequality across different socio-economic groups distinguished by education, occupation, or income levels (van Raalte et al., 2011, 2012, 2014; Sasson, 2016; Brønnum-Hansen et al., 2021; Fabrice et al., 2022; Shi et al., 2023). In general, these studies report greater life span inequality among groups with lower education and incomes. These differences have been associated with differences in behavior (see, e.g. van Raalte et al., 2015). We demonstrate that our approach can also be fruitfully applied to different socio-demographic groups and shed new light on distinct patterns and dynamics of mortality, e.g., across females and males.

By documenting heterogeneity in the components of life expectancy across sub-national regions, our approach also relates to recent empirical literature that has found evidence for a decline in the standard deviation of the distribution of life expectancy across regions (Sauerberg et al., 2024). In fact, our results for the different US states suggest that the variance in the length of life across states has increased over the past decades.

Finally, our evidence also contributes to recent work that has documented that relative life span variation increases while absolute life span variation decreases in the context of epidemic shocks (Vigezzi et al., 2022). In fact, our findings show that the recent Covid-19 pandemic led to an increase in life span inequality in absolute terms, but also in relation to the length of life as reflected by the modal age at death.

In the remainder of the paper, we describe the methodology and the data, and illustrate the usefulness of the approach by presenting several novel stylized facts.

Methodology

The typical empirical framework in economics to study the effects of life expectancy on individual or aggregate outcomes can be written as a regression of some outcome y on life expectancy as in

$$y_i = \alpha + \beta \underbrace{\mathbb{E}[\text{Age at Death}]_i}_{\text{Life Expectancy}} + \gamma X_i + \varepsilon_i$$

with i denoting the unit of observations (e.g., individuals or countries), X denoting control variables, and β denoting the coefficient of interest. This empirical specification, combined with plausibly exogenous variation in life expectancy, forms the core of much of the empirical literature (see, e.g., Acemoglu and Johnson, 2007, for an influential study on the effect of life expectancy on economic growth). However, the use of life expectancy (typically life expectancy at birth) hides important sources of heterogeneity in the variation of mortality or mortality dynamics that are related to changes in infant and child mortality, a shifting and compression of mortality at older ages (rectangularization), or an extension of the life span. Likewise, shocks that are often used as exogenous source of variation that affects mortality might trigger different behavioral reactions among individuals of different ages. Finally, variation in life expectancy hides distributional aspects across different parts of the population and over time – an increase in life expectancy might be associated with an increase or a decrease in the dispersion of the age at death. For these reasons, empirical studies often use different measures, such as life expectancy at different ages or variation in different segments of the mortality distribution, as an alternative to variation in life expectancy.

In this paper, we propose an alternative that can help to enrich the picture while keeping complexity minimal. This alternative is based on a reformulation of the standard parametric models of mortality. Specifically, consider the usual formula for life expectancy at age τ, conditional on having survived until age τ,

$$e(\tau) = \int_{\tau}^{\infty} e^{-\int_{\tau}^{a} \mu(x)dx} da$$

with the force of mortality (the hazard at age a) denoted as $\mu(a)$.[2] Due to its good fit and applicability over a large age range, the probably most frequently used functional representation of mortality risk in demography is the Gompertz–Makeham-Model (see, e.g., Preston et al., 2001, p. 61 and 192–193). This model specifies mortality as a combination of a constant, age-independent force of death (the Makeham constant) and an age-dependent process that increases exponentially with age

[2] In particular, we consider the life expectancy at age τ, conditional on being alive at that age. Practically, we restrict the life table data to ages above a certain age τ in the computation of life expectancy.

and that is governed by two parameters (governing a Gompertz distribution). In general, the Gompertz–Makeham model provides a good representation for mortality and survival during adulthood.[3] Since our aim is to illustrate the usefulness of the information that can be obtained from a decomposition life expectancy, and since most economic applications involve decisions that are made during adulthood we focus attention on this model in the remainder of this paper for the sake of simplicity and transparency. To ensure that this restriction does not affect the model fit, we focus on mortality data for the population aged five and older for the Gompertz–Makeham model, or to ages above 30 for estimates of the Gompertz model without age-independent mortality.

Recent work by Basellini et al. (2019) has shown that a useful reformulation of this model in terms of a location–scale model is given by

$$\mu(a) = A + \frac{1}{s} e^{\frac{a-l}{s}}$$

with A denoting the age-independent mortality (Makeham constant, measured as a rate), l denoting the location (i.e., the life span in terms of the modal age at death, measured in years), and s denoting the scale (i.e., the "spread" in life span around the mode, measured in years).[4] This reformulation is useful as it provides a representation of the life-table information used to compute life expectancy that is parametric and parsimonious, yet considerably richer than merely considering life expectancy by also capturing different moments of the mortality distribution. Moreover, variation (or changes) in life expectancy can be decomposed analytically into (non-linear) effects of changes in A, l, and s on life expectancy, such that

$$\dot{e}(\tau) = \underbrace{\dot{A} \cdot w_A(A,l,s)}_{\Delta_A} + \underbrace{\dot{l} \cdot w_l(A,l,s)}_{\Delta_l} + \underbrace{\dot{s} \cdot w_s(A,l,s)}_{\Delta_s}$$

with w_x denoting analytical weights that are non-linear functions of the parameters (Bergeron-Boucher et al., 2015).[5] For mortality distributions with low early-age mortality, the model can be simplified to a Gompertz model by eliminating the Makeham constant and the corresponding term Δ_A in the decomposition.

This parametric specification lends itself to empirical analysis as the parameter vector $\{A, l, s\}$ can be estimated by Maximum Likelihood using (period) life-table information. Specifically, suppose that death counts of a given age group follow a Poisson distribution (see, e.g., Brillinger, 1986)

$$D_a \sim P(k, \lambda) = \frac{\lambda^k}{k!} e^{-\lambda}$$

Then denoting the parameters by $\theta := \{A, l, s\}$ and the exposure (survivors to age a) by E_a, following Basellini et al. (2019), the distribution of deaths is given by

$$D_a \sim f\left(D_a, E_a \mu(a,\theta)\right) = \frac{[E_a \mu(a,\theta)]^{D_a}}{D_a!} e^{-E_a \mu(a,\theta)}$$

Taking logs, summing over all ages and eliminating constants yields the log-likelihood function

$$\mathcal{L}(\theta) = \sum_a D_a \ln(\mu(a,\theta)) - E_a \mu(a,\theta)$$

Data

We conduct different sets of estimations for different data sets. For the long-run dynamics of mortality we select lifetables from the Human Mortality Database (Max Planck Institute for Demographic Research, Germany, 2024) for all countries that have data available before 1878, which is the approximate onset of large-scale mortality changes (declines) in these countries according to recent estimates (see Supplementary Appendix Table A1 for details). As data source for global age-specific death and exposure counts we make use of the United Nations World Population Prospects (United Nations Department of Economic and Social Affairs, 2024), which provides the most comprehensive global coverage of mortality for the period 1950 to 2021 and covers 237 countries or areas. The data is based on 1,910 national population censuses, includes information from vital registration systems and from 3,189 nationally representative sample surveys (see United Nations Department of Economic and Social Affairs, 2024, for details). Since only a subset of countries provide high-quality vital statistics, the UN population division employs the cohort-component method for (back-) projecting population (CCMPP) to ensure internal consistency by age and sex, and over times.

For our analogous analysis of US mortality by state, we use lifetable data from the United States Mortality Data Base (University of California, Berkeley, 2024), which provides high-quality demographic data based on the methodology of the Human Mortality Database (Max Planck Institute for Demographic Research, Germany). Here, we estimate the Gompertz parameters $\theta_{ct} = \left\{l_{ct}, s_{ct}\right\}$ individually for each state and year.

Data for GDP per capita are obtained from version 10.0 of the Penn World Tables (Feenstra et al., 2015).

Empirical results

In this section, we illustrate the usefulness of the decomposition presented in various contexts.

