What have we learned about mortality patterns over the past 25 years?

Alyson A. van Raalte
Max Planck Institute for Demographic Research

In this paper, I examine progress in the field of mortality over the past 25 years. I argue that we have been most successful in taking advantage of an increasingly data-rich environment to improve aggregate mortality models and test pre-existing theories. Less progress has been made in relating our estimates of mortality risk at the individual level to broader mortality patterns at the population level while appropriately accounting for contextual differences and compositional change. Overall, I find that the field of mortality continues to be highly visible in demographic journals, including *Population Studies*. However much of what is published today in field journals could just as easily appear in neighbouring disciplinary journals, as disciplinary boundaries are shrinking.

Keywords: mortality theory; mortality models; mortality trends; mortality differentials; life expectancy

Introduction

While the past few decades have witnessed near-steady increases in both global life expectancy (UN 2019) and record life expectancy (Oeppen and Vaupel 2002), this progress has been coupled with major challenges. HIV/AIDS caused unprecedented life expectancy declines in much of sub-Saharan Africa throughout the 1990s and 2000s (Titaeus and Jasseh 2004; Dorling et al. 2006; Bongaarts et al. 2011). The collapse of the former Soviet Union unleashed substantial fluctuation in adult mortality rates throughout Central and Eastern Europe in its aftermath (Leon et al. 1997; Shkolnikov et al. 2001; Grigoriev et al. 2014). Deaths both directly and indirectly attributable to violence have severely tempered or reversed life expectancy gains in parts of the Eastern Mediterranean Region (Mokdad et al. 2016), as well as Latin America and the Caribbean (Canudas-Romo and Aburto 2019). Alarms have recently been sounded over midlife mortality and stalling life expectancy in the United States (US) (Case and Deaton 2015; Mehta et al. 2020) and in England and Wales (Leon et al. 2019). Finally, as this paper was being written, mortality again came to the fore of public attention as the world was hit by the Covid-19 pandemic. Individuals were quarantined, schools shut, and borders closed. Public health methods once thought to be archaic were our prime defence against a virus meeting a completely susceptible world population.

This context, coinciding with the 75th anniversary of the *Population Studies* journal, is as good a time as any to take stock of developments in the field of human mortality. Disciplines as diverse as actuarial science, epidemiology, gerontology, and health economics can all claim a fundamental role in having shaped our knowledge about the patterns and determinants of mortality. Each has its own favourite models and outcome measures. Traditionally, demographers favoured the life table and life expectancy, whereas epidemiologists conducted survival analysis and reported relative risks. But the delineation between fields is becoming increasingly blurred, as demographers have moved from classic demographic modelling and description towards seeking explanations for mortality differences, borrowing causal inference techniques from the neighbouring social, statistical, and biological sciences. What continues to distinguish the field of mortality research...
in demography from neighbouring disciplines is less about the models we use and more about the patterns we are trying to estimate and explain: population-level age patterns of mortality.

For the 50th anniversary issue, Preston (1996) provided an overview of 50 years of population studies in mortality, using the publications in this journal as a window into the broader field. He highlighted the success of demographers during these first 50 years in developing indirect techniques to estimate infant and child mortality but noted comparably less success in estimating adult mortality and understanding its key determinants, apart from smoking. Likewise, Preston (1996, p. 535) predicted a movement in the field away from individual-level analyses of the ‘quasi-biological relationships that were investigated with WFS [World Fertility Survey]-style data (birth spacing, parity, age)’ and towards investigating the sources of change in adult mortality.

In this review, I take Preston’s observations as a point of departure and ask what we have learned since then. As mortality is a broad field, I narrow my attention to theoretical and methodological developments to describe and explain aggregate trends and differentials in mortality. These developments are split into several broad themes: life course research, macro-level determinants and social inequalities, theories of ageing, the heritability of longevity, mortality models, and forecasting.

While I attempt to cover a wide range of topics, undoubtedly some major topics and findings will be overlooked in this review, and it is skewed towards my own research interests. In the interests of space, I give short shrift to describing and explaining differences in mortality trends between specific populations, between the sexes, and between subnational groups. Instead, I aim to summarize the theories and models developed over the past 25 years that are general and applicable to all three lines of research. I also restrict this review to the study of mortality, ignoring the substantial advances made in recent years in studying health expectancies (for an overview, see Jagger et al. 2020).

After reviewing the major developments in the field, I examine what has been published in Population Studies specifically over these past 25 years and whether the journal continues to be a mirror reflecting the major developments within the field. I end with some thoughts on the current state of our knowledge. I argue that as the field has become more fragmented, we have become less concerned with overarching theories, such as the classic demographic and epidemiological transition theories. Instead we have pursued explanations covering varied and overlapping parts of the life course, which present a challenge with regard to aggregating up to the population level or ranking in terms of their importance in driving our most basic mortality differentials.

**Mortality theories**

Mortality theories describe both individual- and population-level differences in survival. Many if not most of these theories have been around for a long time, but new data sets and methods have allowed us to test these theories in ways that were not possible even 25 years ago.

**Life course theories**

Life course research investigates how later-life mortality is impacted by events set into motion in early life or other critical periods. It also encompasses research into mortality patterns resulting from long-term exposure to various health-deleterious behaviours and hazards. Over the past 25 years there has been considerable theorizing about how life course events impact mortality and some success in testing these theories, but perhaps less success in understanding to what extent they are driving mortality differentials internationally and subnationally.

Many of the key life course theories have existed for decades, although they continue to be refined and tested. Preston et al. (1998) distinguished four mechanisms linking early-life conditions to adult mortality: two were positively related to later-life mortality and two were negatively related. The first of these mechanisms was mortality **scarring**. Such scarring can arise from adverse events occurring during critical periods; see, for example, the ‘developmental origin of disease’ literature (Barker 1995; Doblhammer and Vaupel 2001; Doblhammer 2004; Schulz 2010). Finch and Crimmins (2004) discussed the idea of a ‘cohort morbidity phenotype’, that is, that inflammation from early-life exposure to infectious disease makes individuals more susceptible to a range of chronic diseases in later life, with the implication that the disease load encountered during childhood will have consequences for later-life mortality patterns. The second mechanism leading to higher later-life mortality was based on **correlated environments**. Detrimental social conditions encountered in childhood weaken educational opportunities and set in motion limited...
opportunities for upward mobility and its associated lower mortality, a process termed the ‘long arm of childhood’ (Hayward and Gorman 2004). The third mechanism, this one leading to lower adult mortality, was acquired immunity. An example here would be the differences in cohort susceptibility to influenza mortality late in life based on the circulating strains encountered in childhood (Gagnon et al. 2018; Acosta et al. 2019). The fourth mechanism was mortality selection (Vaupel et al. 1979), namely that trailer individuals will die in harsh conditions, leading to a more robust group of survivors at older ages.

Testing any of these theories is challenging, generally requiring rich individual-level data covering exceptionally long periods of time. Much of the empirical literature has found a surprisingly small impact of childhood circumstances on aggregate later-life mortality (Myrskylä 2010). This does not necessarily mean that the theories are incorrect. Empirically, it is a major challenge to separate these cohort-based mechanisms—which are likely to be operating simultaneously—even when their individual effects might cancel each other out (e.g. selection vs scarring) (Myrskylä et al. 2014).

Demographers have also long been interested in how generational differences leave their imprint on mortality. This is challenging because cohorts age through changing macro environments as well as changing social norms. Linking life course theory to macro-level environmental changes, Fogel and Costa (1997) argued in their theory of ‘technophysio revolution’ that any explanation of the long-term changes in life expectancy must consider the unprecedented changes in underlying human physiology that have taken place since the Industrial Revolution, brought about by our actions to control the environment.

While progress has been made in identifying the role of cohort smoking patterns on mortality trends and differentials (Preston et al. 2011; Petö et al. 2015), few other behaviours and determinants appear to be so clearly cohort patterned or sufficiently varied across populations that their signal can be easily identified. Obesity is potentially another candidate, and numerous studies have modelled its impact on mortality levels and trends (see, for instance, Peeters et al. 2003; Flegal et al. 2013; Preston et al. 2018). But there are still disagreements on how best to model obesity, due to the methodological challenges associated with observational data and weight change, residual confounding by smoking status, and other modelling choices that may bias results (Stokes and Preston 2016). Unlike lung cancer for smoking, there is no cause of death that is so clearly dominated by obesity that it can act as an indirect marker for the population-level harm. This is also the case for attributing causes of death to other health behaviours, many of which impact mortality on different timescales. For instance, excessive alcohol consumption can contribute to increased short-term mortality risk through accidents, as well as increased long-term risk through diseases such as liver cirrhosis.

Additionally, the increasing usage of biomarker data has opened up promising avenues for exploring how individuals differ ‘under the skin’ (Crimmins and Seeman 2004; Crimmins et al. 2010) and understanding which disease processes are most closely linked with later mortality (Gruenewald et al. 2006; Dowd et al. 2009). This can go some way towards testing the mechanisms in which life course processes impact mortality. Unsurprisingly, the biomarkers most strongly and consistently linked with mortality are indicators of cardiovascular function and metabolic processes (e.g. blood pressure, heart rate, cholesterol levels, glucose control, and markers of weight and adiposity) (Crimmins and Vasunilashorn 2011), since circulatory diseases remain the leading cause of death in most countries (Bongaarts 2014; Bergeron-Boucher et al. 2020).

The major challenge moving forward is to relate our life course theories more closely to aggregate-level mortality patterns. At the moment most life course studies are conducted at the individual level. The extent to which life course mechanisms drive population-level differences in mortality (as opposed to individual-level differences in mortality) remains poorly understood, with the possible exception of cohort smoking patterns. How do populations actually differ in terms of their life courses? Which life course mechanisms are most closely related to different disease processes and to death, and over which ages do they operate? To what extent have these mechanisms changed over time for different population groups and to what extent can they be expected to continue in future? Given the rapid changes in the disease and nutritional environments experienced by cohorts over the last 150 years, these questions remain highly complex.

**Influence of macroeconomic conditions and social inequalities on mortality**

It has long been recognized that macroeconomic conditions impact mortality trends and inequalities
between populations (Preston 1975) and that within-population differences in mortality by socio-economic position can be substantial (Antonovsky 1967; Kitagawa and Hauser 1968). Taking stock of the state of affairs around the early 1990s, we can see that debates emerged surrounding the impact of income inequality on life expectancy (Wilkinson 1992); researchers were digesting the key findings from the Whitehall II study of British civil servants (Marmot et al. 1991); estimates were made of the educational gradient in mortality across high-income countries (Kunst and Mackenbach 1994; Elo and Preston 1996); concerns were raised over growing socio-economic inequalities in child mortality in low-income countries (Cleland et al. 1992); and the theory of fundamental causes was proposed to explain the development and persistence of socio-economic inequalities in mortality (Link and Phelan 1995). In many ways, each of these lines of research has continued to the present.

Preston’s (1975) seminal paper in Population Studies on the cross-sectional curvilinear relationship between gross national income and life expectancy, which shifted upwards over time, is still ‘sparking fires’ (Bloom and Canning 2007). Key debates surround the direction of causality between national income and health (Bloom and Canning 2000), as well as the relative importance of endogenous vs exogenous factors in explaining this relationship (Cutler et al. 2006; Lutz and Kebede 2018). More generally, ‘Preston curves’, as they are now known, remain a key piece of evidence in one of the longest-running debates in mortality circles: what caused the monumental and sustained increases in life expectancy that began around the mid-nineteenth century? On one side are those who argue that improved economic conditions, particularly improved nutrition, were paramount (McKeown and Record 1962; McKeown 1976; Fogel 1994, 2004; Harris 2004). On the other, are those arguing for (Harris 2004). The theory was tested across many countries and time periods, using different study designs. Of 26 aggregate studies conducted by the early 2000s, 15 supported the income inequality hypothesis, six found no association, and five offered mixed support (Lynch et al. 2004). The debate is still active, with more recent papers arguing for (Pickett and Wilkinson 2015) and against (Hu et al. 2015) a causal association between income inequality and mortality. According to the more nuanced view of Torre and Myrskylä (2014), the association holds only over younger ages, not over older ages where most of the chronic disease occurs.

Another macroeconomic perspective debated in mortality research has been how the business cycle influenced mortality trends. The early prevailing view was that at the population level, economic downturns increased mortality (Brenner 1979), and at the individual level, long durations of unemployment were associated with higher mortality (Martikainen 1990). Ruhm (2000) upended these views with an influential study arguing that mortality was procyclical, aside from a few smaller causes of death, such as suicide. Ruhm explained these patterns by behavioural mechanisms, arguing that increases in labour force activity led to increased smoking and reduced physical activity. This was combined with increased workplace and road traffic accidents during economic booms.

Since then, procyclical mortality has been confirmed in many other countries and settings (Neumayer 2004; Tapia Granados 2005, 2008; Tapia Granados and Diez Roux 2009; Van den Berg et al. 2017), although some studies have found either countercyclical mortality (Economou et al. 2008) or a weakening of procyclical mortality (Ruhm 2015) in more recent years. Edwards (2008) found that similar upward-shifting Preston curves. He drew on a wealth of evidence to argue instead that the diffusion of new technologies, especially immunization and improved public health infrastructure, was the key driver of post–Second World War life expectancy increases in less developed countries.
more highly educated men in the US experienced procyclical mortality, whereas lower-educated men experienced countercyclical mortality, suggesting that the personal resources available to withstand economic hardship might play an important role in the employment–mortality nexus.

Research into socio-economic inequalities in mortality has been another rich area of investigation in the last 25 years, in part because of more widely available data sets covering different components of socio-economic position. This has led to a general recognition that ‘although the biological potential for a long life may be stochastically distributed throughout the population, individuals’ opportunities to capitalize upon this potential are not’ (Gutin and Hummer 2021, p. 514). In this period, it became increasingly clear that while all European and Anglo-Saxon nations experienced socio-economic gradients in mortality, levels of inequality could differ substantially (Mackenbach et al. 2008; Avendano et al. 2009). Across European countries (van Raalte et al. 2011) and US states (Montez et al. 2019), life expectancies varied considerably among low-educated groups, but were remarkably similar among more highly educated groups. This suggests that the most advantaged individuals are less dependent on their own population’s circumstances and that differences in inequalities across populations are driven by the extent to which populations succeed in protecting their most vulnerable citizens from premature mortality.

Theories continue to be advanced on the social determinants of mortality (for an overview, see Elo 2009; Pampel et al. 2010; Mackenbach 2017; van Raalte and Seaman 2020). These include behavioural determinants, material explanations, psychosocial factors, and cumulative life course adversity. Such explanations are not mutually exclusive, but they are likely to change in importance over the life course. They may also operate differently across contexts. As with life course theories discussed earlier, there has been excellent research showcasing specific instances of when these theories are operating, but we lack a general understanding of the magnitude of importance of these theories and how they are changing over time.

