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HUMAN HEALTH

Dean T. Jamison
Prabhat Jha
Varun Malhotra
Stéphane Verguet

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The 20th Century Transformation of Human Health: Its Magnitude and Value[1]

Dean T. Jamison[2], Prabhat Jha[3], Varun Malhotra[3], Stéphane Verguet[2]

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[2] Department of Global Health, University of Washington, e-mail: djamison@uw.edu and verguet@uw.edu
[3] Centre for Global Health Research (CGHR), St. Michael's Hospital and Dalla Lana School of Public Health, University of Toronto, e-mail: prabhat.jha@utoronto.ca and varunm@gmail.com

The 20th Century Transformation of Human Health:
Its Magnitude and Value

> "I have tried always to remember a simple truth about the past that the historically inexperienced are prone to forget. Most people in the past either died young or expected to die young, and those who did not were repeatedly bereft of those they loved... the power of death cut people off in their prime and made life seem precarious and filled with grief. It also meant that most of the people who built civilizations of the past were young when they made their contributions."
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> - Niall Ferguson, *Civilization: The West and the Rest* (2011, pp xxii-xxiii).

Ferguson refers to a past with mortality far higher than today, a past in which people not only died young but lived with frequent illness, undernutrition and (for women) the often debilitating consequences of high fertility. This past was not so very long ago. Section 1 will present long trends in life expectancy in the country where it is highest. From a period of virtually no change in mortality prior to 1790, improvements became rapid in the 19th century and extremely rapid in the period 1880-1960. During this latter period life expectancy in the leading country increased by over years every decade. And, as this paper will document, not only how did the leading country rapidly improve but much of the rest of the world converged toward the leader.

Our agenda in this paper is, first, to review briefly the magnitude and likely origins of mortality decline in the 20th century. While some of that decline results from improvements in income – and all the health-related goods that income buys – we conclude that improvements in health technology dominate the explanation for health gains. In part 2, the core of the paper, we develop measurements of 20th century mortality reductions in terms of reduction in the expected number of years of life lost (YLLs) by a typical individual relative to an idealized norm. This norm is the United Nations' projected mortality profile for Japan in 2050. (An alternative to Japan 2050 as a norm is to use the lowest mortality country at any given time as the norm for that time. Annex 2 presents results obtained under this assumption). Part 2 also presents money metric valuation of the YLL declines using methods standardized by the Copenhagen Consensus. The paper conveys results for a

number of individual countries and regions as well as for the world as a whole. Section 3 of the paper presents examples to provide a more granular feel for the origins of mortality decline and the nature of remaining problems. Section 4 concludes.

It is worth noting at the outset that other papers in this collection – on education, nutrition, water and sanitation and air pollution, for examples – explore in detail some of the underlying reasons for mortality change.

1. The magnitude and origins of mortality decline in the 20th century

Figures 1.1 shows female life expectancy levels – in the country with the then highest female life expectancy - and its rate of increase, from the late 18th century to the present time. Figure 1.2 shows the rate of increase in female life expectancy (in years of life expectancy per decade) based on Figure 1.1. It is hard to overstate the magnitude of the improvements in longevity from 1800 on (or how little improvement there had been previously). And rapid as the leader's improvement was for many decades, at 3.2 years per decade, global convergence is more impressive. In India, for example, life expectancy grew at a rate of over 4.5 years per decade between 1960 and 2002.

Mortality[4] declines in the 20th century varied by age group- with the sharpest declines in childhood deaths below age 5 and less marked declines in middle age (defined here as age 30-69 years). Mortality from infectious diseases fell far faster than did mortality from non-communicable diseases. Moreover, the main

[4]Avoidance of disability is also important. Mortality does not capture all illnesses, specifically neuropsychiatric and musculoskeletal diseases. However, the correlation of mortality with morbidity for most major diseases is quite strong, and in low-income countries, a greater proportion of the combined total of deaths and disability arise from mortality than is the case in high-income countries. Moreover, it is important to note that measurement error in disability estimates is much greater than for mortality, and often can exceed the desired change in health outcomes. For example, a health policy planner may desire a 10% improvement in an under-5 health outcome, but if measurement error exceeds 10% in the health outcome measure, she or he will not know if the intervention worked. Since it is usually possible to tell the difference between a dead person and a living one, restricting analyses to mortality should reduce measurement error in health policy-making. This paper focuses on mortality reduction only and for that reason understates both the magnitude of health problems in, say, 1900 and the magnitude of subsequent progress.

contributors to the declines varied over time, in part because the higher levels of income achieved by low and middle income countries in more recent decades have enabled them to purchase more technological progress (at any given level of income). Thus low and middle-income countries have benefited in the second half of the 20th century from the diffusion of technological advances in higher income countries in the first half of the 20th century. In some cases, advances in education have enabled more effective use of these technologies, most notably from improvements in maternal education enabling better use of oral rehydration therapies or case management of sick children (Kidane and Morrow, 2000).

Technological advances and their effective diffusion account for most of the large declines in premature mortality in the 20th century worldwide, particularly for the declines in mortality observed in low and middle income countries from about 1950 onwards. Income and, to a lesser extent, education were less important predictors of these massive declines in premature deaths (Easterlin, 1999; Jamison et al (2012), Jha et al, (2004)). Two caveats on causality relations among income, technology and mortality change are worth considering. First, most of the 20th century had large gaps in evidence on diseases, expenditures, and their outcomes. The gaps persist. For example, less than a third of all deaths worldwide have reasonably reliable causes of death given to them, as they occur without any medical attention (Jha, 2012). Second, income and education influence many aspects of the use of technology. For example, higher income enables better access to improved water supply and to sanitation, which does (albeit quite expensively) reduce childhood deaths from diarrhea. Higher income also supports improved communication, changes in transportation, and other dimensions of infrastructure that might have more distal impacts on mortality reduction. There are also concomitant changes in changing occupation, such as safer, less manually demanding jobs, as well as changes in gender- participation in labour markets. All of these have an impact on reduced mortality. However, as reviewed elegantly by Easterlin (1999), the main contribution to the large declines in mortality arose from more proximate measures of public health including public health institutions.

Additionally, the specific choices made by households (or more commonly by governments) such as the use of smallpox vaccines in the late 19th and early 20th century in turn depended on having some wealth (but smallpox eradication was independent of household decisions). In contrast, public health institutions and regulations that are quite important in interrupting the spread of infectious agents (say the ability of enforcing quarantine laws against suspected smallpox cases), or control of risk factors for chronic diseases (say enforced bans on smoking in public places) are often *poorly* correlated with income levels. Thus, the impact on specific (and usually poorly measured) diseases (such as age-specific smallpox mortality) is difficult to quantify. There are also changes in the natural virulence of infectious agents over time (and much less likely increases in the resistance of humans to these agents). For example, there might well have been changes in unmeasured etiologic factors for tuberculosis that led to its declines in the early 20th century, independent of treatment, which was not introduced widely until the 1950s (Nagelkerke, 2012). These problems in measurement and attribution have contributed, along with ideological perspectives, to a wide range of interpretations on the reasons for mortality decline, ranging from factors like nutrition, changes in societal structures or other more distal effects (see Easterlin 1999 for a relevant review). Even interpretations that suggest income to be an important driver of mortality declines (e.g. Pritchett and Summers, 1996) allow ample scope for the importance of technical change. Moreover, some types of knowledge, such as the germ theory and the understanding of transmission of infectious disease need little income to implement (Preston and Haines, 1991). Analyses might well suggest that income played *no* role. The British-led army in India was instructed to march at right angles to the wind during cholera outbreaks, for example. Applied research that understood cholera transmission and clustering of outbreaks led to use of far more effective measures than wind avoidance (Davis, 1951).

Some studies have attempted to assess what fraction of the decline in under-5 mortality arises from different sources. Jamison, et al (2012) for example estimate improved levels of education and technical

progress are the largest contributors. Panel A of Figure 1.3 shows their results for all low- and middle-income countries for 1970-2000, and Panel B shows their results for India.

Many of these interventions, particularly against infection and micronutrient deficiency, cost little and are highly efficacious. This is not to discount other more distal factors as having a role, for example by generating the wealth needed to purchase these interventions, the education to use them properly, or societal structures to ensure their widespread application. But in the absence of such specific technologies, it is hard to imagine that there would have been decline in mortality for these specific causes.

2. Estimation of the number of years of life lost (YLLs) and its money metric value

This section begins by describing the methods used in order to estimate the number of years of life lost (YLL) for a given country or region and year. The countries and regions analyzed were China, India, Japan, the United States of America, Sub-Saharan Africa, the world, the 'Less developed regions' and the 'More developed regions' as defined by the United Nations (2009). The time span considered for the analysis was 1900-2050. YLL estimates were calculated, for purposes of the CCC analysis, using the UN's projected survival curve for Japan in 2050 as a reference[5]. Results are reported as a snapshot every 10 years for the years 1900, 1910, up to 2050. We then convert to money metric losses using a value of 2 for the ratio of the value of a statistical life year (VSLY) to per capita GDP.

2.1. Background and methods

Notation

[5] An alternative reference population would be that of the best performing country in the year of the analysis. Annex 2 contains alternative calculations based on this assumption.

Consider a country or region *i* in year *t.* We note $e_{i,t}(a)$ the life expectancy at age *a* for the country/region *i* in year *t*. For country or region *i* in year *t*, we denote $s_{i,t}(a)$ to be the survival curve, which shows the probability that an individual of the population considered would survive from birth to age *a* given the age-specific survival rates at time t implied by the survival curve. Figure 2.1.a displays survival curves for the Japanese population for the years 2005-2010 and for the Mozambican population for the year 1990. The age specific mortality rate at age *a* -- or *hazard rate* -- in population *i* in year *t*, $\mu_{i,t}(a)$, is given by:

$$\mu_{i,t}(a) = -\frac{s'_{i,t}(a)}{s_{i,t}(a)}. \qquad (2.1)$$

Figure 2.1.b displays hazard rates by age group for the Japanese population for the years 2005-2010 and for the Mozambican population for the year 1990.

We defined our *reference population*, as that of the country which had the highest (projected) life expectancy at birth, according to the United Nations, for the period we review (1900-2050). The Japanese population in 2050 thus serves as the reference population, which we named JPN2050. In 2050, a Japanese newborn would be expected to live about 87.2 years according to the United Nations (2009), and that is the highest life expectancy in their projections. We noted $e_J(a)$ the life expectancy at age *a* for a Japanese individual from JPN2050. Figure 2.2 displays life expectancy as a function of age for JPN2050, as well as for the Mozambican population in 1990.

For country/region *i*, and year *t*, we define the number of *years of life lost* $YLL_{i,t}$, relative to the Japanese population, to be:

$$YLL_{i,t} = -s'_{i,t} \bullet e_J, \qquad (2.2)$$

where e_J = ($e_J(0)$, $e_J(5)$, …, $e_J(100)$), and $s'_{i,t}$ = ($s'_{i,t}(0)$, $s'_{i,t}(5)$, …, $s'_{i,t}(100)$)[6]. Recall $e_J(5k)$ is the life expectancy at age *5k* for JPN2050, $-s'_{i,t}(5k)$ is the probability of dying between ages *5k* and *5(k+1).* This paper uses YLL as its fundamental measure of health losses relative to the reference population and health gains over time.

We characterized a population from country or region *i* in year *t* by two indicators: 1) the number of $YLL_{i,t,u5}$ for deaths occurring at ages under 5, and 2) the number of $YLL_{i,t,a5}$ resulting from deaths above 5. The first kind of YLL is given by:

$$YLL_{i,t,u5} = -s'_{i,t}(0)e_J(0) = (s_{i,t}(0) - s_{i,t}(5))e_J(0) = q5_{i,t}e_J(0), \quad (2.3)$$

where $q5_{i,t}$ is the probability of dying between ages 0 and 5 in country/region *i*, and year *t*. The over age 5 YLL is given by:

$$YLL_{i,t,a5} = -\sum_{k=1}^{20} s'_{i,t}(5k)e_J(5k), \quad (2.4)$$

where $s'_{i,t}(5k) = s_{i,t}(5k+5) - s_{i,t}(5k)$.

In this study we consistently estimate the YLLs arising from deaths before age 5 and those arising from age 5 and older. Hence in addition to q_5 we need the survival curves for ages ≥ 5. For a given population, we estimated a survival curve $s_{i,t,5}(a)$ for $a \geq 5$. We approximated $s_{i,t,5}(a)$ by the following mathematical formulation:

[6] United Nations (2009) gives life expectancies at ages *a = 5k* where *k = 0, 1, 2,…, 20*.

$$s_{i,t,5}(a) = \frac{\Gamma(\frac{2-b}{b}, \frac{2-b}{b}\frac{a-5}{e_5})}{\Gamma(\frac{2-b}{b})} \qquad 0 < b < 2, \qquad (2.5)$$

where $\Gamma(x,s) = \int_x^{+\infty} t^{s-1}e^{-st}\,dt$ is the incomplete gamma function and $\Gamma(s) = \int_o^{+\infty} t^{s-1}e^{-st}\,dt$ is the complete gamma function. e_5 is the life expectancy at age *5* and corresponds to $e_5 = \int_5^{+\infty} s_{i,t,5}(a)\,da$. The parameter *b* captures the *rectangularity* of the survival curve and draws on the formal identity of survival curves and discount functions. Equation 2.5 is a survival curve based on the gamma discounting function of Jamison and Jamison (2011), and their speed parameter ρ (we have $b = 2 - \rho$). Figure 2.3 presents several shapes of hypothetical survival curves *s* for different values of the couplet *(e_5, b).* Notice how for given e_5, varying *b* varies the rectangularity of the survival curve. Our purpose in using a parametric survival curve (eqn 2.5) is to allow us to generate survival curves when only life expectancy is known by using an empirical relation between e_5 and *b* that we now describe in the next subsection.

This completes our development of notation and basic concepts.

Data and empirical relationship between b and e_5

We determined an empirical relationship *b(e_5)* in order to estimate survival curves once given life expectancy at age 5, i.e. e_5. For that purpose, we fitted survival curves given by (2.5) to demographic life tables presenting a wide range of values for e_5. The life tables collected for our analysis were obtained from several sources. The Human Mortality database (www.mortality.org) provided life tables for England and Wales (1841-2009), France (1816-2007), Iceland (1838-2008), Japan (1947-2009), Sweden (1751-2009), and the

United States (1933-2007). Davis (1951) provided life tables for India for the decades 1911-1921 and 1931-1941. We used life tables for 1990 and 2008 for males and females, provided by the World Health Organization (World Health Organization (2010)) for 19 Sub-Saharan African countries and Bangladesh, Brazil, China, Egypt, India, Indonesia, the Islamic Republic of Iran, Mexico, Pakistan, the Philippines. The life expectancies at age 5 ranged from 31.8 to 78.1 years of age (corresponding to India in 1910 (Davis (1951)) and Japan in 2005-2007 (Human Mortality Database (2011)). The couplets (e_5, b) obtained after fitting of (2.5) are displayed on Figure 2.4.

Estimation of survival curves above age 5

For China (CHN), India (IND), Japan (JPN), the United States of America (USA), Sub-Saharan Africa (SSA), the 'Less developed regions' (LDR), the 'More developed regions' (MDR), and the world (WLD), over the period 1900-2050, we estimated a survival curve $s_{i,t,5}(a)$ for age 5 onward for each year starting a decade i.e. 1900, 1910, 1920, …, 2040, 2050. For 2000-2050, all survival curves were estimated using direct fits to the life tables provided by the United Nations (United Nations (2009)). For the USA and the period 1930-2000, and JPN in the period 1950-2000, the survival curves were estimated using direct fits to the life tables provided by Human Mortality Database (2011). For CHN, IND, SSA, LDR, MDR, and WLD, in the period 1900-2000, the survival curves were estimated using the relationship $b = f(e_5)$, once e_5 was known (Figure 2.4). The same approach was used to estimate the survival curves for USA in the period 1900-1930, and for JPN in the period 1900-1950. For CHN, IND, SSA, over the period 1980-2000, both e_0 and $q5$ (probability of dying before age 5) was given by United Nations (2009) and e_5 was derived in the following manner:

$$e_5 = \frac{1}{1-q5}[e_0 - 5 + \frac{5}{2}q5]\,.^{7} \qquad (2.6)$$

All remaining e_5 values were either derived by linear extrapolation or through relationship (2.6) while using a relationship between e_0 and *q5* extracted from the available data from the United Nations (2009). Input data were extracted from several sources including United Nations (2009), CDC (2004), Human Mortality Database (2011), Davis (1951), Feachem and Jamison (1991). All data inputs used are collected in Table 2.1.

Money metric value of YLLs

For region or country *i* in year *t*, we estimated a money metric value of $YLL_{i,t}$, noted $MMVYLL_{i,t}$ in the following way:

$$MMVYLL_{i,t} = \gamma YLL^{*}_{i,t} I_{c,t} \qquad (2.7)$$

where we derived a weighted measure of *YLL* i.e $YLL^* = YLL_{a5} + 0.54\ YLL_{u5}$ as given by Jamison et al. (2006), I_c is the income per capita in 1990 international Geary Khamis dollars (CCC (2011); Maddison (2011))[8], and γ is the value of YLL in units of per capita income, i.e. it is the VSLY. We take here i.e. $\gamma = 2$, the lower value given in Jamison et al. (2009)[9]. We then estimated lifetime income per capita $LI_{c,i,t}$ in the following manner:

[7] This relation is derived from the identity expressing e_0 as the sum of integrals of the survival curve from 0 to 5 and from 5 to infinity and the approximation that the survival curve is linear between 0 and 5.

[8] For the period 2010-2050, projections of income per capita were estimated based on levels from Maddison (2011) in 2010 and assuming a constant growth rate of 2% for Japan and the United States, and of 5% for China and India for the period 2010-2050.