Model fit

The goal of our analysis is to document the patterns that underlie the observed changes in life expectancy over time. To do so, we consider period life tables and estimate the Gompertz–Makeham parameters $\theta_{ct} = \left\{A_{ct}, l_{ct}, s_{ct}\right\}$ individually for each country-year observation (c and t). For some applications, we restrict our estimation to the Gompertz model and estimate the respective parameters $\theta_{ct} = \left\{l_{ct}, s_{ct}\right\}$ while abstracting from age-independent mortality (the Makeham constant). For estimates of the Gompertz–Makeham model we restrict the life table information used for estimation to the age range above five years of age, for the estimates of the Gompertz model to ages above 30. For all estimates, we restrict the life table information to ages below 90 years. The reported estimates for the modal age parameter l, as well as predictions of life expectancy, survival rates, and death rates accordingly have to be interpreted with reference to these starting ages.

To document the model fit as well as the limitations of our approach, we first focus on estimates for two specific countries, Cambodia and Rwanda. Both countries exhibited, exceptional mortality patterns

[3] The Gompertz–Makeham-Model is known for its poor description of mortality at young ages. Parametric extensions have been proposed that provide a better representation of the survival law by allowing for additional parameters that capture infant and child mortality (see, e.g., Siler, 1979; Heligman and Pollard, 1980).

[4] While Basellini et al. (2019) note that additive hazard models such as the Gompertz–Makeham model do not belong to the family of location–scale models in the strict sense, the reparametrization can still be applied to approximate location and scale (see Missov et al., 2015).

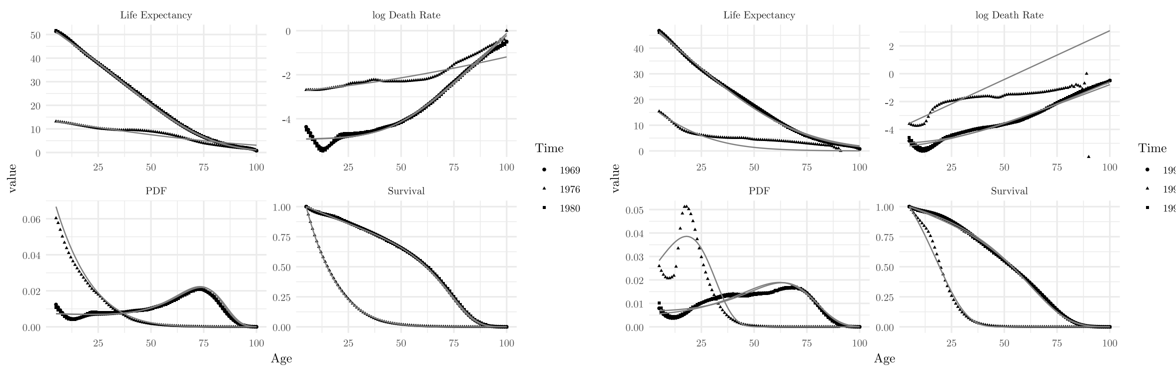
[5] The corresponding analytical weight functions are given by

$$w_A = \int_\tau^\infty -S_t(a) a \, da$$

$$w_l = \int_\tau^\infty -S_t(a) \frac{M_t^G}{s_t} \, da$$

$$w_s = \int_\tau^\infty \frac{-S_t(a)}{s_t^2} \left[M_t^G (a - l_t) + a e^{\frac{-l_t}{s_t}} \right] da$$

with $S(a) = e^{-\int_\tau^a \mu(x) dx}$ denoting the survival function, and M^G denoting the Gompertz cumulative hazard function.



(a) Cambodia (b) Rwanda

Fig. 1. Model fit: specific examples.
Note: The figure plots the raw data for life expectancy, log death rates, density and survival probability across ages gray lines as well as the corresponding predictions based on estimates of the parameters of the age-independent mortality, A, the modal age at death, l, and the spread around the modal age at death, s, for specific period life tables of two countries: Cambodia and Rwanda. Data source: Data source: United Nations World Population Prospects (United Nations Department of Economic and Social Affairs, 2024). See text for details.

that were related to violent conflicts during some years. Specifically, Cambodia experienced exceptional mortality patterns during and after the Vietnam war during the 1970s and Rwanda experienced a genocide in 1994. Such large-scale, temporary mortality events can change the age-at-death distribution to a degree that the distribution might not be approximated well by a Gompertz–Makeham model.

Fig. 1 presents the model fit for the period life tables of these countries for specific years. In particular, the figure plots data from period life tables for life expectancy and the log death rate by age, the pdf of mortality across ages, as well as the age-specific survival rates, while restricting to ages above age five. In addition, the figure plots the corresponding model predictions based on estimates of the parameters of the Gompertz–Makeham model. For Cambodia, shown in Panel (a), the model exhibits an almost perfect fit for the years 1969 and 1980, which were not affected by exceptional mortality. The only exceptions to the good fit refer to deaths below age 20. When considering the year 1976, part of the period in which the Khmer Rouge committed a genocide among the Cambodian population, the life table information looks totally different, with massively higher death rates especially at younger ages, and accordingly much lower life expectancy and survival rates. Nevertheless, the model predictions based on the parameter estimates for A, l, and s fit these patterns very closely. For Rwanda, we obtain a similar pattern as shown in Panel (b). In the years prior and past the genocide, the model fits the data closely, with some minor discrepancies for ages below 20. For the life table of the year of the genocide in 1994, the data patterns are drastically different, and one might be worried about the quality of the life table data in this year. Consequently, also the model fits the data less well, although even for this year the fit is reasonably good. However, obviously, the estimates of the parameters, A, l, and s for this year are also systematically different than the parameter estimates for life tables of less exceptional years.

In the following analysis, we are interested in decomposing the variation of longevity over time into the dynamics of the parameters of the underlying model. To deal with large-scale, temporary mortality events such as violent conflicts or other events like natural catastrophes or epidemics that can lead to drastic changes in the age-at-death distribution from one year to another, we use a natural spline interpolation to smooth the time series of our parameter estimates in the periods where single mortality events exceed 1% of total deaths. This allows us to focus on the "natural" development of mortality in the descriptive analysis. Information about the scale and time of the respective mortality events are contained in the World Population Prospects data set. Appendix Figure A1 illustrates the interpolation for the two example countries, Cambodia and Rwanda. The figure also shows the variability of the respective parameter estimates over the observation period and in response to exceptional mortality events. In particular, the figure shows the sensitivity of the parameters to major and minor changes in period life tables and the long-run trends that are of particular interest for the remainder of the study, where the consideration of smoothed parameter series allows focusing on the global trends and the relation to economic variables.[6]

Decomposing the long-run dynamics of mortality

We begin our analysis by focusing on the long-run dynamics of mortality. The demographic transition is a well-documented process of fundamental changes in population dynamics (see, e.g., Chesnais, 1992). Starting from a scenario of a roughly stable population and high mortality and fertility rates, the stylized pattern of the demographic transition is characterized by an initial decline in mortality, which is followed by a delayed decline in fertility rates. As noted by Delventhal et al. (2021), "from its start in Northern Europe in the late 18th century to the present day, every country on earth has undertaken or is currently undertaking this fundamental transition". Ultimately, both mortality and fertility rates stabilize at much lower levels than prior to the transition.

The left upper panel of Fig. 2 plots the long-run trajectories of life expectancy for all countries in the Human Mortality Database (Max Planck Institute for Demographic Research, Germany, 2024) for which data are available from at least as early as 1878 onwards. The remaining panels depict the corresponding estimates for the parameters of the empirical Gompertz–Makeham model, $\{A, l, s\}$. Specifically, the figure shows the age-independent "background" mortality A (upper right panel), the location of the modal age at death l (lower left panel), and the spread around the mode s (lower right panel). The figure plots the period averages (dotted line) as well as trend lines for different groups of countries distinguished by the status of the mortality transition (pre-transition in blue, in-transition in red, and post-transition in green), as classified by Delventhal et al. (2021). The trends are all remarkably similar for the countries in this sample.[7] In fact, despite the heterogeneity across countries, the model estimates exhibit a remarkable fit to the data.[8]

[6] Following the majority of the previous literature on parametric models of mortality, we abstract from a detailed analysis of parameter uncertainty and leave this for future research.

[7] Note that, due to data availability, the sample is only balanced from 1878 onwards.