A key question remains around how tractable inequalities are in terms of different social policies. To many, it came as a surprise that countries with strongly redistributive and universalistic welfare policies experienced among the highest levels of social inequality: this became known as the Nordic Paradox (Mackenbach 2017). Yet in the US, Montez and colleagues found a strong role for differences in social policies enacted at the state level in driving overall life expectancy trends (Montez et al. 2020) and educational disparities in mortality (Montez et al. 2019).

Increasingly, attention has turned to look beyond mean differences in mortality outcomes. Disadvantaged socio-economic groups tend to experience considerably more variability in their ages at death, a feature also termed lifespan variation or lifespan inequality (Shkolnikov et al. 2003; Edwards and Tuljapurkar 2005; van Raalte et al. 2011). Lifespan variation can be interpreted as both the heterogeneity in population health and the individual uncertainty in the timing of death. A concerning finding is that socio-economic groups are diverging in lifespan variation regardless of trends in life expectancy; this is explained mostly by stalls in the decline of premature mortality (van Raalte et al. 2014; Sasson 2016; Brønnum-Hansen 2017; Pernyman et al. 2018; van Raalte et al. 2018). In other words, advantaged groups are experiencing longer and more predictable lives. But for lower socio-economic groups, even if their average lifetime is generally increasing, the certainty of reaching that average is declining.

Outside Europe and Anglo-Saxon countries, nationally representative data on socio-economic inequalities in mortality remain scarce, and there are few high-quality comparative studies. There is conflicting evidence about just how universal socio-economic gradients in mortality are. Reversed occupational class gradients in mortality have been found in Japan and South Korea (Tanaka et al. 2019), but a positive and growing socio-economic gradient in mortality has been observed among educational groups in South Korea (Bahk et al. 2017) and for various dimensions of socio-economic status among older people in China (Luo and Xie 2014). Still others have argued that Asian populations experience comparable or even higher inequalities than western ones (Woodward et al. 2015). Reversed gradients have also appeared among older adults in Mexico and Costa Rica (Rosero-Bixby and Dow 2009; Rosero-Bixby 2018), whereas no clear gradient was found in Kenya or Zambia (Chapoto et al. 2012). Using harmonized longitudinal data covering China, Costa Rica, Indonesia, Mexico, South Africa, and South Korea, Sudharsanan et al. (2020) showed that although the tertiary educated held a consistent advantage in survival, completing secondary education did not always confer a survival benefit compared with holding no educational qualifications.

Pulling these findings together, we can see that over the past 25 years the important roles of macro-economic conditions and social inequalities in

Mortality patterns over the past 25 years

S109
shaping mortality patterns between and within populations have been confirmed in a subset of developed countries. Hopefully, in the next 25 years, data limitations can be overcome to allow examination of these issues within a broader world context.

The force of mortality at older ages

Until the late twentieth century, interest in mortality at older ages was relatively small. The prevailing view at the time was that old-age mortality was challenging to tackle medically, and it was assumed that little progress had been made in increasing survival at older ages. By convention, national statistical offices aggregated data at ages above 85, further hampering efforts to monitor progress in reducing mortality at the highest ages. This view changed in the mid-1990s after several studies showed that death rates at older ages were declining more sharply than imagined (Kannisto et al. 1994; Manton and Vaupel 1995; Kannisto 1996). This was even occurring at the very oldest ages, as shown by an increase in the maximum attained age (Wilmoth and Lundström 1996) and an increasing number of centenarians, beyond what would be expected based on cohort size (Wilmoth et al. 2000).

Overall, data quality issues continue to be major concerns in the study of centenarians. Age misreporting is common (Robine 2007; Maier et al. 2010). As an extreme example, Nepomuceno and Turra (2020) reported that 4,438 individuals claimed to be centenarians in the 1900 Brazilian Census, a figure that grew to over 24,000 in 2000. Using variable-r relationships and various mortality models, these authors estimated that there were virtually no centenarians in 1900 and fewer than 1,000 in the year 2000. Less extreme, but still considerable, are the concerns raised in several high-income countries around data quality at oldest ages (Wilmouth and Aloisio 1996) and an increasing number of centenarians, beyond what would be expected based on cohort size (Wilmoth et al. 2000).

Debates on the shape of mortality at older ages were prominent during this period. Large collaborative efforts were undertaken to assemble mortality data at older ages across countries with data of reasonably good quality (Kannisto 1996). This resulted first in the Kannisto–Thatcher database and, later, the International Database on Longevity. After considerable study of mortality patterns among older people, the consensus from these collaborations was that mortality could best be described by a type of logistic function now known as the Kannisto function (Thatcher et al. 1998).

The Kannisto function has since become the standard method for period life table creation, including for the Human Mortality Database (HMD) (Wilmoth et al. 2017).

Decelerating death rates, reaching a plateau at the oldest ages, are consistent with the theory of mortality heterogeneity (Vaupel et al. 1979). Importantly, under this theory, individual mortality risks continue to be exponential. A plateau observed at the population level would result from the selective mortality of frail population subgroups (Vaupel and Yashin 1985). The death rates of various insects, worms, and yeasts appear to decelerate with age (Vaupel et al. 1998). Among humans, several theoretical and empirical studies of longevity have also supported deceleration (Horiuchi and Wilmoth 1998; Lynch and Brown 2001; Feehan 2018). By pooling data on supercentenarians (i.e. those who had attained age 110) from 13 populations to attain a large enough sample, Gampe (2010) found that the hazard function appeared constant from ages 110 to 114, after which the data were too sparse to make a reliable estimate. A decade later, Gampe (2021) updated the analysis with double the observations and came to a similar conclusion. Further evidence came from Italian mortality patterns, which Barbi et al. (2018) claimed provided clear evidence of mortality deceleration from about age 80, reaching a plateau around age 105.

This conclusion is not without its controversy. A competing perspective is that a mortality plateau could come about from age misreporting, which is common among centenarians (Newman 2018; Gavrilov and Gavrilova 2019). Using ‘extinct generations’ methods applied to monthly US Social Security data, Gavrilov and Gavrilova (2011) contended that mortality even up to the oldest ages is best characterized by a Gompertz hazard. Based on the bold claims made in the Barbi et al. (2018) study, Camarda et al. (2019) argued that the sample size of survivors was too small to confidently reject other possibilities for the shape of ageing at oldest ages, including a Gompertz hazard. Wrigley-Field (2014) warned that the link between mortality selection and mortality deceleration is often more complex than theorized, with multiple mortality decelerations or even accelerations being possible results of the changing composition of frailty within cohorts.

The heritability of longevity

In the early 1990s, the best estimates of the heritability of longevity came from twin studies. By
comparing the similarity in ages at death between identical twin pairs (who are genetically identical) with fraternal twin pairs (who share 50 per cent of their genes), researchers estimated that about a quarter of the variation in longevity washeritable (McGue et al. 1993; Herskind et al. 1996).

Within-family research continued through the early 2000s. Sibling studies consistently demonstrated a strong familial component to longevity (Gudmundsson et al. 2000; Kerber et al. 2001; Schoenmaker et al. 2006). Perls et al. (2002) estimated that the siblings of American centenarians experienced death rates at around half the level experienced by the US 1900 birth cohort at all ages, a proportion at the high end of these types of studies. Cumulatively this led to male siblings of centenarians being 17 times more likely than other males to become centenarians themselves, and female siblings about eight times as likely. More puzzling, unlike other major individual attributes, such as socio-economic status, sex, or race, these relative differences did not converge at older ages. As the authors pointed out, these familial advantages could relate to shared environments or to shared behaviour, or be genetically determined, and should be seen as an upper bound to the heritability of longevity. Unravelling the importance of these three mechanisms has become an important topic in ageing research.

The Human Genome Project, which took place between 1990 and 2003, was a major international collaborative project to sequence the human genome. It was widely hoped that this endeavour would lead to the discovery of the genes which determine human longevity. Although a few candidate genes were found to be associated with ageing (Corder et al. 1996; Willcox et al. 2008), it became apparent early on that there was no single gene responsible for the large variation in human life-spans. Rather, any genetic component to longevity was likely to result from numerous mutations each conferring small effects (Christensen et al. 2006).

This was disappointing, given that modifying a small combination of genes was able to substantially increase the longevity of simpler organisms, such as the nematode worm or fruit flies (for an overview of studies, see Finch and Tanzi 1997). Adding to the complexity, animal studies also showed that genes might affect mortality only above certain ages (Johnson et al. 2001).

More recently, attention has shifted to estimating the heritability of conditions and behaviour through genome-wide association studies and to calculating polygenic risk scores. Yet it has also become increasingly apparent that estimating any such genetic components cannot be understood without considering gene–environment interactions (Boardman et al. 2014; Tropf et al. 2017). For example, a recent study suggested that living in a neighbourhood perceived to be disorderly triggered a disease process among those with a genetic predisposition for type 2 diabetes (Robinette et al. 2019). Another study argued that the link between obesity and mortality was socio-behavioural rather than genetically determined, by comparing the mortality risks of obese people with high and low genetic predispositions to obesity (Vinneau et al. 2021).

Overall, the extent to which genetic differences across individuals shape our aggregate age patterns of mortality, or contribute to mortality differentials across nations and subpopulations, remains unclear. In the coming years, findings from the nascent field of sociogenomics (Mills and Tropf 2020) will likely provide new insights on the tractability of aggregate mortality patterns and differentials. Nevertheless, when we consider the full extent of mortality decline that humans have experienced within the context of evolutionary history—mortality differences between low-mortality populations and hunter-gatherers have become considerably larger than mortality differences between hunter-gatherers and wild chimpanzees, all within the space of four generations—it is clear that the potential for genetic variation to be an important contributor to population-level mortality differentials is small (Burger et al. 2012).

This section has highlighted numerous developments in the testing and development of mortality theories. To summarize broadly, over the past 25 years, there has probably been more research effort devoted to testing pre-existing theories of mortality with new and richer data sets than to the development of completely new theories. Many if not most of these theories are designed around a specific part of the life course; in other words, they aim to describe individual or within-population differences in survival. It is less clear to what extent they should hold to explain differences in survival between populations and whether they are equally applicable in less developed settings. As data sets covering larger swaths of the world population become available, it will be important to test the universality of these theories and to integrate them into more coherent explanations for population-level mortality trends and differentials.
Mortality models

Crimmins (1993, p. 582) described formal demography as the subfield of demography with the most 'continuity and cumulation'. This description is equally applicable today, particularly to the formal modelling of mortality, where researchers continue to refine and increment classical models that have been around for decades.

Estimating mortality patterns in data-deficient regions

Many countries continue to lack functioning civil registration of vital statistics. Nearly 1 billion people live in the 50 countries of the world without data on adult mortality (Clark 2019). Child mortality tends to be better covered through household survey data. Sub-Saharan Africa, in particular, remains poorly covered. Modelled schedules of mortality are commonly used, supplemented by data from the demographic surveillance sites run by the International Network for the Demographic Evaluation of Populations and their Health (INDEPTH).

Estimates of child mortality obtained from census questions about the survival of recent births have been found to underestimate under-five mortality levels compared with household surveys with full birth histories (Merdad et al. 2016). Although the census method would have provided cheaper and more detailed regional data, the study’s authors argued that the varying quality of the estimates caution against including such questions on censuses.

A major development in the field of demographic estimation in data-poor contexts has been the use of Bayesian estimation methods. The advantage of Bayesian models is their ability to incorporate known prior information, as well as to quantify the uncertainty in the estimates themselves. These methods have been used to estimate subnational mortality (Alexander et al. 2017; Schmertmann and Gonzaga 2018), neonatal mortality (Hug et al. 2019), child mortality for finer spatial units (Wakefield et al. 2019), and maternal mortality (Alkema et al. 2016).

Modelling the prevalence of HIV/AIDS and its associated mortality has also been a major focus of demographers during this 25-year period. Data quality was a key issue, since the most affected countries lacked adequate civil registration of vital statistics. Instead, researchers made use of a range of data sources—including censuses (Blacker 2004), Demographic and Health Survey (DHS) data (Timeus and Jassem 2004), demographic surveillance systems (Hosegood et al. 2004), antenatal clinics (Salomon and Murray 2001), and vital statistics (Feeney 2001)—and estimates were obtained from both direct measurement and indirect methods such as sibling survivorship methods (Timeus and Jassem 2004). These different data sources and models yielded substantially different estimates of prevalence and mortality and were the source of heated debates (Feeney 2001; Blacker 2004).

The HIV/AIDS pandemic also created measurement challenges for key demographic quantities, such as child mortality levels. Often these are estimated using indirect methods from data provided by mothers on the survival of their children. In countries with generalized HIV epidemics and in the absence of antiretroviral therapy use, not accounting for the correlation of mortality risks between mothers and children has been found to bias estimates by up to 25 per cent (Walker et al. 2012).

Model schedules in data-deficient regions

In populations with poor data quality or for applications with sparse data, many of the classic tools of demography continue to be widely used today. These include parametric models of mortality, relational models, and model life tables, particularly the Coale et al. (1983) family of life tables (Heuveline and Clark 2011). However, the Coale–Demeny system has its disadvantages, in particular that it does not capture the relationship between child and adult mortality well when child mortality drops below about 50–60 per 1,000 (Wilmoth et al. 2012). Moreover, none of the model life table systems adequately capture adult mortality patterns in countries with high mortality from HIV/AIDS or conflict (Heuveline and Clark 2011).

Although classic methods continue to serve many purposes, several recent developments are worth mentioning, discussed here in chronological order. First, Murray et al. (2003) developed a modified logit system based on a large collection of life tables from the World Health Organization (WHO) (Lopez et al. 2002), supplemented by non-overlapping life tables from existing collections in Preston et al. (1972) and those used in the United Nations (UN 1982) model life table system. This system followed the logic of the classic Brass (1971) logit system but departed from it in terms of the mathematical transformation used to generate a life table from the standard life table.
Second, the collection of thousands of high-quality life tables from the HMD (Barbieri et al. 2015) was exploited in a new two-parameter, log-quadratic relational model life table system (Wilmoth et al. 2012). The life tables can be estimated based on information either from child mortality only or from child and adult mortality. This is a major advantage in regions where child mortality estimates are known from survey data but estimates of adult mortality are either unknown or of much lower quality. Caution should be applied here though. Using DHS survey data, Masquelier et al. (2014) found that trends in child and adult mortality had diverged in many sub-Saharan African regions over the past 30–40 years. This was particularly the case in countries with sustained HIV/AIDS outbreaks but was not limited to those countries.