[9] Note that we could have values of γ varying with income as suggested by Hammitt and Robinson (2011). We chose here a constant value across income levels in the interest of simplicity of exposition.

$$LI_{c,i,t} = e_{0,i,t} I_{c,i,t}, \quad (2.8)$$

where $e_{0,i,t}$ is the life expectancy at birth in country or region *i* in year *t*. Finally, we define the ratio a as:

$$a_{i,t} = MMVYLL_{i,t} / LI_{c,t}. \quad (2.9)$$

2.2. Reductions in YLLs

We estimated YLL_J i.e. the number of years of life lost for JPN2050, our reference population. We found $YLL_{J,u5} = 0.3$, $YLL_{J,a5} = 10.1$, leading to $YLL_J = 10.4$. (Note that the existence of non-zero YLLs in the reference population results from the non-rectangularity of the survival curve. Figure 2.4 suggests that after a life expectancy of about 75 years, life expectancy improvements cease to be accompanied by increased rectangularity).

For each country and region *i* and year *t*, we subtracted the quantities associated with the reference population, i.e. we estimated:

$$YLL_{i,t,u5} = q5_{i,t} e_J(0) - YLL_{J,u5}, \quad (2.10)$$

and:

$$YLL_{i,t,a5} = -\sum_{k=1}^{20} s'_{i,t}(5k) e_J(5k) - YLL_{J,a5}, \quad (2.11)$$

which leads to the total unweighted YLLs:

$$YLL_{i,t} = q5_{i,t} e_J(0) - \sum_{k=1}^{20} s'_{i,t}(5k) e_J(5k) - YLL_J . \qquad (2.12)$$

Table 2.2 lists the YLL_{u5} (2.10), the YLL_{a5} (2.11), and the total unweighted YLL (2.12) for each year and country/region, for the period 1900-2050. Figure 2.5 graphs the total number of YLLs per birth for the period 1900-2050 for the World, the 'Less developed regions' and the 'More developed regions'.

YLLs due to 'mortality shocks'

For each major 'mortality shock' of the 20th century including World War I, the 'Spanish' pandemic flu of 1918, World War II, the Bengal famine of 1943 in India, the Great Chinese famine of 1958-1961, we estimated YLLs per capita at the world level (except for the Great Chinese famine (at the China level) and for the Bengal famine (at the India level). For World War I & II, we used deaths data provided by Wikipedia (Wikipedia (2011a); Wikipedia (2011b)). We estimated the YLLs corresponding to military casualties with $e_J(20)$. The YLLs corresponding to civil casualties were estimated using the age distribution of the world population in 1910 and 1940, while using a linear regression between the age distribution of the population as a function of life expectancy at birth for the period 1950-2000 extrapolated from United Nations (2009). For the 'Spanish' pandemic flu, we used death numbers from Johnson et al. (2002) and attack rates from Luk et al. (2001) with the extrapolated age distribution of the world population in 1910 as above. Total world population numbers were obtained from the Copenhagen Consensus Center (2011). For the Bengal famine, we used death numbers from Devereux (2000), the extrapolated age distribution of the Indian population in 1940 as above, and the total population of India in 1943. For the Great Chinese famine, we used death numbers from Ashton et al. (1984), the age distribution of the Chinese population in 1950, and the total population of China

in 1957 (United Nations, 2009). World population data at different times were obtained by the Copenhagen Consensus Center (2011). Table 2.3 lists the YLLs associated with each of the major mortality shocks.

2.3. Money metric value of YLL reduction

Table 2.4 lists the values $YLL_{VSL,i,t} = \gamma YLL^{*}_{i,t}$, the $MMVYLL_{m,i,t}$ (2.7), and the ratio $a_{i,t}$ (2.9) for each year and country/region, for the period 1900-2050. Figure 2.6 graphs the ratios $a_{i,t}$ for the period 1900-2050 for: (a) the World, the 'Less developed regions' and the 'More developed regions'; (b) China, India, Japan and the United States.

3. Specific Health Problems: Accomplishments and Challenges

In this section, we examine the statistical picture of gains provided in Section 2 is illustrated by two specific examples of health accomplishments of the 20th century: marked increases in child survival and the eradication of smallpox. Sections 3.1 and 3.2, respectively, discuss these examples. The discussion then turns to one example of a major challenge that remains on the agenda of the 21st century: tobacco-attributable deaths. This is chosen to illustrate the importance of technological diffusion in affecting change (and also, in the case of tobacco and adult chronic diseases, the enormous returns possible if technologies were applied more widely). The other highly quantitatively significant challenge of the 21st century is the AIDS epidemic. That has been extensively covered in a recent Copenhagen Consensus publication so we discuss it no further here.

3.1. Accomplishments – Child Survival

Major declines in childhood mortality started in the late 19th century in the currently high-income countries, and in the mid-20th century the currently low-income countries. The declines are much more complete in high income countries, meaning that today 99% of children born in these countries can expect to reach their fifth birthday. However, the pace of decline has been rapid in low and middle-income countries, especially since 1950.

Staggering declines in child mortality

Declines in childhood mortality explain much of the remarkable improvements in life expectancy in the 20th century as can be seen on Figure 3.1, which plots estimates and projections of the under-5 years of life lost as a percent of total years of life lost for the "More Developed Regions" and "Less Developed Regions" for the period 1900-2050. Between 1900 and 2000, we estimate that crude death rates fell by nearly four-fifths and life expectancy at birth doubled from 32 to about 66 (Table 2.1); while death rates fell from about 40-50 to 10 per 1000, the global population rose from 1.5 billion to over 6 billion. Thus, annual deaths totaled around 50-60 million throughout the last century. All told, there were about 5-6 billion deaths in the 20th century. About 2 billion of these deaths were among children below age 5 years, despite the marked declines seen in recent decades. Child deaths far exceeded the several millions of deaths from more specific epidemics, such as the 20-60 million killed by the influenza epidemic of 1918/19, the 30 million (and growing) deaths from HIV, the 100 million deaths from tobacco, or the 200 million deaths from war and famine (cross reference to Copenhagen paper).

The staggering decline in child mortality is illustrated by a comparison of the levels and causes of child deaths in sub-Saharan Africa in 2008 to that from Liverpool, England in 1861-1870 (Table 3.1). Sub-Saharan Africa's real per capita income in 2008 was just over half of that of England around 1870. However, child

mortality rates were two-thirds lower in Africa now than in England then (460 versus 140 per 1000 live births). By 2008, the contribution of vaccine preventable diseases, most notably diphtheria, measles and scarlet fever had fallen sharply. In contrast, the remaining causes of death arose largely from pneumonias, diarrhea and, in the African case, childhood malaria deaths (most of England had little malaria in the 1870s).

Put differently, if worldwide child mortality rates today were like those seen in England, or most Western countries near the beginning of the 20th century, there would be about 30 million child deaths, rather than the 10 million deaths that occurred in children around 2001 (or 13.9 million of stillbirths are included (Jamison, et al, 2006)). By 2000 child deaths in England had become quite rare. If the world had the same child mortality rates as seen in England today, only 1 million children would die worldwide (Peto, 2006).

The role of technologies in child mortality declines

Specific technologies have had different impacts on the decline in childhood mortality at different time periods. In the first half of the 20th century, the available tools included knowledge of transmission of various infectious diseases (Preston and Haines, 1991) including crude efforts around containment and isolation, contact tracing, improved sanitation, as well as specific vaccines. These tools, once implemented widely in Europe led to substantial declines in child mortality in the early 20th century. In the second half, far greater reductions arose from childhood vaccinations (including the introduction of global campaigns to immunize children), oral rehydration therapies, antibiotic use and malaria control.

Easterlin describes some of the available tools in the first half of the 20th century and their discovery years, and we have modified this table somewhat and added a table on more contemporary tools (Table 3.2). The major tools of control in early 20th century comprised efforts to interrupt transmission of infectious diseases, often crudely. Plague epidemics and outbreaks were a major cause of childhood mortality worldwide. In India, plague deaths at all ages fell from about 500,000 in the 1889-1918 period to below 32,000 by 1935

with much of these deaths concentrated in children. The chief reasons for the decline were increases in rat immunity (rats transmit the *Yersinia pestis* bacteria into human populations). However, declines occurred also due to crude efforts to control the rat population, and to a much more limited extent the use of vaccines and, at a later point, sulfa drugs (Davis, 1951). Similarly, cholera epidemics were substantial in many parts of world, and the understanding of transmission from water sources and via fecal contact led to crude measures involving containment that reduce the spread and severity of periodic outbreaks. Notably, the periodic religious pilgrimages of several million Hindus often led to cholera outbreaks. Simple efforts to bring basic sanitation and (to a more limited extent) temporary vaccination to the large number of annual pilgrims reduced cholera outbreaks. Reductions in famines arising from better agricultural practices and irrigation supply (see CC paper on nutrition), were also partly responsible for the reductions in cholera, as famines can lower human immunity and also contribute to spreading the virus more rapidly.

By 1950-54, the probability of newborns dying before age 5 was still about 23%, but fell to 14% by 1970-74, to 9% in 1990-94, and to about 6% in the present decade (Ahmed, 2002). The declines from about 1950 onward in child mortality mostly arose from the use of modern technologies. Table 3.3 describes the declines in infectious diseases, which is the leading cause of death among children that arose from specific technologies in the 2nd half of the 20th century. Improved environmental living conditions paired with the ability to identify new microbes and develop vaccines as well as antimicrobials account for the 90% or greater reduction in infectious disease mortality in the US. In the last half century, more than 30 common infectious diseases are controllable with live or killed viral or bacterial vaccines, or those based on bacterial sugars and proteins (Jha et al, 2004).

In 1970, perhaps only 5% of the world's children under 5 were immunized against measles, tetanus, pertussis, diphtheria and polio. The Expanded Programme on Immunization (EPI) has raised this to about 85% of children by 2000, saving perhaps 3 million lives a year (England et al, 2000). Diarrheal deaths among

children have fallen by several million partly as a result of the development of oral rehydration therapy - - much of which was the result of population research laboratories in Bangladesh. Delivery of a combination of anti-tuberculosis drugs with direct observation (or DOTS) has lowered case-fatality rates from well over 60% to 5%, and also decreased transmission. The percentage of the world's tuberculosis cases treated with DOTS has risen from about one in ten in 1990 to about one in three today (Dye, 2000). The most spectacular success in immunization is the World Health Organization (WHO)-led eradication of smallpox, which culminated in the eradication of smallpox in human populations by 1979. We discuss smallpox in greater detail below.

Prior to 1950, the only major antibiotics were sulphonamides and penicillin. Subsequently, there has been remarkable growth in discovery and use of antimicrobial agents with different mechanisms of action effective against bacteria fungi viruses, protozoa, and helminths. These new agents contributed importantly to the steady decline in child mortality.

The uncertain, but perhaps large contribution of malaria control

Preston (1980) provides a useful set of estimates of the contribution of specific infectious diseases to reductions in mortality from 1900 to 1970. We provide an updated version here (Table 3.4). Preston's estimates of the contribution of technologies to mortality declines are consistent with others. However, he adds the important, and yet variable estimates of reduced mortality from malaria control. Perhaps 13-33 percent of the overall decline in mortality during these seven decades might have arisen from malaria control, chiefly from indoor residual spraying, but also from early anti-malarial like quinine. Mandle (1970) finds that a very large part of the declines in mortality in British Guiana, especially in the period just after World War II arose from malaria control (Figure 3.2).

In more recent years, artemisinin combination therapies have shown to be powerful tools to reduce malaria mortality (Gomes et al, 2009), and indeed childhood malaria deaths in Africa might be falling in

response to expanded use of insecticide-treated nets and treatment. In this context, important findings from a large Indian mortality survey suggest that India might well have over 200,000 malaria deaths below age 70, as against the WHO estimate of 15,000 at all ages. Malaria appears not only to be a killer of children, but also of adults (Figure 3.3). Indeed, similar patterns are reported in Mozambique and other countries in Africa. If it is true that malaria remains a common killer of adults, then the same strategies that have been applied to reduce childhood deaths from malaria in Africa might well substantially reduce adult deaths from malaria worldwide.

Nutrition and infection

How has nutrition reduced childhood mortality? Nutritional gains have been substantial (cross reference CC chapter on nutrition). For example, physical growth (height-for-age) rose among 10-year-old Norwegian females from 1920 to 1970 from 130.2 cm to 139.6 cm (and was only about 107.4 cm in 1800; Brundtland, 1975). This massive increase of about 1.9 cm/decade or.84 s.d. per generation has also been accompanied by increases in cognitive growth. Dutch males had, in 1982 and 1.2-fold higher relative to that of their own fathers in 1952, and about 10 fold higher than men in 1800. This increase of about 7 IQ points per decade or 1.4 s.d. per generation is also related to better nutrition (Ruger, et al, 2006). Famines and mass droughts have become less and less common in the 20th century (despite short-term fluctuations), in parts due to better food availability, and the effects of the Green Revolution on crop yields and durability. In turn better diets, particularly but not alone during early life, has substantially improved anthropometrics, schooling, adult cognitive skills, earnings, wages, and anthropometrics of the next generation.

Nutrition is not only a function of available energy or protein, and diet alone fails to explain the widely variable prevalence of malnutrition in low and middle-income countries. Nutrition is strongly correlated with childhood infections (Caulfield, et al, 2006). Infectious diseases raise metabolic demands and decreases the absorption of food, and infection control from immunizations, and antimicrobials have helped reduce the

worldwide prevalence of severe malnutrition, such as Kwashiorkor or Marasmus (Caulfield, et al, 2006). Maternal breastfeeding is a key nutritional intervention to protect against infection. Indeed, Chile saw increases in child mortality among more affluent women than among poorer women, as a result of decreases in breastfeeding by the affluent women (Plank and Milanesi, 1973). More recent efforts with specific micronutrients - - such as iron, folate, and zinc have been shown to be effective in reducing childhood anemia (Zlotkin et al, 2005) and subsequent mortality. Randomized trials of insecticide treated mosquito nets and of specific respiratory antigens have often shown a bigger decline in child mortality than expected from malaria and pneumonia, respectively, and this might be attributed to lowering secondary causes of death from reduced malnutrition.

Current and future child mortality

Despite these substantial achievements in child survival, major challenges still exist. As of 2008, about 9 million children still died before age 5. India alone had 2.3 million child deaths in 2005, of which nearly half occur in the first month of life and 30% in the first week of life (MDS Collaborators, 2010). Indian child mortality has fallen by about 2% per year since 1971 as a whole in India and all states have shown declines. Differences in income levels and growth rates across Indian states do not appear to account for the variation in decline in child mortality (Measham et al, 1995). Rather, coverage with the EPI package, treatment of acute respiratory infection in a medical facility and use of oral rehydration therapy for diarrhea show a clear gradient from worst to best performing states on under-5 mortality (Jha, 2001). Today, about three-fifths of all childhood deaths occur in just nine states. At ages 1-59 months, girls in some regions have four to five times higher mortality from pneumonia or diarrhea as boys in other regions (MDS Collaborators, 2010). Discrepancies in child mortality across states are so large that if the worst third and middle third states had under-5 mortality rates equal to that of the best third, over one million under-5 deaths would be avoided annually (Jha, 2001).

Notwithstanding these challenges, child mortality declines are likely to continue. In Africa, for example, overall child mortality fell from 1990 to 2000 despite increases in childhood deaths from malaria and from mother to child transmission of HIV (Ahmed et al, 2002), and despite economic stagnation. Concerted efforts around reducing childhood mortality now focus on reducing neonatal mortality by improving prenatal and intrapartum care (skilled attendance, emergency obstetric care, and simple immediate care for newborn babies), postnatal family-community care (preventive postnatal care, oral antibiotics, and management of pneumonia), and tetanus toxoid immunization as well as expanding the use of highly effective newer antigens in immunization programs.

On current projection (Table 2.1), child mortality is projected to fall from about 77 per 1000 live births in 2000 to 31 per 1000 live births in 2050. These reductions are likely to continue as forthcoming analyses finds the costs of reducing child mortality continue fall yearly. This improving cost function is largely because of 40 years of public attention, donor assistance and research funding have, together, created cost-effective and widely practicable interventions for child and maternal health, and more recently to control of HIV/AIDS, malaria and tuberculosis. Increasing coverage of inexpensive health interventions such as immunization, insecticide-treated nets, prevention of mother-to-child transmission of HIV and micronutrients are contributing to the decline in child mortality and are getting cheaper by the year (Hum et al, 2012).

3.2 Accomplishments – Smallpox Eradication

In 1979, the WHO eradicated smallpox a disease that perhaps had caused 300 million deaths in the course of the 20th century. Successful eradication arose from a combination of two major factors. First, declines in smallpox in the first half of the 20th century were substantial mostly due to widespread use of

vaccination, as well as general understanding of isolation and control of outbreaks (paired with increases in general nutrition and hence resistance of humans to withstand the periodic outbreaks of smallpox). Second, in 1967 WHO initiated a global eradication campaign which succeeded in the courts of 12 years (Figure 3.4).

Preeradication smallpox

Prior to any widespread control, smallpox may have been the leading cause of death worldwide. Smallpox may have killed perhaps 2-15 million of the total Aztec population of 30 million, and was responsible for periodic epidemics killing hundreds of thousands in cities as far apart as London and Tokyo. Nor did smallpox spare the rich and only strike the poor. Smallpox infected Egyptian pharaoh Ramses V in 1157 BC and Queen Elizabeth I in 1562 and it killed a Roman emperor in 180 BC (Fenner, 1988). In India in 1937-1941, smallpox accounted for between 12 to 20% of the deaths in the 1st year of life and about 19-30% of the deaths between ages 1-9 years (Davis, 1951). India had about half of the world's cases in the two decades prior to eradication. Between one in five and one in three of all cases died.

Introduction of smallpox vaccination began in crude forms as early as 10th century in China. The technique called variolation, involved using the scabs of smallpox victims into healthy people so as to provide some protection. The Chinese even used inhalation approaches for vaccination. These technologies spread westward, and were brought from Constantinople to England in the early 18th century. Vaccination using Jenner's discoveries became widespread by the later 19th century, and was far more practicable and less painful than the variolation.

