Are the Wise Also Wizened? Population Aging and Knowledge Production

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Abstract

Traditional theories posit a line of causality running from technological change into mortality decline. I argue that an important line runs in the opposite direction: longer life spans contribute to increased knowledge production. The productivity of scientists declines only gradually with age, which implies that a reduction in adult mortality will stimulate knowledge production by leaving more productive scientists alive. It is true that growth in empirical scientific knowledge in the 17th century preceded widespread mortality decline in the 19th century. But the vital statistics of members of the Royal Society of London indicate that the life spans of scientists were increasing at the same time that scientific knowledge began to grow rapidly, the latter fostered by the Society itself. These perspectives imply that population aging in industrialized countries may not be so costly because it can stimulate knowledge production. Reductions in adult mortality in developing countries may foster expanded knowledge production and thus contribute to economic growth.

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It is not uncommon for the seemingly obvious to mask deeper and more subtle shades of meaning. Although in print they appear related, the origins, meanings, and pronunciations of the words *wise* and *wizened* are completely different. Aging may wizen, or dry and shrink an individual, but there is no etymological guarantee that such an individual has also become wise. In this paper, I explore the connections between these two separate concepts. I argue that like the etymology, the relationship between age and population aging on the one hand, and on the other hand wisdom broadly defined — scientific advancement, technological change, the production of new knowledge — is also more subtle than typically recognized.

Traditional perspectives on economic growth and development usually interpret the process of mortality decline as a product of technological change. Preston (1975) famously reported that 75–90 percent of the increases in world life expectancy early this century were attributable to technological change. Historical work on the course of modern development and the demographic transition typically deduces causality based on the sequence of key events: scientific advancement starting in the 17th century, population growth beginning in the 18th century, economic growth and the Industrial Revolution starting in the early 19th century, and then widespread mortality decline taking hold later in the 19th century. While there is a range of views on exactly how popular improvements in health and mortality decline resulted from earlier developments, the common thread is that lengthening life spans is the end result. Researchers typically assume that technological change is either fostered by the development of institutions or brought about by increases in population or in population density.

This conceptualization of aging as solely an output is also implicit in current perspectives on the future impacts of continued mortality decline in industrialized countries. While much of the historical gains in life expectancy at birth during the demographic transition were attributable to declines in infant and child mortality, which effectively increased productive working years, mortality improvements in advanced countries today tend primarily to lengthen life spent in retirement. Thus many view population aging as a strain on productive resources and a potential threat to future prosperity (Gruber and Wise, 2001; Bongaarts, 2004). To be sure, population aging is a serious issue for modern economies with extensive systems of public old-age support, especially when those systems contain large incentives for aged individuals to cease production and retire regardless of whether they are productive or not. But is it clear whether population aging must necessarily be a drag on economic growth? If aging is solely an output of growth, then the chances are good that it is.

In this paper, I argue that the traditional view of mortality decline and technological change misses an important connection between the two: that gains in adult life span can facilitate more scientific discovery. Put simply, this is an argument about the lifecycle productivity of scientists. Physical functioning naturally deteriorates as a result of aging, as do some intellectual elements. But I show that scientific productivity, much of which builds directly on personal histories of prior output, does not exhibit the same deterioration with age that we see with most other types of productive activity. It is true that many important breakthroughs in theoretical science are contributed by young scientists with fresh perspectives on established knowledge. But a large part of knowledge production and the learning of techniques is facilitated by the application and augmentation of knowledge and techniques acquired earlier. Older scientists clearly have direct access to their own stocks of knowledge, and younger scientists typically acquire their access through learning facilitated by older scientists. Data both in modern and in historical times show that older scientists are productive members of the scientific community, and the productivity of the average scientist declines much more slowly with age than that of the average worker. At least over short periods of time, this pattern suggests that further population aging could stimulate knowledge production and ultimately raise productivity.

Has there been any connection between increasing life spans and accelerating knowledge production over long periods of time? The traditional perspective on historical development in England assigns no role to life span extension, although Hollingsworth (1964) showed that mortality among British elites was declining prior to 1800. But population growth, typically viewed according to a Boserupian (1965, 1981) perspective as the engine for technological growth, was not steady during early scientific development. In this paper, I show that a particularly interesting subgroup of British elites experienced early gains in mortality. Vital records data on members of the Royal Society of London show steady declines in mortality beginning with its inception in 1660. Since the Society is widely seen as an important early institution in the development of empirical and deductive reasoning, these findings are telling. Mortality decline among British elites surely facilitated early knowledge production by extending the lives of those early knowledge pioneers. There is an important feedback from mortality decline into technological change.

It is natural to consider the implications of this new view for contemporary differences in productivity, incomes, and life spans between countries, and for development policies. The new perspective presented here, which I term modified Boserupian, is that the age of individuals, and not just their sheer number, is important in promoting technological change. Policies that lower adult mortality rates are likely to stimulate knowledge production, in addition to promoting health and thus raising labor productivity directly (Bloom, Canning and Sevilla, 2004). This argument is related to but distinct from theories that assign a key role in growth to education, which can be stimulated by low mortality (Kalemli-Ozcan, Ryder and Weil, 2000; Boucekkine, de la Croix and Licandro, 2003).

The sections that follow elaborate on each of these points in turn. First, I review the literature on individual productivity over the life course, and then I explore scientific productivity through age, both in modern and historical periods. Next, I discuss modern theories of historical development and examine the timeline of key events in English history. I present new evidence on early increases in the life spans of Royal Society fellows and offer a reinterpretation of the historical chronology. Finally, I explore differences in life span relative to differences in scientific output in a modern cross section of countries in order to examine the implications of this new view for development policies. In the final section, I offer concluding remarks.

Productivity and age

Perspectives on productivity and age

As they age, individuals tend to follow a distinct trajectory of productive activity that is either rectangularized or follows an inverted U shape. Figure 1 depicts a modern life-cycle pattern of productivity as measured by earned (labor) income per individual. When individuals are young, productivity is typically low, as mental and physical abilities develop and individuals acquire knowledge and learn productive techniques. During the prime working years, productivity is usually high and growing. Workers hone certain skills with repetition, and they may develop new techniques in order to meet challenges. Most individuals retire from market-based work in their 60s, while a small minority continues to work and earn into later years.

We are primarily concerned with the rightmost portion of Figure 1. Why do earnings decline with age? Part of the explanation has to do with incentives to retire. These tend to be implicit financial incentives arising from the design of public pension schemes (Gruber and Wise, 2002), but they can in rarer cases also be explicit. In the U.S., FAA regulations prohibit anyone over the age of 60 to pilot a commercial airliner. This rule is based more on tradition than any clear scientific evidence linking pilot age to accident rates (Aerospace Medical Association, 2004), but a prevailing view is that piloting ability deteriorates with age to unsafe levels.

Aging ultimately leads to a complete cessation of all activity, namely death, but the critical question is how to characterize the intervening period between high productivity and death. It is clear that different abilities degrade at different stages of life, just as they are typically acquired at different stages. Although there are notable outliers, few athletes remain productive past age 40. Many reach their peak in their 20s or even earlier. Political office is typically restricted to individuals over the age of 30 or 35, reflecting the perceived advantages of accumulated life experience and knowledge. Skirbekk (2004) reviews the literature on the evolution of mental and physical aptitude over the life cycle. He finds that skills tend to decline with age in general, but that there are more subtle patterns underlying the overall trend. Problem solving, learning, and speed tend to degrade with age, while experience and verbal abilities decline less slowly or even remain stable.

These patterns bear two key implications. With different rates of deterioration by type of skill, aging need not imply impending uselessness in economies that value different types of skills. When applied here, the law of comparative advantage in economics (Ricardo, 1817) asserts that young and old workers can both benefit by specializing in the skills at which they are relatively better. Gains accrue even when younger workers may be better in absolute terms at performing all tasks, a fairly dubious notion in any event. Although not all workers switch jobs or tasks as they age, mechanisms that promote according to seniority accomplish some of this kind of reallocation.

A second and related implication is that there are industries that depend heavily on certain types of skills that do not appear to decline rapidly with age and may even be improved with age. These industries may not employ many workers, but their impacts on long-term growth may be large owing to the nature of their output. Knowledge production is one such activity.