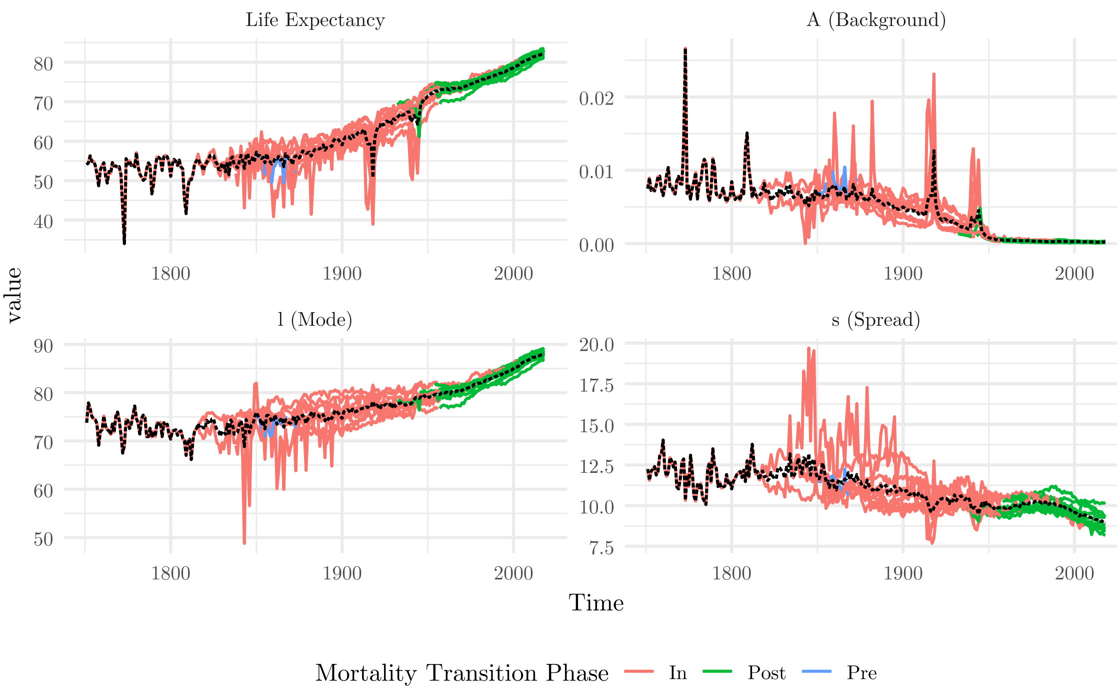


Fig. 2. Long-run dynamics of mortality.
Note: The figure plots the dynamics of life expectancy and the corresponding estimates of background mortality A, the modal age at death, l, and the spread around the modal age at death, s, for an unbalanced sample of 10 countries. Data source: Human Mortality Database (Max Planck Institute for Demographic Research, Germany). The classification of demographic transition status follows Delventhal et al. (2021). See Appendix Table A1 and text for details.

The estimates of life expectancy and the modal age at death document a considerable and stable upward trend prior to 1950, which coincides with the approximate end of most mortality transitions in the sample (which is heavily skewed to Western, high-income countries as result of the sample restriction). After 1950, the consistent upward trend continues until the Covid-19 pandemic in 2020 and 2021. The trajectory of the age-independent mortality A shows a relatively stable downward trend. With the exception of an intermediate increase before 1870 and some outliers during the time of the two world wars, the age-independent mortality shows a steady decline and a convergence to 0 since around 1950. The spread around the modal age at death, s, shows the most interesting dynamics. During the early 19th century, the spread displays a moderate upward trend. Once the majority of countries in the sample with data for this period enter the demographic transition, this trend reverses and the spread declines. During the 20th century, the spread again begins to climb until around 1975, from when on it continued to decline until today.

The different phases of the transition with their distinct mortality and fertility dynamics have been associated with the phases of an epidemiological transition (see, e.g., Omran, 1971). In the early phase of the demographic transition, mortality is high and volatile; this reflects an “age of pestilence and famine”. Although for most countries pre-transitional data is not available in our sample, the volatile parameter estimates displayed in Fig. 2 before 1870, and the increasing convergence afterwards, are a reflection of this early phase. The following decline in mortality at the onset of the demographic transition reflects an “age of receding pandemics” and an associated increase in life expectancy. The main reason for the decline in mortality during this phase is the reduction in the mortality of children and young women, which primarily leads to a decline in the estimated background mortality parameter A. With the advent of clean water supplies, sewer systems, and ultimately effective treatments for, and prevention methods of, infectious disease the volatility in parameter estimates declines. In the final phase, mortality stabilizes at low levels, reflecting the “age of degenerative and man-made diseases”. Remarkably, it is during this phase after the demographic transition, starting around 1975, that the modal age at death, l, shows the most visible increase.

These patterns reflect the ongoing discussion about a rectangularization of mortality and the scope for extensions of the human lifespan. Under the assumption that humans have a fixed maximum lifespan, improvements in mortality will eventually lead to a life with close to perfect health until a person dies - a perfectly rectangular survival curve (see, e.g., Strehler and Mildvan, 1960). The estimates provide limited support for this view with declining background mortality A and spread s, but a roughly constant or moderately increasing modal age at death until the early 20th century. With unprecedented improvements in medical technology after that, the modal age at death l exhibited a continued increase, and only a downward trend in the spread, s. This seemingly contradicts the notion of a fixed human lifespan and instead supports arguments for continuing shifts in the length of human life (see, e.g., Oeppen and Vaupel, 2002; Strulik and Vollmer, 2013; Gavrilova and Gavrilov, 2019, for the ongoing debate).

From 1980 onwards we find a moderately declining trend in the spread, which is in line with the inverse longevity–inequality relationship documented in, among others, Vaupel et al. (2011), Edwards (2011), Seaman et al. (2016), Aburto et al. (2020), Clark and Snawder (2020), Liou et al. (2020), Permanyer and Shi (2022). This inverse relationship would suggest a continuing compression of mortality around the modal age at death. However, in contrast to some accounts in the literature, the relation between life expectancy (or the modal age of death) and the inequality in mortality as reflected by the spread around the modal age at death exhibits some non-monotonicities around the onset and the end of the demographic transition. These non-monotonicities presumably reflect compositional changes in the population with respect to socio-economic factors (such as income or education) that feed back into the spread of mortality rates. It has to

[8] This is further illustrated in Figure A2, which plots Pseudo-R2 measures based on the sum of squared deviations of age-specific values of model-predicted moments from data moments for the Gompertz–Makeham model and the more parsimonious Gompertz model.

be kept in mind, however, that the variation in the age at death also declines due to the sustained reduction in background mortality, A. The decomposition allows for a refined perspective on these issues and the analysis suggests that inequality in terms of the age at death, at least in this selected sample of mainly Western, high-income countries, only shows moderate declines after the demographic transition.

Decomposing mortality dynamics around the world

Due to increasing data availability, it is possible to provide a more comprehensive picture of mortality dynamics from 1950 onwards. The upper left panel of Fig. 3 depicts the dynamics of life expectancy across period life tables from 1950 to 2021. This figure shows the heterogeneity in life expectancy across countries. It also documents the increase in life expectancy all around the globe over the past 70 years and the moderate convergence in life expectancy. Moreover, the figure depicts several outliers that experienced pronounced declines in life expectancy during the 1990s and 2000s. These are mostly African countries that were severely hit by the HIV/AIDS pandemic. Again, the remaining panels show the corresponding estimates for the parameters of the empirical model: the age-independent "background" mortality A (upper right panel), the location of the modal age at death l (lower left panel), and the spread around the mode s (lower right panel).[9]

Several interesting patterns emerge. First, the previously shown secular decline in age-independent mortality (A) is present globally, but shifted over time. While Europe, and Northern America converged to zero in the 1950s to 1970, other continents, and especially Africa, lag behind in this downward trend and show background mortality rates converging to low levels only in more recent decades. Thus, while global public health campaigns to combat infectious diseases seem to have been successful in reducing age-independent deaths and thereby eradicating premature mortality in many Western countries, age-independent mortality is still an important component of life expectancy in less developed nations.