Where vaccination became commonly used, such as in Finland, death rates fell substantially (Figure 3.5). In many currently high income countries, public health infrastructure expanded, including the ability to forcibly quarantine suspected cases, have mandatory examination of incoming ships, and require compulsory

vaccination or revaccination of children and others. London's public health act of 1875 gave broad powers to the police and public health officials to enforce these laws.

Smallpox vaccination spread widely, including to low-income countries. Banthia and Dyson (1991) describe how increases in vaccination were recorded in the Bombay census of 1881-1891, and his comparison of coverage rates with self-reported smallpox shows remarkable declines. Nearly 80% of the roughly 30 million people in Bengal were inoculated and once replaced by vaccination around 1870, smallpox cases and mortality fell dramatically. A spectacular increase in vaccination occurred in Indonesia (then Netherlands' East Indies). The numbers of vaccination rose from under 60 thousand in 1890-99 to nearly 1.7 million by 1900-1909 and to 7.3 million by 1920, from a total population of about 45 million Indonesians. This led to a marked decline in smallpox mortality (Davis, 1951).

Global eradication

The next major phase involved global eradication. A WHO effort organized all countries to launch a global eradication campaign. Eradication was technically possible as the causative virus for smallpox (two variants *Variola majo*r and *Variola minor)* reside only in humans. The initial effort focused on increasing coverage of the routine vaccines. However, two key areas of operational research refocused the program so that it could achieve eradication. These were active case detection and ring vaccination. Under active case detection, mobile teams investigated outbreaks using local information, In the case of India, Bangladesh, Nepal, Pakistan, Ethiopia and Somalia, country-wide house to houses searches were conducted by a large number of health staff over course of 3-4 weeks to discover possible cases. Ring vaccination involved finding people who were exposed to an infected person. Then, the exposed person and those people he or she had been in contact with are given the vaccine. That is, the smallpox vaccine is given to those people who had

been, or could have been, exposed to an infected person. This approach creates a "ring" of vaccinated people around the people who were infected with smallpox and stops the spread of the disease.

The smallpox eradication program cost an estimated $300 million dollars over its 12-year life and displaced routine immunization costs that totaled $300 million in 1968 alone (World Bank, 1993). These financial benefits, and the millions of lives saved annually, are more fully discussed in Fenner (1988).

3.3 Challenges – Tobacco Control

On current smoking patterns, there will be an estimated 1 billion smoking-attributable deaths in this century, mostly in low- and middle-income countries. In contrast, there were “only” 100 million tobacco deaths in the 20th century, mostly in high-income and Eastern European countries who took up smoking en masse generally before or around World War II (Peto et al, 1994; Jha, 2009). Most of these future tobacco deaths will occur in low-income countries, and half or more will occur during productive middle age (ages 30-69 years). A substantial proportion of these deaths will occur among the poorest or least educated members in each of these countries. Currently, about 70% of the 40 million deaths among adults over age 30 years worldwide are due to cancer, vascular and respiratory diseases, and tuberculosis (Lopez et al, 2006), each of which are made more common by smoking. Smoking currently causes about 5-6 million deaths annually worldwide from all causes (WHO, 2009). About 50% of all current smoking deaths occur in low-income countries.

Here, we review the 20th century development in tobacco hazards, and examine in particular, the benefits of cessation, which has now become widespread among males in high income countries. We examine the importance of taxation to increase cessation. The key relevance here is not to the 100 million deaths in the 20th century which have already occurred, but to the avoidablity of the one billion deaths in this century.

Trends in smoking in developed and developing countries

Widespread automation of cigarette production in the early 20th century turned cigarettes into a global commodity. Lung cancer was a rare disease prior to World War II, and the large increase in lung cancer rates lagged behind the onset of consumption by three or more decades. Among British doctors who were born in the first few decades of the 20th century (1900-1930) and followed those born in the second half of it (1951-2001), death rates were three times higher among doctors who smoked than those who did not (Doll et al, 2005). Prolonged smokers lost about 10 years of life compared to non-smokers. Similarly, the main increase in cigarette smoking in the US occurred from 1920-1940, and peaked at about 10 cigarettes per adult only around 1960 (Jha, 2009). Yet the rates of lung cancer in middle age (defined here as about 30-69 years) and at older ages, almost all of which are due to smoking, peaked almost 30 years later.

The full effects of smoking have not yet been observed in low and middle-income countries. China has over 300 million smokers and India has over 120 million smokers, most of whom are male (GATS, CDC 20010). Moreover, China reports a marked increase in cigarette production since 2000, which might be from increased smoking among younger adults. India's per capita adult male consumption is over six bidis (small locally manufactured smoked tobacco products) or cigarettes per day, although there is some uncertainty in this, particularly for bidi use (Jha et al, 2011). This is comparable to the per capita adult consumption in France prior to 1990, and higher than that seen for adults today in Canada, which has declined from about 11 cigarettes per capita in 1960s to below five in 2010.

Effects of cessation on lung cancer and total deaths

Widespread smoking cessation in high-income countries has afforded researchers the opportunity to study the impact of quitting at various ages on the risk of death from tobacco-attributable diseases. UK doctors who quit smoking before the onset of major disease avoided most of the excess hazards of smoking. In comparison to those who continued smoking, the average gain in life expectancy for those who quit smoking at

60, 50, 40, and 30 years of age, was about 3, 6, 9, and nearly 10 years, respectively (Peto et al, 2000). Cessation before middle age prevents more than 90% of the lung cancer mortality attributable to smoking, with quitters possessing a pattern of survival similar to that of persons who have never smoked.

Overall current risks from smoking

Provided due allowance is made for the long delay between smoking onset and disease, reasonably consistent quantitative estimates of risk emerge: about 1 in 2 of all long-term smokers worldwide are killed by their addiction (Jha, 2009). It is already apparent that a substantial portion of tobacco deaths worldwide occur in middle age (defined as 30-69 years): 50% in the US and UK, 50% in China (Liu et al, 1997) and a surprisingly high 70% in India.

At present, about 80% of worldwide smoking deaths occur in men (WHO, 2009), but this is chiefly because men who died recently smoked more commonly and more intensively when they were young than did the female smokers. The smoker: non-smoker mortality risks in US women after 2000 are actually greater than in men (Rostrom, 2011). Additionally, the consequences of smoking vary by socioeconomic group. For example, in several high-income countries and Poland, smoking deaths were shown to account for at least half of the differences in middle age risk of death between rich, educated men and poorer, less educated men (Jha et al, 2006).

Future risks from smoking and estimates

The future risks of smoking among men in low- and middle-income countries and women worldwide will depend on the duration of smoking (and cessation rates) in the population, variation in the diseases which are made common by smoking, and in the products and patterns of smoking. First, the full effects of smoking will be only apparent when the death rates from smoking in middle age among those who have started

smoking as young adults rise 30-40 years later. Death rates from smoking in older age will rise only about 20 years after this (Jha, 2009). For example, of all US male deaths at ages 35-69, the proportion attributable to tobacco in 1950 was only 12%, rising to 33% in 1990, when the increase in US male tobacco deaths had been completed (about three decades after peak male tobacco consumption).

Plausible projections of future smoking deaths rely on smoking prevalence and uptake (cessation is minimal in low- and middle-income countries), growth in population and growth in the age-specific tobacco-attributable death rates. Sir Richard Peto estimates that global tobacco deaths will reach about 450 million between 2000 and 2050. Worldwide annual tobacco mortality will rise to about 10 million a year or 100 million per decade around 2030, with some further increases in later decades. Further estimations are more uncertain, but based upon current initiation and cessation rates and projected population growth, from 2050–2100 there would be, conservatively, an additional 500 million tobacco deaths (i.e., average of 10 million deaths per year).

How can cessation rates be raised rapidly worldwide?

Cessation by today's smokers is the only practicable way to avoid a substantial proportion of tobacco deaths worldwide before 2050. Halving the worldwide per capita adult consumption of tobacco by 2020 (akin to the declines in adult smoking in the UK over the last three decades) would prevent about 160-180 million tobacco deaths over the next few decades (Peto and Lopez, 2001; Jha, 2009). In contrast, halving the percentage of children who become prolonged smokers (from about 30% to 15% over 2 decades) would prevent some 20 million deaths over the next few decades, but its main effect would be to lower mortality rates in 2050 and beyond.

Higher taxation is the single most important intervention to raising global smoking cessation rates. Other interventions, specifically on information for consumers, banning advertising and promotion and restricting public smoking as well as cessation for smokers also raise quit rates. For brevity, only taxes are

discussed here. Detailed reviews of tobacco control strategies are published elsewhere (Jha, 2009; Jha and Chaloupka, 2000; Jha et al, 2006).

Aggressive taxation is the key strategy for low-and middle-income countries to reduce smoking at a rate faster than that achieved by high-income countries. Powerful policy interventions to tax and regulate consumption and to inform consumers have reduced consumption in most high-income countries (WHO, 2009). The US and UK each took about 35 years and Canada about 25 years to halve per adult cigarette consumption (from about 10 per adult per day to about 5 (Forey et al, 2009).

However, France took only 15 years to halve consumption (Hill, 2010). France's uptake of smoking was chiefly after the Second World War and its prevalence rose until the mid-1980s. From 1990 to 2005, cigarette consumption fell from about six cigarettes per adult per day. This sharp decline was mostly due to a sharp increase in tobacco taxation starting in 1990 under the then president Jacques Chirac (Figure 3.6). These price increases raised the inflation-adjusted price threefold. Among men, the corresponding lung cancer rates at ages 35-44, which is a good measure of recent smoking in the population, fell sharply from 1997 onward. During this period, revenues in real terms rose from about 6 to 12 billion euros. Tax levels stagnated from 2004 onward when Nicolas Sarkozy became finance minister as has the declines in per capita cigarette consumption.

An increase in cigarette taxes of 10% globally would raise cigarette tax revenues by nearly 7%, as the fall in demand is less than proportional to the price increase in most countries (Jha and Chalouplka, 2000). However, taxes are underused in most developing countries (WHO, 2010). Taxes tend to be absolutely higher and account for a greater share of the retail price (71% as of 2006) in high-income countries. In low- and middle-income countries, taxes account for 54% of the final price of cigarettes. In South Africa, tax as a percentage of retail price fell to about 20% around 1990, but has subsequently risen to nearly 40% (Van Walbeek, 2005). As a result, consumption fell from about four cigarettes per adult per day to two over a

decade. Poland's recent tax increases have doubled the real price of cigarettes and dropped consumption. Mauritius and Mexico recently raised taxes by about 30%, which has already produced a drop in consumption.

A tax increase needed to raise the street prices of cigarettes by 70% would involve a 2- to 2.8-fold increase across countries (Jha, 2009). The increase would raise the street price for a pack of 20 cigarettes from about USD 0.7 to 1.3 in low-income countries, from about USD 1.3 to USD 2.3 in middle-income countries and from USD 3.7 to USD 6.3 in high-income countries. Such increases, while large, have been achieved in numerous countries, including Canada, France, Poland and South Africa and within the various states of the US. Indeed, the 2.5 fold increase in the US federal cigarette tax as of 2009 (rising by 62 cents to USD 1.01/pack) might get about 1 million Americans to quit smoking and deter another 2 million youth from starting, thus saving over 1 million lives.

Our purposes in this discussion of smoking are twofold. First, the growing consequences of the smoking epidemic provide a quantitatively important exception to the general rule of rapid progress in health. Second, we have attempted to show that knowledge-based approaches to control have every potential for ultimately yielding success of the sort experienced elsewhere in the health sector.

4. Conclusion

The 20th century saw life expectancy rise by about 3 months for every calendar year. This extraordinary transformation of mortality is chiefly, but not exclusively, a result of the creation and widespread use of specific technologies. What was the value of this transformation? And What then are the implications for this century?

First, by any reasonable measure of value, the value of the health gains in the past century has been enormous.

Second, ongoing investments in widely applicable treatments and policies remain the best engine of future reductions. Specifically, the ongoing investments in child health and infectious disease control should continue to make possible the creation of new powerful interventions, and ongoing operations research and public support for child health should enable the use of these interventions much more widely. In contrast, the future looks less rosy for adult health. The costs of achieving adult survival are rising each year, in part due to the effects of the tobacco and HIV epidemic (Hum et al, 2012). Moreover, the major enterprise of public support, research attention, and wide spread operations research remain scanty at best. Nowhere is this demonstrated more powerfully than for tobacco taxation. A worldwide coordinated major increase in tobacco taxation is not hard to make practicable- the only obstacles are widespread indifference or misunderstanding of tobacco hazards among the public and politicians, and well-organized and funded opposition from the tobacco industry. Similar widely cost-effective strategies (Jamison et al, 2008) focused on long term management with combination drugs for heart attacks and strokes are also widely practicable.

The third major implication has to do with institutions. Previous careful reviews (WHO, 1998) have supported worldwide efforts to accelerate research on neglected and unfinished agendas (such as selected tropical diseases) and on chronic diseases. To some extent, the major philanthropy of the Bill & Melinda Gates Foundation will continue research on promising interventions for child health and infectious diseases, although there are limitations to how the foundation chooses and funds innovations (Black et al, 2009; McKoy et al, 2009). Major institutions, are, as seen above, central to gains in health. Similar efforts and philanthropy are needed for chronic diseases.

Finally, while mostly beyond the scope of this paper, a re-think in developmental assistance around health is required. Given income growth, and increased affordability (at least of child health interventions), it can be fairly argued that most funding for delivery of effective interventions should be the responsibility of governments as well as major global funds (such as the Global Fund for AIDS, Tuberculosis and Malaria or the

Global Alliance for Vaccines and Immunization). This suggests that a substantial part of traditional bilateral aid, such as by USAID or the UK DFID, should be re-directed to operations research as well as to chronic disease intervention research. Facilitating the application and diffusion of new health technologies and policies will yield the highest return on the aid dollar.

Finally, as illustrated by Annex Figure 1.1 presenting the total money metric value of years of life lost as per cent of GDP for selected regions for the period 1900-2050, the biggest decline has taken place in less developed regions where the ratio has fallen from 35 per cent to 12 per cent in the last century and expected to fall to 6.5 percent in 2050. The world as a whole has experienced a development bringing it from 32 per cent to 5 per cent in the same period. This is both a result of improved human health and economic growth.

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Table 2.1
Input Parameters -- e_0 and e_5 (years), q_5 (per thousand live births), and b (millions of births), selected countries and country groupings, 1900-2050

Geographical area	Life expectancy at birth, e_0 (years)				Life expectancy at age 5, e_5 (years)				Under-5 mortality rate, q_5 per thousand live births				Births per year (millions)		
	1900	1950	2000	2050	1900	1950	2000	2050	1900	1950	2000	2050	1950	2000	2050
World[a]	32	47	66	76	40	53	67	73	335	167	77	31	98.3	133.9	121.7
China[b]	28	41	72	79	36	49	69	75	344	194	32	12	25.0	18.1	14.2
India[c]	23	38	62	73	32	43	63	71	464	227	90	39	16.9	27.6	19.8
Japan[d]	45	62	82	87	52	62	78	83	220	77	4	3	2.0	1.1	0.7
United States[e]	49	69	78	83	55	66	70	80	182	35	8	5	4.0	4.2	4.6
Sub-Saharan Africa[f]	20	38	50	66	31	43	54	65	500	270	161	58	9.3	28.9	35.1
More developed regions[g]	47	66	76	83	54	65	72	78	190	59	9	5	18.7	13.4	13.0
Less developed regions[g]	26	41	64	74	34	46	65	72	415	219	85	34	79.6	120.5	108.7

Note: Input parameters e_0 (years), e_5 (years), and q_5 (per 1,000) in 1900, 1950, 2000, and 2050. e_0 for 1950, 2000, 2050, e_5 for 2000, 2050, and q_5 for 2000, 2050 were taken from United Nations (2009).

[a]Acemoglu and Johnson (2007) and weighted average from other country/regions using CCC (2011) for the weights.

[b]Riley (2005) and weighted average from other country/regions using CCC (2011) for the weights.

[c]Riley (2005) and authors' assumption.

[d]Davis (1951) and authors' assumption.

[e]Kinsella (1992), Human Mortality database (2011), and authors' assumption.

[f]CDC (2004).

[g]Feachem and Jamison (1991) and authors' assumption.

Table 2.2
Years of life lost per birth (YLLs), Selected countries and country groupings, over and under age 5, and total, 1900-2050

	(a) Under-5 YLLs (YLL_{u5})				(b) Over-5 YLLs (YLL_{a5})				(c = a + b) Total YLLs (unweighted)			
	1900	1950	2000	2050	1900	1950	2000	2050	1900	1950	2000	2050
World	28.9	14.3	6.5	2.4	16.7	15.6	9	5.7	45.6	29.9	15.5	8.2
China	29.7	16.6	2.5	0.8	18.4	17.1	8.1	4.4	48.1	33.7	10.6	5.2
India	40.2	19.5	7.6	3.1	15.1	19.3	11.3	6.7	55.2	38.8	18.9	9.8
Japan	18.9	6.4	0.1	0	14.5	12.3	2.7	0	33.4	18.6	2.8	0
United States	15.6	2.8	0.4	0.2	14	10.4	6.5	1.8	29.6	13.2	6.9	2
Sub-Saharan Africa	43.3	23.3	13.7	4.7	13.7	17.7	14.6	10.8	57	41	28.3	15.5
More developed regions	16.3	4.9	0.5	0.2	14.3	11.3	7.1	2.5	30.6	16.1	7.6	2.6
Less developed regions	35.9	18.8	7.1	2.7	16.3	15.6	9.9	6.4	52.2	34.4	17	9.1

Event	Excess deaths (millions)	Population affected (millions)	YLL per capita[a]
World War I (1914-18)	17	1,803	0.62
Influenza pandemic (1918)	50	1,843	1.22
World War II (1937-45)	71	2,275	3.14
Bengal famine (1943)	3	401	0.50
Chinese famine (1958-61)	29	637	3.03

Table 2.3 Years of Life Lost (YLL) per person, major mortality shocks of the 20th century

[a]The YLLs per capita are calculated based on the total number of excess deaths over the indicated time period, not per year (as are most YLLs reported in this paper).