Productivity by age in science

There are several ways in which age is likely to affect scientific productivity differently than other types of economic productivity. First, knowledge is primarily produced through mental rather than physical activity, and it tends to be very time intensive. While some key innovations in theoretical science are produced by young scientists who challenge conventional wisdom,[1] empirical knowledge is more a product of a large accumulation of interconnected ideas stored within an individual or within closely knit groups of individuals. Hammel (1983) finds these patterns in a sample of mathematicians and chemists at the University of California, while Galenson and Weinberg (2004) discuss these differences in the production of theoretical and empirical knowledge by Nobel prizewinners in economics. Older scientists may not produce as many theoretical innovations as younger mavericks, but they probably contribute disproportionately large amounts of empirical knowledge with their large accumulated stocks of knowledge that are important for inductive reasoning. If a large component of knowledge production is characterized by increasing returns to scale in time inputs, long life spans may be critical ingredients of knowledge growth.[2]

Second, preferences among knowledge producers and the institutional constraints they face suggest they will have relatively long working careers. Scientific research is conducted by some of the most highly educated members of society, who by virtue of their education have a wide array of other, more lucrative career opportunities available to them than research science. Their revealed preference suggests that knowledge production in and of itself is valuable compensation. This contrasts with prevailing views of work in many other fields, where workers see productive years as the price of consumption during retirement. Knowledge producers probably enjoy their occupations more on average and thus probably would not choose to reduce their working time as sharply with age. Institutional constraints still exist, but tenure and emeritus status generally facilitate longer productive working lives than the average.

Third, knowledge production directly begets more knowledge production. University researchers themselves train the next generation of researchers. The process of instruction often results in both an increase in knowledge for the students and the gaining of new perspective by the instructor, who through teaching may reevaluate conventional wisdom and identify open questions for future research.

Fourth, older scientists directly facilitate the growth and health of scientific institutions that foster further growth in knowledge. Institution building requires the focusing of many resources, chief among them being the prestige of individuals who have developed reputations as knowledgeable scientists, their advice, and their knowledge of how to build institutions. Aged researchers lend external legitimacy to the development of new and existing institutions, and they can provide crucial guidance to members on achieving internal and external harmony within institutions.

The first two points describe ways in which individual scientific productivity is likely to follow a different, less rapidly declining trajectory through age. The third and fourth points describe components of value added by aged scientists that are more difficult to capture in traditional measures. These can be termed spillover effects in order to capture how these particular impacts of an older scientist are likely to felt by many entities other than the scientist. Contributions of older scientists to the development of institutions, for example, is a particularly elusive topic. For brevity, I examine simple measures of only the individual productivity of scientists and not the spillovers, which I leave to future work.

First, I examine cross-sectional patterns of individual productivity in science using modern survey data. The National Opinion Research Center conducts a biennial Survey of Doctorate Recipients (SDR) on behalf of the U.S. National Science Foundation and National Institutes of Health. The SDR contains data on career development for 40,000 doctorate recipients in the sciences and engineering. Figure 2 displays average scientific productivity among doctorate recipients in the U.S. as measured by journal articles authored or coauthored between 1990 and 1995.

A decline in average productivity after age 45 is apparent in Figure 2, but the decline is not large. On average, doctorate recipients at ages 65 and over authored 4 journal articles over this 5-year period, while those at ages 30 to 45 had a little over 5 new published articles. Viewed relative to age profiles of earnings or hours worked across all occupations, such as displayed in Figure 1, the decline in research productivity through age appears quite small. Rather, research productivity even at ages 70 and over, which typically are retirement years for the general population, remains high on average among scientists.

I obtain a remarkably similar picture using data on scientific activity from a completely different time period and setting. Figure 3 displays an age profile of activity among fellows in the Royal Society of London before 1700. The data represent life-cycle, or longitudinal rather than cross-sectional, activity by individuals as measured in the Society's minutes and interpreted by Hunter (1982). He examined the minutes over many years and categorized members at each measurement into qualitative groups from lowest to highest activity as reflected by mentions by name in the minutes. I translate these qualitative groups into ordinal rankings and take simple averages by age of the individual. Figure 3 shows that average activity peaked between ages 30 and 50 for these individuals, but the decline in activity with age is once again not particularly large, about half of one qualitative category.

These moderate declines in individual productivity across a diverse array of scientists are consistent with the hypothesis that increasing life spans contribute to growth in scientific knowledge, all else equal. Next, I examine historical trends in preindustrial England in order to explore this proposition about changes over time more directly. I motivate my inquiry with a review of the literature on the origins of modern growth.

Mortality decline and knowledge production

Theories of development and unanswered questions

The determinants of economic growth remain a perennial topic of inquiry. Modern theories of development typically focus on the role of population growth and density in incentivizing technical innovation, in the spirit of the classic work by Boserup (1965, 1981) on agricultural technology and the incentives to innovate conveyed by population density.[3] Recent efforts in this vein include Lee (1988), Tsoulouhas (1992), Kremer (1993), Galor and Weil (2000) and Jones (2001), among others.

At first glance, the sequence of historical events appears to fit this Boserupian perspective quite well. The Industrial Revolution followed a vast increase in population size and density in Western Europe, typically attributed to a reduction in crisis mortality, such as famines (Wrigley and Schofield, 1981; Wrigley et al., 1997), or to a reduction in chronic malnutrition (Fogel, 1994). Population grew by about 50 percent over the course of the 18th century, while mortality rates for the population as a whole remained stable at high levels, with e_0 averaging about 40. After this growth in population, income per capita accelerated rapidly, rising at an annual rate of 1.2 percent after 1820, up from about 0.05 percent since 1000 A.D.(Maddison, 2001).

After the Industrial Revolution, life spans also began to increase at a roughly linear rate. Oeppen and Vaupel (2002) find annual increases in best practices female life expectancy of about 0.25 years of life per year of time since 1840. Whether these vast improvements in population health were caused by the Industrial Revolution or achieved in spite of it, or whether they were not directly associated with economic development at all, is a matter of much debate. McKeown (1976) posited that increases in income brought about by the Industrial Revolution led directly to the increases in nutrition that fostered improvements in health. Szreter (1997) concurs with the timing but disagrees on the causality, preferring instead to attribute importance to concerted efforts in public health and the political will necessary to engender them. Meanwhile, Preston (1975) clearly prefers to characterize the motive force behind mortality decline, at least in the 20th century, as technological progress and not income per capita at all.

Easterlin (1995) adopts a view similar to Preston's and suggests a reinterpretation of the timing of historical events. He perceives both the Industrial Revolution and the Mortality Revolution, which refers to the epidemiological transition of the late 19th and early 20th centuries, as twin products of a much earlier revolution in scientific thought. The earlier period is commonly referred to as Enlightenment, and it is typically defined as occupying the 17th and 18th centuries. As measured by numbers of scientific publications, the production of scientific knowledge in England and Europe as a whole was indeed growing rapidly during this early period (Tsoulouhas, 1992; Easterlin, 1995). This line of reasoning, which I refer to as the Easterlin view, has clear merit but certainly raises the question of what engendered and facilitated the revolution in scientific thought.

A Boserupian view would attribute technological development to population growth or density. But it seems unsatisfactory to attribute early technological advancement solely to population growth, because population growth was not stable during the period in question, while technological change was proceeding steadily. Figure 4 plots English population data as reported by Tsoulouhas (1992) based on Wrigley and Schofield (1981). Population growth was indeed rapid prior to 1650 but then entered a period of relative stagnation, leaving total population essentially stable until 1740. Meanwhile, basic scientific advancement and innovation in production techniques were growing more steadily. Figure 5 plots two of Easterlin's data series on scientific development together with Tsoulouhas's series on agricultural production techniques using a log scale. Tsoulouhas's data is noisy, and I have superimposed a simple trend line. Although the growth rates of the three series are different, all show steady increases. Taken together, these data suggest that scientific development was well underway during the 17th century, prior to the period of sustained population growth starting in the 18th century. An alternative view, attributing early growth in science to the transitory upswing in population prior to 1650, holds relatively little appeal. The traditional view of population dynamics in England prior to 1700 is one of a closed Malthusian system (Lee, 1973).

What else might have led to early scientific development, if not population growth? Many modern theories explore the role of institutions. Hall and Jones (1999) find that institutions and infrastructure are key in explaining modern cross-sectional differences in income per capita between rich and poor countries in modern times. Early scientific institutions certainly did exist and were important; the Royal Society of London, founded in 1660, played a key role in the development of modern empirical science (Hunter, 1982). The same is true of counterpart institutions elsewhere in Europe during this period. Education is another potential focal point, although widespread increases in education occurred much later than the Enlightenment. But Boucekkine, de la Croix and Licandro (2003) explore urban educational attainment in 17th and 18th century Europe, and they find that early improvements in urban mortality coincided with increases in education. Their results echo the work of Hollingsworth (1964), who discovered early mortality improvements among aristocratic families in England before 1800. The timing of these disparate strands — preindustrial mortality declines among urban populations and aristocrats, institutional development, and growth in scientific knowledge — prompts the question of whether they are linked.