Third, de Beer (2012) introduced the TOPALS (tool for projecting age-specific rates using linear splines) relational model. Essentially this model uses a linear spline to model the ratios between age-specific probabilities of death and a standard age schedule. The advantage of the model is that it is flexible to the choice of any standard age schedule (e.g. it could be a population aggregate or a best-practice mortality age schedule), but the pattern must be smooth. Generally, the choice of schedule depends on the intention in applying the model: whether for estimating smooth age-specific mortality schedules or for making projections about future age patterns of mortality. The model has proved particularly well suited for small-area mortality estimation, often in combination with Bayesian models (Gonzaga and Schmertmann 2016; Schmertmann and Gonzaga 2018; Rau and Schmertmann 2020).

Fourth, a series of papers has presented new methods to estimate age patterns of mortality in regions experiencing high HIV/AIDS mortality. Countries in such regions depart from traditional mortality schedules in that they report elevated mortality at very young ages and over middle adult ages. Bayesian methods have been developed to fit the eight-parameter Heligman–Pollard method, with the advantage that Bayesian estimation accounts for uncertainty (Sharrow et al. 2013). Clark (2019) developed a general, singular-value-decomposition (SVD), component-based mortality modelling framework. This framework models mortality schedules as a function of known covariates that relate to the variation in age-specific mortality schedules. Sharrow et al. (2014) used an HIV-calibrated version of this SVD-component method for countries with generalized HIV/AIDS epidemics.

Altogether, the increasing usage of Bayesian estimation models together with new, flexible model life table systems has no doubt increased the accuracy of mortality estimates in much of the world. Nevertheless, the lack of ground-truth data in much of the world, with which to test our models properly, remains problematic. We can only hope that by the next anniversary of Population Studies, a much larger proportion of the world will be covered by well-functioning civil registration and vital statistics systems.

Mortality patterns and models in data-rich settings

One of the most widely talked about demographic analyses of the past 25 years was Oeppen and Vaupel’s (2002) seminal paper showing that increases in record period life expectancy for females were characterized by a straight line, with a gain of 2.5 years per decade. Although subsequent analysis showed that when populations with poorer data quality were excluded the trend line was more segmented (Vallin and Meslé 2009), the long-running steady progress of the leaders in life expectancy continued to hold. From a birth cohort perspective, the decadal increase was even stronger (Shkolnikov et al. 2011). Even global average life expectancy was estimated to have increased by 1.9 years per decade between 1800 and 2001 (Riley 2005). Such findings went against widely held notions of future limits to life expectancy, which were often included as asymptotes in national statistical projections.

Pessimists were sceptical that gains made in the past could be replicated in the future, since much of the gain in life expectancy in the twentieth century had come from reducing mortality from infectious disease, particularly during infancy where it had already reached low levels. They argued that tackling complex chronic disease and obesity would be comparatively more challenging (Olshansky et al. 2001, 2005). The counterargument to the Olshansky camp was the general finding of an ‘ageing of mortality decline’: namely that the ages at which death rates decline the most have been shifting higher and higher, mirroring the shifting societal priorities accompanying population ageing (Horiuchi and Wilmoth 1995; Rau et al. 2008, 2018).

While the debate remains unsettled, demographers have made important contributions to the study of long-term mortality trends using cause-of-death reconstruction and analysis (Meslé 1999;
Pechholdová et al. (2017). Based largely on these long-term reconstructions, Vallin and Meslé (2004) argued that as novel social and biomedical innovations are first adopted by leading populations, mortality trends in any given country are better reflected by a series of divergence and convergence cycles with respect to leading countries, which may differ by cause of death.

Beyond looking at trends in mean survival, researchers have increasingly begun to compare the variation in ages at death across populations. This has led to the emergence of terms including rectangularization of the survival curve, mortality compression, lifespan/length-of-life inequality, or lifespan variation. Throughout most of the last 150 years, lifespan variation has been highly negatively correlated with life expectancy (Vaupel et al. 2011), particularly when examined with relative measures of variation (Smits and Monden 2009; Aburto et al. 2020). But there is no a priori reason for this to be the case (Wilmoth and Horiuchi 1999). Compared with life expectancy, lifespan variation as a measure is particularly sensitive to changes or differences in early adult mortality (Shkolnikov et al. 2003; Edwards and Tuljapurkar 2005; Firebaugh et al. 2014; Gillespie et al. 2014; van Raalte et al. 2018; García and Aburto 2019). Meanwhile, modal age at death has come back in fashion as an indicator that is particularly well suited to capturing the dynamics of mortality change at older ages (Kannisto 2001; Cheung et al. 2005; Cheung and Robine 2011). From this perspective, long-run mortality compression has existed since the mid-1950s in most countries, but this has been accompanied by considerable sub-periods of mortality expansion or shifting.

Other researchers have instead looked at trends in compression before and after a moving ‘threshold age’ (Vaupel et al. 2011; Gillespie et al. 2014). This is the age above which declines in mortality lead to increases in lifespan variation, and it is unique to each age schedule of mortality and index of variability (Zhang and Vaupel 2009; van Raalte and Caswell 2013; Gillespie et al. 2014; Aburto et al. 2019; Aburto et al. 2020). Over the long run, trends in lifespan variation across the whole age range are driven mainly by mortality change below the threshold age. Since 1840, mortality above the threshold age has only experienced modest compression in HMD countries (Vaupel et al. 2011). This is consistent with a recent study showing that trends in lifespan variation calculated beyond fixed percentiles of survivors (instead of fixed age categories) were constant. Or as the authors put it, old age ‘follows an advancing front, like a traveling wave’ (Zuo et al. 2018, p. 11209).

Whether mortality age patterns were best described by compression, expansion, or shifting (i.e. roughly whether the variation in ages at death was narrowing, increasing, or staying unchanged as mortality declined) has remained a hot topic over these past 25 years. Early disputes centred around disproving Fries’ (1980) theory of morbidity compression. In it, he argued that the maximum human lifespan was fixed and biologically determined. As a consequence, as life expectancy approached this upper age limit, any further mortality decline would sharply compress deaths into a narrow age window below this upper limit.

Since the theory was based around the distribution of mortality at older ages, early studies used truncated age distributions to test for mortality compression. This was not a neutral decision. Generally, the older the truncation age, the more likely the finding of mortality expansion (Robine 2001; Engelman et al. 2010). Yet when the whole age range was examined, it was seen that sharp declines in infant mortality generally led to sharp declines in variation, all but obscuring the role of mortality dynamics over adult ages on changing patterns of variation (Wilmoth and Horiuchi 1999; Shkolnikov et al. 2003). Other empirical strategies examined trends in the standard deviation above the modal age at death (Kannisto 2001; Cheung et al. 2005; Cheung and Robine 2007; Ouellette and Bourbeau 2011). From this perspective, long-run mortality expansion has existed since the mid-1950s in most countries, but this has been accompanied by considerable sub-periods of mortality expansion or shifting.

Demographic decomposition

One area in which we have made substantial methodological progress is demographic decomposition. Decomposition has a long history in demography, reaching back to the Kitagawa (1955) method to separate changes in rates into direct and compositional components. This line of research has continued, with more general methods developed in continuous time (Vaupel and Canudas-Romo 2002, 2003).
A second line of decomposition quantifies the contribution of different covariates to a change or difference in an aggregate measure. By the mid-1990s, life expectancy decomposition by age or by age and cause of death was a standard feature of the demographic toolkit (Andreev 1982; Arriaga 1984; Pressat 1985; Pollard 1988). But how decomposition related to other demographic methods, such as cause-deleted life tables, remained unclear, and similar analytic methods for other aggregate measures of mortality had not been derived.

Addressing the unclear relationship between decomposition and other tools of demography, Beltrán-Sánchez et al. (2008) derived a series of formulas showing the linkage between cause-deleted life tables and cause-of-death decomposition. Cause-of-death analysis was further developed by a new measure of life years lost based on the cumulative incidence of death (Andersen et al. 2013). Unlike cause-deleted life tables and some of the other methods for calculating years of life lost, this formulation does not require the often-untenable assumption of independence between causes of death. Also, it has the advantageous property that the numbers of life years lost from each of the different causes of death sum to the total life years lost from all causes of death, making it straightforward to decompose.

As far as extending the decomposition toolkit to other summary measures of mortality beyond life expectancy is concerned, two general methods were derived in the 2000s. In essence, these decompose differences in any aggregate measure into the contributions from differences in the covariates (for instance age-specific mortality) used to calculate the measure. The stepwise decomposition method (Andreev et al. 2002) does this by changing the covariates one at a time and recalculating the aggregate measure after each intermediate step to determine the impact of each covariate. The “continuous change” method (Caswell 1996; Horiuchi et al. 2008) approximates the changes in an aggregate function between two populations by a linear combination of partial derivatives of the function with respect to the covariates. Since these measures are general, they have been widely used in applications for which no analytic decomposition of a measure has been derived, for example in measures of life-span variation.

**Mortality forecasting**

Mortality forecasting is an area that has blossomed over the past 25 years. In 1996, the UN and most statistical offices around the world relied on deterministic, scenario-based projections of mortality—often with high, medium, and low variants. Scenarios were limited in that they were typically seen as fixed throughout the projection period—for example, the ‘low’ mortality scenario was one in which rapid declines in mortality were expected to continue unabated, without allowing for stalls and accelerations. Moreover, these models required subjective expert opinion, and it was unclear how likely a population was to experience low or high scenarios.

Since the 1990s, there has been a general shift away from deterministic, scenario-based projections to probabilistic forecasting methods (Booth 2006). Lee and Carter (1992) led the way, with their model that extracts a time-varying index of the level of mortality via SVD on the matrix of log death rates, which is then forecasted using a random walk with drift. The model quickly became popular because it was simple, interpretable, and provided statistical uncertainty. Further vindication for the Lee–Carter model came from early applications showing that the time-varying mortality index was linear and remarkably similar across Group of Seven (G7) countries from 1950 to 1995, although Japan experienced a notably steeper decline than the other countries (Tuljapurkar et al. 2000).

Early reviews of the performance of the Lee–Carter model found that it tended to underestimate life expectancy increases (Lee and Miller 2001; Booth et al. 2006), in part because of the assumption of a fixed age pattern of mortality decline. In reality, mortality decline has been shifting to older ages (Rau et al. 2013). Additionally, the fixed age parameter could result in implausible forecasts at the age-specific level (e.g. crossovers), and there were challenges in forecasting subpopulations coherently or accounting for cohort deviations from the linear trend. This led to a flurry of extensions to the model (Booth et al. 2002; Renshaw and Haberman 2003, 2006; Li and Lee 2005; De Jong and Tickle 2006; Delwarde et al. 2007). Notably, for their projections, the UN adopted an extended model which allowed for both coherence and a rotating age parameter (Li et al. 2013).

In the most recent decade, researchers have moved away from the Lee–Carter method and explored the utility of extrapolating other mortality inputs (Bergeron-Boucher et al. 2019). This has included extrapolating life expectancy trends (Torri and Vaupel 2012; Pascariu et al. 2018) and death density (Bergeron-Boucher et al. 2017; Basellini and Camarda 2019), in the process adopting
statistical methods such as compositional data analysis and generalized additive models that are well suited for mortality data. There have also been recent developments in forecasting methods specifically designed to account for changes in the age patterns of mortality resulting from HIV/AIDS (Sharrow et al. 2018) and smoking (Wang and Preston 2009; Janssen et al. 2013). The idea here is that such epidemics are both predictable in their cohort incidence and cause non-linearity in period trends. Meanwhile, although the majority of forecasting models were designed for period forecasts, recent advances have homed in on the problem of completing cohort mortality schedules (Basellini et al. 2020; Rizzi et al. 2021).

Overall, the shift in interest towards modelling and forecasting older segments of the population has mirrored population ageing as a whole. Undoubtedly the ageing of the baby boomer cohorts has been one of the major reasons why mortality forecasting is seeing a renaissance and can no longer be considered an unenviable task in demography. Even slight inaccuracies in projecting these large cohorts could be very expensive for public finances.

In short, formal modelling continues to be an active subfield in demography, particularly within mortality circles. One of the unending discussions that keeps resurfacing in demography is the divide between micro and macro levels of analysis, with a fear that traditional macro models are being abandoned in favour of sophisticated individual-level statistical estimation. Far from demography ‘abandoning its core’, as Lee (2001) feared, this review has demonstrated that formal models continue to play a strong role in mortality analysis.

An overview of how Population Studies has covered mortality

What has been published in Population Studies since the 50th anniversary? Altogether from volume 51, issue 1, in 1997 to volume 74, issue 3, in 2020, there were 117 papers using mortality as the main outcome measure by my counting. In the late 1990s, only one to four papers were published per year on mortality. This has grown to between four and seven over the past five years.

There is no perfect way to categorize studies, but what interested me was to see a rough breakdown of the types of questions addressed by these studies. At the 50th anniversary, Preston (1996) noted that a gradual shift in attention from infant and child mortality towards older-age mortality was underway, aligning with a shift in the age structure of the population in developed countries. Over the past 25 years, this trend has continued and probably accelerated. By my rough calculations, about 10 per cent of all mortality papers since 1996 have focused on infant mortality, with a further 10–15 per cent on child mortality. The remaining papers covered the entire life course or were restricted to adult mortality.

Around 40 per cent of the mortality studies focused on low- and middle-income countries, a little over half used data exclusively from high-income countries, and the rest covered either global mortality estimates or theoretical models that were equally applicable to countries at all levels of development. In low- and middle-income countries, major recurring themes included descriptions of inequalities in mortality patterns, be they socio-economic, sex based, or regional (Gupta 1997; Murphy and Wang 2001; Yount 2001; Saikia et al. 2011), as well as the impact of family composition and family circumstances on own and on children’s mortality (Muhuri and Menken 1997; Arnold et al. 1998; Rahman 1999; Saha and van Soest 2011; DeRose et al. 2017; Kravdal 2018).

In comparison to the previous 50 years (Brass 1996; Preston 1996), this most recent 25-year period saw fewer papers on the development of new models to estimate mortality patterns from deficient data. Notable exceptions were two highly influential papers describing new flexible model life table systems (Murray et al. 2003; Wilmoth et al. 2012) currently used by the UN and WHO, respectively. Perhaps surprisingly, no studies in this journal were concerned with the methods and models used to estimate the age patterns of mortality from the HIV/AIDS epidemic, a field of study in which demographers have been deeply involved during the past 25 years. However, Sharrow et al. (2018) developed methods to forecast future mortality patterns in countries with generalized HIV/AIDS epidemics.

