Declining Mortality Among British Scientists During Enlightenment

Ryan D. Edwards[*]

June 30, 2006

Abstract

Traditional theories posit a line of causality running from technological change into mortality decline. But that relationship could be self-sustaining if longer life spans contribute to increased knowledge production. The productivity of scientists appears to decline only gradually with age, implying that a reduction in adult mortality will stimulate knowledge production by leaving more productive scientists alive. The growth in empirical scientific knowledge in the 17th century preceded any widespread mortality declines, which occurred in the 19th century. But the vital statistics of members of the Royal Society of London indicate that the life spans of British scientists were increasing at the same time that scientific knowledge began to grow rapidly, the latter fostered by the Society itself. How significantly the emergence of these early health inequalities contributed to the massive increases in population health following industrialization is unclear and deserving of further inquiry.

---

[*] Assistant professor of economics, Queens College – CUNY. `redwards@qc.cuny.edu`. An earlier version of this paper was prepared for the December 2004 Symposium on Population Ageing and Economic Growth hosted by the Vienna Institute of Demography and the International Institute for Applied Systems Analysis, and it was supported by NIA grant T32 AG000244 during my time as a postdoctoral schoalr in the study of aging with the RAND Corporation. The author wishes to thank Ronald Lee, Shripad Tuljapurkar, seminar participants at RAND and the Vienna Institute of Demography, and two anonymous referees for helpful comments.

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, in part because of defined-benefit public pensions (Bongaarts, 2004), but also because of the structure of fiscal policy and markets (Kotlikoff and Burns, 2005). 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 life-cycle productivity of scientists. Physical functioning naturally deteriorates as a result of aging, and so 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. This pattern suggests that mortality decline, by lengthening the life spans of scientists, may stimulate knowledge production and thus raise productivity, other things equal.

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. Exactly how much life span matters to scientific production is a natural next question, but I leave the answer to future efforts.

The sections that follow lay out the evidence and the argument for why longer life was probably good for early scientific development. 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 discuss some of the broader issues and policy implications to which these insights speak.

Productivity and age in modern economies

We perceive population aging to be costly because we view older individuals as less productive than younger individuals. In the case of old-age mortality decline, we view an additional year of life as one spent unproductively, with consumption financed by transfers or savings rather than by productive activities. Gains against infant mortality are notably different, since they increase productive years. Evidence for this simple view is shown in Figure 1, which depicts the age schedule of labor income per living individual in the U.S. during the 1990s. This locus is the schedule of age-specific productivity per living person, and to a first approximation, it represents the contribution to market output by an individual alive at each age.[1]

For young individuals, market productivity is low because participation is near zero, but it would be low in any case. Education, which is typically rival to labor force participation, develops mental abilities and imparts knowledge and productive techniques. Physical development also occurs during adolescence. During the prime working years, productivity is high and growing. Participation is high, and workers hone skills with repetition while developing new techniques in order to meet challenges.

By age 65, individuals are retiring from market-based work, while a minority may continue to work and earn into later years. The retirement decision is a function of attitudes, abilities, and external circumstances. We know that public pension programs strongly incentivize retirement (Gruber and Wise, 2002), but it is also clear that many abilities degrade with age (Skirbekk, 2004). The ability of individuals to produce surely does not decline as precipitously as Figure 1 depicts, but the confluence of social and economic policies, preferences, and vitality produces a steep decline in market productivity.

Given this relationship, reductions in mortality during adult years will tend to result in more economic dependency, not an increase in productive potential. An additional person-year lived past age 65 will produce no additional market output, ceteris paribus. But is this a universal characteristic of all productive activities, or is it just true for the average wage earner?

Productivity and 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,[2] 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 Weinberg and Galenson (2005) 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 accumulated stocks of knowledge that are important for inductive reasoning. If a significant component of knowledge production is characterized by increasing returns to scale in time inputs, long life spans may be critical ingredients of knowledge growth.

A more pessimistic view, at least for industrialized countries today, 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 now threatens to slow technological change. 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. currently. Underlying both these views is the belief that knowledge production requires the acquisition of a person-specific stock of knowledge, which yields a stream of dividends in the form of new ideas over time. Transmission of knowledge via books, or in modern times via the Internet, is a requisite component of knowledge production, but not a substitute for the scientist's stock of knowledge. The length of a trained scientist's professional career therefore still matters for knowledge production, even if the medium of knowledge transmission improves. If individual stocks of knowledge are important, so too is the associated rate of depreciation. If it were high, say during periods of rapid growth in knowledge, the benefits of a longer scientific career might appear diminished. But Weinberg and Galenson (2005) find that empirical researchers typically produce prizewinning research only later in life, after many years of inductive reasoning using accumulated knowledge. It would appear that stocks of knowledge do not rapidly depreciate, at least in the case of empirical science.

A second way in which knowledge producers are likely to be different as regards their working life spans concerns their preferences over working and leisure. 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.

A third point is that 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.

Scientists in the U.S. today

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.

The measure of productivity I use in Figure 2 is meant to be illustrative, and it does not value output particularly well. Being author or coauthor says nothing about actual contributions made to the published research, and we do not know the quality of the research. If there were trends by age in either of these unmeasured characteristics, an age profile of valuable scientific production may be different than what is shown in Figure 2. Weinberg and Galenson (2005) value the works of Nobel Laureates in economics by counting citations, revealing that empirical thinkers often produce prize-winning research around age 60, while theoretical thinkers tend to do so earlier, by age 40. The SDR data shows that among a representative sample of all doctorate recipients in many disciplines, a cruder measure of scientific output is remarkably flat. The common finding is that older scientists are not unproductive.

Scientists in the Royal Society of London in 1660

I obtain a remarkably similar picture using data on scientific activity from a completely different time period and setting. Hunter (1982) examines the meeting minutes of the Royal Society of London, a scientific organization in Britain begun in 1660 that played a vital role in the development of empirical scientific knowledge (Hall, 1991). The Society was founded 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. Members in good standing served for life, and 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.