I argue that precisely such a link exists. Vital statistics drawn from the records of the Royal Society of London indicate that mortality rates among its members were declining throughout its history. In particular, the life spans of these early scientists were steadily lengthening at exactly the same time that scientific development was proceeding apace, while overall population was stagnant.

Mortality decline among early scientists

The Royal Society of London was founded in 1660 by a small group of natural philosophers wishing to promote experimental learning of the type proposed and developed by Francis Bacon, who had died in 1626. Early members included Christopher Wren, the architect and astronomer, and Robert Boyle, the first modern chemist. The Royal Society quickly expanded to around 200 members and in later years would include such notables as Sir Isaac Newton and Charles Darwin. Many of the early members were aristocrats with few direct ties to science other than sponsorship. Still, the Royal Society is widely seen as a key institution that fostered the nascent growth of empirical knowledge and techniques. Like academies of science in other countries, it remains active today and has nearly 1,300 members.

With nearly 350 years in existence and more than 8,000 members since its inception, the history of the Royal Society provides a unique look at how life spans among scientists and associated elites have evolved since 1660. The Society has collected vital statistics on its members and made them conveniently accessible through its website, along with a selection of biographical information. Records on dates of birth, induction, and death facilitate the analysis of mortality among this select group of scientists. Induction into the Society is of course conditional on survival to the age of induction, which has averaged between 40 and 50 years and has grown steadily during the life of the Society. As a result, I examine adult mortality conditional on reaching the age at induction.

Figure 6 plots the natural logarithm of period mortality rates in 10-year age groups from 30 to 79 against time, using data up until the middle of the 20th century. The overall picture is one of fairly steady declines in all age-specific mortality rates over the entire period, although there is considerable temporal fluctuation apparent in all five series. Rates of decrease are greater at younger ages, a relatively consistent pattern in mortality decline. Still, the figure shows that even 60–69 year olds enjoyed persistent decreases in mortality rates, although fellows over 70 experienced more static mortality. Annual rates of decline in mortality rates averaged around 0.34 percent, which produces a half-life of about 200 years. By comparison, rates of mortality decline averaged around 1 percent per year in the U.S. during the 20th century. Fellows aged 30–39 saw their mortality rates fall from around 2 percent in 1660 to 1 percent by 1860, while those aged 50-59 saw declines from 4 percent to 2 percent, and fellows aged 60-69 experienced a decline from 9 percent to 4.5 percent.

These gains in mortality rates translated into steady increases in remaining life expectancy. Figure 7 shows average years remaining in the sample by age at induction at 6 time intervals. Increases averaged about 0.03 years of remaining life for every year of time during this period. These findings mirror those of Hollingsworth (1964), whose cohort life tables based on the British Peerage during the same period also imply average annual increases in adult life expectancies of about 0.03.

Of key interest is the timing of these early increases in life expectancy among scientists. While mortality among the general population remained high at preindustrial levels until the 19th century, members of the Royal Society were clearly experiencing steady declines in mortality throughout its entire history. How do these mortality declines among scientists fit into the timeline of key events in English preindustrial history that we have established thus far?

Trends in period life expectancy among members of the Royal Society afford a clearer picture of the timing of mortality declines. Using the mortality rates depicted in Figure 6, I construct period life expectancy at age 40, e_{40}, and plot it against time in the top panel of Figure 8. Circles plot actual data points, while the dark line is a least-squares fit of the series over the time period shown. The middle panel depicts the natural logarithm of Tsoulouhas's series on agricultural techniques, the same series that appeared in Figure 5. Data points are shown by x's, with a least-squares trend line superimposed. The bottom panel shows the same series on English population seen in Figure 4, beginning in 1650.

Figure 8 shows that e_{40} among scientists was growing linearly during this early period, at around 0.06 year per year, while publications on agricultural techniques were increasing at about 1.5 percent per year. Population growth did not begin to increase until 1740, having waned considerably around 1640 as a wave of infectious disease spread through England. While traditional theories emphasize the role of population growth in technological growth, this timeline suggests that increasing life spans of scientists preceded population growth and more closely accompanied technological change.

A new view of the chronology of preindustrial events

Figure 9 summarizes several competing views of the historical sequence of events and the causal progression leading to the modern period of steady mortality decline and economic growth. Each of the three columns in the graphic depicts major events in order from the earliest at the top to the latest at the bottom. The leftmost portion of the figure depicts the standard Boserupian view, in which population growth ignites technological change, which is followed by economic growth and then mortality decline. In the middle of the figure is the Easterlin view, in which the Scientific Revolution fosters both the Industrial Revolution and the Mortality Revolution. The middle graphic is taller, reflecting Easterlin's belief that the causal impetus behind both developments began earlier.

The new hybrid view advanced here is depicted on the right side of Figure 9 and labeled "Modified Boserupian." Preindustrial decreases in mortality among elites, and among scientists in particular, plays a key role in facilitating Easterlin's Scientific Revolution. The modified Boserupian view allows population growth to affect technology, which in turn stimulates the Industrial and Mortality Revolutions. The new view remains agnostic over the relative importance of the Industrial Revolution and technological change in explaining the Mortality Revolution.

Thus mortality decline feeds back into technological change as well as eventually stemming from it in this new perspective. This insight bears potential implications for developed and developing countries alike. In the next section, I explore the modern relationship between average life spans and scientific development across countries in order to address these points.

Knowledge production and life spans in an international cross section

The modified Boserupian perspective implies that differences in scientific advancement across countries are attributable to differences in life spans, as well as to differences in population size. If this view is correct, policies aimed at reducing adult mortality in developing countries become considerably more attractive. A large portion of differences in economic well-being between rich and poor countries is attributable not to observable differences in factories, equipment, labor supply, or education, but in how those inputs are combined to make output (Hall and Jones, 1999). Knowledge production, along with other concepts like social capital, infrastructure, and institutions, feeds directly into that residual category of production factors that consist of ideas, techniques, and productive environments. If reducing adult mortality spurs knowledge production, development policies that target adult mortality can add to the productive potential of the macroeconomy while directly raising individual well-being by improving health.

We obtain our first look at this issue in an international cross section using data from the World Development Indicators (WDI) database of the

World Bank (2004). The WDI measures knowledge production in the form of scientific and technical journal articles published annually by country.[4] The measure of life spans most consistently available across countries is life expectancy at birth, e_0. This measure is the least bad of a number of less-than-ideal measures. There is well-known measurement error in e_0, owing to poor data collection in developing countries. It is arguably less relevant to the current analysis that would be a measure of life span conditional on early survival, such as e_{20}. But adult mortality in developing countries is frequently estimated using Coale-Demeny model life tables, a procedure that estimates overall conditions based on observables such as infant mortality. Thus a summary measure of mortality such as e_0 probably has less measurement error than derived data.

The WDI data show a large amount of cross-sectional variation in knowledge production across countries, just as there are large differences in e_0 and in income per capita across rich and poor countries. Figure 10 depicts a histogram of scientific and technical journal articles per capita among 188 countries in 1997. Five countries — the U.S., Japan, the UK, Germany, and France — produce 60 percent of the articles, but they are also among the more populous developed countries. Relative to population, the top ten publishing countries in 1997 were Switzerland, Sweden, Israel, Finland, Denmark, the Netherlands, Canada, the UK, Australia, and the U.S. Sixteen countries produced zero articles, and the vast majority produced a very small number per person. The extremely long right tail of the distribution in Figure 10 suggests that we should take logs of scientific output per capita in our empirical analysis.

Life expectancies in developing countries have converged toward industrialized levels since 1950 (Wilson, 2001), and convergence in life expectancy has been stronger than convergence in income per capita (Becker, Philipson and Soares, 2005). Still, considerable gaps remain between rich and poor countries in life expectancy at birth, as shown in Figure 11. The bimodal distribution of e_0 among nearly 200 countries in 1997 has a concentration of poor countries centered around age 50 and an upper mode around age 73, almost 50 percent higher. The overall distribution spans more than 40 years, from just below 40 years to over 80.