Among studies of high-income countries, recurring themes were remarkably similar to those for low-income settings. A large number of papers set out to understand the impact of reproductive history on mortality (Doblhammer 2000; Dribe 2004; Hurt et al. 2006; Hank 2010; Einiö et al. 2016; Barclay and Myrskyla 2018), or to estimate mortality risks following bereavement (Lusyne et al. 2001) or divorce (Metsä-Simola and Martikainen 2013). Inequalities in mortality by socio-economic status, migration history, and marital status were also well
represented (Murphy et al. 2007; Martikainen et al. 2009; Luy et al. 2011; Omariba et al. 2014; Bijwaard et al. 2019).

If there was comparatively less work on mortality modelling for less developed countries during this 25-year period than previously, the same cannot be said about modelling mortality patterns in high-income countries. Models were developed and used to gain a deeper understanding of the relationship between period and cohort mortality (Guillot 2003; Goldstein and Wachter 2006; Canudas-Romo and Guillot 2015; Guillot and Payne 2019). Patterns of ageing, broadly defined, were investigated using formal demographic methods (McGlynn et al. 2003; Glei and Horiuchi 2007; Bongaarts 2009; Goldstein and Cassidy 2012; Li and Anderson 2015). New summary measures of mortality were developed and compared across countries, with a particular interest in variability in ages at death (Cheung and Robine 2007; Ebeling et al. 2018; Alvarez et al. 2020).

Overall, 15 papers that either used or developed formal demographic models of mortality on aggregate data have been published in Population Studies in the past five years alone.

In the 50th anniversary issue, mortality forecasting did not feature at all in Preston’s (1996) review of mortality studies, while Coale and Trussell (1996) touched on mortality forecasts only as an added benefit of using model life tables. By contrast, mortality forecasts and projections have featured prominently in the past 25 years, with at least one paper published annually over the past five years.

Over the same period, around 15 per cent of mortality papers estimated mortality patterns using exclusively historical data. Two major themes emerged from these studies: estimating mortality patterns during extreme events, such as pandemics and genocide (Thornton and Olson 2011; Chandra 2013; Heuveline 2015; Alfani and Bonetti 2019) and examining how mortality patterns shift with urbanization, modernization, and changing political regimes (Notkola et al. 2000; Reher and Sanz-Gimeno 2000; Babiarz et al. 2015; Torres et al. 2019).

To summarize, we can make out a few major recurring themes among papers published in Population Studies over the past 25 years. At the micro level, there has been a keen interest in how events central to an individual’s life course—in particular their early-life circumstances, their reproductive history, and the long-term consequences of experiencing adverse events, such as marital dissolution or the death of family members—impact their subsequent survival. Macro-level analyses have focused on how social inequalities translate into survival inequalities over various stages of the life course and how these inequalities are impacted by macroeconomic conditions. The use of formal demographic models has also been well represented, in particular for estimating mortality patterns, enhancing our general understanding of ageing processes, and building better mortality forecasts.

How well do these studies map on to the general field of mortality? Summarizing the general progress of mortality studies requires an eye towards the themes and major findings that are moving the field. In the 50th anniversary issue, Preston (1996, p. 526) argued that since ‘nearly half of the most important studies in this field were published in its pages, the journal provides a very convenient vehicle for such a review’. Although Population Studies remains an important outlet for mortality researchers, its field dominance is certainly lower today. Preston’s publication record itself could be considered a good representation of publication trends in the field: he published eleven papers in Population Studies between 1970 and 1996, but only three papers since then. This does not reflect lower productivity (quite the opposite, which in itself is an extraordinary feat considering the additional administrative duties he took on as dean of his college). Nor does it signal a new favourite journal, but rather it suggests a strategy of diversification towards a broader mixture that includes public health/epidemiology and general science journals in addition to traditional demographic journals.

Although I lack data to back this up, I suspect that this is a general trend within the field, and to ignore mortality research outside Population Studies nowadays would be to ignore key developments in the field—theoretical, empirical, and methodological.

Discussion

The content described in this paper has demonstrated the substantial growth and diversification in both the theoretical and methodological approaches taken within the field of mortality research over the past 25 years.

When first asked to review how the field of mortality has evolved over the past 25 years, my immediate thought was about the enormous technological change since 1996. We couldn’t possibly discuss developments in the field without first describing the profound shifts in the way we collect and analyse empirical data. Perhaps, I thought, there has never been another 25-year period where
studies that are routinely performed today would have been unthinkable 25 years earlier. Then I read the paper by Eileen Crimmins (1993), which came to the same conclusion 28 years ago, describing changes in the field of demography that had taken place over the previous 30 years:

Because almost all areas of demography rest on empirical work, changes in demographic analysis over the past 30 years have been related closely to changes in the technology available for information processing; this factor has been largely exogenous, and probably was unpredictable by demographers looking toward the future 30 years ago. I address this topic first because it may have been the necessary condition that allowed many of the other major changes in the field to take place. (Crimmins 1993, p. 579)

The advent of the internet and the enormous increases in computational power transformed what was possible in terms of access to research and complex estimation. A detailed overview of the technological developments that have enabled both discovery and explanation of demographic patterns can be found in the accompanying paper by Kashyap (2021). Alongside these technological changes came the digitization and sharing of data. Increasingly we are moving towards open science: open data sets, reproducible results, and code sharing, all of which are healthy developments for the field.

Since 1996 the availability of numerous online harmonized data sets has allowed researchers to compare phenomena across multiple populations, strengthening our evidence base and informing our demographic models. Population registers and alternative administrative data sources have also opened up the possibility of exploring new research questions that were previously underpowered from survey data. These have been exploited to great length in this journal and in the field more generally.

This wealth of data has no doubt been fantastic for testing theories. But it might also have come at a price. With data-rich environments capturing key and not-so-key aspects of the life course, we are increasingly able to answer more detailed questions of less importance. This is not a problem unique to demography but has been remarked on more generally in the social sciences. As we seek answers to hundreds of questions, it becomes easy to be overloaded with less consequential information, losing sight of the broad, more consequential patterns that defined early demographic enquiry.

Moreover, what we are learning about mortality risk is not always being adequately translated into its population-level impacts. For example, excellent studies have emerged showing the impact of divorce, of differences in childbearing, and of extra years of education on individual-level mortality risks. We know that there have been major compositional changes in the population on all of these counts. In a field that venerates Evelyn Kitagawa for instigating a line of scholarship devoted to quantifying the impact of compositional change on demographic rates (Kitagawa 1955), why is it that we so rarely combine estimates of the changes in both mortality risk and population structure to say something about population-level differences in mortality? For example, how much of the pace of life expectancy increase is driven by educational expansion, and how does this differ across time and populations? Which changes in family arrangements (i.e. living arrangements, parity, etc.) have been most important to longevity increases, given the combined impact of mortality risk and shifting family composition? Can some of these major compositional changes tell us why the US and United Kingdom are experiencing recent slowdowns in life expectancy improvement, whereas other European and East Asian populations are experiencing sustained increases?

The primary challenge in aggregating individual-level effects to the population level is how to account for contextual differences. Kravdal (2004) made this argument in assessing the importance of educational expansion on child mortality levels in India. In the context of educational expansion, there are two important mechanisms that link higher levels of education with lower child mortality. The first is compositional change. The shift to a higher proportion of children born to more highly educated women would lower child mortality overall. The second is the contextual change that may come about from educational expansion. At the community level, having a more highly educated population could be expected to confer benefits even to those who remain at lower levels of education. There are no easy answers here, but this remains an important challenge to consider in the years ahead if we are to keep our eyes on the broader picture.

Increasingly there has also been a move towards understanding the causal processes shaping mortality. This is healthy. But it might also be dangerous if we do not fully grasp the role played by context. For example, few continue to argue against the premise that additional education confers wide-ranging advantages that are protective against...
mortality. But the question remains of how embedded the effect size of any causal estimate of education’s effect on mortality is in the particular population and time period under study. In a special issue of *Social Science & Medicine*, Montez and Friedman (2015) curated a series of papers seeking to rephrase the question of whether education was causally related to health to an understanding of under what conditions education was causally related to health. This same rephrasing should be used in any hypothesis testing of mortality risks and determinants.

In an ideal world, we would be able to quantify how these causal estimates are operating across time and populations in a comparable way. But many causal techniques rely on unusual and specific events to identify causal relationships. Returning to the example of education and mortality, researchers have often exploited policy changes that increased the years of mandatory schooling to estimate how the extra schooling impacted individuals affected by the policy change compared with those born a few months earlier who were not exposed to the new policy (Lleras-Muney 2005; Lager and Torssander 2012; Gathmann et al. 2015; Andriano and Monden 2019). Such policy changes do not come about at regular intervals and differ in timing across populations, hampering our ability to test whether these relationships are stable across different conditions.

Until we can be confident that context is not impacting our causal estimates of risk factors, a healthy dose of scepticism is warranted towards studies that incorporate such risk factors into mortality models, particularly those that extrapolate mortality patterns into a distant future or across widely different contexts. For example, the Global Burden of Disease forecasting methods incorporate relationships between risk factors and health outcomes estimated in epidemiological studies for 79 drivers of health to model and forecast 250 causes of death in 195 countries of the world (Foreman et al. 2018). This assumes that the effect sizes of the risk factors estimated from selected contemporary populations are useful in modelling different future populations. When coupled with a complex modelling strategy, it becomes enormously challenging to unpack the key drivers of the modelled aggregate mortality patterns across populations (Gietel-Basten and Sobotka 2021; Mathers 2020).

The alternative is to return to classic descriptive models—essentially extrapolation methods. Wilmoth’s (1998) paper provided ‘A demographer’s perspective’ against criticism that extrapolative forecasts of all-cause mortality are inferior because they ignore the underlying mechanisms of mortality decline. As he put it (p. 395), ‘this critique is valid only insofar as such mechanisms are understood with sufficient precision to offer a legitimate alternative method of prediction’. More than 20 years later, many demographers, myself included, continue to share this view. If we are unable to assume confidently that the same causal relationship would apply, had it impacted cohorts born a decade earlier or later, the question remains of whether this line of research will really deepen our understanding of mortality trends and differentials and aid in mortality modelling. Moreover, if effect sizes vary across cohorts and change in unpredictable ways, do these estimates really improve our understanding of aggregate mortality patterns compared with simpler demographic description and modelling? Causal inference is certainly an exciting field that is yielding new insights and hypotheses, with direct policy relevance. The challenge for demographers moving forward will be to understand the opportunities and limitations that these causal estimates can provide for mortality modelling more generally.

**Conclusion**

In summary, this review has found a field rich in data, methods, and theories that are often looking to address very specific questions or populations. We demographers have been less successful at integrating these theories into our broadest descriptions of mortality change and differentials at the population level. Compared with 25 years ago, are we in any better position to say why Japan’s life expectancy is the highest in the world and the US is falling further and further behind? We can offer up a host of competing explanations—mortality selection, health behaviours, healthcare, the built environment, socio-economic inequalities, etc.—but have been less successful in ranking these determinants in terms of their importance. Given the complex interrelationships between these explanations, we may never know. But our disciplinary strength has always been in our careful description of population-level changes. And we shouldn’t shy away from developing broad theories that are consistent with contemporary trends, predictive of future mortality patterns, and testable with mortality models.

**Notes and acknowledgements**

1 Please direct all correspondence to Alyson A. van Raalte, Max Planck Institute for Demographic
Research, Konrad-Zuse Str. 1, Rostock 18057, Germany; or by Email: vanraalte@demogr.mpg.de

2 Funding: This work was supported by the European Research Council [grant number 716323].

3 I thank my past and present colleagues at the Max Planck Institute for Demographic Research for enriching discussions on the field of mortality research. I also thank Wendy Sigle, Ronald Skeldon, and the two reviewers for their wonderful suggestions to improve the manuscript.

References

Aburto, José Manuel, Jesús-Adrián Alvarez, Francisco Villavicencio, and James W. Vaupel. 2019. The threshold age of the lifetable entropy, *Demographic Research* 41: 83–102. doi:10.4054/DemRes.2019.41.4

Aburto, José Manuel, Francisco Villavicencio, Ugofilippo Basellini, Søren Kjærgaard, and James W. Vaupel. 2020. Dynamics of life expectancy and life span equality, *Proceedings of the National Academy of Sciences* 117(10): 5250–5259. doi:10.1073/pnas.1915884117

Acosta, Enrique, Stacey A. Hallman, Lisa Y. Dillon, Nadine Ouellette, Robert Bourbeau, D. Ann Herring, Kris Inwood et al. 2019. Determinants of influenza mortality trends: Age-period-cohort analysis of influenza mortality in the United States, 1959–2016, *Demography* 56(5): 1723–1746. doi:10.1007/s13524-019-00809-y

Alexander, Monica, Emilio Zagheni, and Magali Barbieri. 2017. A flexible Bayesian model for estimating subnational mortality, *Demography* 54(6): 2025–2041. doi:10.1007/s13524-017-0618-7

Alfani, Guido, and Marco Bonetti. 2019. A survival analysis of the last great European plagues: The case of Nonantola (northern Italy) in 1630, *Population Studies* 73(1): 101–118. doi:10.1080/00324728.2018.1457794

Alkema, Leontine, Doris Chou, Daniel Hogan, Sanqian Zhang, Ann-Beth Moller, Alison Gemmill, Doris Ma Fat et al. 2016. Global, regional, and national levels and trends in maternal mortality between 1990 and 2015, with scenario-based projections to 2030: A systematic analysis by the UN maternal mortality estimation inter-agency group, *The Lancet* 387(10017): 462–474. doi:10.1016/S0140-6736(15)00838-7

Alvarez, Jesús-Adrián, José Manuel Aburto, and Vladimir Canudas-Romo. 2020. Latin American convergence and divergence towards the mortality profiles of developed countries, *Population Studies* 74(1): 75–92. doi:10.1080/00324728.2019.1614651

Andersen, Per Kragh, Vladimir Canudas-Romo, and Niels Keiding. 2013. Cause-specific measures of life years lost, *Demographic Research* 29: 1127–1152. doi:10.4054/DemRes.2013.29.41

Andreev, Evgenii M. 1982. Metod komponent v analize prodoljitelnosti zizni [The method of components in the analysis of length of life], *Vestnik Statistiki* 9: 42–47.