Examining the minutes of the Society, Hunter (1982) assigns a qualitative ranking to the activity of Society members as indicated by the mentioning of their meeting interventions. For each member, Hunter also charts the trend in participation over time. I translate these qualitative groups into ordinal rankings, spread them over the life of the member according to Hunter's observations in time, and take averages of the index by age in order to produce a cohort-based age profile of productivity.

The resulting schedule measures the intensity of participation in Society meetings through age. In one clear sense, it is not as good a measure of productivity as we could obtain from publications data if they were available. Meeting interventions probably vary in quality much more than published works. In modern times, attending meetings of official societies may reflect the lack of anything better to do rather than time spent productively. But a key purpose of the Royal Society was to present and discuss scientific experiments (Hall, 1991). Meeting participation was undoubtedly the mechanism for much early scientific development, so a measure of the intensity of participation is an entirely appropriate index of scientific productivity during this early period. And Hunter provides an ordinal scale of activity, not a binary measure of whether or not the individual was present. Although expulsion from the Society was rare and lifetime membership was standard, consistently absent fellows were removed from the rolls entirely. The index measures activity, not just presence.

Figure 3 plots the age profile of Hunter's index averaged over the lives of 74 early members. The locus shows that average activity at meetings peaked between ages 30 and 50 for these individuals. But the decline in activity with age is not particularly large, about half of one qualitative category. Advancing age apparently did little to reduce the participation at meetings of early Royal Society members who survived.

In contrast to the the sharply humped age schedule of economic productivity per living person shown in Figure 1, the age profiles of scientific productivity per surviving doctorate holder in Figure 2 and per surviving Royal Society member in Figure 3 are both relatively flat. Age does not appear to be synonymous with the lack of production in scientific fields. Following the thought experiment, this suggests that expansions in adult life spans among scientists may result in more productive scientists and more scientific productivity, other things equal.

To examine this hypothesis, I proceed to examine historical trends in scientific discovery and development in preindustrial England alongside demographic data on members of the Royal Society. I preface my inquiry with a review of the literature on the origins of modern growth. One of the unanswered questions is how early scientific development took hold, and I find that trends in mortality among early scientists provide new insights, given the shape of the age profile of scientific productivity.

Unanswered questions about historical development

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 the 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, 2004). 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. A related question is whether increases in life expectancy actually represented improvements in health and reductions in morbidity, as we often assume. 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 and life expectancy, a view similar to that of Fogel (2004). 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 at all. When life spans expand through improved medical treatment, the surviving population may in fact become more frail depending on the nature of the illness and treatment (Alter and Riley, 1989). Based on trends observed among Union Army veterans, Fogel (2004) argues that reductions in morbidity have accompanied declines in mortality, at least from the 19th into the 20th century.

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 attributes technological development to population growth or density. But 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. Although these patterns do not refute the Boserupian view, they raise the question of whether other factors may have influenced early growth in science.

What else might have led to early scientific development, if not just population growth? Acemoglu, Johnson and Robinson (2005) emphasize the role of Atlantic trade in promoting institutional change in Western Europe that later facilitated economic growth. Exposure to world markets probably revealed gains to innovations in thought, as well as leading to the rise of the merchant class, property rights, and constraints on the powers of monarchies. The Royal Society of London was founded in 1660, not long after the restoration of a weakened British monarchy. The French analogue to the Society, the Académie des Sciences, was founded 6 years later by the powerful Louis XIV.

Many modern theories of growth attach importance to the role of institutions in general. 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 were important. The Royal Society of London played a key role in the development of modern empirical science (Hall, 1991; Hunter, 1982), and the same was true of scientific societies 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 synchronous timing of these disparate strands — preindustrial mortality declines among urban populations and aristocrats, institutional development, and growth in scientific knowledge — prompts the question of how they may be linked. Vital statistics drawn from the records of the Royal Society of London indicate that mortality rates among its members were declining throughout its history. That is, the life spans of 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 British scientists

With nearly 350 years in existence and more than 8,000 members since its inception, the history of the Royal Society of London 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.

To my knowledge, this study is the first to examine the life spans of early scientists alongside trends in scientific development. I focus on members of Britain's Royal Society because their vital statistics are as readily available as are indicators of knowledge production in Britain, courtesy of Tsoulouhas (1992) and others. In a separate study, Leridon (2004) examines the demography of France's Académie des Sciences, with a focus on trends in the composition of the society, and the average age of members in particular. That paper addresses scientific productivity only indirectly, as an implicit outcome associated with the average age of the group. Leridon documents an inexorably rising average age of Académie members after 1840, which he attributes to secular declines in mortality above age 60 beginning then.

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 roughly 0.03.

In his examination of the much smaller French Académie des Sciences, which averaged only about 20 members prior to 1800, Leridon (2004) reports the average age at death among members by calendar year from 1666 to the present. This is the appropriate measure for analysis of the group, but not for the individuals within. For easier comparison, I calculate the average age at death for Royal Society members by year of death and graph the results in Figure 8, alongside the average age at induction, which also appears in Leridon's Figure 3a. The top line shows the average age at death increasing relatively steadily at a trend rate of 0.068 year per year. This is considerably faster than Leridon's series, which is noisier around an upward trend of about 0.025 per year. The latter also shows less clear direction prior to 1840, which is consistent with Leridon's interpretation of the timeline.[4] To be sure, Figure 8 reveals the same components of graying in the Royal Society that Leridon finds in the Académie des Sciences; the average ages at induction and death are both increasing. But we also see declines in mortality and expansions in adult life spans for Royal Society members far earlier than 1840.

The timing of these early increases in life expectancy among scientists is clearly of key interest. While mortality among the general population remained high at preindustrial levels until the 19th century, we have seen that 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?

A new view of the chronology of preindustrial events

Trends in period life expectancy afford a clearer picture of historical trends in mortality than do the cohort and group rates we have examined prior to now. Using the mortality rates depicted in Figure 6, I construct period life expectancy at age 40, e_{40}, for Royal Society members starting in 1670. Wrigley et al. (1997) provide age-specific mortality rates for both sexes combined in England between 1640 and 1800, from which I then calculate e_{40}. Hollingsworth (1964) reports age-specific mortality for birth cohorts of the British peerage separately by sex, from which I derive period rates and period e_{40} starting in 1625. Males and females in this group of artistocrats experienced similar e_{40} during the period, with an initial female disadvantage of 1–3 years disappearing by about 1750 and becoming an advantage by 1850.