In the left panel of Figure 12, I plot log scientific journals against e_0 in the WDI cross section. An upward sloping relationship is apparent, although a large amount of noise clearly remains. Deviations from an upward-sloping schedule could be due to a wide number of factors, including language, political stability and warfare, institutions, and of course population. I explore the role of population in the right panel, which plots log scientific journals against log population. A similar upward sloping relationship is revealed. Both panels in Figure 12 clearly depict interesting patterns, and together they suggest a modified Boserupian perspective in which both life span and population stimulate technological change.

To explore the modified Boserupian framework further, I plot the logarithm of scientific articles per capita against life expectancy in Figure 13. Of the 168 countries whose data are plotted, I identify 16 noteworthy examples by name and note their locations with larger marks. As before the countries are arrayed in a cloud around an upward sloping line, but the correlation coefficient for this bivariate relationship is 0.71, higher than either of those shown in the two panels of Figure 12. There is regional variation in the positioning of countries in Figure 13, which reflects geographic variation in development. Developing countries in Africa and Asia occupy the southwestern segment of the figure, where scientific output per capita and e_0 are both low. Industrialized countries like Sweden, the U.S., and Japan appear at the northeastern tip, where journal articles and life expectancy are plentiful. The figure also depicts considerable variation within broad geographic regions. Cuba and El Salvador are outliers on the southeastern edge of the cloud, where life expectancy is relative high but scientific output is low. Other countries in the Americas are closer to the center of the cloud, such as Brazil, which lies to the northeast of India. India's log per capita scientific production is about 1.6 units higher than neighbor Pakistan's, which translates into almost a five-fold difference in per capita scientific output, even though the difference in life expectancy is only about half a year. Myanmar enjoys 3.4 years more life expectancy at birth than the neighboring Lao People's Democratic Republic, but produced less than a sixth as many journal articles per capita.

There clearly are other factors than influence scientific output beyond e_0 and population, but how strong is the relationship we see in Figure 13? In order to answer that question, I propose the following modified Boserupian regression model, where population and life span affect scientific production:

$$\log a(i) = \alpha + \beta_P \log P(i) + \beta_e \; e_0 + \epsilon(i). \tag{1}$$

In this model, i indexes countries; α is a constant; $a(i)$ is knowledge production, measured by the number of scientific and technical journal articles published in country i; $P(i)$ is population; $e_0(i)$ is life expectancy at birth;

and $\epsilon(i)$ is a white-noise error. As in a basic Boserupian model, population increases technology in (1) provided that $\beta_P > 0$. The innovation of this modified Boserupian model is that life expectancy also increases technology when $\beta_e > 0$. This framework is consistent with linear increases over time in e_0 combined with exponential growth in knowledge and in population. White (2002) has found linear increases in e_0 among industrialized countries since 1955; exponential growth in knowledge is the standard assumption in growth theory because it is consistent with exponential growth in per capita incomes; and population grows exponentially.

As is the case with the traditional Boserupian perspective, which emphasizes the causal link running from population size to technology, it is difficult to determine the direction of causality between life spans and knowledge production without more information. The timing of events, which I explored in historical data above, is one such source. Without additional information, we cannot tell whether the positive correlation that we see between knowledge production and life span reflects the impact of mortality reduction on technology, or the reverse, or the effects of a third omitted variable on both. The WDI does not cover developing countries over long periods of time, so instead I will use the technique of instrumental variables. If there are exogenous instruments that affect e_0 but not knowledge production, the method of instrumental variables can isolate the effect of e_0 on knowledge production as opposed to the effect of knowledge production on e_0. Climatic or geographic variables are good candidate instruments for e_0, since they should influence some baseline level of mortality and are not easily affected by technology. Distance from the equator is a reasonable summary measure and is provided by Hall and Jones (1999) for most countries in the dataset.[5]

Table 1 displays four sets of regression results estimating the modified Boserupian model (1) using ordinary least squares and instrumental variables. Models 1 and 2 use the entire sample of developed and developing countries, while Models 3 and 4 restrict attention to developing countries alone, as defined by the United Nations. Models 1 and 3 estimate with ordinary least squares, while Models 2 and 4 instrument for e_0 using distance from the equator. Estimates of the coefficients are listed with their standard errors appearing beneath them in parentheses. All coefficients are significantly different from zero at the 5 percent level, and they are appropriately signed across the entire table. The coefficient on log population, β_P, which is the population elasticity of knowledge production, is indistinguishable from unity across all four columns. That is, a one percent rise in population is associated with a one percent rise in scientific output. The coefficient on life expectancy, β_e, is positive, averages about 0.15, and increases in magnitude when instrumented. This last pattern could be explained by the presence of measurement error in e_0, which would attenuate the OLS estimates toward zero. When the sample is restricted to developing countries, the coefficients on log population and life expectancy drop but remain significant and fairly large. As shown by the R^2's of the OLS models, these models are able to explain a large amount, around two-thirds, of the variation in log scientific output. In the instrumental variables regressions, first-stage regression fit is quite good, with large F-statistics rejecting all coefficients equal to zero and reasonably high R^2's.

The results in Table 1 are supportive of the modified Boserupian hypothesis, and they bear unique implications both for development policies and for the future of developed societies that are aging. Increases in life span stimulate growth in knowledge. Population growth does as well, but only one-for-one. Traditional development advice is heavily influenced by neoclassical views of economic growth that emphasize the negative effects of population growth through capital dilution. If knowledge grows with population, productivity might grow as well, and the consequences of population growth may not be so dire. But more importantly, increasing life spans achieve growth in knowledge that is faster than population growth. Policies that reduce adult mortality in developing countries stimulate long-term economic growth by fostering growth in scientific thought.

For developed countries facing continued mortality declines, these results suggest that prospects for future growth may be better than commonly expected. It would be unwise to predict that scientific output will definitely increase in industrialized countries that are aging, since trends in a wide cross section of countries today do not necessarily imply anything about longitudinal trends for a small group of advanced countries. Similarly, it is unclear whether the historical relationship between increases in the life spans of preindustrial English scientists and early growth in scientific knowledge is likely to repeat itself in the future.

But my findings certainly call for guarded optimism. They echo in spirit the results of Cutler et al. (1990), who examine trends in labor productivity in a panel of industrialized countries since 1960 and find evidence of more rapid productivity growth during periods of labor shortages. We may find that even as population age pyramids become increasingly rectangular due to aging, and as the supply of physical labor inputs slackens, economic growth might not suffer. Innovation in ideas and techniques is a reactive, dynamic force that appears to be positively related to age. Knowledge may increasingly substitute for other inputs and thus impart considerable economic resilience in the face of population aging.

Conclusion

It is widely recognized that the discovery and application of new technologies is responsible for most of the robust growth in life expectancies enjoyed since the dawn of the modern era. In this paper, I have argued that this growth is self-sustaining: improved knowledge fosters lengthened life, which in turn fosters more productive scientific life spans and faster rates of discovery, and so the cycle continues. More often than not, the wise are indeed wizened, even though that relationship is not formally guaranteed.

Life-cycle productivity among scientists does not appear to decline rapidly with age, as is the case in other sectors of the economy. Longer life spans allow scientists to invest their most precious resource, time, in greater allotments to projects that may exhibit increasing returns. The training of new scientists, the building of institutions through accumulated prestige and experience, and other spillover effects may further increase the benefits to knowledge production of increasing life spans. These microeconomic patterns suggest that the wise may not always be wizened, but a wizened society is likely to be more wise.

Patterns of mortality decline among members of the Royal Society of London suggest that lengthening life spans among early elites probably fueled scientific innovation during a crucial early period. Although Hollingsworth (1964) first recognized this pattern of preindustrial mortality decline, in his case among British nobility widely defined, previous research has largely ignored this dynamic in interpreting the flow of preindustrial history. This paper joins Boucekkine, de la Croix and Licandro (2003) in advising a reinterpretation that takes account of these developments. These early mortality declines among elite groups are certainly overshadowed by postindustrial trends in population health, which were unprecedented. The fruits of mortality decline became much more widely distributed after the epidemiological transition beginning in the late 19th century, and for obvious reasons we tend to be more concerned with broad-based improvements in population health.

We are also interested in a broader view of how large-scale improvements in public health can be achieved, however, and the evidence I present suggests that isolated gains against mortality among the elite may sometimes be important in this regard. It is therefore striking that recent research on the distribution of mortality decline across socioeconomic groups suggests widening disparities (Schalick et al., 2000). These are clearly cause for concern, but one is also tempted to ponder the similarities with historical trends, which also exhibited great inequality in the access to mortality decline. Do modern patterns presage another major mortality revolution, for example? Are long-run social returns to temporary inequalities a pattern in development or more an aberration? These are important questions for future investigators to address.