Source: Ashton et al. (1984), Devereux (2000), Wikipedia (2011), Johnson et al (2002), Copenhagen Consensus Center (2011), United Nations (2009).

Table 2.4
Value of statistical life years of life lost per birth (YLL_{VSL}), money metric value of years of life lost per birth (MMVYLL), and ratio *a* of MMVYLL over lifetime income per capita, selected countries and country groupings, 1900-2050

	YLL_{VSL}				MMVYLL				Ratio *a*			
	1900	1950	2000	2050	1900	1950	2000	2050	1900	1950	2000	2050
World	64.7	46.6	25	14.1	$40,737	$49,347	$74,140	$132,008	2.1	1.5	0.8	0.5
China	68.9	52.1	19	9.6	37,545	23,349	64,883	200,644	2.4	1.9	0.7	0.3
India	73.5	59.7	30.8	16.8	44,038	36,977	58,343	154,800	3.5	2.9	1.5	0.8
Japan	49.5	31.4	5.5	0	58,384	63,054	113,222	0	1.1	0.7	0.1	0
United States	44.8	23.8	13.5	3.8	179,985	221,036	370,334	212,861	0.9	0.5	0.3	0.1
Sub-Saharan Africa	74.2	60.5	44	26.7	22,305	27,688	31,398	40,643	3.9	3.1	2.3	1.4
More developed regions	46.2	27.8	14.7	5.1	56,588	65,027	128,389	112,704	1	0.6	0.3	0.1
Less developed regions	71.3	51.5	27.5	15.6	22,417	22,071	42,646	127,586	3	2.2	1.2	0.7

Note: YLL_{VSL} are calculated from the per person YLLs reported in Table 2.3 in the following: $YLL_{VSL} = 2\ (YLL_{a5} + 0.54\ YLLu_5)$; MMVYLL are calculated from the YLL_{VSL} in the following: MMVYLL = YLL_{VSL} x GDP per capita, where GDP per capita is expressed in 1990 international Geary Khamis dollars; *a* is calculated as MMVYLL divided by the lifetime income per capita as defined by eqn 2.8 in the main text.

Table 3.1 Child mortality in Liverpool (1860s) and Sub-Saharan Africa (2008)

	Liverpool	sub-Saharan Africa
Under-5 mortality rate (per 1000 live births)	460	140
Per capita income (USD)*	3000	1700
Diseases		
Acute respiratory infections	17%	18%
Birth trauma/asphyxia	11%	8%
Diarrhea	12%	19%
Pulmonary vascular disease	19%	6%
TB	4%	-
Smallpox	1%	-
Malaria	0%	16%
Other infections	1%	18%
Injuries	4%	2%
Sub-total	**69%**	**87%**

* Adjusted to 1990 level

Source: Farr (1876), cited in Humphreys et al (2000) and Lopez et al (2006).

Table 3.2 Key discoveries in disease transmission and vaccines

Knowledge of transmission (and discoverer)	Vaccines (and discoverers)
1847 Measles (Panum)	1798 Smallpox (Jenner, plus 8th century China)
1847 Puerperal fever (Semmeweiss, Holmes)	1885 Rabies (Pasteur)
1854 Cholera (Snow)	1892 Diptheria (von Behring)
1859 Typhoid (Budd)	1896 Cholera (Kolle)
1867 Surgical sepsis (Lister)	1906 Pertussis (Bordet-Gengou)
1898 Malaria (Ross)	1921 TB (BCG)
1900 Yellow Fever (Reed)	1927 Tetanus (Ramon, Zoeller)
1850-1920s, quarantine methods, sanitation improvements, case detection, contact tracing, and other public health efforts	1930 Yellow Fever (Theiler)
	1935 Sulfonamides (Ehrlich)
	1941 Penicillin (Fleming)
	1944 Streptomycin (Waksman)
	1948 Broad spec antibiotics (various)
	1948 DTP (various)
	1950 Polio (Salk)
	1954 Measles (Enders, Pebbles)

Source: Modified from Easterlin (1999).

Table 3.3 Examples of science contribution to declines in infectious disease mortality in the second half of the 20th century

Condition and intervention	Annual deaths prior to intervention (and ref year) in thousands	Annual deaths after intervention (and ref year) in thousands
Immunization services - against polio, diphtheria, pertussis, tetanus and measles	~5,200 (1960)	1,400 (2001)
Eradication campaign – smallpox	~3,000 (1950)	0 (1979)
Diarrhea- oral rehydration therapy	~ 4,600 (1980)	1,600 (2001)

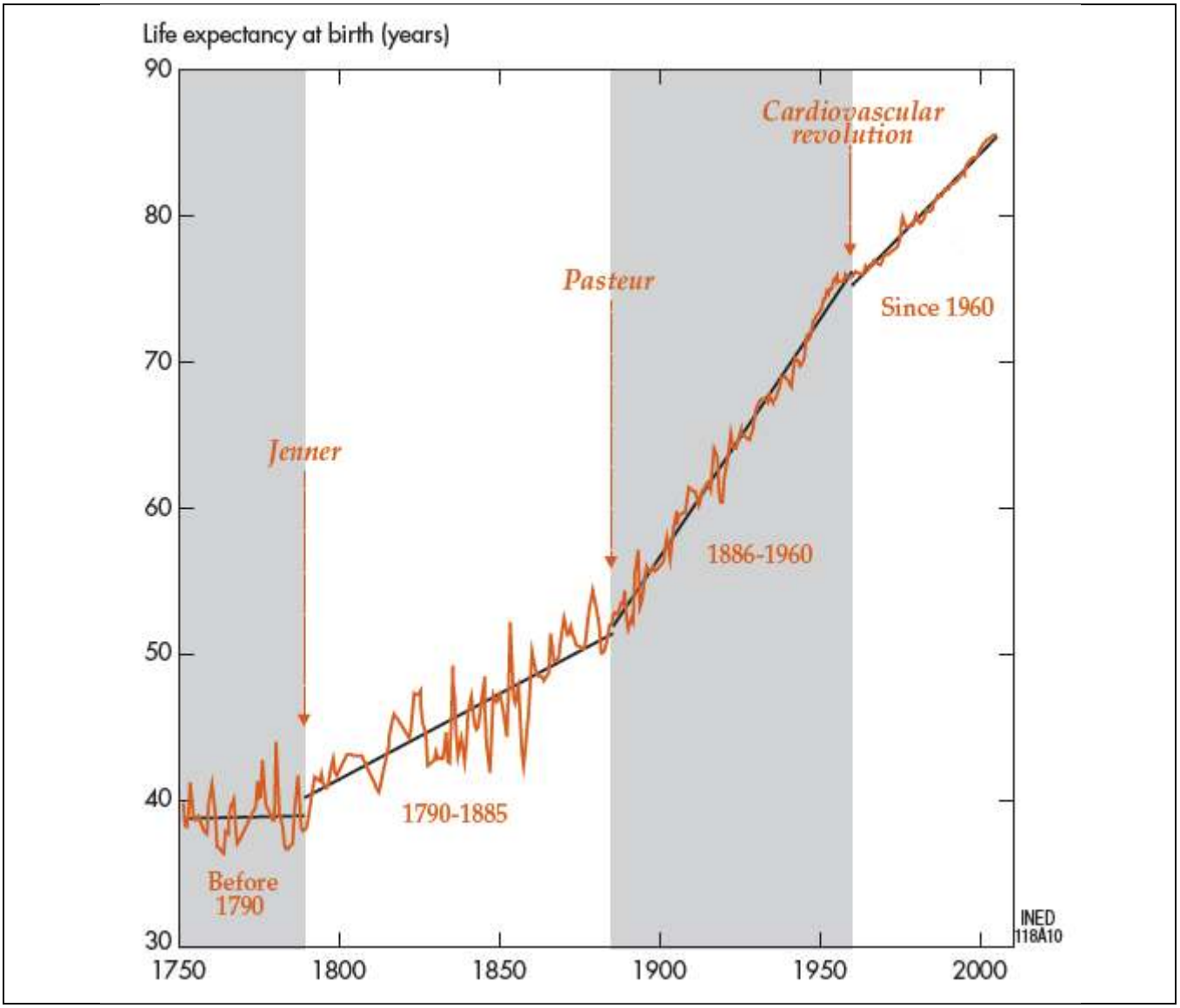
Source: Jamison, D.T., Jha, P. and Bloom, D.E. (2008).

Table 3.4 Infectious Diseases Responsible for LDC Mortality Declines and Related Control Measures

Dominant Mode of Transmission	Diseases	Approximate Percentage Of Mortality Decline In LDCs, 1900-1970, accounted for by disease	Principal Method of Prevention Deployed*	Principal Methods of Treatment Deployed*
Airborne	Influenza/Pneumonia/Bronchitis	30		Antibiotics
	Respiratory tuberculosis	10	Immunization; identification and isolation	Chemotherapy
	Smallpox	2		Chemotherapy
	Measles	1	} Immunization	
	Diphtheria and pertussis	2		Antibiotics
	Sub-total Airborne	**45**		
Water, food, and feces borne	Gastroenteritis	7	} Purification and increased supply of water; sewage disposal; personal sanitation	Rehydration
	Cholera	1		
	Typhoid	1		Rehydration, antibiotics
	Sub-total water, food, feces borne	**9**		
Vector borne	Malaria	13-33	Insecticides, drainage, larvicides	Quinine drugs
	Typhus	1	Insecticides, partially effective vaccines	Antibiotics
	Plague	1	Insecticides, rat control, quarantine	
	Sub total vector-borne	**15-35**		
	TOTAL	**69-89**		

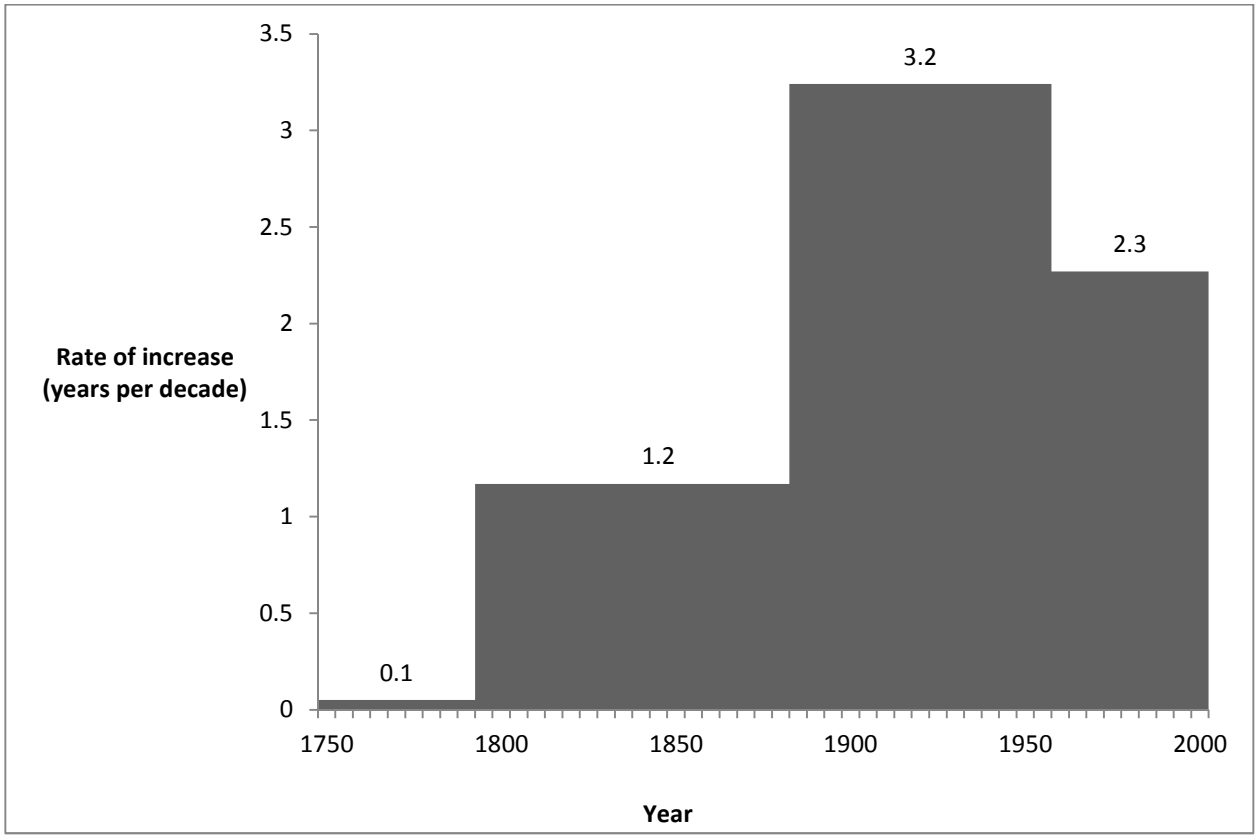
Source: Modified from Preston (1980).

Figure 1.1 Highest observed national female life expectancies at a given moment in the world (1750-2005)



Source: Vallin and Meslé (2010).

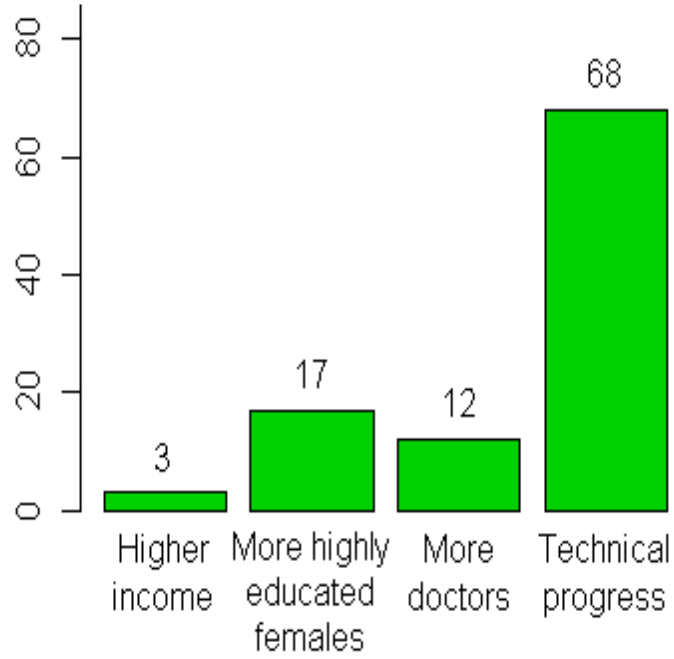
Figur 1.2: The rate of increase in highest female life expectancy, years per decade



Source: Adapted from Vallin and Meslé (2009, Figure 9).

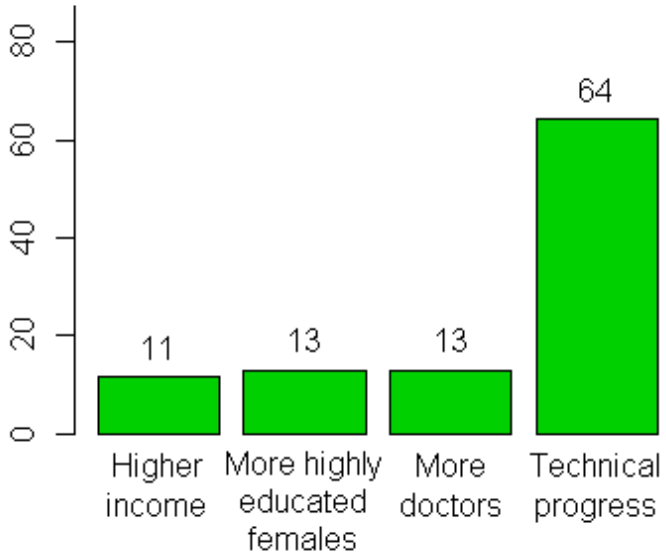
Figure 1.3 Factors accounting for decline in child mortality, 1970-2000

Panel A: All low- and middle-income countries:



Note: Child mortality (5q0) across all low- and middle-income countries declined by 52% between 1970 and 2000 - from 130 per thousand to 62 per thousand, ie at an average rate of 3.5% per year. This graph shows the fraction of the decline that can be attributed to several specific factors.

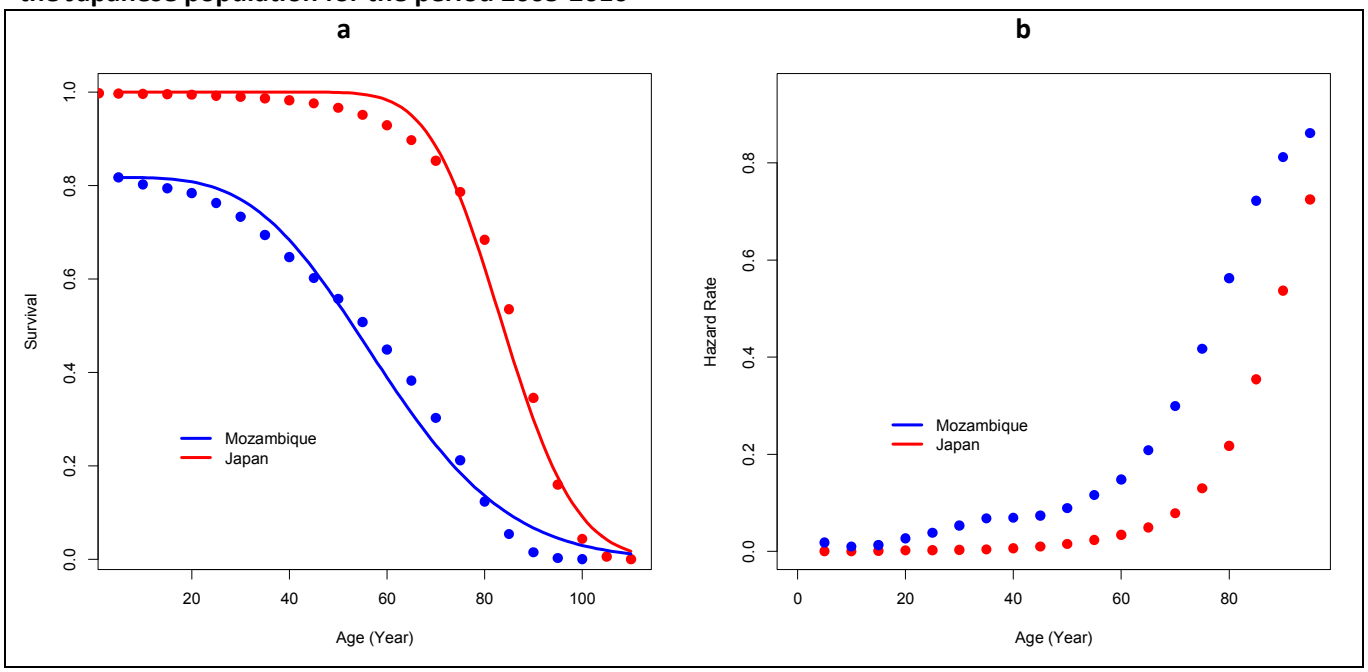
Panel B: India:



Note: Child mortality (5q0) in India declined by 58% between 1970 and 2000 - from 188 per thousand to 80 per thousand, ie at an average rate of 2.9% per year. This graph shows the fraction of the decline that can be attributed to several specific factors.