Fig. 4 plots the same data, but differentiates between countries that successfully completed their mortality transition by 1950 and hence were post-transitional afterwards, complementing the long-run patterns shown in Fig. 2. There, the data suggested that the modal age at death, l, only began to increase once the mortality transition was completed, accompanied by a hump-shaped development of the spread s. A very similar pattern emerges for post-transitional countries, now defined by the status of the demographic transition in 1950. Despite the much larger sample, the data exhibit very similar trends as those in the previous section. Specifically, the data confirm that, overall, the inequality in mortality within populations, as reflected by the spread around the modal age at death, s, shows a decline. This suggests that part of the increase in life expectancy was due to a rectangularization of the survival distribution. However, the figure also confirms the finding of a non-monotonic pattern and a trend reversal in the variability of mortality at older ages, as reflected by the spread around the modal age at death, s. The dynamics of this spread show a temporary increase among pre-transitional countries. This suggests that the inverse relationship between longevity and life span inequality is not universal. Specifically, for the group of countries that are undergoing the demographic transition, both the modal age at death and the spread around this mode are temporarily increasing in Fig. 4, and similarly so for pre-transitional countries. This suggests the importance of taking the process of the demographic transition into account when analyzing global mortality trends and the relation between lifespan length and lifespan inequality.

Apart from these overall patterns, the figures also reveal that the decline in life expectancy due to the HIV/AIDS pandemic was mostly associated with an increase in the spread of mortality and a decline in the modal age at death, indicating a temporary "reversal" of rectangularization in this context. However, with the increasing availability of anti-retroviral therapy during the early 2000s, this reversal came to an end.

Moreover, with mortality decreasing, one would expect that populations are aging worldwide. This conjecture is confirmed in view of the positive association between life expectancy and average population age (see Appendix Figure A4). Again, the decomposition provides additional insights regarding the changes in the mortality distribution that underlie this pattern. Specifically, the increasing average age is associated with a decline in age-independent mortality across countries and in the spread in mortality around the modal age at death — as the average age of the population increases the spread of mortality is decreasing. A higher average age is also associated with a higher modal age at death. Overall, the cross-sectional variability in the estimates is smaller the higher the average age of the population. This suggests that, with a continuing rectangularization of the survival law, population aging is increasingly the result of an extension of the maximum life span, confirming earlier findings in the literature (see, e.g., Strulik and Vollmer, 2013).

Decomposing the preston curve and comparative development

The positive association between life expectancy and (log) income per capita that has become known as "Preston Curve" (Preston, 1975) represents one of the most robust stylized facts in the social sciences, even if the direction of causality and the underlying mechanisms remain debated. Fig. 5 depicts the Preston Curve for the year 2019 (before the Covid-19 pandemic) and shows that the relationship between life expectancy and log real GDP per capita across countries is positively sloped and approximately linear.

The log-linear association between life expectancy and economic development has been rationalized in various ways, including explanations that focus on one-way causation or co-determination. The decomposition of life expectancy provides additional insights by broadening the set of empirical regularities that are associated with the Preston Curve, and patterns of comparative development in general. Fig. 6 presents a decomposition of the Preston Curve into the variation in the location of the modal age at death and the spread around this mode.[10] The graph illustrates that the positive relationship of the Preston Curve translates into a positive and almost linear relationship of (log) income per capita with the modal age at death, l. At the same time, higher income is associated with a smaller degree of inequality in age-dependent mortality, as suggested by the negative relation with the spread parameter, s. These patterns again suggest that the rectangularization of the survival distribution implies a smaller variability in the estimates of the spread parameter at higher levels of income per capita.[11] An important new insight from this analysis is that the Preston Curve is not restricted to higher incomes being associated with longer lives on average, but also with lower uncertainty regarding (and inequality in) the length of life. To some extent, this reflects a force of equalization in the length of life that is associated with higher levels of economic development.

To investigate the relevance of the decomposition of life expectancy for explaining comparative development, Table 1 presents the results of multivariate regressions of changes in comparative development outcomes on changes in life expectancy in long differences, in the

[9] The corresponding estimates of the analytical weights are shown in Appendix Figure A3.

[10] For comparability and transparency, the estimates are based on a restricted (Gompertz) model with the Makeham constant A constrained to be 0, which is an adequate representation of most high income countries as seen above.

[11] Similar patterns emerge for other years, see Appendix Figures A5, A6, and A7.

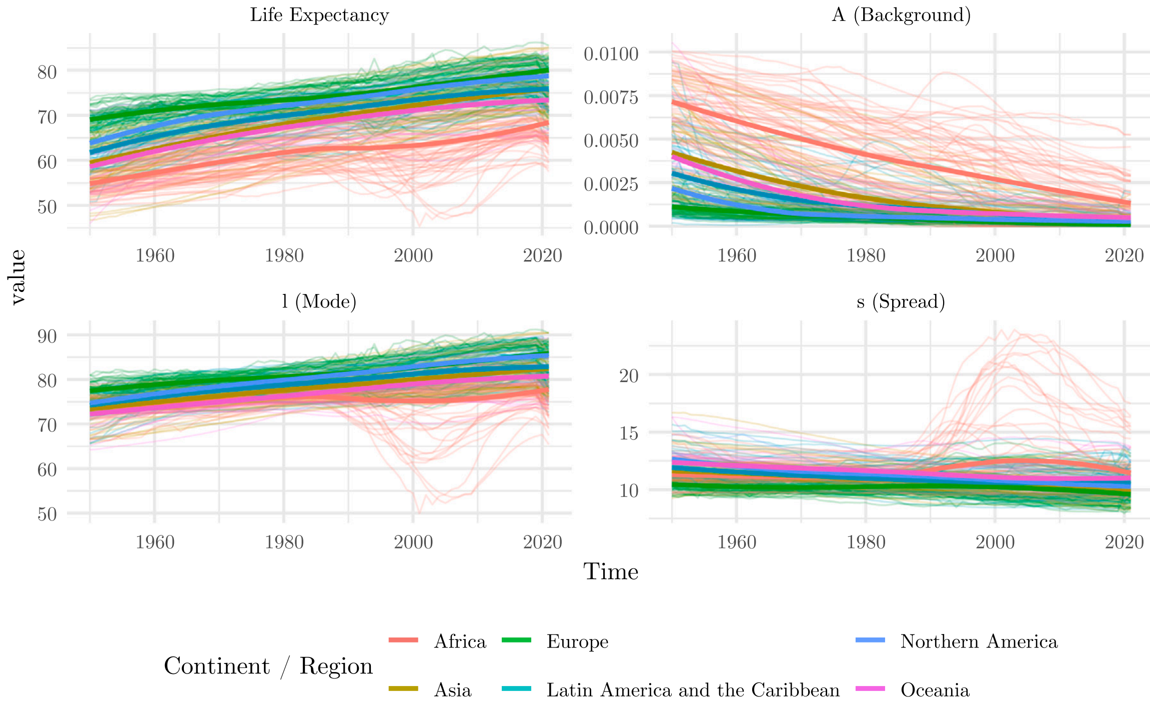


Fig. 3. Life expectancy and parameter estimates.
Note: The figure plots the dynamics of life expectancy and the corresponding estimates of background mortality A, the modal age at death, l, and the spread around the modal age at death, s, for a balanced sample of 236 countries. Data source: United Nations World Population Prospects (United Nations Department of Economic and Social Affairs, 2024). See text for details.