Cross-sectional evidence on longevity and aggregate knowledge production in modern countries suggests that along with population, life span is also an engine for growth in knowledge. Tests of a modified Boserupian framework find support for the view that increases in life span and increases in population beget further increases in technology. It would be risky to predict rosy future scenarios for aging industrialized countries based solely on these cross-sectional patterns. But economic development may be better served by these insights. Declines in adult mortality are likely to be highly desirable not only because they directly increase individual well-being and labor productivity, but also because they stimulate knowledge production that benefits the entire economy.

Notes

[1] That major theoretical innovations are attributable to young maverick scientists seems to be especially true in the physical sciences, as has been pointed out by Lehman (1953) and Levin and Stephan (1991), among others.

[2] A more pessimistic view is offered by Jones (2005). He argues that increases in the existing stock of all knowledge have made acquiring that knowledge more costly for young scientists, which threatens to slow technological change. His argument is that if the years spent by students to acquire an ever-expanding basic level of knowledge grow faster than life spans, the productive working years of scientists must effectively shrink. Jones reports evidence that this may be the case in the U.S. today. A potential problem with the analysis is that it focuses on major inventions and high-profile achievements, which may not be representative of knowledge production.

[3] The argument as to why population growth may spur innovation can proceed in several ways. Increased population density strains the ability of traditional production techniques to sustain the population. Producers then face heightened incentives to innovate and expand food output, and if they are successful, their actions break the system out of a

Malthusian population trap. Another perspective is that there are fixed costs to conducting innovative activity. With more people across whom to spread those costs, innovation becomes cheaper and is increased. Population density may also simply facilitate more rapid spreading of ideas between individuals.

[4] Articles are assigned to countries according to the nationality of the authors. When there are multiple authors, authorship fractions are constructed, and national totals are rounded sums of those fractions.

[5] For the remaining countries, and for those which changed political boundaries since the 1980s, I obtained supplemental data from the CIA World Factbook.

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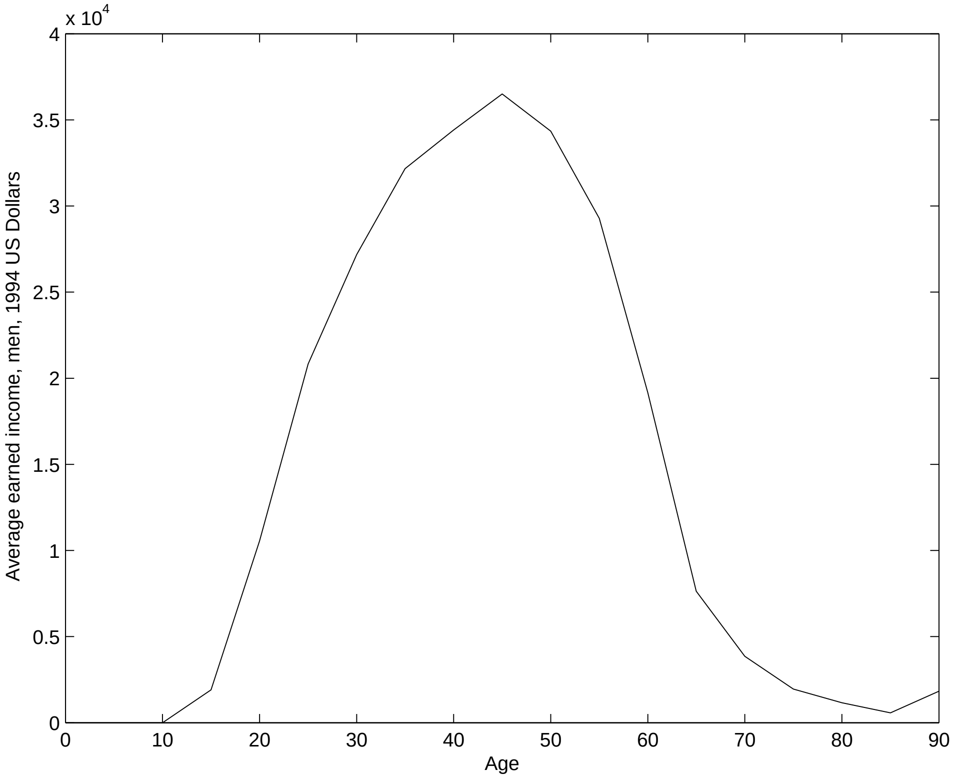
Table 1: Estimating the modified Boserupian knowledge model

Independent variable: log scientific and technical journal articles

Variable	Model 1	Model 2	Model 3	Model 4
constant (α)	-21.44	-27.49	-16.42	-18.76
	(1.35)	(2.03)	(1.34)	(2.31)
log population (β_P)	1.05	1.10	0.90	0.94
	(0.07)	(0.08)	(0.07)	(0.07)
life expectancy (β_e)	0.14	0.22	0.09	0.12
	(0.01)	(0.02)	(0.01)	(0.03)
R^2	0.69		0.65	
n	168	168	124	124
sample	all	all	developing	developing
IV?	no	yes	no	yes
first-stage F-stat		44.34		16.79
first-stage R^2		0.35		0.22

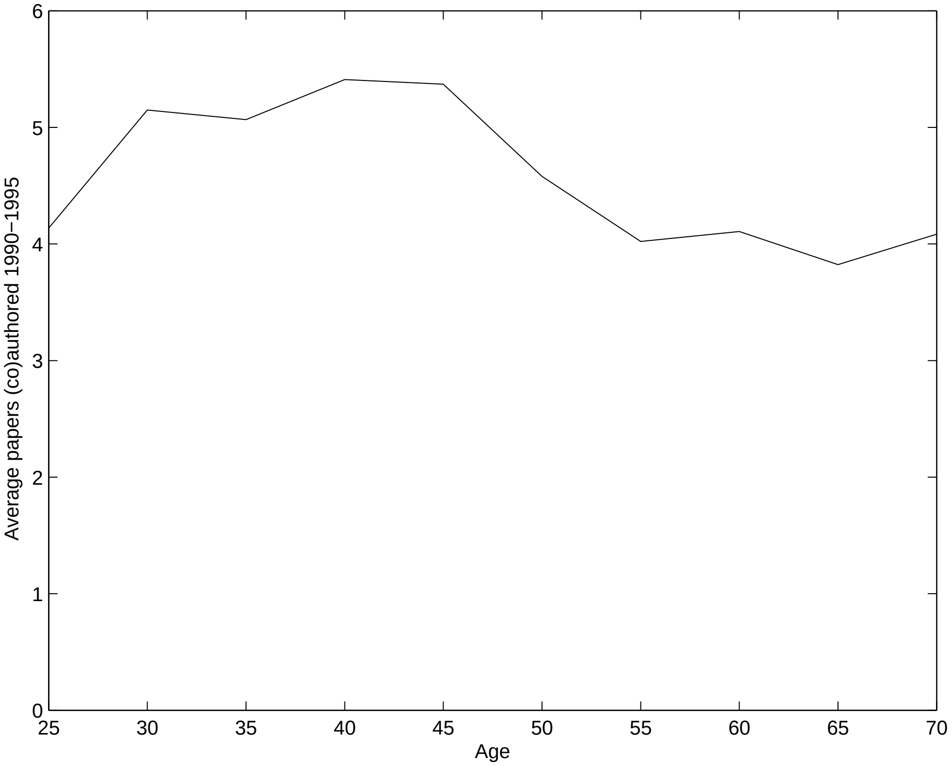
Notes: This table reports results of estimating (1) by ordinary least squares (Models 1 and 3) and instrumental variables (Models 2 and 4). Standard errors are in parentheses. Data are provided by the World Bank (2004). Life expectancy is measured from birth, e_0. Models 2 and 4 instrument for e_0 using distance from the equator (and population, the other regressor). Models 3 and 4 restrict the sample to countries classified by the UN as developing.