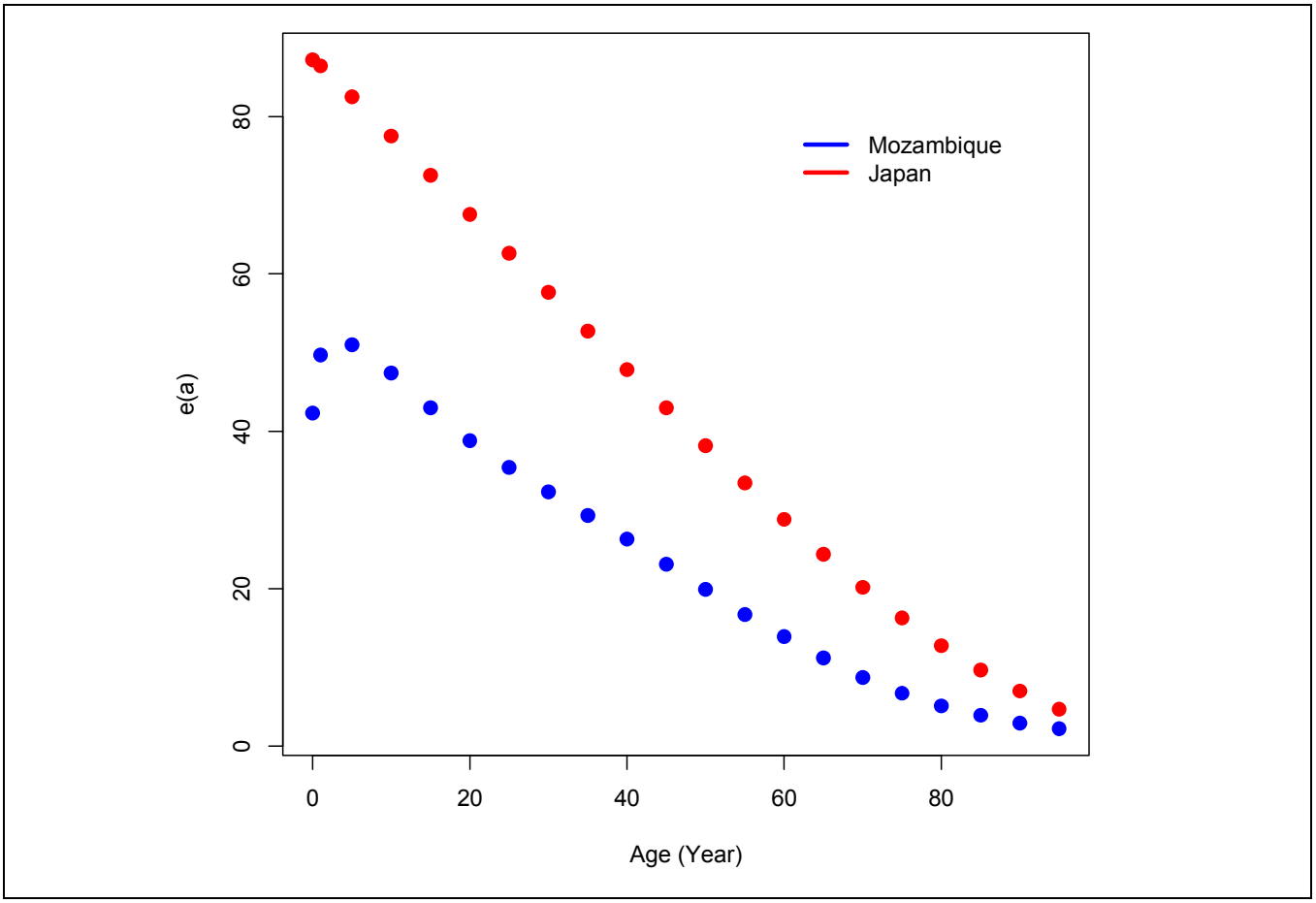
Source: Jamison, et al (2012).

Figure 2.1 Empirical (dots) and fitted (line) survival curves (a), and hazard rates (b) as a function of age, for the Japanese population for the period 2005-2010



Sources: For Japan, United Nations (2009); For Mozambique, World Health Organization (2004).

Figure 2.2 Life expectancy as a function of age for JPN2050 (red), and the Mozambican population in 1990 (blue)



Source: United Nations (2009), World Health Organization (2004).

Figure 2.3 Hypothetical survival curves for different values of the couplet *(e_5, b).* On the left-hand side, *e_5 = 40*; on the right hand side *e_5 = 80.* On both figures, *b* takes the following values: *b* = 0.1 (purple), 0.5 (green), 1.3 (gray)

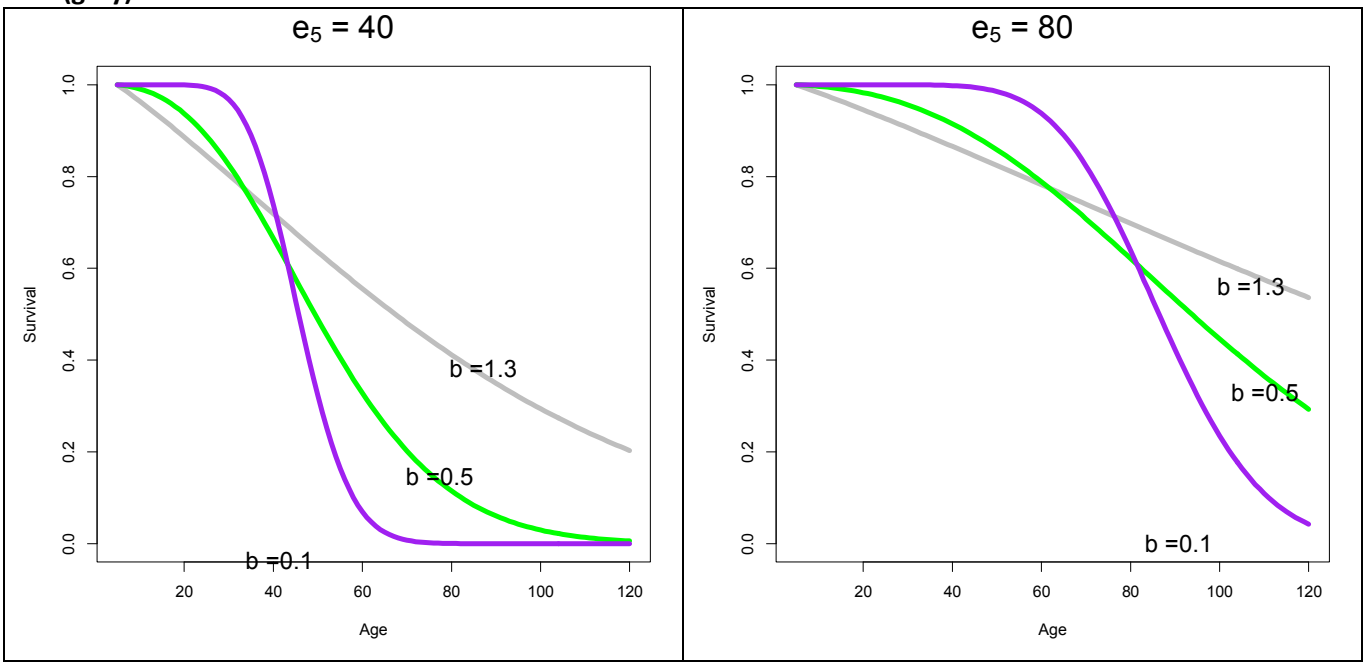


Figure 2.4 Empirical relationship between rectangularity of the survival curve age 5 onward, *b,* as a function of life expectancy at age 5, *e_5*. The regression line for lower life expectancies (*e_5 < 65*) is *$b = 1.19 - 0.017\ e_5$, $R^2 = 0.86$*

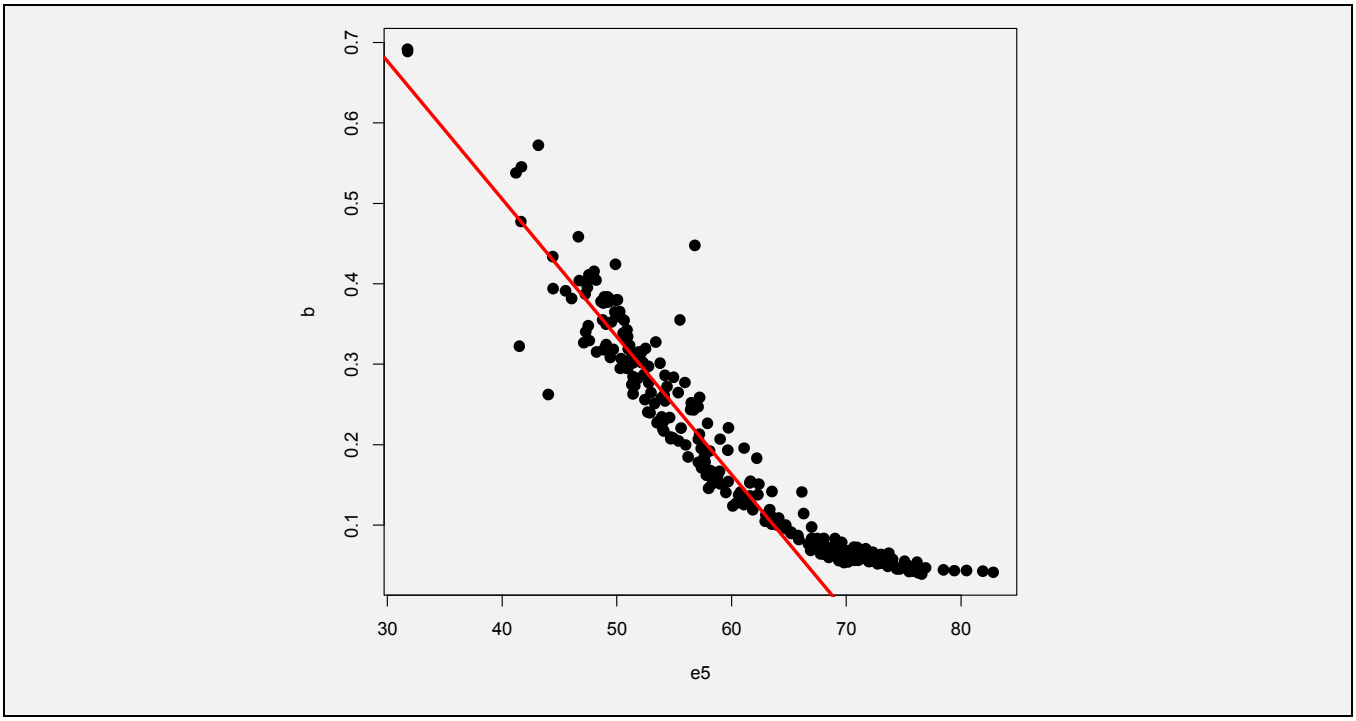


Figure 2.5 Years of life lost (YLL*) over the period 1900-2050 for the world, the 'less developed regions' and the 'more developed regions'

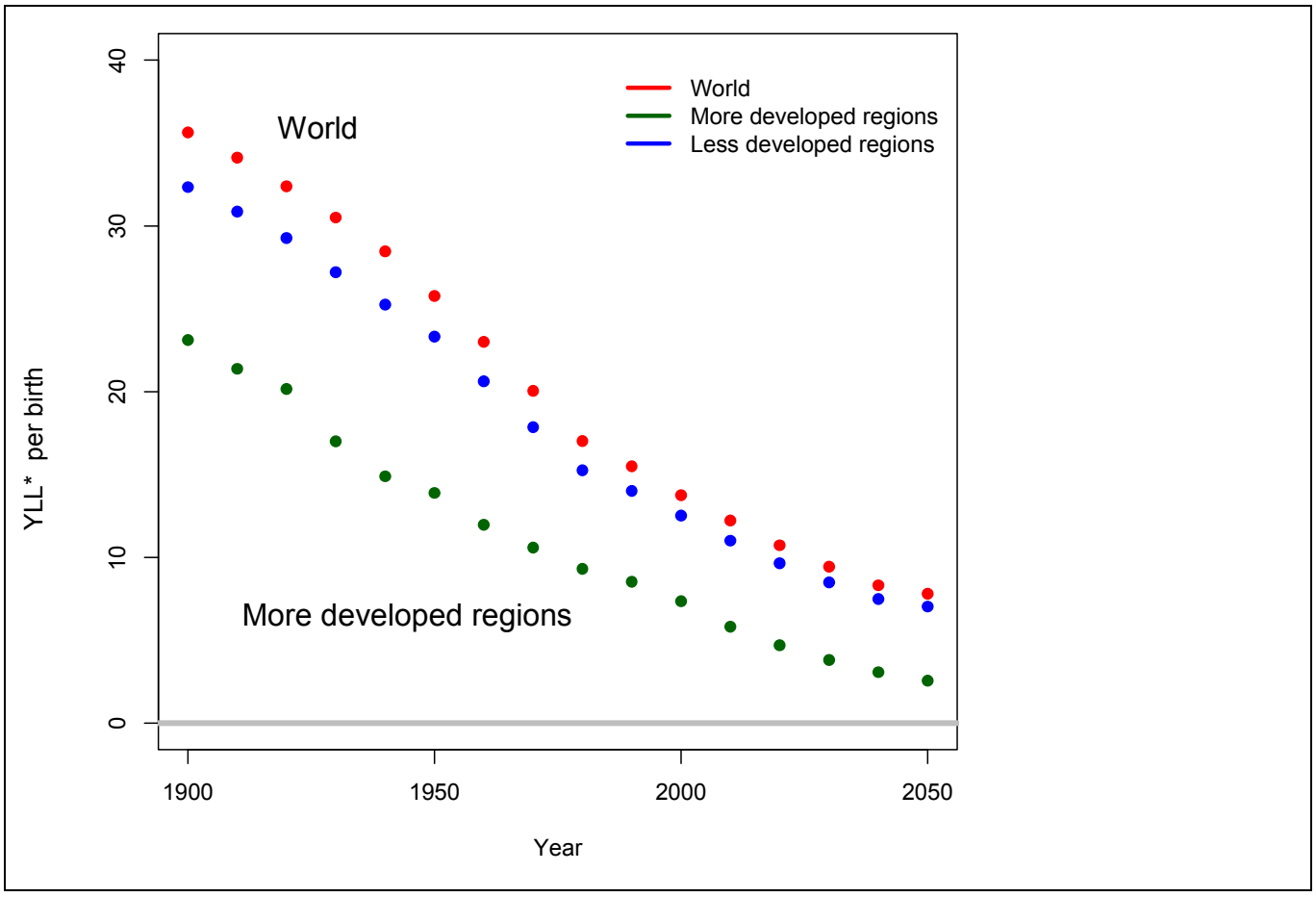
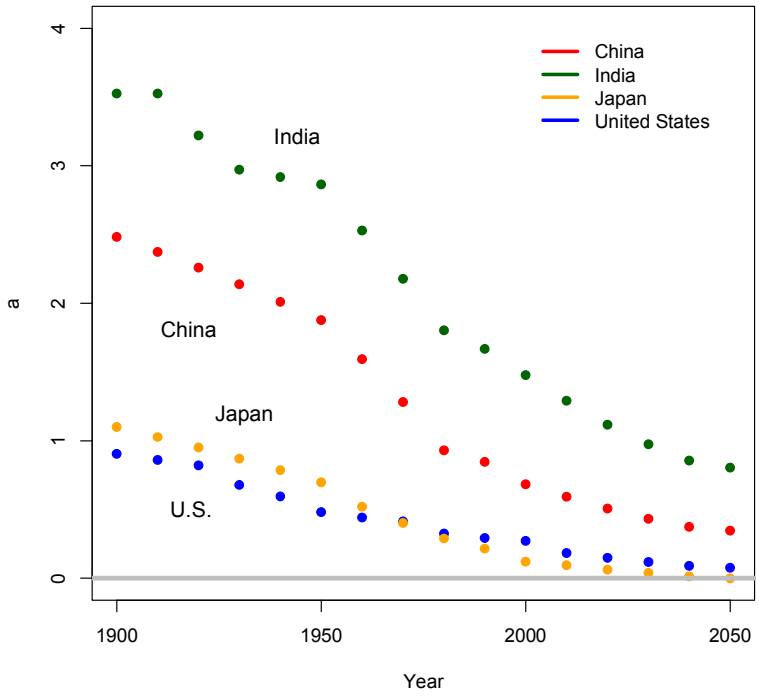


Figure 2.6 Ratio *a* over the period 1900-2050 for: (a) country groupings i.e the world, the 'less developed regions', the 'more developed regions', Sub-Saharan Africa; (b) countries i.e. India, China, Japan, the United States

a)



b)