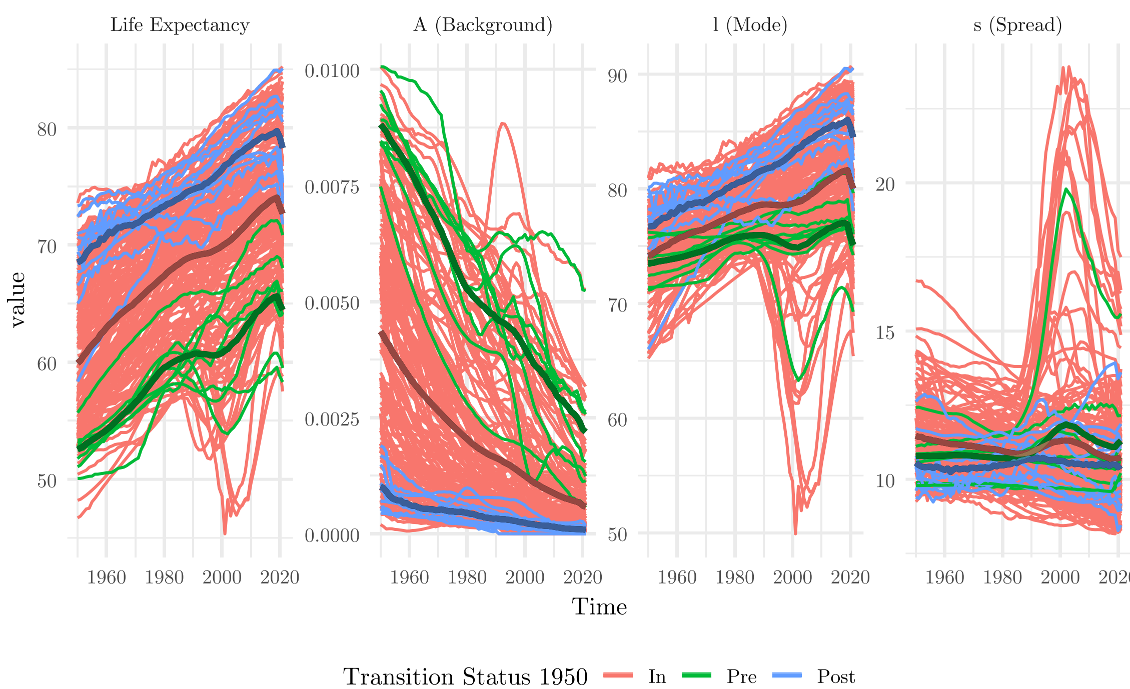


Fig. 4. Life expectancy and parameter estimates.
Note: The figure plots the dynamics of life expectancy and the corresponding estimates of background mortality A, the modal age at death, l, and the spread around the modal age at death, s. Data source: United Nations World Population Prospects (United Nations Department of Economic and Social Affairs, 2024). The classification of demographic transition status follows Delventhal et al. (2021) and restricts the sample to a balanced panel of 178 countries. See text for details.

spirit of Acemoglu and Johnson (2007).[12] Panel A contains estimates of the elasticities with respect to variation in life expectancy of GDP, GDP per capita, population, as well as the old-age dependency ratio, the employment share (proxying the labor force participation) and total factor productivity. The estimates suggest that increases in life expectancy exhibit a significant association with increases in income and population, but no significant association with GDP per capita.

[12] These estimates are equivalent to a panel regressions in (log-)levels with country and period fixed effects. For simplicity, we restrict attention to OLS estimates with no ambition to uncover causal relationships.

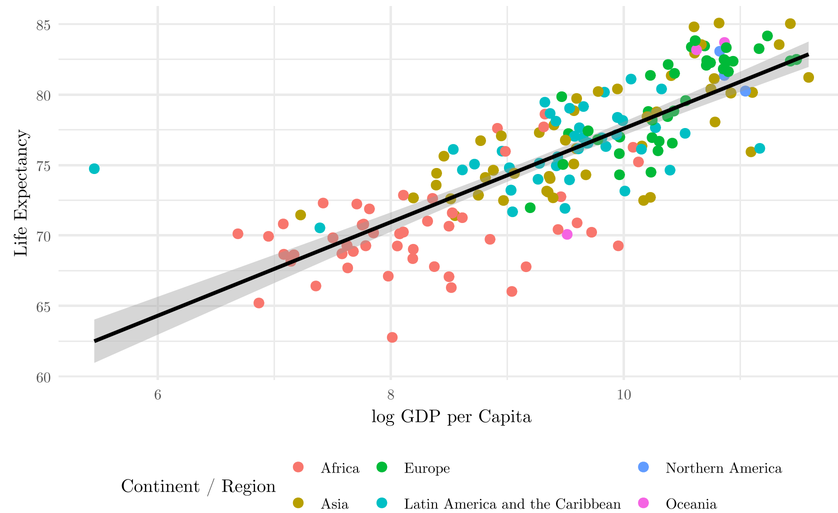


Fig. 5. The Preston Curve (2019).
Note: The figure plots the level of life expectancy and the corresponding level of GDP per capita for a sample of 183 countries. Data source: United Nations World Population Prospects (United Nations Department of Economic and Social Affairs, 2024). Data for GDP per capita are from the Penn World Tables (Feenstra et al., 2015). See text for details.

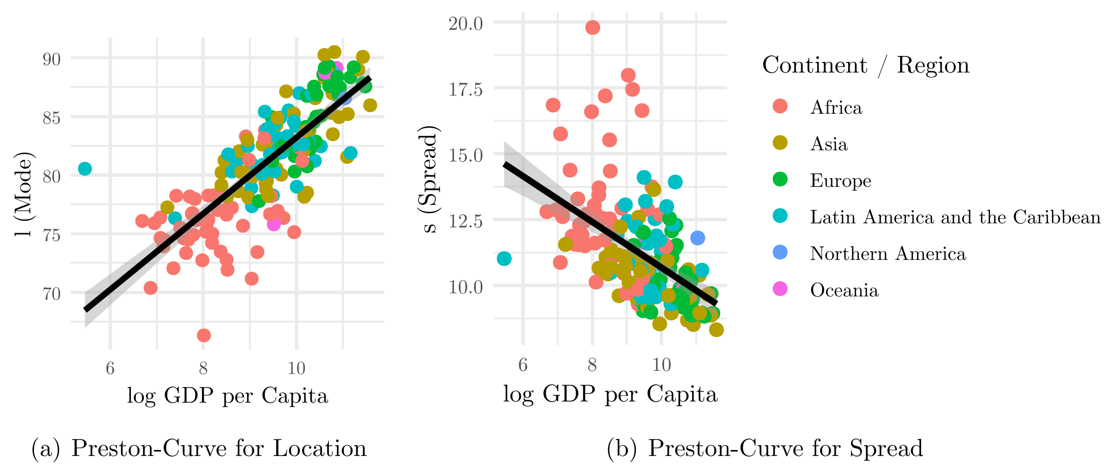


Fig. 6. Decomposing the Preston Curve (2019).
Note: The figure plots estimates the modal age at death, l, and the spread around the modal age at death, s, for a sample of 183 countries. Data source: United Nations World Population Prospects (United Nations Department of Economic and Social Affairs, 2024). Data for GDP per capita are from the Penn World Tables (Feenstra et al., 2015). See text for details.

Likewise, there is no significant association between life expectancy and the old-age dependency ratio and total factor productivity, but a positive association with the employment share.

Panel B contains the corresponding results for changes in the estimated parameters after decomposing life expectancy. These estimates reveal much more subtle patterns. Age-independent mortality, A, is positively associated with significant GDP and population, as well as with GDP per capita, although the latter correlation is not statistically significant. A is also negatively associated with the old age dependency ratio, but effectively unrelated with employment share and TFP. In contrast, an increase in the life span, reflected by the modal age at death, l, exhibits no significant positive association with GDP, but a negative and significant association with population. This also implies a positive and significant association of longevity in terms of the length of the life span with income per capita. In addition, an increase in the life span is related with a significant increase in the old-age dependency ratio, employment share, and total factor productivity. Finally, a greater spread in mortality rates, s does not exhibit significant associations with aggregate outcomes, except a marginally significant negative association with the old age dependency ratio and factor productivity. In view of the fact that these are conditional effects, they correspond to changes in, e.g., the length of the life span everything else, such as age-independent mortality and inequality in mortality, equal. These patterns thus provide support for the hypothesis that changes in life expectancy affect macroeconomic development through different channels. Holding other changes fixed, declines in mortality that affect all age groups the same, and especially also younger age groups, are associated with more moderate population growth, but no clear pattern regarding incomes per capita. In contrast, extensions of the life span are associated with slower population growth and significantly higher incomes per capita, but also a significant aging of the population, a higher employment rate, and a higher factor productivity. Interestingly, the length of the life span and the inequality in mortality show associations of opposite signs with proxies of aggregate development. This is an indication that the length of life and social inequality reflected in mortality might have distinct economic consequences that are undetected when focusing attention exclusively to life expectancy. Finally, the estimates reveal that the decomposition provides a much better fit to comparative development patterns, even when accounting for the difference in the degrees of freedom, as suggested by the larger values of the adjusted R-squared measure for all dependent variables.

Table 1
Life expectancy and aggregate development: long differences.