Andreev, Evgenii M., Vladimir M. Shkolnikov, and Alexander Z. Begun. 2002. Algorithm for decomposition of differences between aggregate demographic measures and its application to life expectancies, healthy life expectancies, parity-progression ratios and total fertility rates, *Demographic Research* 7: 499–522. doi:10.4054/DemRes.2002.7.14

Andriano, Liliana, and Christiana W. S. Monden. 2019. The causal effect of maternal education on child mortality: Evidence from a quasi-experiment in Malawi and Uganda, *Demography* 56(5): 1765–1790. doi:10.1007/s13524-019-00812-3

Antonovsky, Aaron. 1967. Social class, life expectancy and overall mortality, *Milbank Memorial Fund Quarterly* 45 (2): 31–73. doi:10.2307/3348839

Arnold, Fred, Minja Kim Choe, and Tarun K. Roy. 1998. Son preference, the family-building process and child mortality in India, *Population Studies* 52(3): 301–315. doi:10.1080/0032472031000150486

Arriaga, Eduardo E. 1984. Measuring and explaining the change in life expectancies, *Demography* 21(1): 83–96. doi:10.2307/2061029

Avendano, Mauricio, M. Maria Glymour, James Banks, and Johan P. Mackenbach. 2009. Health disadvantage in US adults aged 50 to 74 years: A comparison of the health of rich and poor Americans with that of Europeans, *American Journal of Public Health* 99(3): 540–548. doi:10.2105/AJPH.2008.139469

Babiarz, Kimberly Singer, Karen Eggleston, Grant Miller, and Qiong Zhang. 2015. An exploration of China’s mortality decline under Mao: A provincial analysis, 1950–80, *Population Studies* 69(1): 39–56. doi:10.1080/00324728.2014.972432

Bahk, Jinwook, John W. Lynch, and Young-Ho Kang. 2017. Forty years of economic growth and plummeting mortality: The mortality experience of the poorly educated in South Korea, *Journal of Epidemiology and Community Health* 71(3): 282–288. doi:10.1136/jech-2016-207707

Barbi, Elisabetta, Francesco Lagona, Marco Marsili, James W. Vaupel, and Kenneth W. Wachter. 2018. The plateau of human mortality: Demography of longevity pioneers, *Science* 360(6396): 1459–1461. doi:10.1126/science.aat3119

Barbieri, Magali, John R. Wilmoth, Vladimir M. Shkolnikov, Dana Glei, Domantas Jasilionis, Dmitri Idanov, Carl Boe et al. 2015. Data resource profile: The Human Mortality Database (HMD), *International Journal of Epidemiology* 44(5): 1549–1556. doi:10.1093/ije/dyv105
Barclay, Kieron, and Mikko Myrskylä. 2018. Parental age and offspring mortality: Negative effects of reproductive ageing may be counterbalanced by secular increases in longevity, Population Studies 72(2): 157–173. doi:10.1080/00324728.2017.1411969

Barker, David J. P. 1995. Fetal origins of coronary heart disease, BMJ 311(6998): 171–174. doi:10.1136/bmj.311.6998.171

Basellini, Ugofilippo, and Carlo Giovanni Camarda. 2019. Modelling and forecasting adult age-at-death distributions, Population Studies 73(1): 119–138. doi:10.1080/00324728.2018.1545918

Basellini, Ugofilippo, Søren Kjærgaard, and Carlo Giovanni Camarda. 2020. An age-at-death distribution approach to forecast cohort mortality, Insurance: Mathematics and Economics 91: 129–143. doi:10.1016/j.ijsmteco.2020.01.007

Beltrán-Sánchez, Hiram, Samuel H. Preston, and Vladimir Canudas-Romo. 2008. An integrated approach to cause-of-death analysis: Cause-deleted life tables and decompositions of life expectancy, Demographic Research 19: 1323–1350. doi:10.4054/DemRes.2008.19.35

Bergeron-Boucher, Marie-Pier, José Manuel Aburto, and Alyson van Raalte. 2020. Diversification in causes of death in low-mortality countries: Emerging patterns and implications, BMJ Global Health 5(7): e002414. doi:10.1136/bmjgh-2020-002414

Bergeron-Boucher, Marie-Pier, Vladimir Canudas-Romo, Jim Oeppen, and James W. Vaupel. 2017. Coherent forecasts of mortality with compositional data analysis, Demographic Research 37: 527–566. doi:10.4054/DemRes.2017.37.17

Bergeron-Boucher, Marie-Pier, Søren Kjærgaard, Jim Oeppen, and James W. Vaupel. 2019. The impact of the choice of life table statistics when forecasting mortality, Demographic Research 41: 1235–1268. doi:10.4054/DemRes.2019.41.43

Bijwaard, Govert E., Per Tynelius, and Mikko Myrskylä. 2019. Education, cognitive ability, and cause-specific mortality: A structural approach, Population Studies 73(2): 217–232. doi:10.1080/00324728.2018.1493135

Blacker, John. 2004. The impact of AIDS on adult mortality: Evidence from national and regional statistics, AIDS 18: S19–S26. doi:10.1097/00002030-200406002-00003

Bloom, David E., and David Canning. 2000. The health and wealth of nations, Science 287(5456): 1207–1209. doi:10.1126/science.287.5456.1207

Bloom, David E., and David Canning. 2007. Commentary: The Preston curve 30 years on: Still sparking fires, International Journal of Epidemiology 36(3): 498–499. doi:10.1093/ije/dym079

Boardman, Jason D., Benjamin W. Domingue, Casey L. Blalock, Brett C. Haberstick, Kathleen Mullan Harris, and Matthew B. McQueen. 2014. Is the gene-environment interaction paradigm relevant to genome-wide studies? The case of education and body mass index, Demography 51(1): 119–139. doi:10.1007/s13524-014-0259-4

Bongaarts, John. 2005. Long-range trends in adult mortality: Models and projection methods, Demography 42(1): 23–49. doi:10.1353/dem.2005.0003

Bongaarts, John. 2009. Trends in senescent life expectancy, Population Studies 63(3): 203–213. doi:10.1080/00324720903165456

Bongaarts, John. 2014. Trends in causes of death in low-mortality countries: Implications for mortality projections, Population and Development Review 40(2): 189–212. doi:10.1111/j.1728-4457.2014.00670.x

Bongaarts, John P., François Pelletier, and Patrick Gerland. 2011. Global trends in AIDS mortality, in R. G. Rogers and E. M. Crimmins (eds), International Handbook of Adult Mortality. Dordrecht: Springer Netherlands, pp. 171–183.

Booth, Heather, Rob J. Hyndman, Leonie Tickle, and Piet De Jong. 2006. Lee-Carter mortality forecasting: A multi-country comparison of variants and extensions, Demographic Research 15: 289–310. doi:10.4054/DemRes.2006.15.9

Booth, Heather, John Maindonald, and Len Smith. 2002. Applying Lee-Carter under conditions of variable mortality decline, Population Studies 56(3): 325–336. doi:10.1080/00324720215935

Bourbeau, Robert, and André Lebel. 2000. Mortality statistics for the oldest-old: An evaluation of Canadian data, Demographic Research 2(2). doi:10.4054/DemRes.2000.2.2

Brass, William. 1971. On the scale of mortality, in W. Brass (ed.), Biological Aspects of Demography. London: Taylor & Francis, pp. 69–110.

Brass, William. 1996. Demographic data analysis in less developed countries: 1946–1996, Population Studies 50(3): 451–467. doi:10.1080/0032472031000149566

Bremer, M. Harvey. 1979. Mortality and the national economy: A review, and the experience of England and Wales, 1936–76, The Lancet 314(8142): 568–573. doi:10.1016/S0140-6736(79)91626-X

Brønnum-Hansen, Henrik. 2017. Socially disparate trends in lifespan variation: A trend study on income and mortality based on nationwide Danish register data, BMJ Open 7(5): e014489. doi:10.1136/bmjopen-2016-014489

Burger, Oskar, Annette Baudisch, and James W. Vaupel. 2012. Human mortality improvement in evolutionary context, Proceedings of the National Academy of Sciences 109(44): 18210–18214. doi:10.1073/pnas.1215627109
Camarda, Carlo Giovanni, Linh Hoang Khanh Dang, France Meslé, Jean-Marie Robine, and Jacques Vallin. 2019. Re: Premature claim of a plateau of human mortality: The role of sample size. eLetter Science. Available: https://science.sciencemag.org/content/360/6396/1459/tab-e-letters.

Canudas-Romo, Vladimir. 2008. The modal age at death and the shifting mortality hypothesis. Demographic Research 19(30): 1179–1204. doi:10.4054/DemRes.2008.19.30

Canudas-Romo, Vladimir. 2010. Three measures of longevity: Time trends and record values, Demography 47(2): 299–312. doi:10.1353/dem.0.0098

Canudas-Romo, Vladimir, and José Manuel Aburto. 2019. Truncated cross-sectional average length of life: A measure for comparing the mortality history of cohorts, Population Studies 69(2): 147–159. doi:10.1080/00324728.2015.1019955

Case, Anne, and Angus Deaton. 2015. Rising morbidity and mortality in midlife among white non-Hispanic Americans in the 21st century, Proceedings of the National Academy of Sciences 112(49): 15078–15083. doi:10.1073/pnas.1518393112

Caswell, Hal. 1996. Demography meets ecotoxicology: Untangling the population level effects of toxic substances, in M. C. Newman and C. H. Jagoe (eds), Ecotoxicology: A Hierarchical Treatment. Chelsea, MI: CRC/Lewis Press, Inc., pp. 255–292.

Chandra, Siddharth. 2015. Mortality from the influenza pandemic of 1918–19 in Indonesia, Population Studies 67(2): 185–193. doi:10.1080/00324728.2012.754886

Chapoto, Antony, Lilian Kirimi, and Sunetha Kadiyala. 2012. Poverty and prime-age mortality in Eastern and Southern Africa: Evidence from Zambia and Kenya, World Development 40(9): 1839–1853. doi:10.1016/j.worlddev.2012.04.022

Cheung, Siu Lan Karen, and Jean-Marie Robine. 2007. Increase in common longevity and the compression of mortality: The case of Japan, Population Studies 61(1): 85–97. doi:10.1080/00324720601103833

Cheung, Siu Lan Karen, Jean-Marie Robine, Edward Jow-Ching Tu, and Graziella Caselli. 2005. Three dimensions of the survival curve: Horizontalization, verticalization, and longevity extension, Demography 42(2): 243–258. doi:10.1353/dem.2005.0012

Christensen, Kaare, Thomas E. Johnson, and James W. Vaupel. 2006. The quest for genetic determinants of human longevity: Challenges and insights, Nature Reviews Genetics 7(6): 436–448. doi:10.1038/nrg1871

Clark, Samuel J. 2019. A general age-specific mortality model with an example indexed by child mortality or both child and adult mortality, Demography 56(3): 1131–1159. doi:10.1007/s13524-019-00785-3

Cleland, John, George Bicego, and Greg Fegan. 1992. Socioeconomic inequalities in childhood mortality: The 1970s to the 1980s, Health Transition Review 2(1): 1–18. doi:1885/41512/2

Coale, Ansley J., Paul Demeny, and Barbara Vaughan. 1983. Regional Model Life Tables and Stable Populations (Second edition). London: Academic Press.

Coale, Ansley, and James Trussell. 1996. The development and use of demographic models, Population Studies 50(3): 469–484. doi:10.1080/0032472031000149576

Corder, Elizabeth H., Lars Lannfelt, Matti Viitanen, Larry S. Corder, Kenneth G. Manton, Bengt Winblad, and Hans Basun. 1996. Apolipoprotein E genotype determines survival in the oldest old (85 years or older) who have good cognition, Archives of Neurology 53(5): 418–422. doi:10.1001/archneur.1996.00550050048022

Crimmins, Eileen M. 1993. Demography: The past 30 years, the present, and the future, Demography 30(4): 579–591. doi:10.2307/2061807

Crimmins, Eileen, Jung Ki Kim, and Sarinnapha Vasunilashorn. 2010. Biodemography: New approaches to understanding trends and differences in population health and mortality, Demography 47(1): S41–S64. doi:10.1353/dem.2010.0005

Crimmins, Eileen M., and Teresa E. Seeman. 2004. Integrating biology into the study of health disparities, Population and Development Review 30: 89–107.

Crimmins, Eileen M., and Sarinnapha Vasunilashorn. 2011. Links between biomarkers and mortality, in R. G. Rogers and E. M. Crimmins (eds), International Handbook of Adult Mortality. Dordrecht: Springer Netherlands, pp. 381–398.

Cutler, David, Angus Deaton, and Adriana Lleras-Muney. 2006. The determinants of mortality, Journal of Economic Perspectives 20(3): 97–120. doi:10.1257/jep.20.3.97

Cutler, David M., and Grant Miller. 2005. The role of public health improvements in health advances: The twentieth-century United States, Demography 42(1): 1–22. doi:10.1353/dem.2005.0002

Deaton, Angus. 2013. The Great Escape: Health, Wealth, and the Origins of Inequality. Princeton and Oxford: Princeton University Press.

de Beer, Joop. 2012. Smoothing and projecting age-specific probabilities of death by TOPALS, Demographic Research 27: 543–592. doi:10.4054/DemRes.2012.27.20

De Jong, Piet, and Leonie Tickle. 2006. Extending Lee–Carter mortality forecasting, Mathematical Population Studies 13(1): 1–18. doi:10.1080/08898480500452109
Mortality patterns over the past 25 years

Delwarde, Antoine, Michel Denuit, and Paul Eilers. 2007. Smoothing the Lee–Carter and Poisson log-bilinear models for mortality forecasting: A penalized log-likelihood approach, *Statistical Modelling* 7(1): 29–48. doi:10.1177/1471082X0700700103

DeRose, Laurie F., Andrés Salazar-Arango, Paúl Córceua García, Montserrat Gas-Aixendri, and Reynaldo Rivera. 2017. Maternal union instability and childhood mortality risk in the global south, 2010–14, *Population Studies* 71(2): 211–228. doi:10.1080/00324728.2017.1316866

Diacou, Viorela, Nadine Ouellette, Carlo G. Camarda, and Robert Bourbeau. 2016. Insight on ‘typical’ longevity: An analysis of the modal lifespan by leading causes of death in Canada, *Demographic Research* 35: 471–504. doi:10.4054/DemRes.2016.35.17

Doblhammer, Gabriele. 2000. Reproductive history and mortality later in life: A comparative study of England and Wales and Austria, *Population Studies* 54 (2): 169–176. doi:10.1080/713779087

Doblhammer, Gabriele. 2004. *The Late Life Legacy of Very Early Life*. Berlin: Springer.