Figure 9 plots these three series of period e_{40} for different British groups on the same axes. Adult life spans among the peerage, shown by the dashed line, were considerably shorter than among the general population, shown by the thick line. This is the well-known urban penalty: communicable diseases could spread more easily in dense cities than in rural areas, and the aristocracy spent much of their time in cities (Johannson, 1999). Life expectancy at 40 among Royal Society fellows is higher than both of these series, and it exhibits rapid growth prior to 1800. Between 1670 and 1920, the average annual increase, measured by the slope of a least-squares regression line, was 0.045 year. Adult life spans among the peerage also expanded rapidly after 1675, which Johannson (1999) attributes to innovative medical practices and improved hygiene, of the type advocated by Francis Bacon. Before 1820, these increases averaged 0.047 year each calendar year. By comparison, e_{40} was also increasing among the general population of England, but the pace was slower, perhaps due to a relative lack of access to new techniques or a distrust of them. During the sample period shown, the average annual increase in e_{40} for English men and women was 0.027.

Were these early increases in adult life expectancy accompanied by declines in morbidity? We have indirect evidence that they were, at least for scientists: the relatively flat age profile of meeting participation intensity shown in Figure 3. Johannson (1999) reports many innovations in treating chronic diseases among the British aristocracy during this early period, which also suggests concomitant declines in morbidity.

During this early period, infant and youth mortality remained quite high, and so life expectancy at birth showed little upward trend. This is why demographers have traditionally dated the escape from the Malthusian trap as occurring around industrialization and not before. But this focus on adult life spans, and on the lifetime productivity of scientists, prompts a revisitation of the historical timeline. The top panel of Figure 10 plots the same e_{40} series for Royal Society Fellows. 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 10 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.

If the productivity of scientists does not degrade with age, then expansions in adult life spans among scientists should result in more scientific productivity. Early declines in adult mortality among scientists and among the peerage were obviously caused by some prior occurrence, and it seems reasonable that improvements in the scientific understanding of disease indeed produced them and came first. This is a modification of the standard view of knowledge and mortality. But the new perspective I propose is that scientists enjoyed the fruits of their own labor, living longer to produce yet more knowledge, and so the cycle continued.

In Figure 11, I summarize 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 11 and labeled "Modified Boserupian." Preindustrial decreases in mortality among elites, and among scientists in particular, facilitates 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.

Discussion

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 laid out the case for an augmented view, in which this growth in technology may be self-sustaining. When improved knowledge fosters lengthened life, scientists can enjoy longer and more productive working careers, facilitating more innovation that helps lengthen life, and so the cycle continues.

This view begins with the observation that life-cycle productivity among scientists does not appear to decline rapidly with age, as is the case in other sectors of the economy. We also hypothesize that 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.

Patterns of mortality among members of the Royal Society of London reveal large and steady improvements in adult life spans among early scientists during a crucial period in the development of empirical scientific thought. Hollingsworth (1964) first recognized this pattern of preindustrial mortality decline, in his case among British nobility widely defined. But previous research has largely ignored this dynamic in interpreting the flow of preindustrial history, concentrating instead on the role of population growth in facilitating development of new knowledge and production techniques. This paper joins Boucekkine, de la Croix and Licandro (2003) in advising a reinterpretation that takes account of early developments in life expectancy. These early mortality declines among scientists and elites are certainly overshadowed by postindustrial trends in population health, which were of unprecedentedly large scale. 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.

But we are also interested in a broader view of how large-scale improvements in public health can be conceptualized, 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, at least in Britain. 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.

Future research should also explore how life spans and the production of ideas and techniques may be related in modern economies, both industrialized and developing. We believe that 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 may add to the productive potential of the macroeconomy while directly raising individual well-being by improving health. This argument is similar to one found in the development literature today, in which there is debate regarding whether better health improves economic growth (Bloom and Sachs, 1998; Acemoglu, Johnson and Robinson, 2003). But scientific production in developing economies is very different from physical production there, and it is also different than scientific production in advanced economies, either in the past or in the present. Still, more research in this area seems promising.

My results also bear implications, albeit weak ones, for the impacts of population aging in industrialized countries. Cutler et al. (1990) find that trends in labor productivity among industrialized countries since 1960 suggest that aging and labor shortages may result in more rapid productivity growth. The mechanism my results suggest, which is more older but productive scientists as a result of population aging, is completely different, but the relatively more positive outlook is similar. If longer adult life spans result in more scientific productivity, the costs of population aging may be somewhat offset. But historical relationships between increases in the life spans of scientists and scientific production may not be easily repeated. We do not know whether further mortality declines at advanced ages will produce life years that are as scientifically productive as produced by prior mortality declines at adult ages. Industrial structures in advanced economies today are quite different than during historical periods. But a trend toward producing ideas and services rather than physical goods probably bodes well for the futures of aging societies, since older workers are probably more likely to remain productive in ideas and services.

Notes

[1] The schedule is based on cross-sectional data and is therefore analogous to a quantity in a period rather than a cohort life table.

[2] 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.

[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] It remains unclear whether mortality declines among French elite and scientists really began later than they did in Britain or not. The small sample size that Leridon must confront in his examination of the Académie des Sciences may obscure these early trends prior to 1800.

References

Acemoglu, Daron, Simon Johnson and James Robinson. 2003. "Disease and Development in Historical Perspective." *Journal of the European Economic Association* 1(2–3):397–405.

Acemoglu, Daron, Simon Johnson and James Robinson. 2005. "The Rise of Europe: Atlantic Trade, Institutional Change, and Economic Growth." *American Economic Review* 95(3):546–579.

Alter, George and James C. Riley. 1989. "Frailty, Sickness, and Death: Models of Morbidity and Mortality in Historical Populations." *Population Studies* 43(1):25–45.

Bloom, David E. and Jeffrey D. Sachs. 1998. "Geography, Demography, and Economic Growth in Africa." *Brookings Papers on Economic Activity* 2:207–295.

Bongaarts, John. 2004. "Population Aging and the Rising Cost of Public Pensions." *Population and Development Review* 30(1):1–23.