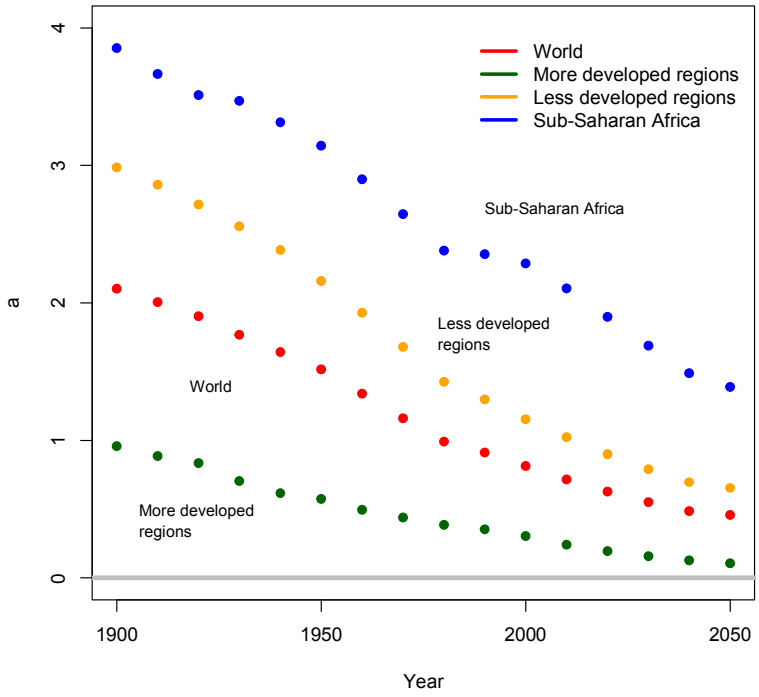


Figure 3.1 Under-5 Years of Life Lost Per Person (YLLs) as a Percent of Total YLLs, 1990-2050

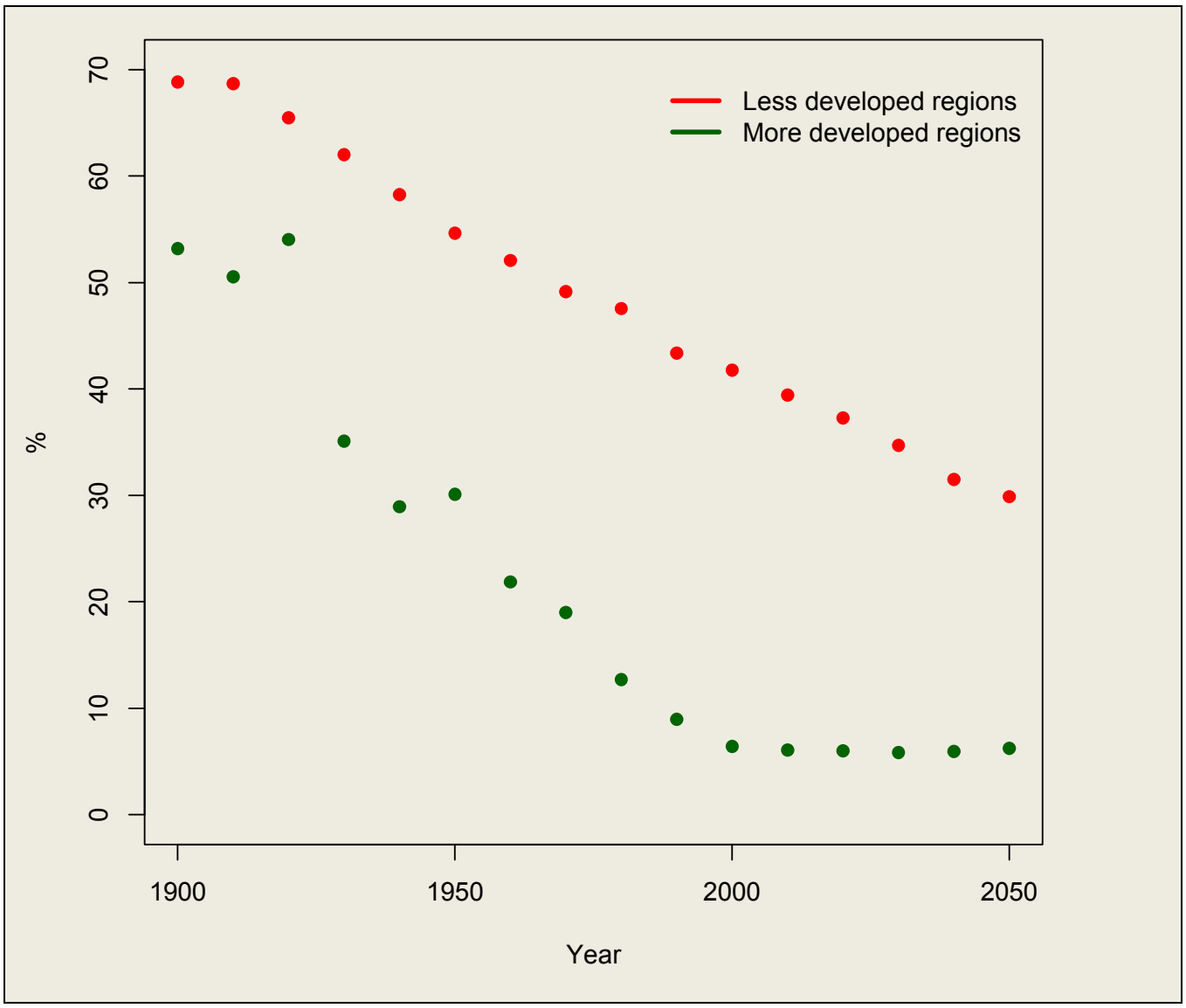
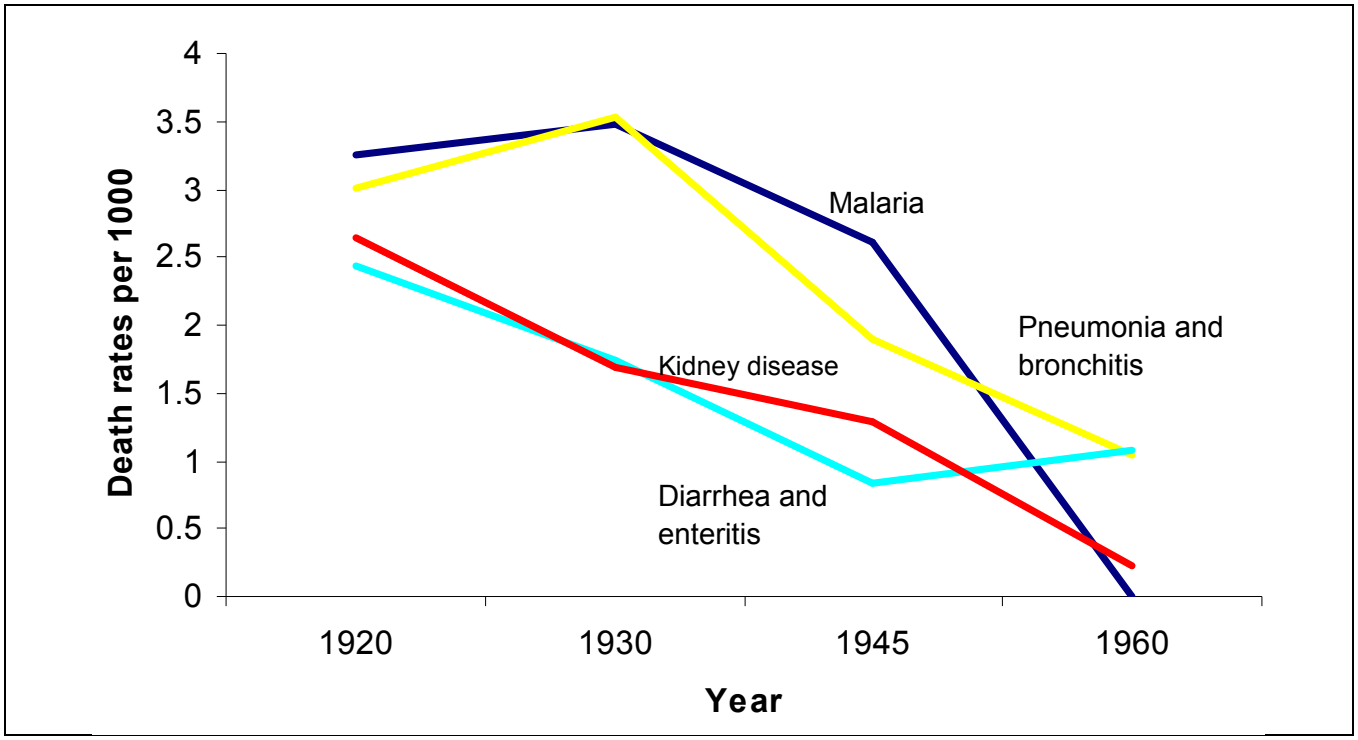
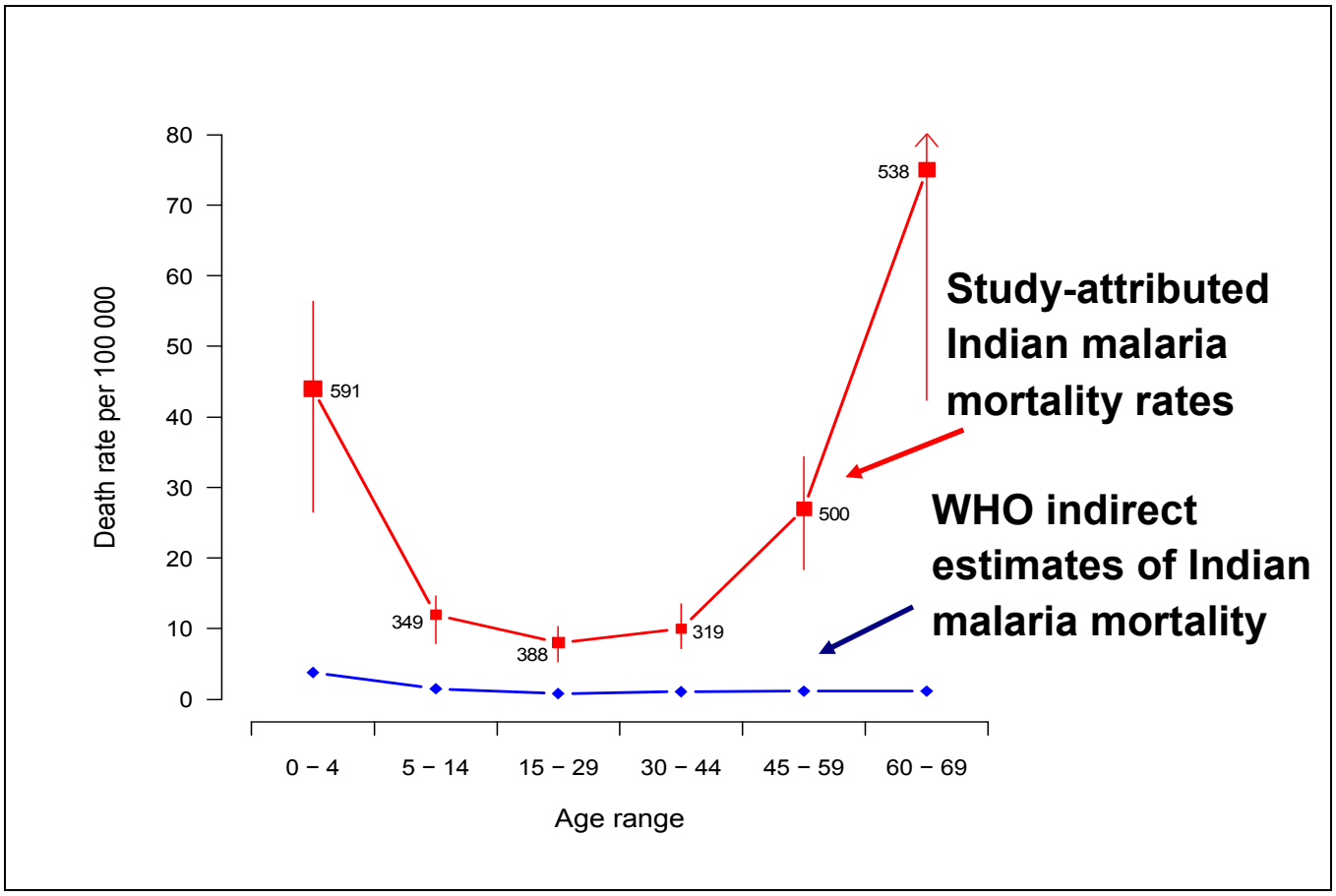


Figure 3.2 British Guyana mortality trends and specific diseases



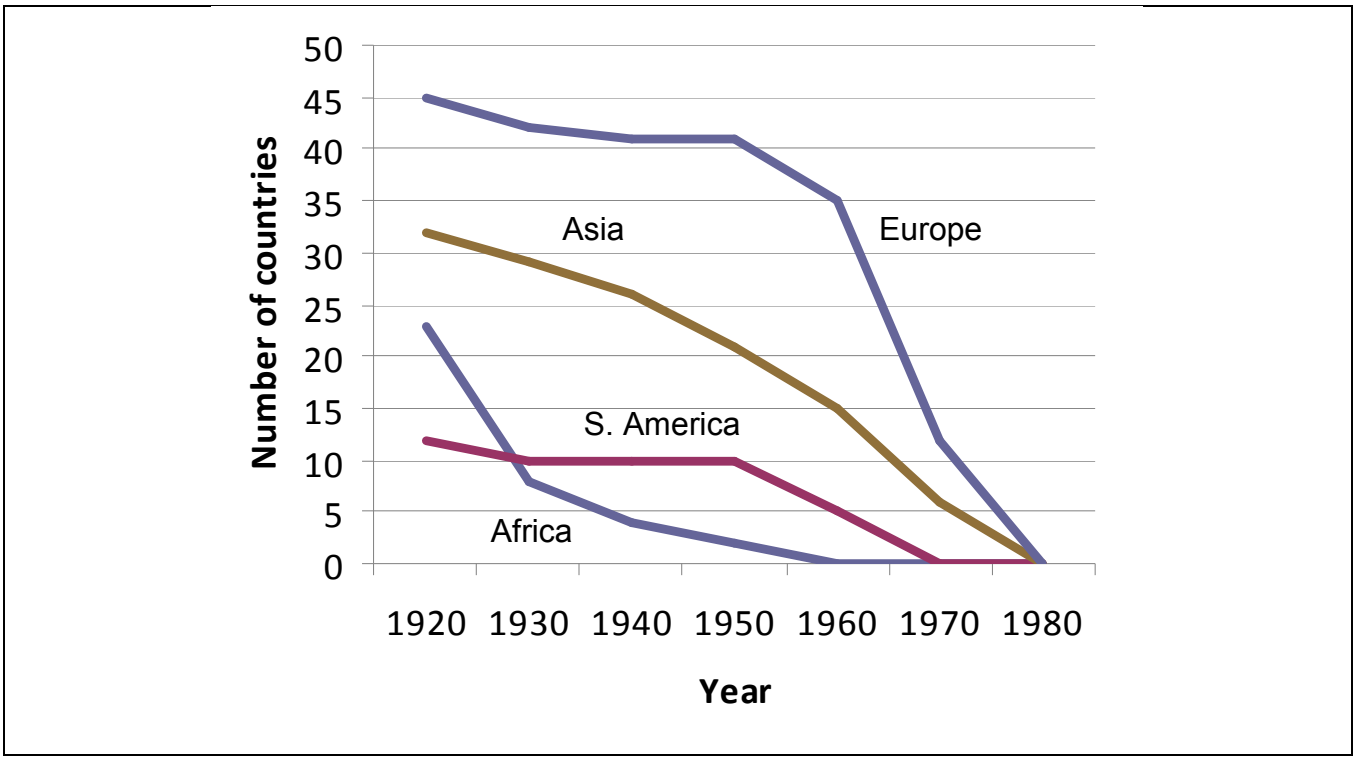
Source: Author calculation from Mandle (1970).

Figure 3.3 Age-specific all-India malaria-attributed death rates estimated from a large mortality study and those estimated indirectly for WHO



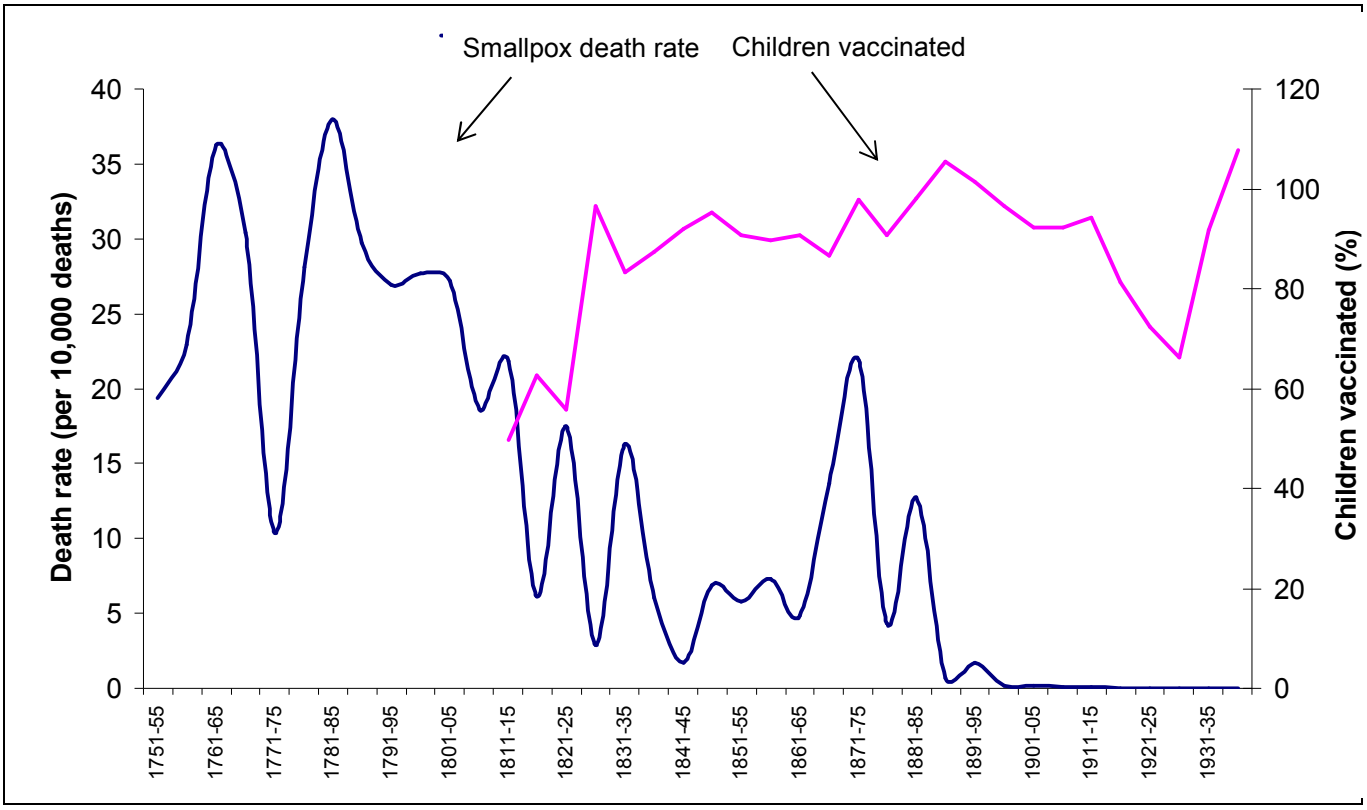
Source: Dhingra et al (2010).