Figure 1: The modern age profile of earned income



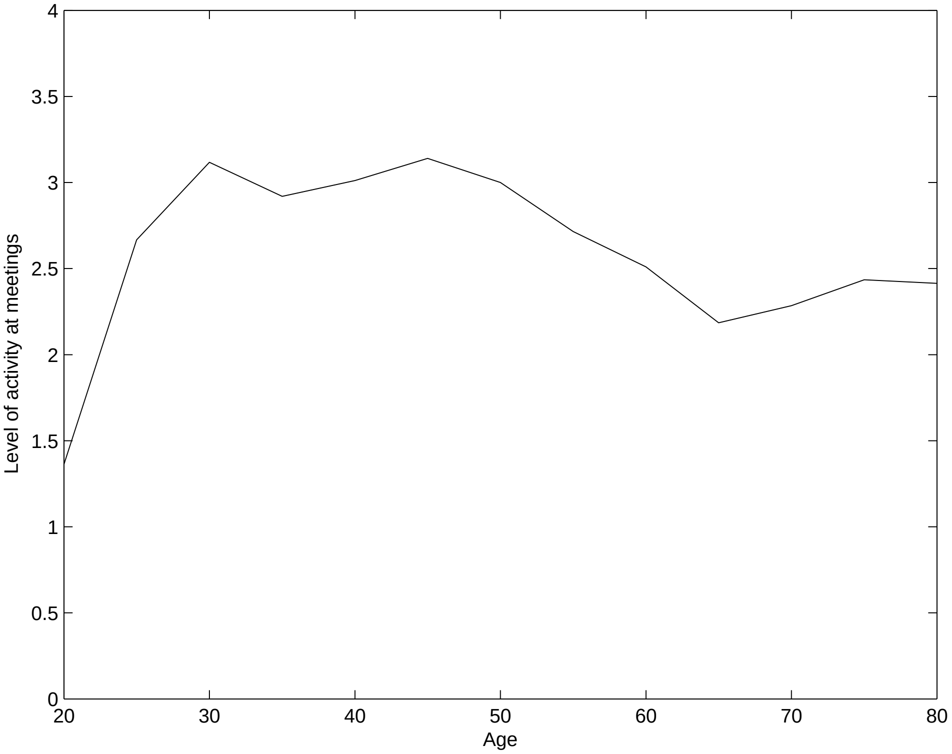
Source: March Current Population Surveys, 1992–96. Data are earned income for males, averaged by 5-year age group.

Figure 2: Individual scientific productivity in the U.S., 1990–95



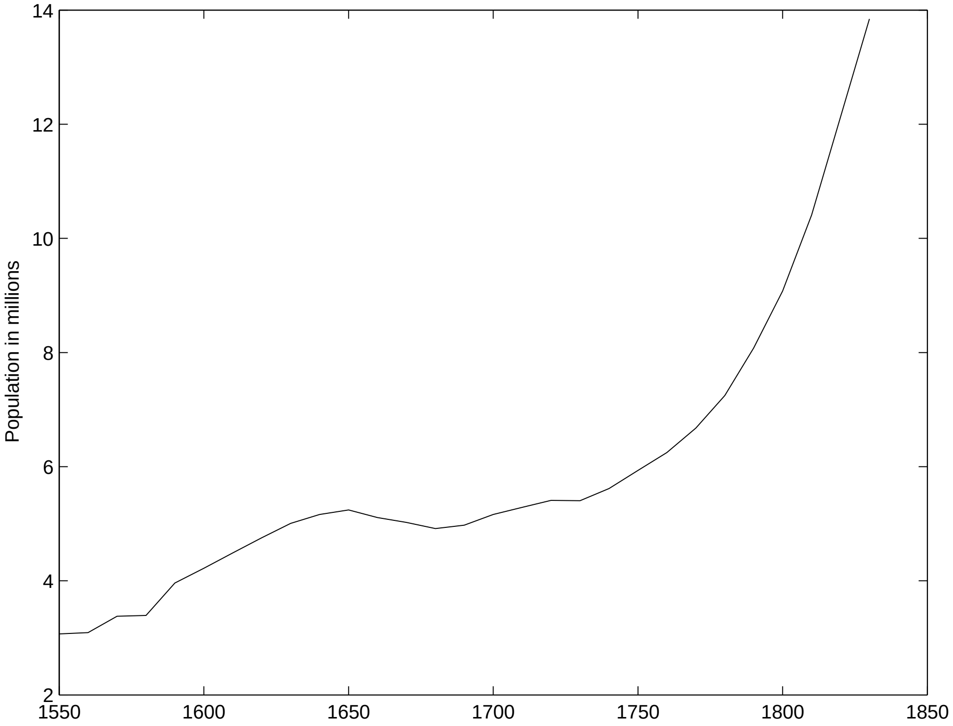
Source: 1995 Survey of Doctorate Recipients, National Science Foundation. Data are the number of journal articles authored or coauthored between 1990 and 1995, averaged over 5-year age groups. Age 25 is an open-ended group of individuals younger than age 29; age 30 is ages 30–34; and age 70 refers to ages 70 and over.

Figure 3: Activity among fellows of the Royal Society of London, 1660–1700



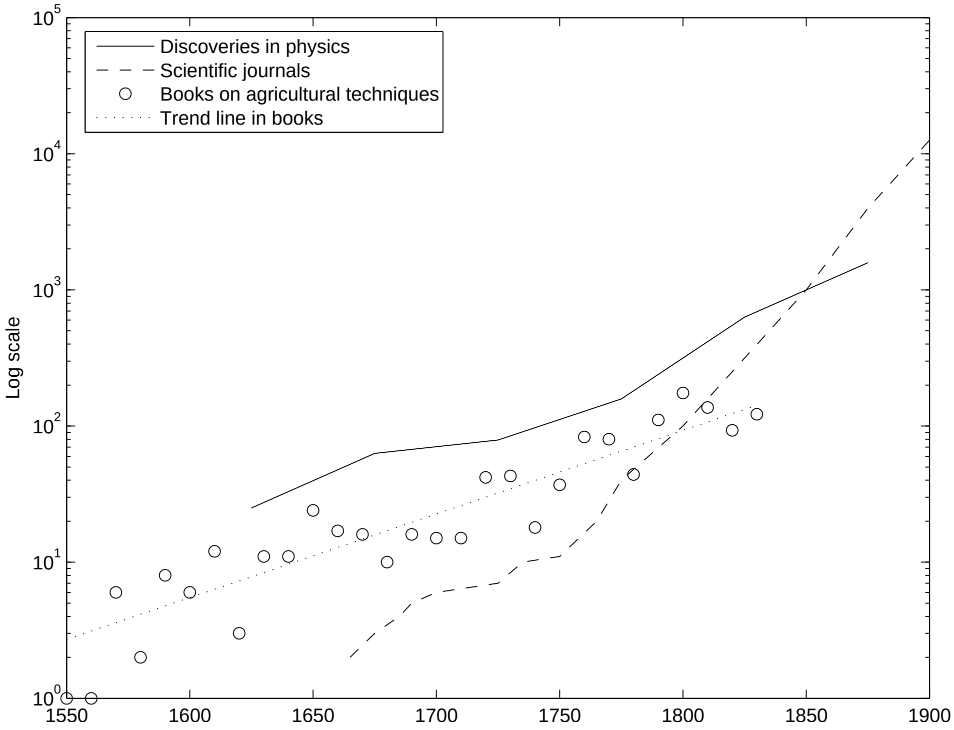
Source: Hunter's (1982) characterization of Fellows' activity based on meetings minutes. Six ordinal rankings of activity are scored as 1–6 with 1 being inactive; 2 barely active; 3 slightly active; 4 fairly active; 5 active; and 6 very active. The data are then averaged over 5-year age groups. The data in this graph cover 74 Fellows inducted between 1661 and 1663. A small fraction of them resigned or were expelled and are included in the denominator.