Boserup, Ester. 1965. *The Conditions of Agricultural Growth: The Economics of Agrarian Change Under Population Pressure.* New York: Aldine.

Boserup, Ester. 1981. *Population and Technological Change: A Study of Long-Term Trends.* Chicago: University of Chicago Press.

Boucekkine, Raouf, David de la Croix and Omar Licandro. 2003. "Early Mortality Declines at the Dawn of Modern Growth." *Scandinavian Journal of Economics* 105(3):401–418.

Cutler, David M., James M. Poterba, Louise M. Sheiner and Lawrence H. Summers. 1990. "An Aging Society: Opportunity or Challenge?" *Brookings Papers on Economic Activity* 1:1–56.

Easterlin, Richard A. 1995. "Industrial Revolution and Mortality Revolution: Two of a Kind?" *Journal of Evolutionary Economics* 5(4):393–408.

Fogel, Robert W. 2004. *The Escape from Hunger and Premature Death, 1700–2100.* Cambridge: Cambridge University Press.

Galor, Oded and David N. Weil. 2000. "Population, Technology, and Growth: From Malthusian Stagnation to the Demographic Transition and Beyond." *American Economic Review* 90(4):806–828.

Gruber, Jonathan and David Wise. 2002. "Social Security Programs and Retirement Around the World: Micro Estimation." *NBER Working Paper* 9407.

Hall, Marie Boas. 1991. *Promoting Experimental Learning: Experiment and the Royal Society 1660-1727*. Cambridge: Cambridge University Press.

Hall, Robert E. and Charles I. Jones. 1999. "Why Do Some Countries Produce So Much More Output Per Worker Than Others?" *Quarterly Journal of Economics* 114(1):83–116.

Hammel, E. A. 1983. "The Productivity of Chemists and Mathematicians at the University of California: An Age/Cohort Analysis." *U.C. Berkeley Program in Population Research Working Paper* No. 11.

Hollingsworth, T. H. 1964. "The Demography of the British Peerage: Supplement." *Population Studies* 18(2).

Hunter, Michael. 1982. *The Royal Society and Its Fellows, 1660-1700: The Morphology of an Early Scientific Institution*. Chalfont St. Giles, Bucks, England: British Society for the History of Science.

Johannson, S. Ryan. 1999. "Death and the Doctors: Medicine and Elite Mortality in Britain from 1500 to 1800." *Cambridge Group for the History of Population and Social Structure Working Paper Series* No. 7.

Jones, Benjamin F. 2005. "Age and Great Invention." *NBER Working Paper* 11359.

Jones, Charles I. 2001. "Was an Industrial Revolution Inevitable? Economic Growth Over the Very Long Run." *Advances in Macroeconomics* 1(2):1–43.

Kotlikoff, Laurence J. and Scott Burns. 2005. *The Coming Generational Storm: What You Need to Know about America's Economic Future*. Cambridge, MA: MIT Press.

Kremer, Michael. 1993. "Population Growth and Technological Change: One Million B.C. to 1990." *Quarterly Journal of Economics* 108(3):681–716.

Lee, Ronald. 1988. "Induced Population Growth and Induced Technological Progress: Their Interaction in the Accelerating Phase." *Mathematical Population Studies* 1(3):265–288.

Lehman, Harvey C. 1953. *Age and Achievement.* Princeton, NJ: Princeton University Press.

Leridon, Henri. 2004. "The Demography of a Learned Society: The Académie des Sciences (Institut de France) 1666–2030." *Population-E* 59(1):81–114.

Levin, Sharon G. and Paula E. Stephan. 1991. "Research Productivity Over the Life Cycle: Evidence for Academic Scientists." *American Economic Review* 81(1):114–132.

Maddison, Angus. 2001. *The World Economy: A Millennial Perspective.* Paris: OECD Development Centre.

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

Oeppen, Jim and James W. Vaupel. 2002. "Broken Limits to Life Expectancy." *Science* 296:1029–1031.

Preston, Samuel H. 1975. "The Changing Relationship between Mortality and Level of Economic Development." *Population Studies* 29(2):231–248.

Royal Society. 2004. Lists of Royal Society Fellows 1660–2004. Available at http://www.royalsoc.ac.uk.

Schalick, Lisa Miller, Wilbur C. Hadden, Elsie Pamuk, Vincente Navarro and Gregory Pappas. 2000. "The Widening Gap in Death Rates Among Income Groups in the United States from 1967 to 1986." *International Journal of Health Services* 30(1):13–26.

Skirbekk, Vegard. 2004. Age and Individual Productivity: A Literature Survey. In *Vienna Yearbook of Population Research 2004*, ed. Gustav Feichtinger. Vienna: Austrian Academy of Sciences Press pp. 133–153.

Szreter, Simon. 1997. "Economic Growth, Disruption, Deprivation, Disease, and Death: On the Importance of the Politics of Public Health for Development." *Population and Development Review* 23(4):693–728.