Dep. Var.	GDP	GDP per Capita	Population	OADR	LFP	TFP
	Panel A: Life Expectancy					
Life Expectancy	6.171***	4.938***	1.352	7.092	0.339**	0.094
	(1.109)	(1.386)	(0.884)	(9.763)	(0.129)	(1.104)
Adj. R^2	0.349	0.218	0.020	−0.011	0.069	−0.017
	Panel B: Parametric Decomposition					
A (Background)	7.486***	1.445	6.171***	−53.480***	0.041	−2.307
	(1.539)	(1.649)	(1.119)	(9.711)	(0.185)	(1.387)
l (Mode)	6.466***	9.269***	−2.744***	60.090***	0.614***	3.753***
	(1.939)	(2.006)	(0.939)	(13.278)	(0.196)	(1.346)
s (Spread)	−4.368	−12.140	8.338	−93.956*	−0.293	−17.698*
	(9.660)	(10.594)	(5.892)	(48.029)	(1.156)	(8.931)
Adj. R^2	0.357	0.349	0.444	0.412	0.104	0.173
N (both panels)	61	61	61	61	61	61

Note: Regression results. Dependent variables are long differences in log Gross Domestic Product, log Gross Domestic Product per capita, log Population, Old Age Dependency Rate, Labor Force Participation (measured as the share of employment in the total population) and log Total Factor Productivity. All coefficients correspond to elasticities of changes over the period 1960–2019 in long differences (equivalent to a specification with country and period fixed effects in (log-)levels). $^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$.

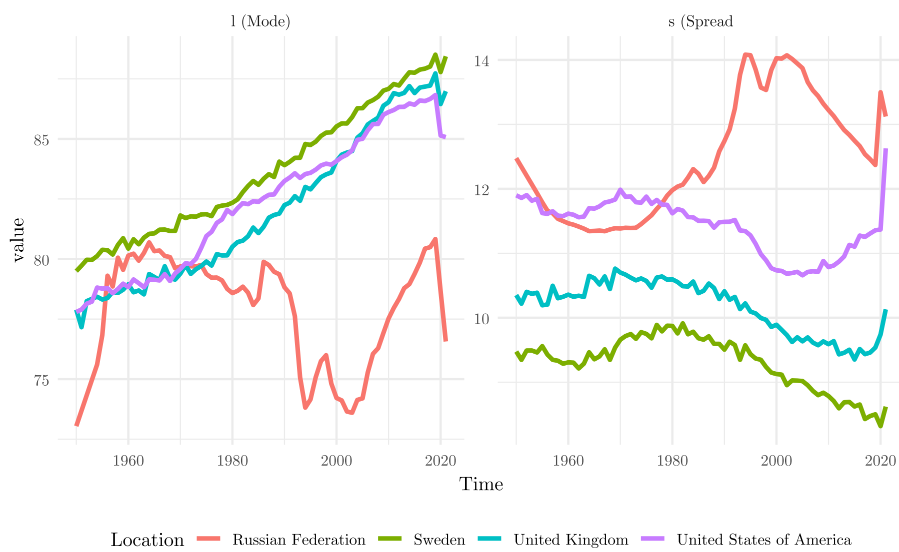


Fig. 7. Decomposing length of life and social inequality.
Note: The figure plots the dynamics of the modal age at death, l, and the spread around the modal age at death, s, for Russia, Sweden, the United Kingdom and the United States. Data source: United Nations World Population Prospects (United Nations Department of Economic and Social Affairs, 2024). See text for details.

Decomposing life expectancy and social inequality

The previous finding indicates that the decomposition of life expectancy provides novel insights regarding social inequality. As has been recognized previously, measures of life span inequality can be informative about inequality along the life course (see, e.g., the discussion by van Raalte, 2021a,b). To illustrate this aspect, we consider a sample of four exemplary countries: Russia, Sweden, the United Kingdom and the USA. We do so having in mind the heterogeneous economic and institutional setting and development of these countries. In 2022, life expectancy in Russia was 73 years, in Sweden 83 years, in the UK 82 years, and in the USA 77 years.[13] It is well known that the pattern of life expectancy, especially across these countries, does also reflect the differences in economic development and, particularly, health spending. The USA being the richest of these countries spends almost twice as much on health in per capita terms as Sweden and the UK, and about twelve times as much as Russia.[14]

Fig. 7 depicts the estimates of the decomposition of life expectancy dynamics into the modal age at death (l) and the spread around the mode (s) for these four countries over the period 1950 to 2021.[15] Several interesting patterns emerge. First, the left panel of Fig. 7 shows that the modal age at death, proxying the length of the lifespan, has been highest for Sweden, comparable in the UK and USA, and lowest in Russia. Thus, despite the lower income and health expenditures, the modal age at death in Sweden is higher than in the USA — on average people live longer in Sweden than in the USA, and also longer than in the UK. In addition, there has been a pronounced upward trend in Sweden over time. A similar trend is visible for the UK and the USA over the entire sample period. In contrast, for Russia, there is no visible trend between the mid 1950s and the mid 1980s, and the length of life has even declined visibly between the mid 1980s and the early 2000s. Only since about 2005, one sees a visible upward trend. The fallout of the Covid-19 pandemic is visible in all four countries, as indicated by the

[13] Numbers are from the World Bank, retrieved on July 30, 2024.

[14] According to data from the World Bank (retrieved on July 30, 2024), average health expenditures per capita in 2022 amounted to 12,474 U.S. dollars in the USA, 5,980 U.S. dollars in Sweden, and 5,138 U.S. dollars in the UK. Average health care expenditure in Russia was estimated at 936 U.S. dollars in 2021.

[15] As before, the estimates are based on a restricted (Gompertz) model with the Makeham constant A constrained to 0.

decline in the modal age at death at the end of the observation window in 2020 and 2021. However, also here there are visible differences, with the decline being less pronounced in Sweden than in the UK and particularly the USA, and the decline being largest in Russia.

The right panel of Fig. 7(b) shows the corresponding estimates for the spread of mortality. Here, the ordering of countries is reversed: the spread is consistently lowest for Sweden, higher for the UK, even higher for the USA, and highest for Russia. Moreover, there has been a downward trend in inequality in mortality rates (equivalent to a progressive rectangularization of the survival curve) for Sweden and the UK since the 1970s. A similar decline was visible for the USA until about 2000, after which the spread in mortality rates has reversed and exhibited an accelerating upward trend. The opposite is found for Russia, where the social inequality reflected in the spread of mortality has been trending up from the 1960s until the mid 1990s, after which it has stagnated and even declined moderately until around 2020, but never again reached the levels before the late 1980s. These estimates for Russia suggest that the demise of the Soviet Union and the increasing inequality in living conditions is visible in the different components of mortality long before 1990. They also illustrate the social inequality dynamics, as proxied by lifespan inequality s, that have been prevalent in Russia after the break-up of the Soviet Union. The consequences of the Covid-19 pandemic are also visible in terms of an increase in the spread parameter after the outbreak in 2020. Again, it is noteworthy that the extent of this fallout is smallest in Sweden and the UK, and larger in the USA and Russia.

These results are suggestive of substantial differences in longevity patterns (in terms of the modal age at death and the spread of mortality rates around the mode) across high-income countries. The results for the USA are particularly disturbing in light of the comparably high health expenditures in the country and the comparably low life expectancy. This well-known fact has been the subject of considerable debate and research. One of the aspects that has been raised in this debate is the seemingly low efficiency of the public health system and the difficulty to provide access to health insurance to large parts of the population at the lower end of the income distribution, especially in light of increasing income inequality at least since the 1980s (see, e.g., Finkelstein et al., 2019; Baicker et al., 2023, and the references therein). The social consequences of this rise in inequality have become increasingly visible after the financial crisis and the following Great Recession. In the aftermath of this crisis, deaths due to drug abuse, especially in the context of the opioid crisis that already started in the late 1990s and early 2000s, due to suicides, which have seen a steady increase since around 2000, and due to gun violence, which virtually exploded since around 2010, have increased substantially, presumably as a reflection of social inequality and a lack of economic perspectives (Case and Deaton, 2020; Couillard et al., 2021).

One way to document this is by zooming in on the dynamics of the spread of mortality in the USA over time. Fig. 8 plots the dynamics of the estimates for the modal age at death, l, and the spread parameter s since 1950, disentangling the total dynamics by gender. The figure documents that the spread in mortality is more than 10 years, and more than one year larger for men than for women. More to the point, the decline in the spread, which is an indication of a rectangularization of the survival distribution and seen in most countries, has stopped in the USA around 2000, and exhibits a pronounced increase ever since. For men, the spread has increased by about two years since 2000, with an acceleration since around 2010 and during the Covid-19 pandemic.