Figure 4: Population in England since 1550



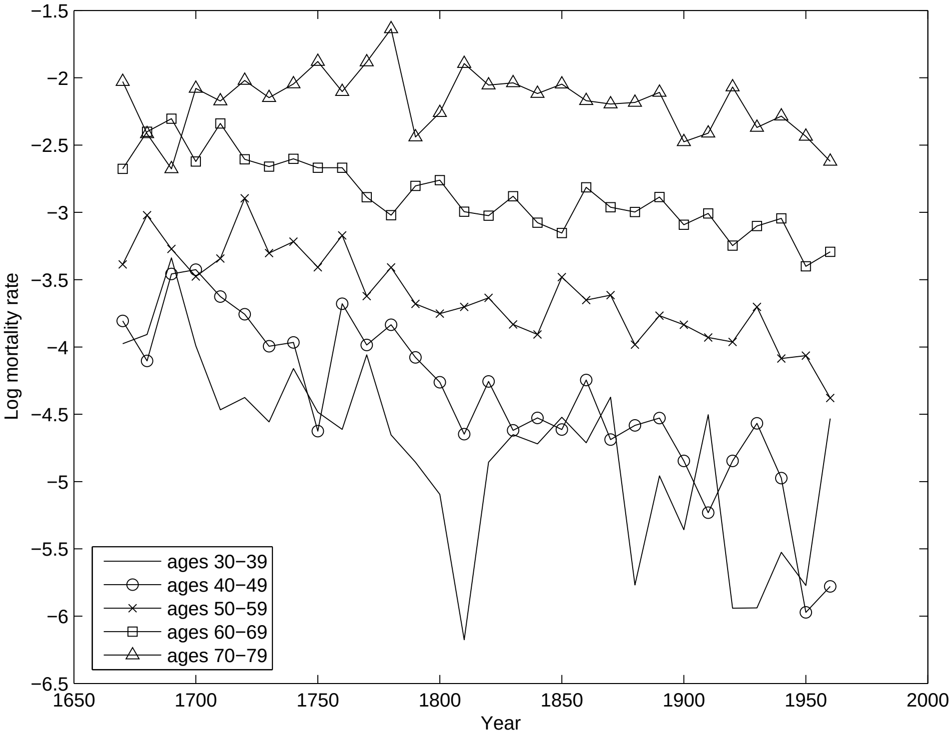
Source: Tsoulouhas (1992).

Figure 5: Scientific knowledge and production techniques since 1550



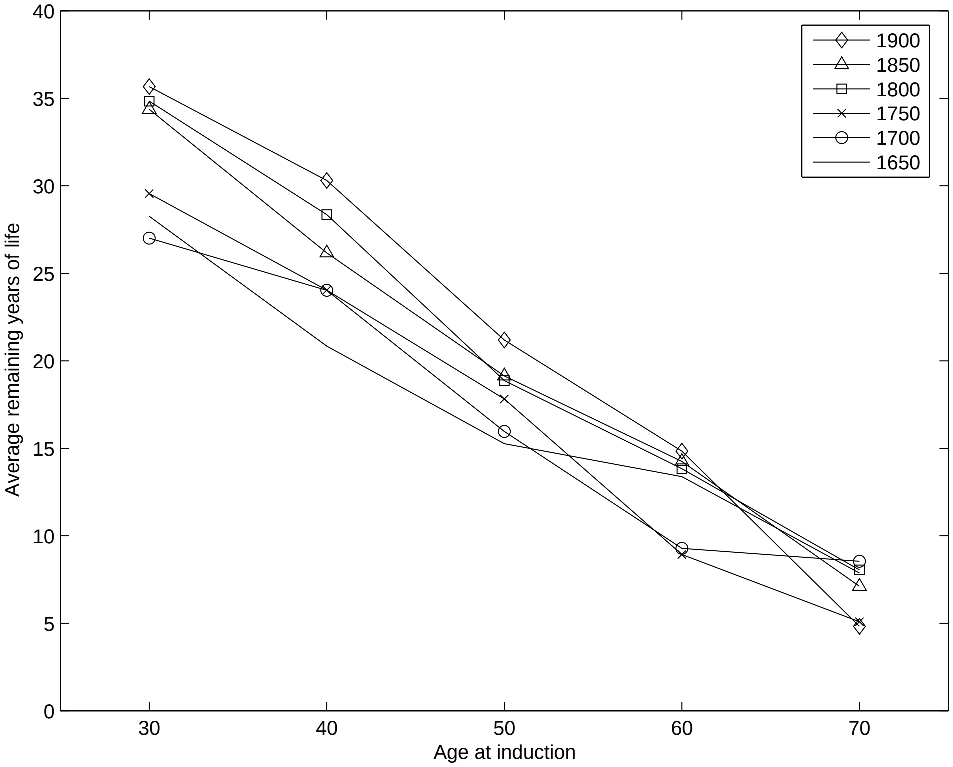
Source: Tsoulouhas (1992) and Easterlin (1995). The dotted line is a simple trendline fitted to the data on books on agricultural techniques, which are shown by the circles. The data are graphed on a base-10 logarithmic scale.

Figure 6: Log mortality rates among fellows of the Royal Society of London since 1660



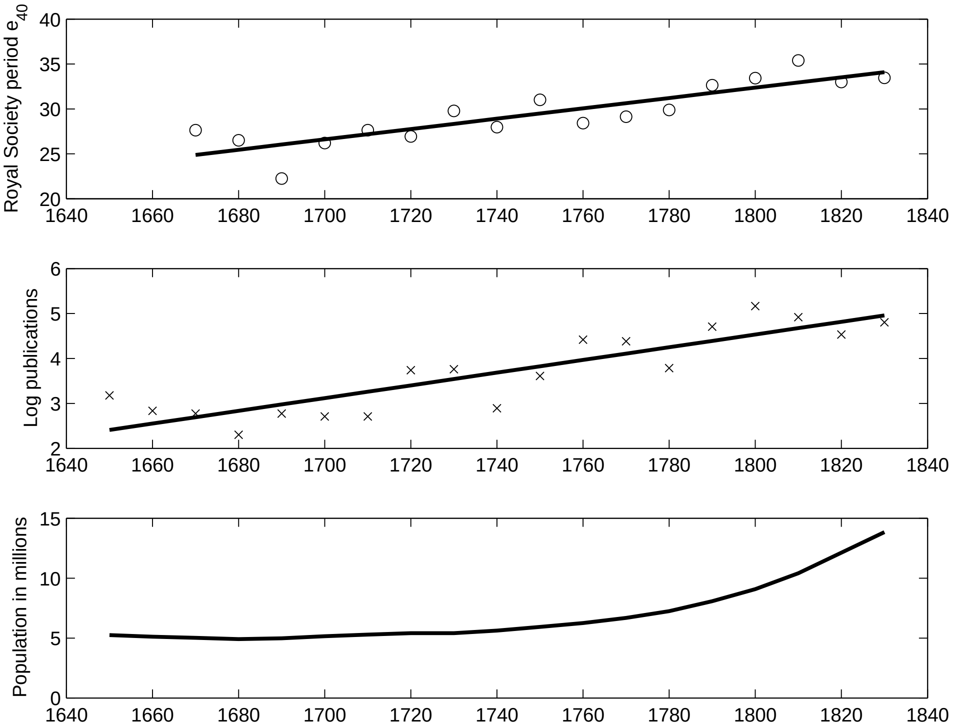
Source: Royal Society (2004) and author's calculations. The data are period mortality rates constructed using 10-year age groups observed over 10 years of time and then logged.

Figure 7: Average years of life remaining by age at induction



Source: Royal Society (2004) and author's calculations. These curves show cohort life expectancies: average years remaining on the y-axis by age at induction on the x-axis at six points in time.

Figure 8: Life spans of Royal Society fellows, science, and population in England before 1830



Sources: Tsoulouhas (1992), Royal Society (2004) and author's calculations. The top panel shows period life expectancies at age 40, e_{40}, for Royal Society fellows, constructed using the period mortality rates depicted in Figure 6. Data points are shown by circles, with a least-squares trendline superimposed. The middle panel depicts the logarithm of new publications on agricultural techniques, a data series representing technology that is compiled by Tsoulouhas. The same series appears in Figure 5. Data points are shown by x's, with a least-squares trendline superimposed. The bottom panel depicts English population in millions, also supplied by Tsoulouhas.