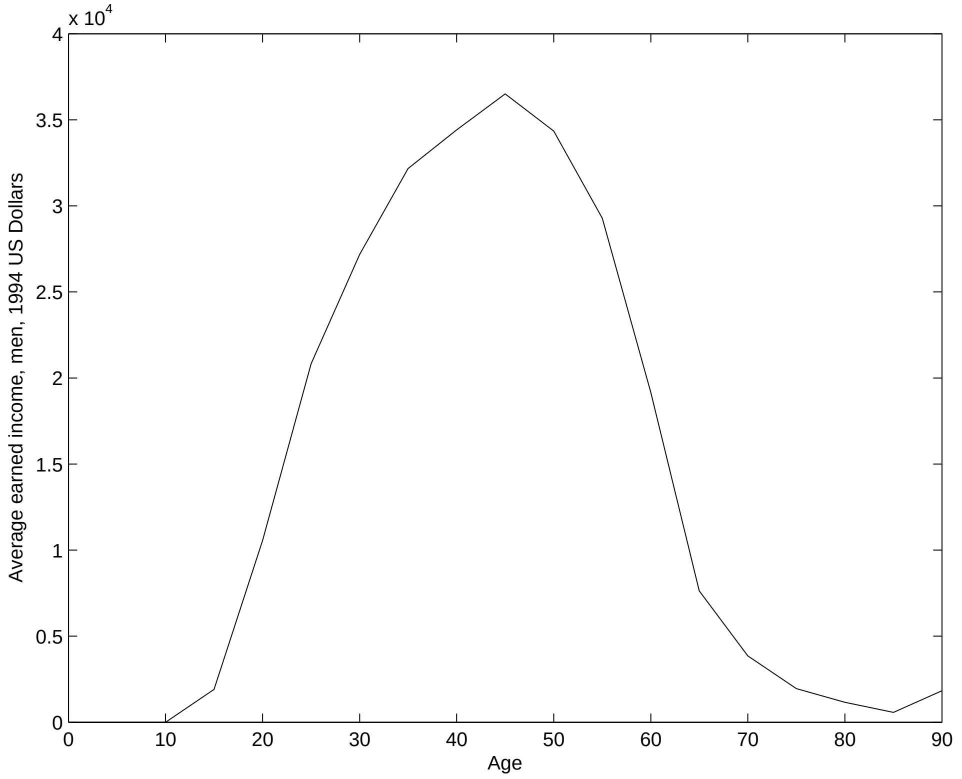
Tsoulouhas, Thefanis C. 1992. “A New Look at Demographic and Technological Changes: England, 1550 to 1839.” *Explorations in Economic History* 29(2):169–203.

Weinberg, Bruce A. and David W. Galenson. 2005. “Creative Careers: The Life Cycles of Nobel Laureates in Economics.” *NBER Working Paper* 11799.

Wrigley, E. A., R. S. Davies, J. E. Oeppen and R. S. Schofield. 1997. *English population history from family reconstitution 1580–1837.* Cambridge: Cambridge University Press.

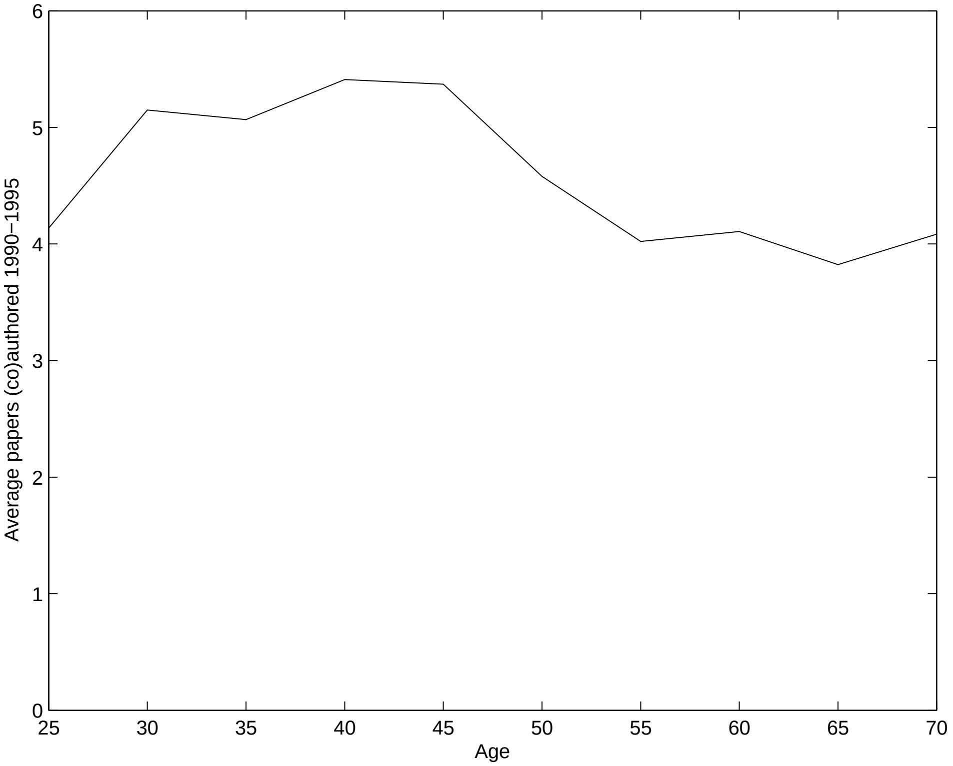
Wrigley, E. A. and R. S. Schofield. 1981. *The Population History of England 1541–1871: A Reconstruction.* Cambridge: Harvard University Press.

Figure 1: The modern age profile of earned income



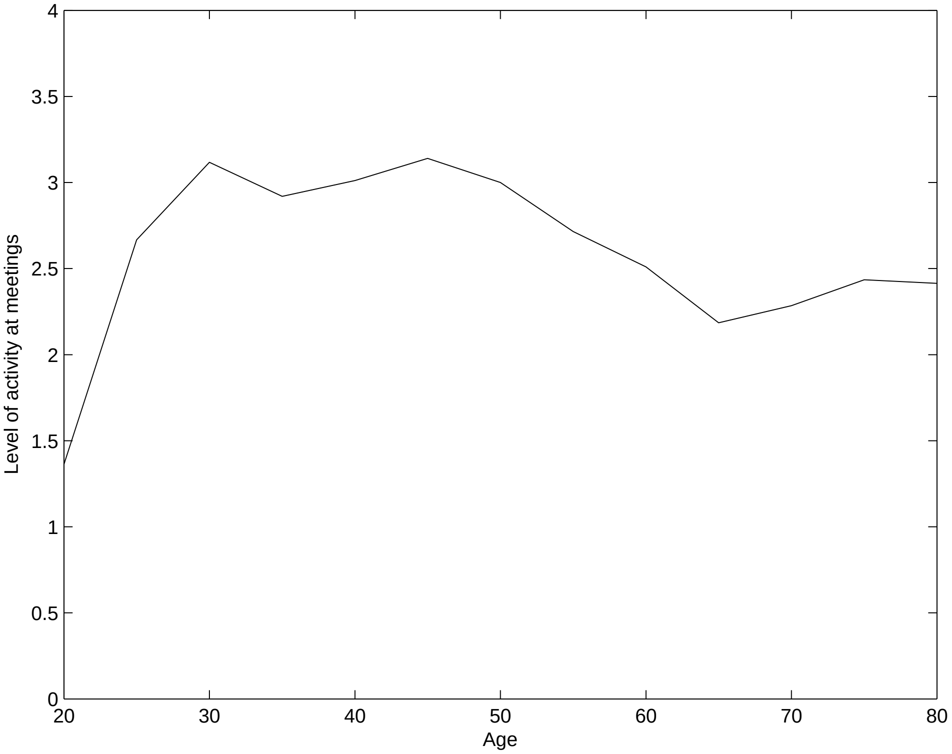
Source: March Current Population Surveys, 1992–96. Data are earned income for males, averaged by 5-year age group.