Doblhammer, Gabriele, and James W. Vaupel. 2001. Lifespan depends on month of birth, *Proceedings of the National Academy of Sciences* 98(5): 2934–2939. doi:10.1073/pnas.041431898

Dorling, Danny, Mary Shaw, and George Davey Smith. 2006. Global inequality of life expectancy due to infection, health, and socioeconomic status in US children, *Social Science & Medicine* 68(4): 699–707. doi:10.1016/j.socscimed.2005.09.032

Ebeling, Marcus, Roland Rau, and Annette Baudisch. 2008. Separating the signal from the noise: Evidence for deceleration in old-age death rates, *Demography* 55(6): 2025–2044. doi:10.1007/s13524-018-0728-x

Engelman, Michal, Vladimir Canudas-Romo, and Emily M. Agree. 2010. The implications of increased survivorship for mortality variation in aging populations, *Population and Development Review* 36(3): 511–539. doi:10.1111/j.1728-4457.2010.00344.x

Feehan, Dennis M. 2018. Inflammatory exposure and historical changes in human life-spans, *Science* 305(5691): 1736–1739. doi:10.1126/science.1092556

Finch, Caleb E., and Eileen M. Crimmins. 2004. Long-term effects of childhood bearing on mortality: Evidence from pre-industrial Sweden, *Population Studies* 58(3): 297–310. doi:10.1080/0032472042000272357

Firebaugh, Glenn, Francesco Acciai, Aggie J. Noah, Christopher Prather, and Claudia Nau. 2014. Why life-spans are more variable among blacks than among whites in the United States, *Demography* 51(6): 2025–2045. doi:10.1177/0032472014541632

Flegel, Katherine M., Brian K. Kit, Heather Orpana, and Barry I. Graubard. 2013. Association of all-cause mortality with overweight and obesity using standard body mass index categories: A systematic review and meta-analysis, *JAMA* 309(1): 71–82. doi:10.1001/jama.2012.113905

Fogel, Robert W. 1994. Nutrition and the decline in mortality since 1700: Some preliminary findings, *Quarterly Journal of Economics* 109(2): 293–328. Available at SSRN: http://ssrn.com/abstract=2545881.

Fogel, Robert W. 2001. *The Escape from Hunger and Premature Death, 1700–2100: Europe, America, and the Third World*. Cambridge: Cambridge University Press.

Fogel, Robert W., and Dora L. Costa. 1997. A theory of technophysio evolution, with some implications for forecasting population, health care costs, and
Harris, Bernard. 2004. Public health, nutrition, and the decline of mortality: The McKeown thesis revisited, *Social History of Medicine* 17(3): 379–407. doi:10.1093/shm/17.3.379

Hayward, Mark D., and Bridget K. Gorman. 2004. The long arm of childhood: The influence of early-life social conditions on men’s mortality, *Demography* 41(1): 87–107. doi:10.1353/dem.2004.0005

Herskind, Anne, Matthew McGue, Niels Holm, Thorkild Sørensen, Bent Harvald, and James Vaupel. 1996. The heritability of human longevity: A population-based study of 2872 Danish twin pairs born 1870–1900, *Human Genetics* 97(3): 319–323. doi:10.1007/BF02185763

Heuveline, Patrick. 2015. The boundaries of genocide: Quantifying the uncertainty of the death toll during the Pol Pot regime in Cambodia (1975–79), *Population Studies* 69(2): 201–218. doi:10.1080/00324728.2015.1045546

Heuveline Patrick, and Samuel J. Clark. 2011. Model schedules of mortality, in R. G. Rogers and E. M. Crimmins (eds), *International Handbook of Adult Mortality*. Dordrecht: Springer Netherlands, pp. 511–532.

Hill, Mark E., Samuel H. Preston, and Ira Rosenwaike. 2000. Age reporting among White Americans aged 85+: Results of a record linkage study, *Demography* 37(2): 175–186. doi:10.2307/2648119

Horiuchi, Shiro, Nadine Ouellette, Siu Lan Karen Cheung, and Jean-Marie Robine. 2013. Modal age at death: Lifespan indicator in the era of longevity extension, *Vienna Yearbook of Population Research* 11: 37–69.

Horiuchi, Shiro, and John Wilmoth. 1995. *Aging of mortality decline*. Paper presented at the Annual Meeting of the Population Association of the United States, San Francisco California, April 6–8, 1995.

Horiuchi, Shiro, and John R. Wilmoth. 1998. Deceleration in the age pattern of mortality at older ages, *Demography* 35(4): 391–412. doi:10.2307/3004009

Horiuchi, Shiro, John R. Wilmoth, and Scott D. Fletcher. 2008. A decomposition method based on a model of continuous change, *Demography* 45(4): 785–801. doi:10.1353/dem.0.0033

Hosegood, Victoria, Anna-Maria Vanneste, and Ian M. Timaeus. 2004. Levels and causes of adult mortality in rural South Africa: The impact of AIDS, *AIDS* 18(4): 663–671. doi:10.1097/00002030-200403050-00011

Hu, Yannan, Frank J. van Lenthe, and Johan P. Mackenbach. 2015. Income inequality, life expectancy and cause-specific mortality in 43 European countries, 1987-2008: A fixed effects study, *European Journal of Epidemiology* 30(8): 615–625. doi:10.1007/s10654-015-0066-x

Hug, Lucia, Monica Alexander, Danzhen You, and Leontine Alkema, and UN Inter-agency Group for Child. 2019. National, regional, and global levels and trends in neonatal mortality between 1990 and 2017, with scenario-based projections to 2030: A systematic analysis, *The Lancet Global Health* 7(6): e710–e720. doi:10.1016/S2214-109X(19)30163-9

Hurt, Lisa S., Carine Ronstarps, and Suzanne L. Thomas, 2006. The effect of number of births on women’s mortality: Systematic review of the evidence for women who have completed their childbearing, *Population Studies* 60(1): 55–71. doi:10.1080/00324720500436011

Jagger, Carol, Eileen M. Crimmins, Yasuhiko Saito, Renata Tiene De Carvalho Yokota, Herman Van Oyen, and Jean-Marie Robine. 2020. *International Handbook of Health Expectancies*. Springer. doi:10.1007/978-3-030-37668-0

Janssen, Fanny, Leo J. G. van Wissen, and Anton E. Kunst. 2013. Including the smoking epidemic in internationally coherent mortality projections, *Demography* 50(4): 1341–1362. doi:10.1007/s13524-012-0185-x

Johnson, Thomas E., Edouard de Castro, Sarah Hegi de Castro, James Cypser, Sam Henderson, and Pat Tedesco. 2001. Relationship between increased longevity and stress resistance as assessed through gerontogene mutations in caenorhabditis elegans, *Experimental Gerontology* 36(10): 1609–1617. doi:10.1016/S0535-5565(01)00144-9

Kannisto, V. 1996. *The Advancing Frontier of Survival: Life Tables for Old Age*. Monographs on Population Aging 3. Odense: Odense University Press.

Kannisto, Vaino. 2001. Mode and dispersion of the length of life, *Population* 13(1): 159–171.

Kannisto, Vaino, Jens Lauritsen, A. Roger Thatcher, and James W. Vaupel. 1994. Reductions in mortality at advanced ages: Several decades of evidence from 27 countries, *Population and Development Review* 20(4): 793–810. doi:10.2307/2137662

Kashyap, Ridhi. 2021. Has demography witnessed a data revolution? Promises and pitfalls of a changing data ecosystem, *Population Studies* 75(S1). doi:10.1080/00324728.2021.1969031

Kerber, Richard A., Elizabeth O'Brien, Ken R. Smith, and Richard M. Cawthon. 2001. Familial excess longevity in humans, *Demography* 38(4): 923–945. doi:10.2307/1360305

Kitagawa, Evelyn M. 1955. Components of a difference between two rates, *The Journals of Gerontology Series B* 10(1): 87. doi:10.1093/gerona/56.3.B130

Kitagawa, Evelyn M., and Philip M. Hauser. 1968. Education differentials in mortality by cause of death:
United States, 1960, *Demography* 5(1): 318–353. doi:10.1007/BF00320857

Kravdal, Øystein. 2004. Child mortality in India: The community-level effect of education, *Population Studies* 58 (2): 177–192. doi:10.1007/s0023802400021372

Kravdal, Øystein. 2018. New evidence about effects of reproductive variables on child mortality in sub-Saharan Africa, *Population Studies* 72(2): 139–156. doi:10.1007/s00238-018-1439180

Kunst, Anton E., and Johan P. Mackenbach. 1994. The size of mortality differences associated with educational level in nine industrialized countries, *American Journal of Public Health* 84(6): 932–937. doi:10.2105/AJPH.84.6.932

Li, Ting, and James J. Anderson. 2015. The Strehler–Mildvan correlation from the perspective of a two-process vitality model, *Demography* 52(2): 177–192. doi:10.1007/s13524-013-0232-2

Link, Bruce G., and Jo Phelan. 1995. Social conditions as fundamental causes of disease, *Journal of Health and Social Behavior* 35: 80–94. doi:10.2307/2626958

Lleras-Muney, Adriana. 2005. The relationship between education and adult mortality in the United States, *The Review of Economic Studies* 72(1): 189–221. doi:10.1111/0034-6527.00329

Lopez, Alan D., Omar B. Ahmad, Michel Guillot, Mie Inoue, Brodie D. Ferguson, Joshua A. Salomon, Christopher J. L. Murray et al. 2002. *World Mortality in 2000: Life Tables for 191 Countries*. Geneva: World Health Organization.

Luo, Weixiang, and Yu Xie. 2014. Socio-economic disparities in mortality among the elderly in China, *Population Studies* 68(3): 305–320. doi:10.1080/00324728.2014.934908

Lusyne, Patrick, Hilary Page, and John Lievens. 2001. Mortality following conjugal bereavement, Belgium 1991-96: The unexpected effect of education, *Population Studies* 55(3): 281–289. doi:10.1080/0032472420172701

Lutz, Wolfgang, and Endale Kebede. 2018. Education and health: Redrawing the Preston curve, *Population and Development Review* 44(2): 343–361. doi:10.1111/padr.12141

Luy, Marc, Paola Di Giulio, and Graziella Caselli. 2011. Differences in life expectancy by education and occupation in Italy, 1980-94: Indirect estimates from maternal and paternal orphanhood, *Population Studies* 65(2): 137–155. doi:10.1080/00324728.2011.568192

Lynch, Scott, and J. Brown. 2001. Reconsidering mortality compression and deceleration: An alternative model of mortality rates, *Demography* 38(1): 79–95. doi:10.1353/dem.2001.0007

Lynch, J., G. D. Smith, S. Harper, M. Hillemeier, N. Ross, G. A. Kaplan, and M. Wolfson. 2004. Is income inequality a determinant of population health? Part 1. A systematic review, *Milbank Quarterly* 82(1): 5–99. doi:10.1111/j.0887-378X.2004.00302.x

Mackenbach, Johan P. 2017. Persistence of social inequalities in modern welfare states: Explanation of a paradox, *Scandinavian Journal of Public Health* 45(2): 113–120. doi:10.1177/1403494816683878

Mackenbach, Johan P., Irina Stirbu, Albert-Jan R. Roskam, Maartje M. Schaap, Gwenn Menvielle, Mall Leinsalu, Anton E. Kunst, and the European Union Working Group on Socioeconomic Inequalities in Health. 2008. Socioeconomic inequalities in health in 22 European countries, *New England Journal of Medicine* 358(23): 2468–2481. doi:10.1056/NEJMsa0707519

Maier, Heiner, Jutta Gampe, Bernard Jeune, Jean-Marie Robine, and James W. Vaupel. 2010. *Supercentenarians.*
Mortality patterns over the past 25 years

Demographic Research Monographs. Heidelberg: Springer.

Manton, Kenneth G., and James W. Vaupel. 1995. Survival after the age of 80 in the United States, Sweden, France, England, and Japan, New England Journal of Medicine 333(18): 1232–1235. doi:10.1056/NEJM199511023331824

Marmot, M. G., G. D. Smith, S. Stansfeld, C. Patel, F. North, J. Head, I. White et al. 1991. Health inequalities among British civil servants – the Whitehall II study, Lancet 337(8754): 1387–1393. doi:10.1016/0140-6736(91)93068-K

Marmot, Michael, and Richard G. Wilkinson. 2001. Psychosocial and material pathways in the relation between income and health: A response to Lynch et al, BMJ 322(7296): 1233–1236. doi:10.1136/bmj.322.7296.1233

Martikainen, Pekka T. 1990. Unemployment and mortality among Finnish men, 1981-5, BMJ 301(6749): 407–411. doi:10.1136/bmj.301.6749.407

Martikainen, Pekka, Tapani Valkonen, and Heta Moustgaard. 2009. The effects of individual taxable income, household taxable income, and household disposable income on mortality in Finland, 1998–2004, Population Studies 63(2): 147–162. doi:10.1080/00324720902938416

Masquelier, Bruno, Georges Reniers, and Gilles Pison. 2014. Divergences in trends in child and adult mortality in sub-Saharan Africa: Survey evidence on the survival of children and siblings, Population Studies 68(2): 161–177. doi:10.1080/00324728.2013.856458

Mathers, Colin D. 2020. History of global burden of disease assessment at the World Health Organization, Archives of Public Health 78(1): 1–13. doi:10.1186/s13690-019-0383-8

McGlynn, Elizabeth A., Steven M. Asch, John Adams, Joan Keesey, Jennifer Hicks, Alison DeCristofaro, and Eve A. Kerr. 2003. The quality of health care delivered to adults in the United States, New England Journal of Medicine 348(26): 2635–2645. doi:10.1056/NEJMsa022615

McGue, Matthew, James W. Vaupel, Niels Vilstrup Holm, and Bent Harvald. 1993. Longevity is moderately heritable in a sample of Danish twins born 1870-1880, The Journal of Gerontology 48(6): 237–244. doi:10.1093/geront/48.6.B237

McKeown, Thomas. 1976. The Modern Rise of Population. New York: Academic Press.