Figure 9: Views of the historical record and causality

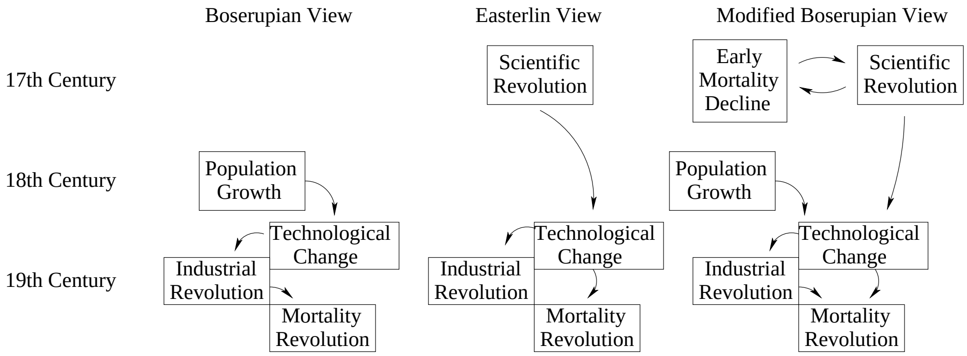
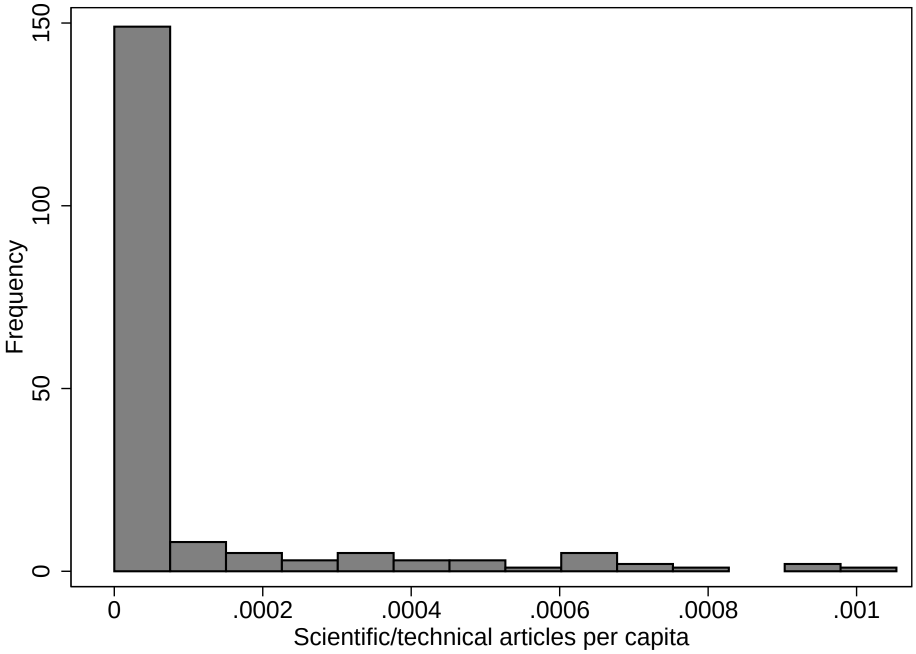
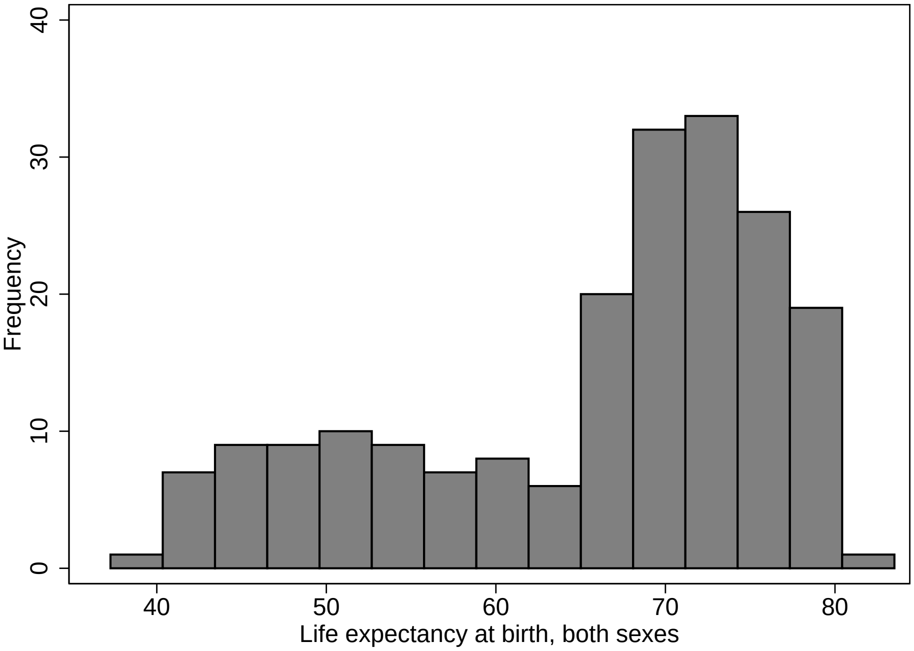


Figure 10: Scientific and technical articles per capita in 188 countries, 1997



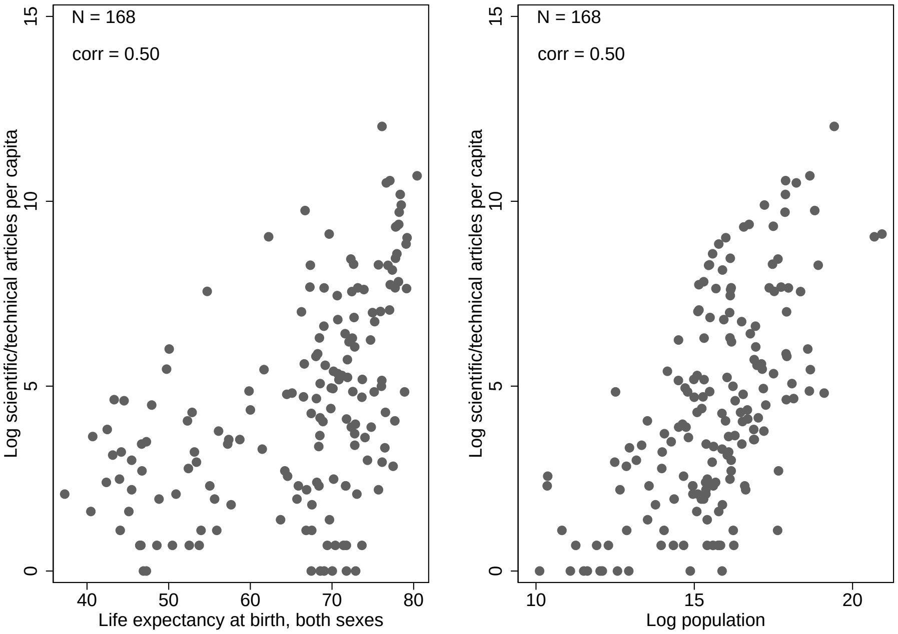
Source: World Development Indicators provided by the World Bank (2004) and author's calculations.

Figure 11: Life expectancy at birth in 197 countries, 1997



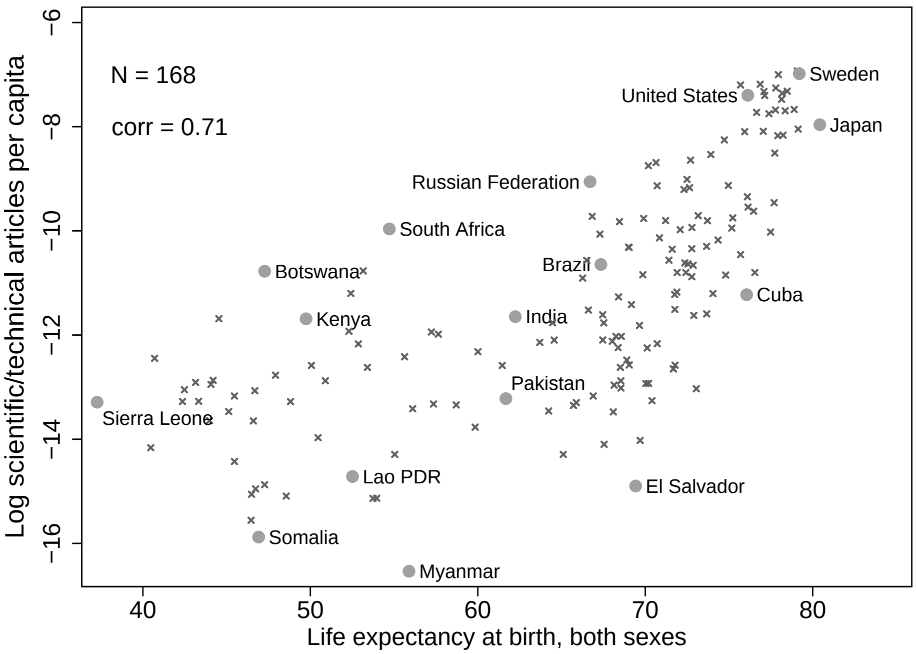
Source: World Development Indicators provided by the World Bank (2004) and author's calculations.

Figure 12: Log of scientific articles vs. e_0 and vs. log population, 1997



Source: World Development Indicators provided by the World Bank (2004) and author's calculations.

Figure 13: Log of scientific articles per capita vs. e_0, 1997



Source: World Development Indicators provided by the World Bank (2004) and author's calculations.