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



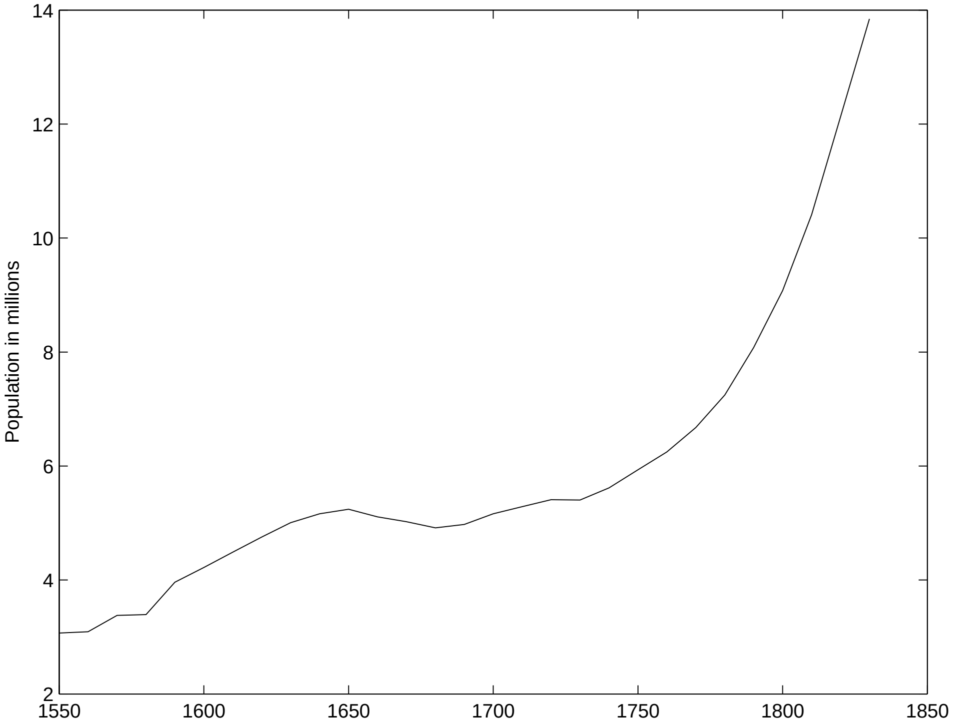
Source: 1995 Survey of Doctorate Recipients, National Science Foundation. Data are the number of journal articles authored or coauthored between 1990 and 1995, averaged over 5-year age groups. Age 25 is an open-ended group of individuals younger than age 29; age 30 is ages 30–34; and age 70 refers to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

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



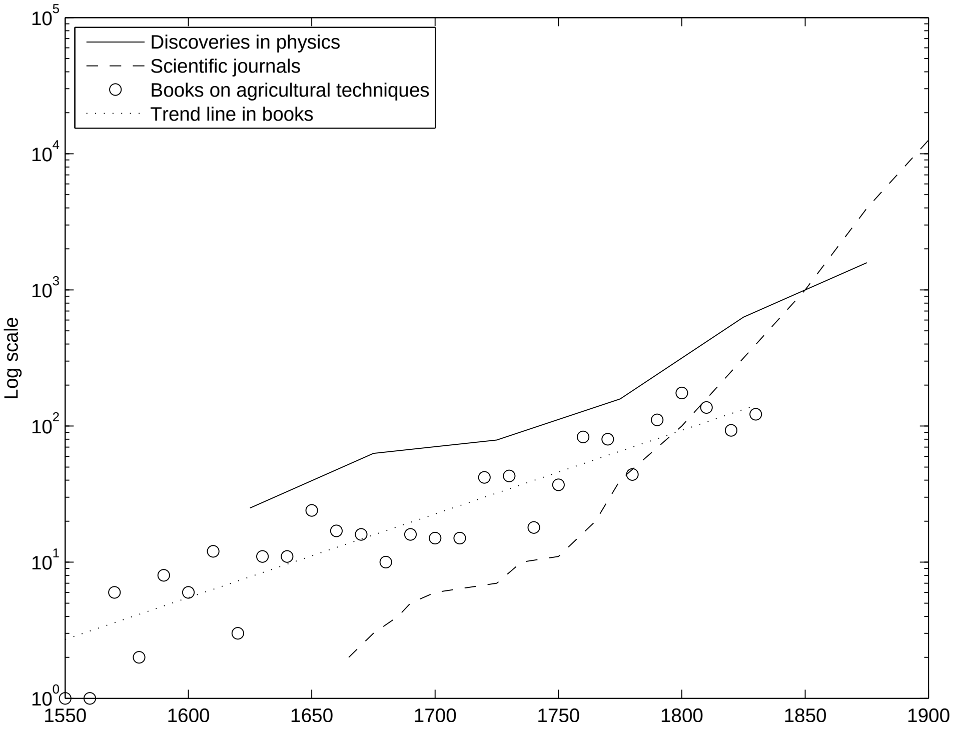
Source: Hunter's (1982) characterization of Fellows' activity based on meetings minutes. Six ordinal rankings of activity are scored as 1–6 with 1 being inactive; 2 barely active; 3 slightly active; 4 fairly active; 5 active; and 6 very active. The data are then averaged over 5-year age groups. The data 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