McKeown, Thomas, and R Graham Record. 1962. Reasons for the decline of mortality in England and Wales during the nineteenth century, Population Studies 16(2): 94–122. doi:10.1080/00324728.1962.10414870

Mehta, Neil K., Leah R. Abrams, and Mikko Myrskylä. 2020. US life expectancy stalls due to cardiovascular disease, not drug deaths, Proceedings of the National Academy of Sciences 117(13): 6998–7000. doi:10.1073/pnas.1920391117

Merdad, Leena, Kenneth Hill, and Michael Levin. 2016. Data on survival of recent births as a source of child mortality estimates in the developing world: An assessment of census data, Population Studies 70(3): 345–358. doi:10.1080/00324728.2016.1225786

Meslé, F. 1999. Classifying causes of death according to an aetiological axis, Population Studies 53: 97–105. doi:10.1080/003247203080871

Metsä-Simola, Niina, and Pekka Martikainen. 2013. The short-term and long-term effects of divorce on mortality risk in a large Finnish cohort, 1990–2003, Population Studies 67(1): 97–110. doi:10.1080/00324720.2012.746386

Mills, Melinda C., and Felix C. Tropf. 2020. Sociology, genetics, and the coming of age of sociogenomics, Annual Review of Sociology 46: 553–581. doi:10.1146/annurev-soc-121919-054756

Mokdad, Ali H., Mohammad Hossein Forouzanfar, Farah Daoud, Charbel El Bcheraoui, Maziar Moradi-Lakeh, Ibrahim Khalil, Ashkan Afshin et al. 2016. Health in times of uncertainty in the Eastern Mediterranean region, 1990–2013: A systematic analysis for the Global Burden of Disease study 2013, The Lancet Global Health 4(10): e704–e713. doi:10.1016/S2214-109X(16)30168-1

Montez, Jennifer Karas, Jason Beckfield, Julene Kemp Cooney, Jacob M. Grumbach, Mark D. Hayward, Huseyn Zeyd Koytak, Steven H. Woolf et al. 2020. US state policies, politics, and life expectancy, The Milbank Quarterly 98(3): 668–699. doi:10.1111/1468-0009.12469

Montez, Jennifer Karas, and Esther M. Friedman. 2015. Educational attainment and adult health: Under what conditions is the association causal? Social Science & Medicine 127: 1–7. doi:10.1016/j.socscimed.2014.12.029

Montez, Jennifer Karas, Anna Zajacova, Mark D. Hayward, Steven H. Woolf, Derek Chapman, and Jason Beckfield. 2019. Educational disparities in adult mortality across US states, The Milbank Quarterly 98(1): 1–34. doi:10.1111/1468-0009.12487

Muhuri, Pradip K., and Jane Menken. 1997. Adverse Mental Health Outcomes of the Conflict Pacific War Victims, and Their Offspring, Demographic Research Monographs. Heidelberg: Springer.

Mutter, Lisa, and Michael Zelnik. 2005. Fertility, child mortality, and long-term earnings in Jamaica, Demography 42(4): 717–747. doi:10.1353/dem.2005.0122

Murphy, Michael, Emily Grundy, and Stamatis Kalogirou. 2007. The increase in marital status differences in mortality up to the oldest age in seven European countries, 1990–99, Population Studies 61(3): 287–298. doi:10.1080/00324720701524466
Murphy, Michael, and Duolao Wang. 2001. Do previous birth interval and mother’s education influence infant survival? A Bayesian model averaging analysis of Chinese data, *Population Studies* 55(1): 37–47. doi:10.1080/00324720127679

Murray, Christopher J. L., Brodie D. Ferguson, Alan D. Lopez, Michel Guillot, Joshua A. Salomon, and Omar Ahmad. 2003. Modified logit life table system: Principles, empirical validation, and application, *Population Studies* 57(2): 165–182. doi:10.1080/0032472032000097083

Myrskylä, Mikko. 2010. The relative effects of shocks in early- and later-life conditions on mortality, *Population and Development Review* 36(4): 803–829. doi:10.1111/j.1728-4457.2010.00358.x

Myrskylä, M., A. Gagnon, and T. Bengtsson. 2014. Pathways to health and well-being, *Social Science & Medicine* 119: 175–179. doi:10.1016/j.socscimed.2014.09.031

Nepomuceno, Marília R., and Cássio M. Turra. 2020. The population of centenarians in Brazil: Historical estimates from 1900 to 2000, *Population and Development Review* 46(4): 813–833. doi:10.1111/padr.12355

Neumayer, Eric. 2004. Recessions lower (some) mortality rates: Evidence from *Social Science & Medicine* 58(6): 1037–1047. doi:10.1016/S0277-9536(03)00276-4

Newman, Saul Justin. 2018. Errors as a primary cause of late-life mortality deceleration and plateaus, *PLoS Biology* 16(12): e2006776. doi:10.1371/journal.pbio.2006776

Notkola, Veijo, Ian Timeus, and Harri Siiskonen. 2000. Mortality transition in the Ovamboland region of Namibia, 1930-1990, *Population Studies* 54(2): 153–167. doi:10.1080/713779086

Oeppen, Jim, and James W. Vaupel. 2002. Broken limits to life expectancy, *Science* 296(5570): 1029–1031. doi:10.1126/science.1069675

Olszansky, S. Jay, Bruce A. Carnes, and Aline Désesquelles. 2001. Prospects for human longevity, *Science* 291(5508): 1491–1492. doi:10.1126/science.291.5508.1491

Olszansky, S. Jay, Douglas J. Passaro, Ronald C. Hershow, Jennifer Layden, Bruce A. Carnes, Jacob Brody, Leonard Hayflick et al. 2005. A potential decline in life expectancy in the United States in the 21st century, *New England Journal of Medicine* 352(11): 1138–1145. doi:10.1056/NEJMsr043743

Omariba, D. Walter Rasugu, Edward Ng, and Bilkis Vissandjée. 2014. Differences between immigrants at various durations of residence and host population in all-cause mortality, Canada 1991–2006, *Population Studies* 68(3): 339–357. doi:10.1080/00324728.2014.915050

Ouellette, Nadine, and Robert Bourbeau. 2011. Changes in the age-at-death distribution in four low mortality countries: A nonparametric approach, *Demographic Research* 25(19): 595–628. doi:10.4054/DemRes.2011.25.19

Pampel, Fred C., Patrick M. Krueger, and Justin T. Denney. 2010. Socioeconomic disparities in health behaviors, *Annual Review of Sociology* 36(1): 349–370. doi:10.1146/annurev.soc.012809.102529

Pascariu, Marius D., Vladimir Canudas-Romo, and James W. Vaupel. 2018. The double-gap life expectancy forecasting model, *Insurance: Mathematics and Economics* 78: 339–350. doi:10.1016/j.insmatheco.2017.09.011

Pechholdová, Markéta, Carlo-Giovanni Camarda, France Meslé, and Jacques Vallin. 2017. Reconstructing long-term coherent cause-of-death series, a necessary step for analyzing trends, *European Journal of Population* 33(5): 629–650. doi:10.1007/s10680-017-9453-1

Peeters, Anna, Jan J. Barendregt, Frans Willekens, Johan P. Mackenbach, Abdullah Al Mamun, and Luc Bonneux. 2003. Obesity in adulthood and its consequences for life expectancy: A life-table analysis, *Annals of Internal Medicine* 138(1): 24–32. doi:10.7326/0003-4819-138-1-200301070-00008

Perls, Thomas T., John Wilmoth, Robin Levenson, Maureen Drinkwater, Melissa Cohen, Hazel Bogan, Erin Joyce et al. 2002. Life-long sustained mortality advantage of siblings of centenarians, *Proceedings of the National Academy of Sciences* 99(12): 8442–8447. doi:10.1073/pnas.122587599

Permanyer, Iñaki, Jeroen Spijker, Amand Blanes, and Elisenda Renteria. 2018. Longevity and lifespan variation by educational attainment in Spain: 1960–2015, *Demography* 55(6): 2045–2070. doi:10.1007/s13524-018-0718-z

Peto, R., A. D. Lopez, H. Pan, J. Boreham, and M. Thun. 2015. Mortality from smoking in developed countries 1950-2020. Available: https://gas.ctsu.ox.ac.uk/tobacco/.

Pickett, Kate E., and Richard G. Wilkinson. 2015. Income inequality and health: A causal review, *Social Science & Medicine* 128: 316–326. doi:10.1016/j.socscimed.2014.12.031

Pollard, John H. 1988. On the decomposition of changes in expectation of life and differentials in life expectancy, *Demography* 25: 265–276. doi:10.2307/2061293

Pressat, Roland. 1985. Contribution des écarts de mortalité par âge à la différence des vies moyennes (The contribution of differences in age-specific mortality to the difference in average lives), *Population* 40(4/5): 766–770. doi:10.2307/1532986
Preston, Samuel H. 1975. The changing relation between mortality and level of economic development, *Population Studies* 29(2): 231–248. doi:10.1080/00324728.1975.10410201

Preston, Samuel H. 1996. Population studies of mortality, *Population Studies* 50(3): 525–536. doi:10.1080/003247203100149596

Preston, Samuel H., and Irma T. Elo. 1999. Effects of age misreporting on mortality estimates at older ages, * Population Studies* 53(2): 165–177. doi:10.1080/0032472030808075

Preston, Samuel H., Dana A. Glei, and John R. Wilmoth. 2011. Contribution of smoking to international differences in life expectancy, in E. Crimmins, S. Preston, and B. Cohen, *International Differences in Mortality at Older Ages: Dimensions and Sources*. Washington, DC: The National Academy Press, pp. 105–131.

Preston, Samuel H., and Michael R. Haines. 1991. *Fatal Years: Child Mortality in Late Nineteenth-Century America*. Princeton: Princeton University Press.

Preston, Samuel H., Yana C. Vierboom, and Andrew Stokes. 2018. The role of obesity in exceptionally slow US mortality improvement, *Proceedings of the National Academy of Sciences* 115(5): 957–961. doi:10.1073/pnas.1716802115

Rahman, M. Omar. 1999. Family matters: The impact of kin on the mortality of the elderly in rural Bangladesh, *Population Studies* 53(2): 227–235. doi:10.1080/0032472030808080

Rau, Roland, Christina Bohk, Magdalena Muszyńska, and James W. Vaupel. 2013. Rates of mortality improvement on the Lexis surface. Visualizing age-, period- and cohort-effects, Paper presented at the Annual Population Association of America meeting, New Orleans, USA, April 11–13, 2013.

Rau, Roland, Christina Bohk-Ewald, Magdalena M. Muszyńska, and James W. Vaupel. 2018. Surface plots of rates of mortality improvement, in *Visualizing Mortality Dynamics in the Lexis Diagram*. Cham: Springer International Publishing, pp. 43–67.

Rau, Roland, and Carl P. Schmertmann. 2020. District-level life expectancy in Germany, *Deutsches Ärzteblatt International* 117(29-30): 493–499. doi:10.3238/arztebl.2020.0493

Rau, Roland, Eugeny Soroko, Domantas Jasilionis, and James W. Vaupel. 2008. Continued reductions in mortality at advanced ages, *Population and Development Review* 34(4): 747–768. doi:10.1111/j.1728-4457.2008.00249.x

Reher, David S., and Alberto Sanz-Gimeno. 2000. Mortality and economic development over the course of modernization: An analysis of short-run fluctuations in Spain, 1850–1990, *Population Studies* 54(2): 135–152. doi:10.1080/713779081

Renshaw, Arthur E., and Steven Haberman. 2003. Lee–Carter mortality forecasting with age-specific enhancement, *Insurance: Mathematics and Economics* 33(2): 255–272. doi:10.1016/S0167-6687(03)00138-0

Renshaw, Arthur E., and Steven Haberman. 2006. A cohort-based extension to the Lee–Carter model for mortality reduction factors, *Insurance: Mathematics and Economics* 38(3): 556–570. doi:10.1016/j.insmatheco.2005.12.001

Riley, James C. 2005. Estimates of regional and global life expectancy, 1800–2001, *Population and Development Review* 31(3): 537–543. doi:10.1111/j.1728-4457.2005.00083.x

Rizzi, Silvia, Søren Kjærgaard, Marie-Pier Bergeron-Boucher, Carlo Giovanni Camarda, Rune Lindahl-Jacobsen, and James W. Vaupel. 2021. Killing off cohorts: Forecasting mortality of non-extinct cohorts with the penalized composite link model, *International Journal of Forecasting* 37(1): 95–104. doi:10.1016/j.ijforecast.2020.03.003

Robine, Jean-Marie. 2001. Redefining the stages of the epidemiological transition by a study of the dispersion of life spans: The case of France, *Population: An English Selection* 13(1): 173–193.

Robine, Jean-Marie. 2007. Extreme longevity and data quality, *Annual Review of Gerontology and Geriatrics* 27(1): 151–172. doi:10.1891/0198-8794.27.1.151

Robinette, Jennifer Williams, Jason D. Boardman, and Eileen M. Crimmins. 2019. Differential vulnerability to neighbourhood disorder: A gene×environment interaction study, *Journal of Epidemiology and Community Health* 73(5): 388–392. doi:10.1136/jech-2018-211373

Rodgers, Gerry B. 1979. Income and inequality as determinants of mortality: An international cross-section analysis, *Population Studies* 33(2): 343–351. doi:10.1080/00324728.1979.10410449

Rosenwaike, Ira, and Leslie F. Stone. 2003. Verification of results of a matching study, *Demography* 40(4): 727–739. doi:10.1353/dem.2003.0038

Rosero-Bixby, Luis. 2018. High life expectancy and reversed socioeconomic gradients of elderly people in Mexico and Costa Rica, *Demographic Research* 38(3): 95–108. doi:10.4054/DemRes.2018.38.3

Rosero-Bixby, Luis, and William H. Dow. 2009. Surprising SES gradients in mortality, health, and biomarkers in a Latin American population of adults, *The Journals of
Ruhm, Christopher J. 2000. Are recessions good for your health? *The Quarterly Journal of Economics* 115(2): 617–650. doi:10.1162/003355300554872

Ruhm, Christopher J. 2015. Recessions, healthy no more? *Journal of Health Economics* 42: 17–28. doi:10.1016/j.jhealeco.2015.03.004

Saikia, Nandita, and Arthur van Soest. 2011. Infant death clustering in families: Magnitude, causes, and the influence of better health services, Bangladesh 1982–2005, *Population Studies* 65(3): 273–287. doi:10.1080/00324728.2011.602100

Saikia, Nandita, Domantas Jasilionis, Faujdar Ram, and Unnati Rani Saha, and Arthur van Soest. 2011. Infant death clustering in families: Magnitude, causes, and the influence of better health services, Bangladesh 1982–2005, *Population Studies* 65(3): 273–287. doi:10.1080/00324728.2011.602100

Salomon, Joshua A., and Christopher J. L. Murray. 2001. Modelling HIV/AIDS epidemics in sub-Saharan Africa using seroprevalence data from antenatal clinics, *Bulletin of the World Health Organization* 79: 596–607

Sasson, Isaac. 2016. Trends in life expectancy and lifespan variation by educational attainment: United States, 1990–2010, *Demography* 53(2): 269–293. doi:10.1007/s13524-015-0453-7

Schmidtmann, Carl P., and Marcos R. Gonzaga. 2018. Bayesian estimation of age-specific mortality and life expectancy for small areas with defective vital records, *Demography* 55(4): 1363–1388. doi:10.1007/s13524-018-0695-2