Figure 3.4 Number of Countries Reporting Smallpox by Region, 1920-80



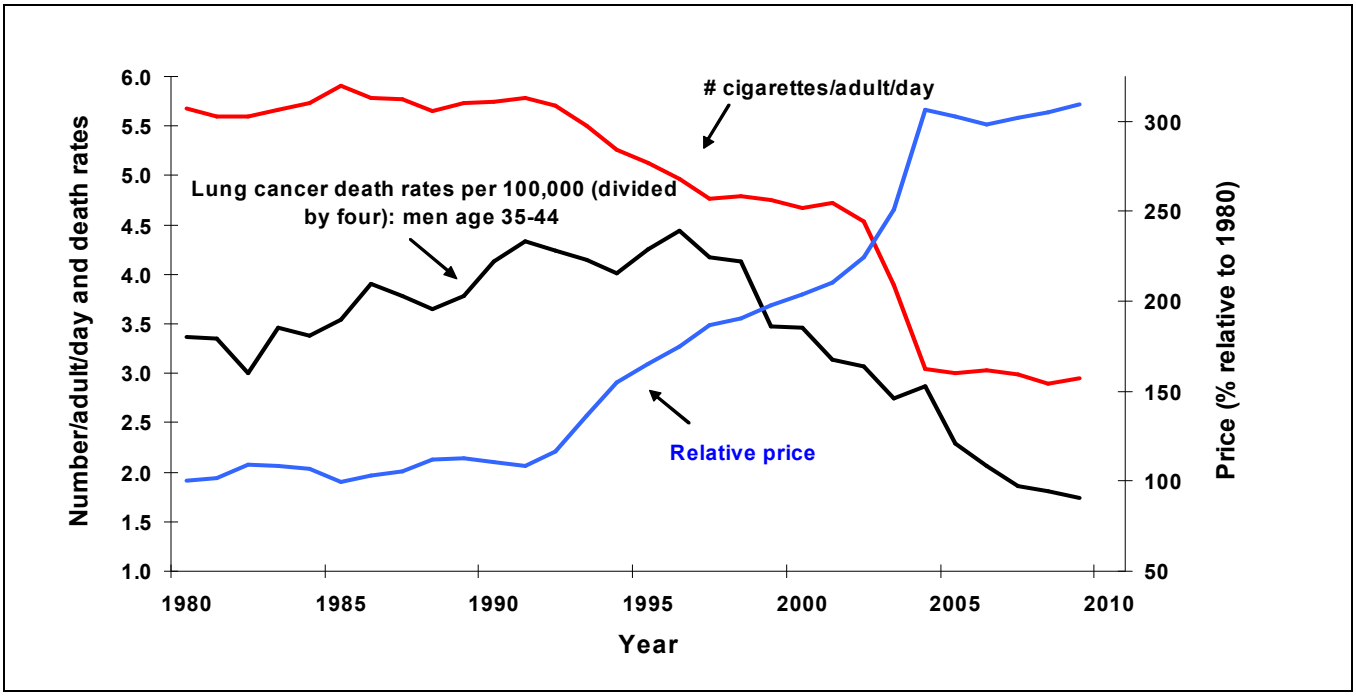
Source: Fenner (1988).

Figure 3.5 Trends in smallpox deaths and immunization, Finland, 1750-1935



Source: Pitkanen, K.J., Mielke, J.H., and Jorde, L.B. (1989).

Figure 3.6 France: Smoking, tobacco prices, and male lung cancer rates at young ages, 1980-2010



Source: Hill (2010).

Annex 1:

In this paper, we developed measurements of 20th century mortality reductions in terms of reduction in the expected number of years of life lost (YLLs) by a typical individual relative to an idealized norm. The norm chosen in the main text of the paper is the United Nations' projected mortality profile for Japan in 2050, named 'Japan 2050'. This Annex 1 presents all the results obtained under this assumption (Annex Tables 1.1 – 1.5).

Annex Figure 1.1 illustrates the total money metric value of years of life lost as per cent of GDP for selected regions for the period 1900-2050. The biggest decline has taken place in less developed regions where the ratio has fallen from 35 per cent to 12 per cent in the last century and expected to fall to 6.5 percent in 2050. The world as a whole has experienced a development bringing it from 32 per cent to 5 per cent in the same period. This is both a result of improved human health and economic growth.

Annex Table 1.1 Years of life lost per person under 5 (YLL_{u5}) (in years), selected countries and regions, 1900 – 2050

Year	China	India	Japan	USA	Sub-Saharan Africa	More Developed Regions	Less Developed Regions	World
1900	29.7	40.2	18.9	15.6	43.3	16.3	35.9	28.9
1910	27.1	40.2	16.4	13.8	39.3	14.1	34.3	27.1
1920	24.5	35.0	13.9	14.2	35.3	14.5	30.4	24.8
1930	21.9	29.7	11.4	6.7	31.3	7.1	26.5	19.8
1940	19.2	24.6	8.3	4.7	27.3	5.0	22.6	16.6
1950	16.6	19.5	6.4	2.8	23.3	4.9	18.8	14.3
1960	12.8	16.9	2.6	2.3	21.2	2.9	15.8	11.8
1970	9.0	14.3	1.1	1.7	19.1	2.2	12.7	9.8
1980	5.1	11.7	0.5	0.8	17.1	1.3	10.4	9.2
1990	3.2	9.4	0.2	0.6	15.8	0.8	8.4	7.6
2000	2.5	7.6	0.1	0.4	13.7	0.5	7.1	6.5
2010	2.0	6.1	0.1	0.3	11.3	0.4	5.9	5.3
2020	1.5	4.9	0.0	0.3	9.1	0.3	4.8	4.4
2030	1.2	4.1	0.0	0.2	7.1	0.2	3.9	3.5
2040	0.9	3.4	0.0	0.2	5.4	0.2	3.1	2.8
2050	0.8	3.1	0.0	0.2	4.7	0.2	2.7	2.4

Annex Table 1.2 Years of life lost per person above 5 (YLL_{a5}) (in years), selected countries and regions, 1900-2050

Year	China	India	Japan	USA	Sub-Saharan Africa	More Developed Regions	Less Developed Regions	World
1900	18.4	15.1	14.5	14.0	13.7	14.3	16.3	16.7
1910	18.3	15.1	14.3	13.9	14.1	13.8	15.6	16.2
1920	18.1	14.7	13.9	12.7	14.7	12.3	16.0	15.9
1930	17.9	14.9	13.5	13.2	16.5	13.2	16.2	16.5
1940	17.5	17.1	12.9	12.2	17.2	12.2	16.2	16.3
1950	17.1	19.3	12.3	10.4	17.7	11.3	15.6	15.6
1960	15.2	17.2	10.3	9.7	16.4	10.4	14.5	14.3
1970	12.9	15.0	8.5	9.3	15.1	9.4	13.2	12.6
1980	10.2	12.5	6.2	7.6	13.7	8.6	11.4	10.3
1990	10.0	12.3	4.7	6.9	14.1	8.1	11.0	9.9
2000	8.1	11.3	2.7	6.5	14.6	7.1	9.9	9.0
2010	7.1	10.2	2.1	4.4	14.2	5.6	9.0	8.1
2020	6.2	9.0	1.4	3.6	13.4	4.5	8.1	7.3
2030	5.4	8.0	0.8	2.8	12.4	3.7	7.3	6.6
2040	4.7	7.1	0.3	2.2	11.4	3.0	6.7	6.0
2050	4.4	6.7	0.0	1.8	10.8	2.5	6.4	5.7

Annex Table 1.3 Total years of life lost per person, selected countries and regions, 1900-2050

Year	China	India	Japan	USA	Sub-Saharan Africa	More Developed Regions	Less Developed Regions	World
1900	48.1	55.2	33.4	29.6	57.0	30.6	52.2	45.6
1910	45.4	55.2	30.6	27.6	53.4	27.9	49.9	43.3
1920	42.6	49.7	27.8	26.9	50.0	26.8	46.4	40.7
1930	39.7	44.7	24.8	19.9	47.8	20.3	42.7	36.3
1940	36.8	41.8	21.8	16.9	44.4	17.2	38.9	32.9
1950	33.7	38.8	18.6	13.2	41.0	16.1	34.4	29.9
1960	28.0	34.2	12.9	12.0	37.7	13.3	30.3	26.0
1970	21.9	29.3	9.6	11.0	34.3	11.6	25.9	22.4
1980	15.3	24.2	6.7	8.4	30.8	9.9	21.8	19.5
1990	13.2	21.7	5.0	7.5	29.9	8.9	19.4	17.5
2000	10.6	18.9	2.8	6.9	28.3	7.6	17.0	15.5
2010	9.1	16.3	2.2	4.7	25.5	6.0	14.9	13.5
2020	7.7	13.9	1.4	3.8	22.5	4.8	13.0	11.7
2030	6.6	12.0	0.8	3.0	19.5	3.9	11.2	10.1
2040	5.6	10.5	0.3	2.3	16.8	3.2	9.7	8.8
2050	5.2	9.8	0	2.0	15.5	2.6	9.1	8.2

Note: Values in this table are the sum of the values in the corresponding columns of Annex Tables 1 and 2.

Annex Table 1.4 Money metric value of years of life lost, MMVYLL, selected countries and regions, 1900-2050

Year	China	India	Japan	USA	Sub-Saharan Africa	More Developed Regions	Less Developed Regions	World
1900	$37,545	$44,038	$58,384	$179,985	$22,305	$56,588	$22,417	$40,737
1910	36,360	51,242	60,279	209,524	22,200	61,397	23,338	45,089
1920	35,106	42,665	72,592	219,538	24,049	68,458	24,410	48,913
1930	33,707	45,009	72,512	202,389	25,411	63,308	24,543	49,180
1940	31,373	41,759	101,726	201,551	25,947	60,974	24,499	49,545
1950	23,349	36,977	63,054	221,036	27,688	65,027	22,071	49,347
1960	29,267	39,726	93,383	240,188	30,018	78,018	25,765	57,497
1970	27,656	39,436	175,897	297,719	34,401	102,065	28,604	66,633
1980	27,424	35,273	174,749	291,074	34,556	114,580	31,135	68,588
1990	43,910	45,546	182,260	323,635	31,964	127,442	35,213	71,084
2000	64,883	58,343	113,222	370,334	31,398	128,389	42,646	74,140
2010	125,591	88,164	100,540	285,432	36,019	120,677	58,017	84,808
2020	151,431	110,980	80,206	276,589	35,347	115,508	66,593	89,386
2030	169,830	126,952	56,363	255,791	35,529	111,768	78,947	98,168
2040	181,503	138,210	24,224	222,368	36,229	109,962	96,236	109,584
2050	200,644	154,800	0.0	212,861	40,643	112,704	127,586	132,008

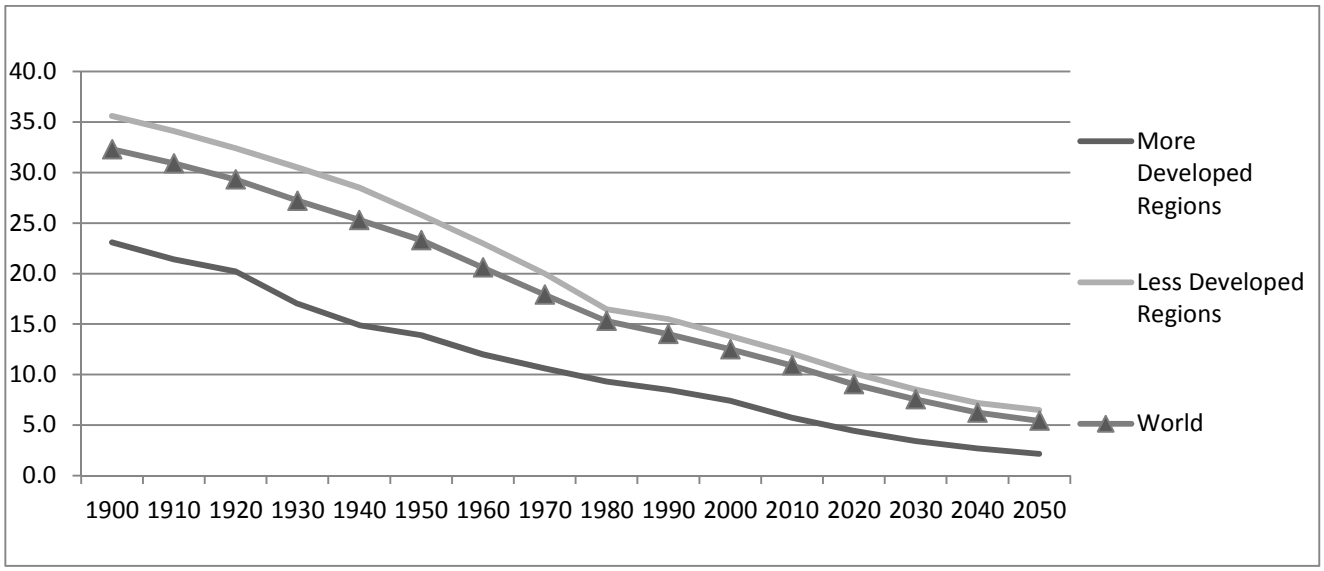
Note: Entries in this table are calculated from the per person YLLs reported in Annex Tables 1 and 2 by multiplying those $YLL^{*} = YLL_{a5} + 0.54YLL_{u5}$ by twice per capita GDP expressed in 1990 international Geary Khamis dollars.

Annex Table 1.5 Ratio *a* of money metric value of years of life lost (MMVYLL) per lifetime income per capita (LI) (no units), selected countries and regions, 1900-2050

Year	China	India	Japan	USA	Sub-Saharan Africa	More Developed Regions	Less Developed Regions	World
1900	2.4	3.5	1.1	0.9	3.9	1.0	3.0	2.1
1910	2.4	3.5	1.0	0.9	3.7	0.9	2.9	2.0
1920	2.3	3.2	1.0	0.8	3.5	0.8	2.7	1.9
1930	2.1	3.0	0.9	0.7	3.5	0.7	2.6	1.8
1940	2.0	2.9	0.8	0.6	3.3	0.6	2.4	1.6
1950	1.9	2.9	0.7	0.5	3.1	0.6	2.2	1.5
1960	1.6	2.5	0.5	0.4	2.9	0.6	1.9	1.3
1970	1.3	2.2	0.4	0.4	2.6	0.5	1.7	1.2
1980	0.9	1.8	0.3	0.3	2.4	0.4	1.4	1.0
1990	0.8	1.7	0.2	0.3	2.4	0.4	1.3	0.9
2000	0.7	1.5	0.1	0.3	2.3	0.3	1.2	0.8
2010	0.6	1.3	0.1	0.2	2.1	0.2	1.0	0.7
2020	0.5	1.1	0.1	0.1	1.9	0.2	0.9	0.6
2030	0.4	1.0	0.0	0.1	1.7	0.2	0.8	0.6
2040	0.4	0.9	0.0	0.1	1.5	0.1	0.7	0.5
2050	0.3	0.8	0.0	0.1	1.4	0.1	0.7	0.5

Note: Entries in this table are calculated from the money metric value of years of life lost MMVYLL reported in Annex Table 4 divided by the lifetime income per capita as defined by eqn 2.8 in the main text.

Annex Figure 1.1 Money metric value of years of life lost, selected regions, 1900-2050, per cent of GDP


40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
1900 1910 1920 1930 1940 1950 1960 1970 1980 1990 2000 2010 2020 2030 2040 2050
More Developed Regions
Less Developed Regions
World

Annex 2

In this paper, we developed measurements of 20th century mortality reductions in terms of reduction in the expected number of years of life lost (YLLs) by a typical individual relative to an idealized norm. The norm chosen in the main text of the paper is the United Nations' projected mortality profile for Japan in 2050, named 'Japan 2050'. An alternative to Japan 2050 as a norm is to use the lowest mortality country at any given time as the norm for that time, named 'frontier country'. This Annex 2 presents all the results obtained under this second assumption. Precisely, Annex Table 2.1 describes the characteristics of countries on this life expectancy frontier. Annex Tables 2.2 through 2.6 are the variants of Annex Tables 1.1 through 1.5. Annex Figure 2.1 compares the YLLs per birth for the 'less developed regions' for the period 1900-2050 for the two different norms, Japan 2050 and frontier country.

Finally, Annex Figure 2.2 illustrates the total money metric value of years of life lost as per cent of GDP for selected regions for the period 1900-2050. The biggest decline has taken place in less developed regions where the ratio has fallen from 23 per cent to 12 per cent in the last century and expected to fall to 7.5 percent in 2050. The world as a whole has experienced a similar but less drastic development from 23 per cent to 8 per cent in the same period. For more developed regions the ratio has been declining expected to reach just 2.2 per cent in 2050.