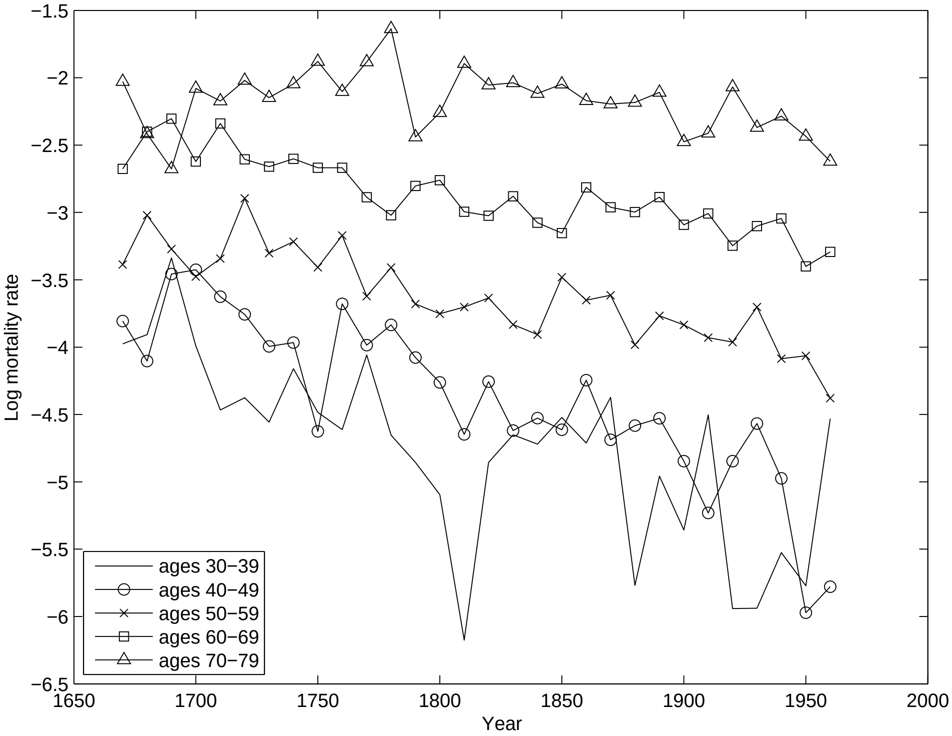
Source: Tsoulouhas (1992).

Figure 5: Scientific knowledge and production techniques since 1550



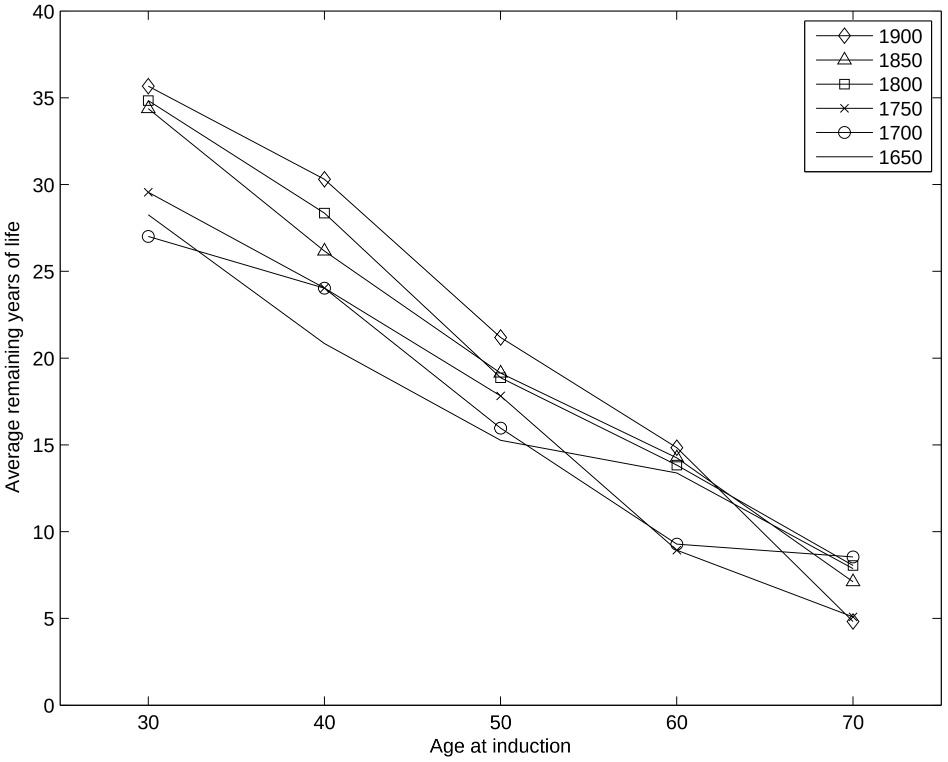
Source: Tsoulouhas (1992) and Easterlin (1995). The dotted line is a simple trendline fitted to the data on books on agricultural techniques, which are shown by the circles. The data are graphed on a base-10 logarithmic scale.

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



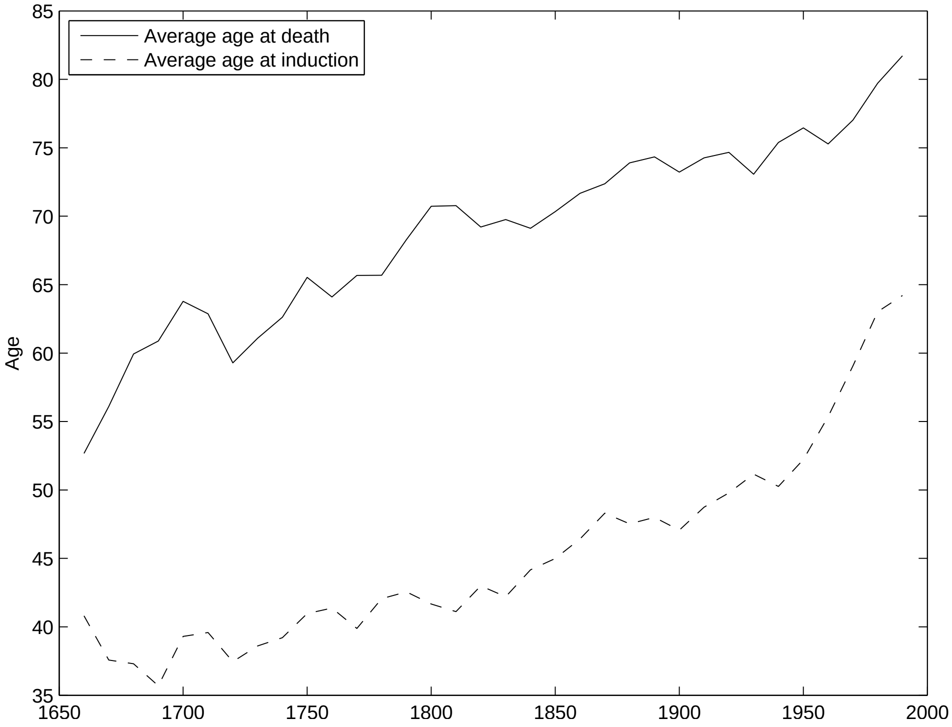
Source: Royal Society (2004) and author's calculations. The data are period mortality rates constructed using 10-year age groups observed over 10 years of time and then logged.