Schoenmaker, Manja, Anton J. M. de Craen, Paul H. E. M. de Meijer, Marian Beekman, Gerard J. Blauw, P. Eline Slagboom, and Rudi G. J. Westendorp. 2006. Evidence of genetic enrichment for exceptional survival using a family approach: The Leiden Longevity Study, *European Journal of Human Genetics* 14(1): 79–84. doi:10.1038/sj.ejhg.5201508

Schulz, Laura C. 2010. The Dutch hunger winter and the developmental origins of health and disease, *Proceedings of the National Academy of Sciences* 107(39): 16757–16758. doi:10.1073/pnas.102911107

Sharrow, David J., Samuel J. Clark, and Adrian E. Raftery. 2014. Modeling age-specific mortality for countries with generalized HIV epidemics, *PLoS ONE* 9(5): e96447. doi:10.1371/journal.pone.0096447

Sharrow, David J., Samuel J. Clark, Mark Collinson, Kathleen Kahn, and Stephen Tollman. 2013. The age pattern of increases in mortality affected by HIV: Bayesian fit of the Heligman-Pollard model to data from the Agincourt HDSS field site in rural northeast South Africa, *Demographic Research* 29: 1039–1096. doi:10.4054/DemRes.2013.29.39

Sharrow, David J., Jessica Godwin, Yanjun He, Samuel J. Clark, and Adrian E. Raftery. 2018. Probabilistic population projections for countries with generalized HIV/AIDS epidemics, *Population Studies* 72(1): 1–15. doi:10.1080/00324278.2017.1401654

Shkolnikov, V. M., E. M. Andreev, and Alexander Z. Begun. 2003. Gini coefficient as a life table function. Computation from discrete data, decomposition of differences and empirical examples, *Demographic Research* 8: 305–358. doi:10.4054/DemRes.2003.8.11

Shkolnikov, V. M., D. A. Jdanov, E. M. Andreev, and J. W. Vaupel. 2011. Steep increase in best practice cohort life expectancy, *Population and Development Review* 37(3): 419–434. doi:10.1111/j.1728-4457.2011.00428.x

Shkolnikov, Vladimir, Martin McKee, and David A. Leon. 2001. Changes in life expectancy in Russia in the mid-1990s, *The Lancet* 357(9260): 917–921. doi:10.1016/S0140-6736(00)04212-4

Smits, Jeroen, and Christiaan Monden. 2009. Length of life inequality around the globe, *Social Science & Medicine* 68(6): 1114–1123. doi:10.1016/j.socscimed.2008.12.034

Soares, Rodrigo R. 2007. On the determinants of mortality reductions in the developing world, *Population and Development Review* 33(2): 247–287. doi:10.1111/j.1728-4457.2007.00169.x

Stokes, Andrew, and Samuel H. Preston. 2016. How dangerous is obesity? Issues in measurement and interpretation, *Population and Development Review* 42(4): 595–614. doi:10.1111/padr.12015

Sudharsanan, Nikkil, Yuan Zhang, Collin Payne, William Dow, and Eileen Crimmins. 2020. Schooling and adult mortality in middle-income countries: Surprising gradients in six nationally-representative longitudinal surveys, *SSM-Population Health* 12(1): 100649. doi:10.1016/j.ssmph.2020.100649

Szreter, Simon. 1988. The importance of social intervention in Britain’s mortality decline c.1850-1914: A re-interpretation of the role of public health, *Social History of Medicine* 1(1): 1–17. doi:10.1093/shm/1.1.1

Tanaka, Hirokazu, Wilma J. Nusselder, Matthias Bopp, Henrik Bronnum-Hansen, Ramune Kaliediene, Jung Su Lee, Mall Leinsalu et al. 2019. Mortality inequalities by occupational class among men in Japan, South Korea and eight European countries: A national register-based study, 1990–2015, *Journal of Epidemiology and Community Health* 73(8): 750–758. doi:10.1136/jech-2018-211715

Tapia Granados, José A. 2005. Recessions and mortality in Spain, 1980–1997, *European Journal of Population* 21(4): 393–422. doi:10.1007/s10680-005-4767-9

Tapia Granados, José A. 2008. Macroeconomic fluctuations and mortality in postwar Japan, *Demography* 45: 323–343. doi:10.1353/dem.0.0008
Tapia Granados, José A., and Ana V. Diez Roux. 2009. Life and death during the Great Depression, *Proceedings of the National Academy of Sciences* 106(41): 17290–17295. doi:10.1073/pnas.0904491106

Thatcher, Roger A., Väinö Kannisto, and J. W. Vaupel. 1998. *The Force of Mortality at Ages 80 to 120*. Odense: Odense University Press.

Thornton, Patricia, and Sherry Olson. 2011. Mortality in late nineteenth-century Montreal: Geographic pathways of contagion, *Population Studies* 65(2): 157–181. doi:10.1080/00324728.2011.571385

Timeus, Ian M., and Momodou Jasseh. 2004. Adult mortality in sub-Saharan Africa: Evidence from demographic and health surveys, *Demography* 41(4): 757–772. doi:10.1353/dem.2004.0037

Torre, Roberta, and Mikko Myrskylä. 2014. Income inequality and population health: An analysis of panel data for 21 developed countries, 1975-2006, *Population Studies* 68(1): 1–13. doi:10.1080/00324728.2013.856457

Torres, Catalina, Vladimir Canudas-Romo, and Jim Oeppen. 2019. The contribution of urbanization to changes in life expectancy in Scotland, 1861–1910, *Population Studies* 73(3): 387–404. doi:10.1080/00324728.2018.1549746

Torri, Tiziana, and James W. Vaupel. 2012. Forecasting life expectancy in an international context, *International Journal of Forecasting* 28(2): 519–531. doi:10.1016/j.ijforecast.2011.01.009

Tropf, Felix C., S. Hong Lee, Renske M. Verweij, Gert Stulp, Peter J. Van Der Most, Ronald De Vlaming et al. 2017. Hidden heritability due to heterogeneity across seven populations, *Nature Human Behaviour* 1(10): 757–765. doi:10.1038/s41562-017-0195-1

Tuljapurkar, Shripad, Nan Li, and Carl Boe. 2000. A universal pattern of mortality decline in the G7 countries, *Nature* 405(6788): 789–792. doi:10.1038/35015561

UN. 1982. *Model Life Tables for Developing Countries*. New York: United Nations.

UN. 2019. World Population Prospects 2019: Highlights. Edited by D.o.E.a.S.A. United Nations, Population Division (ST/ESA/SER.A/423).

Vallin, Jacques, and Frances M. Meslé. 2004. Convergences and divergences in mortality. A new approach to health transition, *Demographic Research* 2(2): 11–44. doi:10.4054/DemRes.2004.S2.2

Vallin, Jacques, and Frances Meslé. 2009. The segmented trend line of highest life expectancies, *Population and Development Review* 35(1): 159–187. doi:10.1111/j.1728-4457.2009.00264.x

van den Berg, Gerard J., Ulf-G Gerthdahm, Stephanie von Hinke, Maarten Lindeboom, Johannes Lissdaniels, Jan Sundquist, and Kristina Sundquist. 2017. Mortality and the business cycle: Evidence from individual and aggregated data, *Journal of Health Economics* 56: 61–70. doi:10.1016/j.jhealeco.2017.09.005

van Raalte, Alyson A., and Hal Caswell. 2013. Perturbation analysis of indices of lifespan variability, *Demography* 50(5): 1615–1640. doi:10.1007/s13524-013-0223-3

van Raalte, Alyson A., Anton E. Kunst, Patrick Deboosere, Mall Leinsalu, Olle Lundberg, Pekka Martikainen, Bjorn H. Strand et al. 2011. More variation in lifespan in lower educated groups: Evidence from 10 European countries, *International Journal of Epidemiology* 40(6): 1703–1714. doi:10.1093/ije/dyr146

van Raalte, Alyson A., Pekka Martikainen, and Mikko Myrskylä. 2014. Lifespan variation by occupational class: Compression or stagnation over time? *Demography* 51(1): 73–95. doi:10.1007/s13524-013-0253-x

van Raalte, Alyson A., Isaac Sasson, and Pekka Martikainen. 2018. The case for monitoring life-span inequality, *Science* 362(6418): 1002–1004. doi:10.1126/science.aau5811

van Raalte, Alyson A., and Rosie Seaman. 2020. Social determinants of life expectancy and inequality in lifespan, in S. I. S. Rattan (ed.), *Encyclopedia of Biomedical Gerontology*. Oxford: Academic Press, pp. 239–246.

Vaupel, James, and Vladimir Canudas-Romo. 2002. Decomposing demographic change into direct vs. compositional components, *Demographic Research* 7: 1–14. doi:10.4054/DemRes.2002.7.1

Vaupel, James W., and Vladimir Canudas-Romo. 2003. Decomposing change in life expectancy: A bouquet of formulas in honor of Nathan Keyfitz’s 90th birthday, *Demography* 40(2): 201–216. doi:10.10133/dem.2003.0018

Vaupel, James W., James R. Carey, Kaare Christensen, Thomas E. Johnson, Anatoli I. Yashin, Niels V. Holm, Ivan A. Iachine et al. 1998. Biodemographic trajectories of longevity, *Science* 280(5365): 855–860. doi:10.1126/science.280.5365.855

Vaupel, James W., Kenneth G. Manton, and Eric Stallard. 1979. The impact of heterogeneity in individual frailty on the dynamics of mortality, *Demography* 16(3): 439–454. doi:10.2307/2061224

Vaupel, James W., and Anatoli I. Yashin. 1985. Heterogeneity’s rules: Some surprising effects of selection on population dynamics, *The American Statistician* 39(3): 176–185.

Vaupel, James W., Zhen Zhang, and Alyson A. van Raalte. 2011. Life expectancy and disparity: An international comparison of life table data, *BMJ Open* 1(1): 1–6. doi:10.11136/bmjopen-2011-000128

Vinneau, Justin M., Brooke M. Huijbregts, Thomas M. Laidley, Joshua A. Goode, and Jason D. Boardman. 2021. Mortality and obesity among US older adults:
The role of polygenic risk, *The Journals of Gerontology: Series B* 76(2): 343–347. doi:10.1093/geronb/gbx156

Wakefield, Jon, Geir-Arne Fuglstad, Andrea Riebler, Jessica Godwin, Katie Wilson, and Samuel J. Clark. 2019. Estimating under-five mortality in space and time in a developing world context, *Statistical Methods in Medical Research* 28(9): 2614–2634. doi:10.1177/0962280218767988

Walker, Neff, Kenneth Hill, and Fengmin Zhao. 2012. Child mortality estimation: Methods used to adjust for bias due to AIDS in estimating trends in under-five mortality, *PLoS Medicine* 9(8): e1001298. doi:10.1371/journal.pmed.1001298

Wang, Haidong, and Samuel H. Preston. 2009. Forecasting United States mortality using cohort smoking histories, *Proceedings of the National Academy of Sciences* 106(2): 393–398. doi:10.1073/pnas.0811809106

Wilmoth, John, Sarah Zureick, Vladimir Canudas-Romo, Mie Inoue, and Cheryl Sawyer. 2012. A flexible two-dimensional mortality model for use in indirect estimation, *Population Studies* 66(1): 1–28. doi:10.1080/00324728.2011.611411

Woodward, Mark, Sanne A. E. Peters, G. David Batty, Hirotsugu Ueshima, Jean Woo, Graham G. Giles, Federica Barzi et al. 2015. Socioeconomic status in relation to cardiovascular disease and cause-specific mortality: A comparison of Asian and Australasian populations in a pooled analysis, *BMJ Open* 5(3): e006408. doi:10.1136/bmjopen-2014-006408.

Wrigley-Field, Elizabeth. 2014. Mortality deceleration and mortality selection: Three unexpected implications of a simple model, *Demography* 51(1): 51–71. doi:10.1007/s13524-013-0256-7

Yount, Kathryn M. 2001. Excess mortality of girls in the Middle East in the 1970s and 1980s: Patterns, correlates and gaps in research, *Population Studies* 55(3): 291–308. doi:10.1080/00324720127703

Zhang, Zhen, and J. W. Vaupel. 2009. The age separating early deaths from late deaths, *Demographic Research* 20: 721–730. doi:10.4054/DemRes.2009.20.29

Zuo, Wenyun, Sha Jiang, Zhen Guo, Marcus W. Feldman, and Shripad Tuljapurkar. 2018. Advancing front of old-age human survival, *Proceedings of the National Academy of Sciences* 115(44): 11209–11214. doi:10.1073/pnas.1812337115

https://www.mortality.org/Public/Docs/MethodsProtocol.pdf.

Wilmoth, J. R., L. J. Deegan, H. Lundström, and S. Horiuchi. 2000. Increase of maximum life-span in Sweden, 1861-1999, *Science* 289(5488): 2366–2368. doi:10.1126/science.289.5488.2366

Wilmoth, John R., and Shiro Horiuchi. 1999. Rectangularization revisited: Variability of age at death within human populations, *Demography* 36(4): 475–495. doi:10.2307/2648085

Wilmoth, John R., and Hans Lundström. 1996. Extreme longevity in five countries, *European Journal of Population* 12(1): 63–93. doi:10.1007/BF01797166

Wilmoth, John, Sarah Zureick, Vladimir Canudas-Romo, Mie Inoue, and Cheryl Sawyer. 2012. A flexible two-dimensional mortality model for use in indirect estimation, *Population Studies* 66(1): 1–28. doi:10.1080/00324728.2011.611411

Woodward, Mark, Sanne A. E. Peters, G. David Batty, Hirotsugu Ueshima, Jean Woo, Graham G. Giles, Federica Barzi et al. 2015. Socioeconomic status in relation to cardiovascular disease and cause-specific mortality: A comparison of Asian and Australasian populations in a pooled analysis, *BMJ Open* 5(3): e006408. doi:10.1136/bmjopen-2014-006408.

Wrigley-Field, Elizabeth. 2014. Mortality deceleration and mortality selection: Three unexpected implications of a simple model, *Demography* 51(1): 51–71. doi:10.1007/s13524-013-0256-7

Yount, Kathryn M. 2001. Excess mortality of girls in the Middle East in the 1970s and 1980s: Patterns, correlates and gaps in research, *Population Studies* 55(3): 291–308. doi:10.1080/00324720127703

Zhang, Zhen, and J. W. Vaupel. 2009. The age separating early deaths from late deaths, *Demographic Research* 20: 721–730. doi:10.4054/DemRes.2009.20.29

Zuo, Wenyun, Sha Jiang, Zhen Guo, Marcus W. Feldman, and Shripad Tuljapurkar. 2018. Advancing front of old-age human survival, *Proceedings of the National Academy of Sciences* 115(44): 11209–11214. doi:10.1073/pnas.1812337115