When contrasting these dynamics in the mortality spread with the dynamics of the location of the modal age at death, which reflects the average length of life, we also find a reversal in the relationship, as can be seen from the left panel of Fig. 9. As long as an increase in the modal age at death is associated with a decline in the spread around this mode, the distribution of age-specific survival probabilities becomes more rectangular — people get older and the population gets more homogeneous in terms of the age of death. This is the pattern

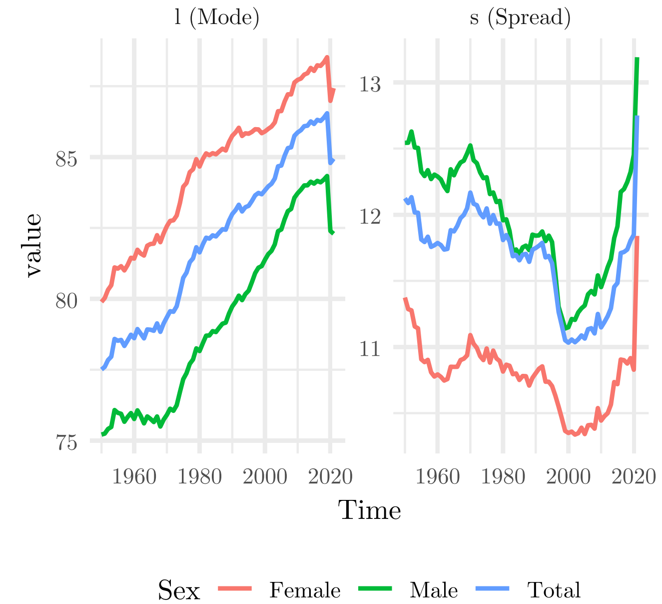


Fig. 8. Dynamics of the spread in mortality: social inequality in the USA.
Note: The figure plots the dynamics of the modal age at death, l, and the spread around the modal age at death, s, for the United States. Data source: United States Mortality Data Base (University of California, Berkeley, 2024). See text for details.

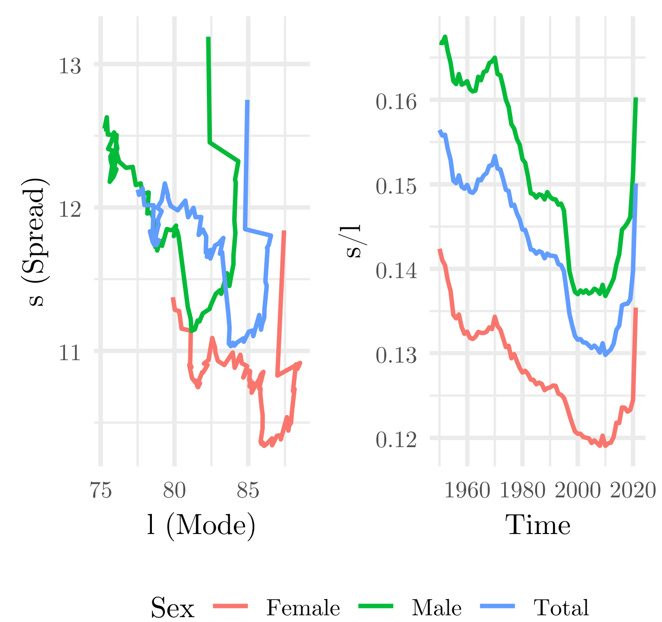


Fig. 9. The dynamics of mortality location and spread: USA.
Note: The figure plots the dynamics of the modal age at death, l, and the spread around the modal age at death, s, for the United States. Data source: United States Mortality Data Base (University of California, Berkeley, 2024). See text for details.

seen in most countries over the past decades (see Fig. 3). In the USA, however, the relationship exhibits a reversal around the year 2010, as suggested by the right panel of Fig. 9, which plots the ratio of spread over the modal age at death (s/l) over time. Thus, while the modal age at death still kept increasing, the spread, which reflects inequality in the age of death, also began to increase, indicating an increase in social inequality relative to the average length of life. Eventually, during the Covid-19 pandemic, even the modal age at death experienced a setback, while the spread in mortality kept increasing, which led to an

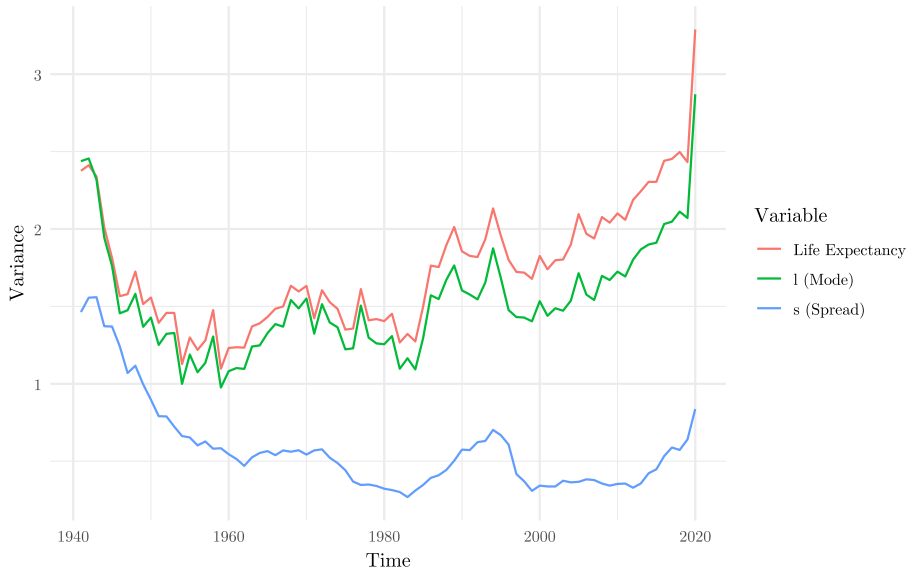


Fig. 10. The dynamics of variability in mortality across US States: life expectancy, modal age at death, and spread.
Note: The figure plots the dynamics of the period-specific variance in life expectancy at age 30, modal age at death, l, and the spread around the modal age at death, s, for the United States. Data source: United States Mortality Data Base (University of California, Berkeley, 2024). See text for details.

acceleration in the ratio s/l. These graphs paint an unsettling picture of the social inequality contained in mortality data in the USA, which is not visible in the data on life expectancy. This further demonstrates the usefulness of the mortality decomposition as a diagnostic tool, with the findings complementing recent evidence that suggests that inequality in mortality rates, as reflected in coefficients of variation of state-level life expectancy, has increased within the United States.

Moreover, the dynamics of social inequality are not homogeneous within the USA, as illustrated by the dynamics of the spread parameter by state.[16] While the inequality in mortality patterns across US states is known (see, e.g., Couillard et al., 2021), it is less clear whether the mortality patterns tend to become more similar or dissimilar across US states over time. Fig. 10 sheds light on this question by plotting the variance in life expectancy as well as in the estimates of the modal age at death, l, and the spread around the modal age, s, over time. The results show that the cross-state variance in life expectancy has increased steadily since about 1960. The decomposition illustrates that most of this increase is associated with an increase in the cross-state variance in the modal age at death. In other words, the differences in the length of life across US states have increased over time. Interestingly, the trend in the variance in the spread around the modal age at death shows a slightly different pattern. In fact, the cross-state variance in the spread has steadily declined until about 1980, then increased in two waves, one from the mid-1980s until the mid 1990s, and another wave since the early 2010s. In view of the overall trend in the spread s, this indicates that the increase in inequality in mortality within the United States has affected some states more than others.

Decomposing life expectancy: Covid-19 in Africa

The previous results suggest that the Covid-19 pandemic had pronounced effects on mortality patterns. In fact, this health shock led to very heterogeneous life expectancy responses across countries, as the increase in deaths due to Covid-19 infections was counterweighted by a decline in other infections, especially in the context of severe lock-down measures. Fig. 11 illustrates the consequences of Covid-19 by plotting the changes in life expectancy in African countries between 2020 and 2022. In the countries most severely hit by the pandemic, such as Algeria, Niger, or South Africa, life expectancy declined by almost 2 years. In contrast, in some countries, like Botswana or Rwanda, life expectancy did not decline but rather increased. This raises the question about the reasons for this heterogeneous pattern.