Annex Table 2.1 Characteristics of countries on the life expectancy frontier

Year	Frontier reference (female life expectancy)	e_0 (females)	e_0 (males)	e_0 (both)	e_5 (both)	q_5 (per 1,000 live births)	YLLs under age 5 per birth	YLLs from age 5 per birth	YLLs per birth[a]
Estimates									
1900	New Zealand[a]	60.3	57.8	59.0	60.4	99	5.9	13.3	19.2
1910	New Zealand	63.6	60.6	61.9	61.8	73	4.6	13.0	17.5
1920	New Zealand	65.0	62.4	63.6	62.7	62	5.0	12.7	17.8
1930	New Zealand	68.2	65.5	66.8	64.7	43	2.8	12.4	15.2
1940	New Zealand	69.4	65.8	67.6	65.3	39	2.6	11.9	14.6
1950	Norway	74.4	70.8	72.6	69.8	30	2.2	11.0	13.2
1960	Norway	75.9	71.1	73.5	70.1	22	1.6	10.8	12.3
1970	Norway	77.6	71.3	74.4	70.5	15	1.1	10.9	12.0
1980	Iceland	79.9	73.8	76.8	72.4	8	0.6	11.3	12.0
1990	Japan	82.3	76.2	79.4	74.9	6	0.5	10.6	11.0
2000	Japan	85.1	78.2	81.9	77.2	4	0.3	10.6	10.9
Projections									
2010	Japan	87.2	80.1	83.7	79.0	4	0.3	10.6	10.9
2020	Japan	88.4	81.2	84.9	80.2	4	0.3	10.4	10.8
2030	Japan	89.5	82.2	85.8	81.1	4	0.3	10.3	10.6
2040	Japan	90.5	83.1	86.8	82.0	3	0.3	10.2	10.5
2050	Japan	91.0	83.5	87.2	82.5	3	0.3	10.1	10.4

Sources: Oeppen and Vaupel (2002), Human Mortality Database (www.mortality.org), United Nations (2009).
Note: The e_0 (females, males, both), and e_5 (both) columns are extracted from full life tables for the frontier country.
[a]This column shows YLLs for the frontier country relative to its own survival curve.
[b]The New Zealand estimates are for New Zealand's non-Maori population.

Annex Table 2.2 Years of life lost per person under 5 (YLL_{u5}) (in years), selected countries and regions, 1900 – 2050 (Variant of text Annex Table 1.1)

Year	China	India	Japan	USA	Sub-Saharan Africa	More developed regions	Less developed regions	World
1900	14.4	21.5	7.1	4.9	23.6	5.3	18.6	13.9
1910	14.9	24.2	7.3	5.4	23.6	5.7	20.0	14.9
1920	13.0	20.7	5.3	5.5	20.9	5.8	17.3	13.3
1930	14.1	20.1	6.1	2.5	21.3	2.8	17.7	12.5
1940	12.5	16.7	4.5	1.3	18.7	1.5	15.2	10.5
1950	11.9	14.3	3.4	0.4	17.5	2.1	13.7	10.0
1960	9.4	12.9	0.8	0.6	16.5	1.1	11.9	8.6
1970	6.8	11.4	0.1	0.7	15.5	1.0	10.0	7.5
1980	4.2	10.0	0.1	0.4	14.7	0.8	8.8	7.8
1990	2.7	8.4	0	0.3	14.2	0.5	7.4	6.7
2000	2.3	7.1	0	0.3	12.8	0.4	6.6	6.0
2010	1.8	5.8	0	0.2	10.8	0.3	5.6	5.1
2020	1.4	4.8	0	0.2	8.8	0.2	4.7	4.2
2030	1.1	4.0	0	0.2	7.0	0.2	3.8	3.4
2040	0.9	3.4	0	0.2	5.4	0.2	3.0	2.7
2050	0.8	3.1	0	0.2	4.7	0.2	2.7	2.4

Annex Table 2.3 Years of life lost per person above 5 (YLL_{a5}) (in years), selected countries and regions, 1900-2050 (Variant of text Annex Table 1.2)

Year	China	India	Japan	USA	Sub-Saharan Africa	More developed regions	Less developed regions	World
1900	5.2	3.3	1.7	1.2	2.4	1.4	3.9	3.9
1910	5.6	3.9	1.9	1.4	3.0	1.3	4.0	4.0
1920	6.0	3.9	2.0	1.0	3.9	0.8	4.6	4.2
1930	6.5	4.6	2.2	1.6	6.0	1.6	5.4	5.2
1940	6.4	6.5	1.9	1.0	6.7	1.2	5.6	5.2
1950	8.8	11.0	3.8	2.4	9.8	3.0	7.6	7.4
1960	7.0	9.1	2.0	1.6	8.7	2.4	6.6	6.1
1970	4.8	7.0	0.5	1.3	7.4	1.6	5.2	4.5
1980	3.5	5.6	0	1.1	7.0	2.1	4.6	3.7
1990	4.8	7.1	0	2.0	9.1	3.1	5.8	4.9
2000	4.9	7.9	0	3.4	11.3	3.9	6.6	5.8
2010	4.6	7.6	0	2.1	11.6	3.2	6.5	5.7
2020	4.5	7.2	0	2.0	11.6	3.0	6.4	5.6
2030	4.4	6.9	0	1.9	11.3	2.7	6.3	5.6
2040	4.3	6.7	0	1.8	11.0	2.6	6.3	5.6
2050	4.4	6.7	0	1.8	10.8	2.5	6.4	5.7

Annex Table 2.4 Total years of life lost per person, selected countries and regions, 1900-2050 (Variant of text Annex Table 1.3)

Year	China	India	Japan	USA	Sub-Saharan Africa	More developed regions	Less developed regions	World
1900	19.7	24.8	8.9	6.0	26.0	6.8	22.6	17.8
1910	20.5	28.1	9.2	6.8	26.6	7.0	24.0	18.9
1920	19.0	24.6	7.3	6.6	24.8	6.5	21.9	17.5
1930	20.7	24.7	8.3	4.1	27.3	4.5	23.1	17.8
1940	19.0	23.2	6.4	2.3	25.4	2.6	20.8	15.7
1950	20.7	25.3	7.2	2.8	27.2	5.2	21.4	17.3
1960	16.5	22.0	2.8	2.2	25.2	3.5	18.5	14.7
1970	11.6	18.4	0.6	2.0	22.9	2.7	15.3	12.0
1980	7.6	15.6	0	1.5	21.7	2.8	13.4	11.5
1990	7.5	15.5	0	2.3	23.3	3.6	13.3	11.6
2000	7.1	15.0	0	3.7	24.1	4.3	13.3	11.8
2010	6.5	13.4	0	2.3	22.4	3.5	12.1	10.7
2020	6.0	12.0	0	2.2	20.4	3.2	11.1	9.8
2030	5.5	10.9	0	2.1	18.3	2.9	10.1	9.0
2040	5.2	10.1	0	2.0	16.4	2.8	9.3	8.3
2050	5.2	9.8	0	2.0	15.5	2.6	9.1	8.2

Note: Values in this table are the sum of the values in the corresponding columns of Annex Tables 2.2 and 2.3.

Annex Table 2.5 Money metric value of years of life lost, MMVYLL, selected countries and regions, 1900-2050 (Variant of text Annex Table 1.4)

Year	China	India	Japan	USA	Sub-Saharan Africa	More developed regions	Less developed regions	World
1900	$14,195	$17,838	$13,177	$30,485	$15,631	$16,656	$14,231	$22,449
1910	15,091	23,637	15,127	42,644	16,729	20,083	16,426	27,579
1920	14,555	19,105	16,436	43,200	17.076	21,012	15,972	28,213
1930	16,008	22,422	20,218	35,544	20,770	16,758	18,589	32,184
1940	14,838	21,258	24,765	23,141	20,660	10,649	17,880	30,745
1950	13,658	23,167	21,507	48,725	24,855	24,327	18,308	36,640
1960	16,039	24,238	19,092	41,479	27,113	22,755	20,724	41,029
1970	13,153	22,784	10,816	49,263	30,893	25,998	21,882	44,670
1980	12,062	20,173	0	47,273	32,745	34,497	25,330	51,554
1990	23,394	30,425	0	96,596	32,809	53,976	30,215	58,898
2000	41,594	44,379	0	192,245	34,396	74,604	41,101	69,988
2010	83,412	70,117	0	139,174	39,745	72,822	57,542	82,495
2020	114,007	93,291	0	159,886	39,404	78,644	69,083	91,248
2030	140,065	112,921	0	174,357	39,889	85,297	84,826	103,942
2040	167,924	131,815	0	187,828	41,549	99,320	107,831	121,273
2050	200,644	154,800	0	212,861	47,012	112,704	148,850	154,638

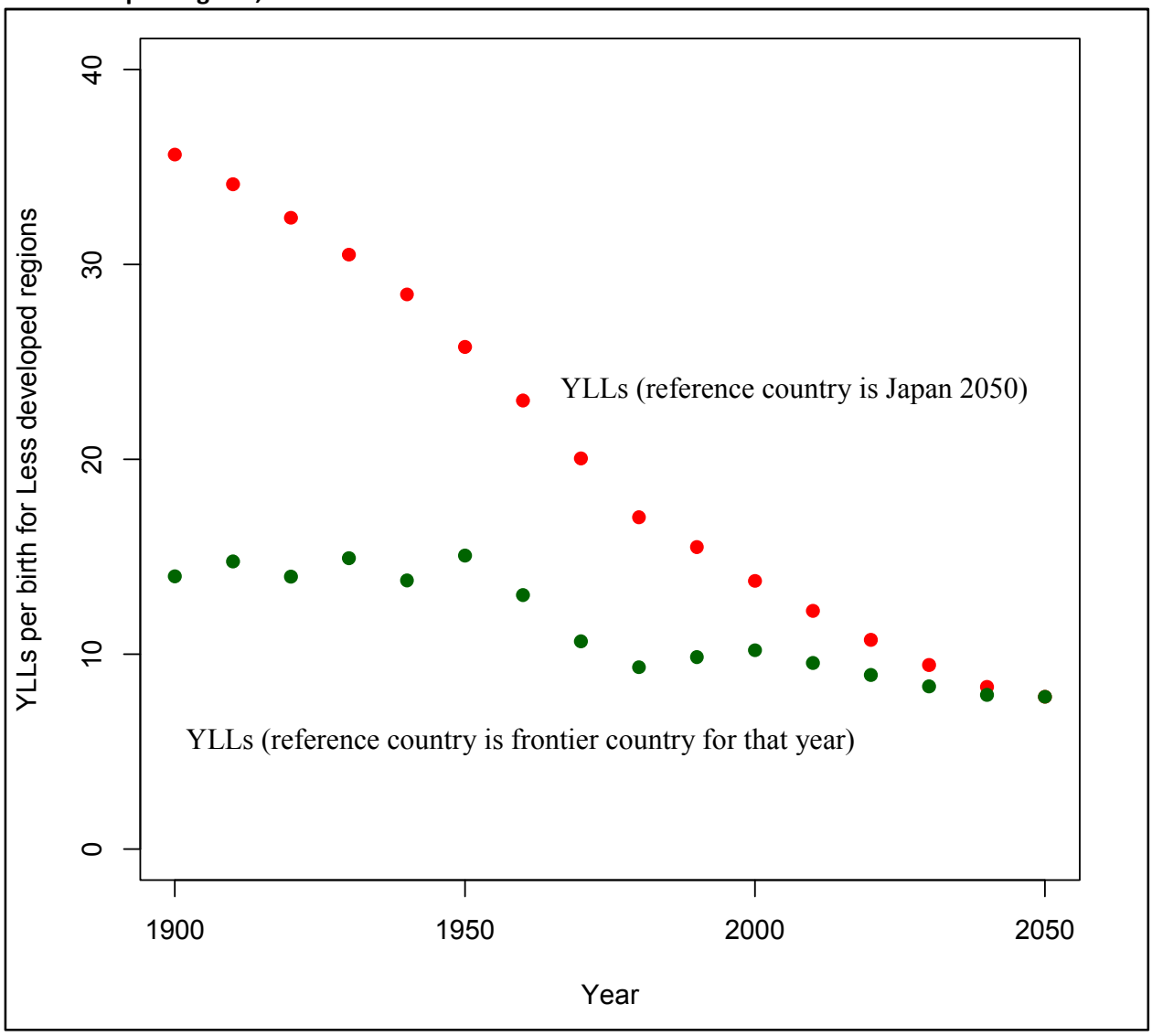
Note: Entries in this table are calculated from the per person YLLs reported in Annex Tables 2.2 and 2.3 by multiplying those $YLL^{*} = YLL_{a5} + 0.54YLL_{u5}$ by twice per capita GDP expressed in 1990 international Geary Khamis dollars.

Annex Table 2.6 Ratio *a* of money metric value of years of life lost (MMVYLL) per lifetime income per capita (LI) (no units), selected countries and regions, 1900-2050
(Variant of text Annex Table 1.5)

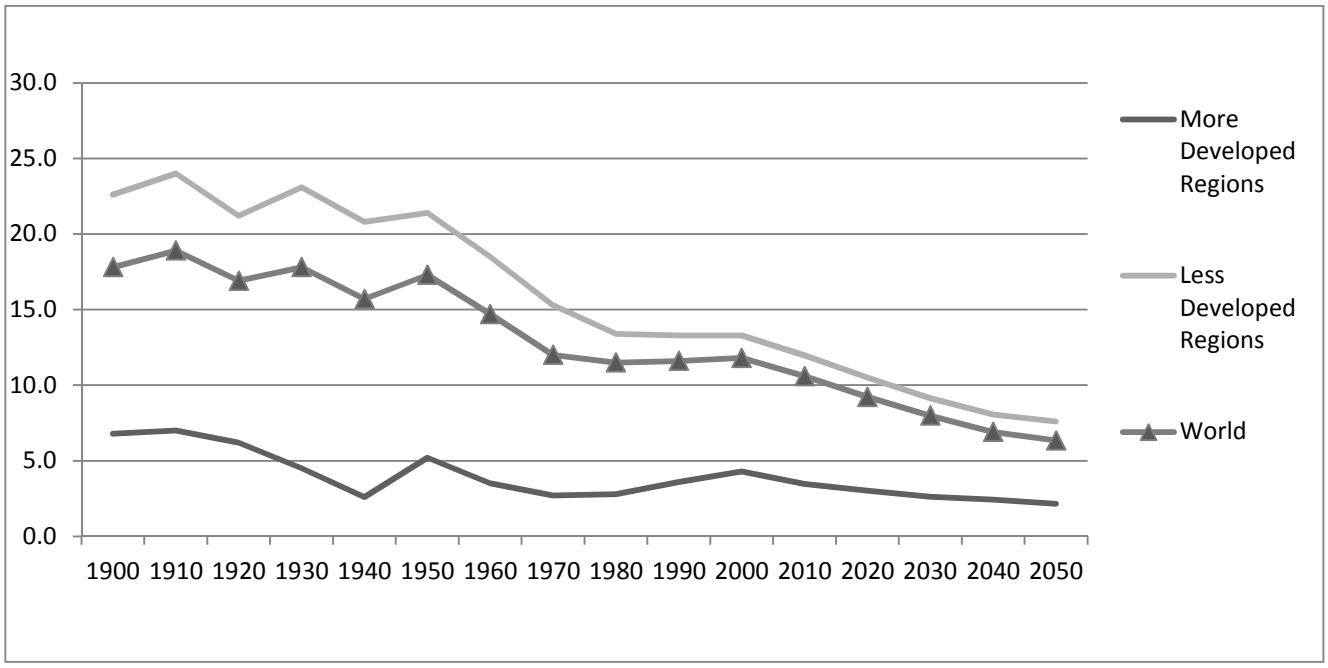
Year	China	India	Japan	USA	Sub-Saharan Africa	More developed regions	Less developed regions	World
1900	0.9	1.4	0.2	0.2	1.6	0.2	1.2	0.7
1910	1.0	1.6	0.3	0.2	1.6	0.2	1.2	0.8
1920	0.9	1.4	0.2	0.2	1.6	0.2	1.2	0.7
1930	1.0	1.5	0.2	0.1	1.8	0.1	1.3	0.8
1940	1.0	1.5	0.2	0.1	1.7	0.1	1.2	0.7
1950	1.1	1.8	0.2	0.1	2.0	0.2	1.3	0.8
1960	0.9	1.5	0.2	0.1	1.8	0.1	1.1	0.7
1970	0.6	1.3	0.1	0.1	1.6	0.1	0.9	0.6
1980	0.4	1.0	0	0.0	1.6	0.1	0.8	0.5
1990	0.5	1.1	0	0.1	1.7	0.1	0.8	0.6
2000	0.4	1.1	0	0.1	1.9	0.2	0.9	0.6
2010	0.4	1.0	0	0.1	1.8	0.1	0.8	0.5
2020	0.4	0.9	0	0.1	1.7	0.1	0.7	0.5
2030	0.4	0.9	0	0.1	1.6	0.1	0.7	0.5
2040	0.3	0.8	0	0.1	1.4	0.1	0.7	0.5
2050	0.3	0.8	0	0.1	1.4	0.1	0.7	0.5

Note: Entries in this table are calculated from the money metric value of years of life lost MMVYLL reported in Annex Table 2.5 divided by the lifetime income per capita as defined by eqn 2.8 in the main text.

Annex Figure 2.1 Years of life lost (YLLs) per birth, reference country is either frontier country or Japan 2050, less developed regions, 1900-2050



Annex Figure 2.2: Money metric value of years of life lost, MMVYLL, selected regions, 1900-2050, per cent of GDP


30.0
25.0
20.0
15.0
10.0
5.0
0.0
1900 1910 1920 1930 1940 1950 1960 1970 1980 1990 2000 2010 2020 2030 2040 2050
More Developed Regions
Less Developed Regions
World