The decomposition method described before can be used to decompose the changes in life expectancy into changes of the underlying parameters — the age-independent mortality component A, the location of the modal age at death l, and the spread around this mode s. Fig. 12 presents the results of this decomposition of the changes in life expectancy depicted in Fig. 11. The figure illustrates opposing effects of reductions in life expectancy due to a decline in the length of life as indicated by a decline in the modal age at death, and latent increases in life expectancy due to reduced age-independent mortality A, presumably due to a reduction of infections with other infectious diseases, e.g., influenza. A part of the decline in life expectancy in some countries is also due to an increase in the spread s, whereas in other countries like South Africa, variation in the spread was even responsible for an increase in life expectancy that helped to moderate the negative effects of Covid-19 on life expectancy.

Concluding discussion

This paper has presented a parametric decomposition of the mortality distribution that can be readily applied to life table data and that provides novel insights into longevity dynamics across and within countries. The methodology is based on a parsimonious parametric representation of mortality and mortality dynamics that goes beyond the concept of life expectancy and allows decomposing variation in life expectancy into various underlying mechanisms. Based on this approach, we presented several novel empirical facts regarding the global dynamics of mortality, regarding the social inequality embodied in the distribution of age-specific mortality, and regarding the mortality dynamics after the Great Recession and the Covid-19 pandemic.

The analysis of our paper has been deliberately descriptive, with a focus on variation of life expectancy of adults. A natural next step could be an extension to mortality during younger ages, at the cost of parametric parsimony to cover the systematically different mortality patterns during childhood and adolescence. This would allow extending the analysis to the consideration of systematic variation in infant and child mortality, thereby further broadening the perspective.

[16] See Appendix Figure A8.

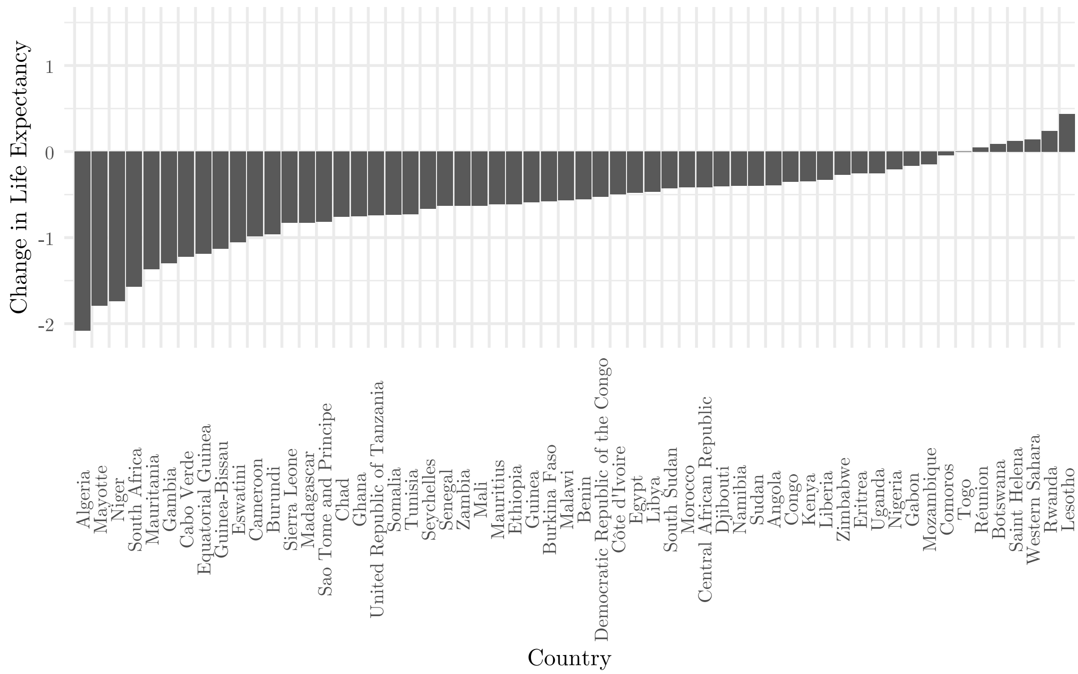


Fig. 11. The consequences of Covid-19 on life expectancy: Africa.
Note: The figure plots changes in life expectancy between 2019 and 2022 in African countries. Data source: United Nations World Population Prospects (United Nations Department of Economic and Social Affairs, 2024). See text for details.

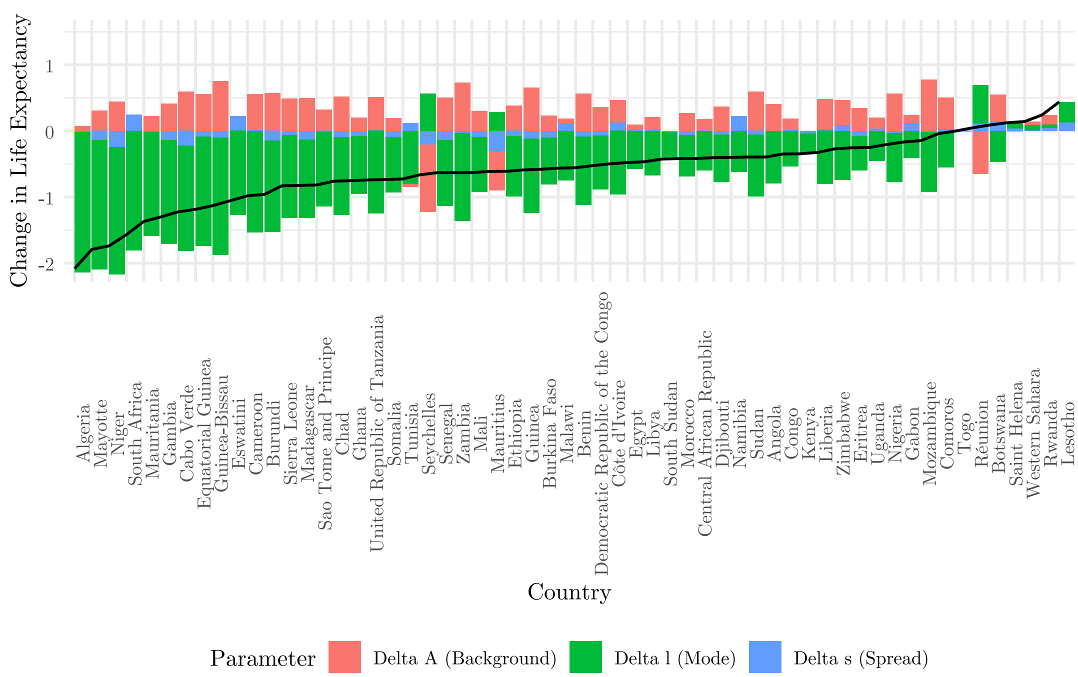


Fig. 12. Decomposing the consequences of Covid-19 on life expectancy: Africa.
Note: The figure plots a decomposition of the changes in life expectancy between 2019 and 2022 in African countries using estimates of the age-independent mortality, A, the modal age at death, l, and the spread around the modal age at death, s, for a sample of African countries. Data source: United Nations World Population Prospects (United Nations Department of Economic and Social Affairs, 2024). See text for details.

The decomposition method can be a useful tool for quantitative economic modeling. Specifically, it allows researchers to conduct quantitative experiments with controlled variation of different dimensions of life expectancy in age-structured models and to disentangle the distinct effects of variation in, e.g., location and scale for economic decisions and aggregate outcomes. Possible applications for the decomposition are investigations of the consequences of mortality changes for schooling choices, labor supply, and retirement decisions in economic models in which mortality is an exogenous state variable (as in BenPorath, 1967). Future work should also establish links to the shape of the age-specific mortality distributions that emerge from structural models of mortality at the individual level (e.g., Lleras-Muney and Moreau, 2022), or from models in which individuals make deliberate decisions about health investments along with other economic decisions such as savings (e.g., Grossman, 1972; Dalgaard and Strulik, 2014; Dalgaard et al., 2021).

CRediT authorship contribution statement

Martin G. Haas: Conceptualization, Data curation, Formal analysis, Methodology, Software, Visualization, Writing – review & editing. **Uwe Sunde:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors have no conflicts of interest to declare.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.jeoa.2025.100587.

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