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



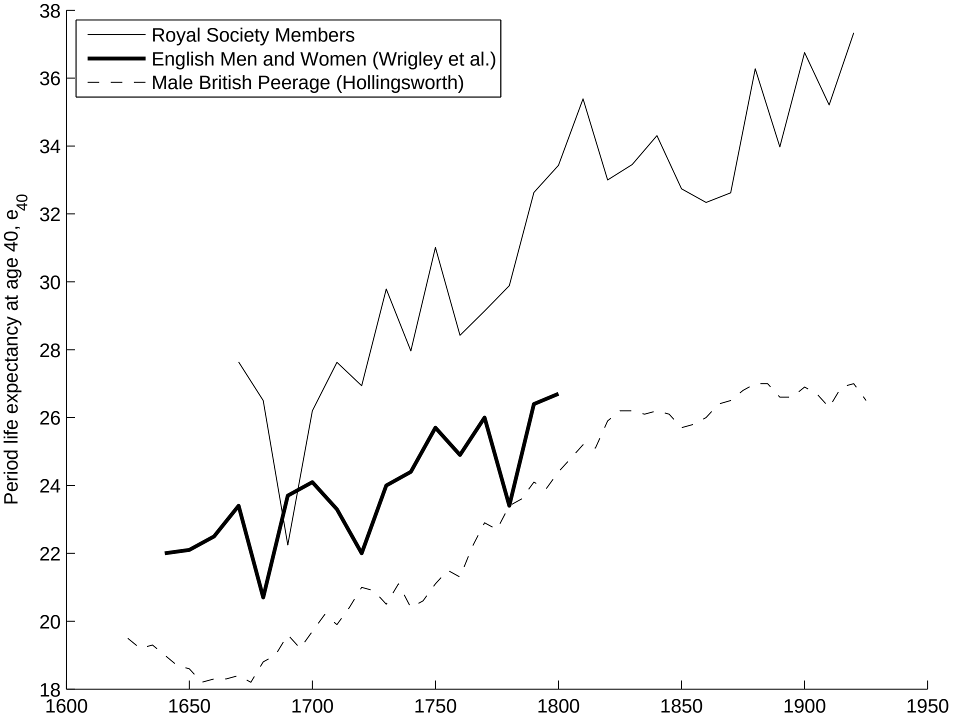
Source: Royal Society (2004) and author's calculations. These curves show cohort life expectancies: average years remaining on the y-axis by age at induction on the x-axis at six points in time.

Figure 8: Average age at death and average age at induction, Royal Society of London



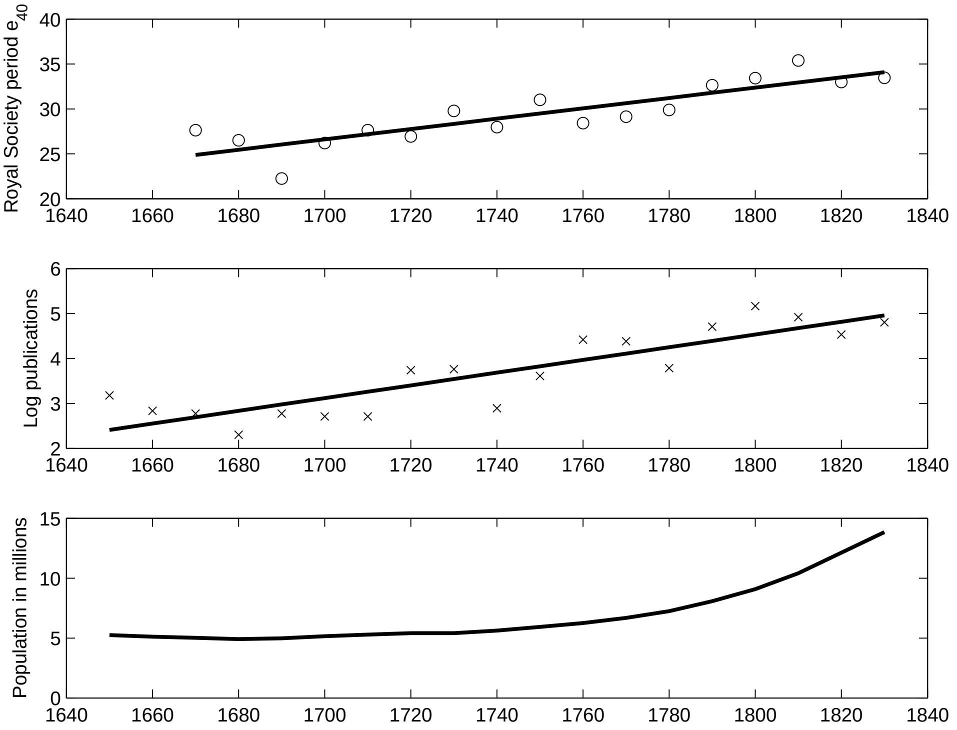
Source: Royal Society (2004) and author's calculations. The top line shows the average age at death among those dying by decade of death. The bottom, dashed line shows the average age at induction among those inducted by the decade of induction.

Figure 9: Life spans of Royal Society fellows, science, and population in England before 1830



Sources: , and author's calculations based on biographical records from the Royal Society of London. The thin solid line plots period life expectancy at age 40, e_{40}, for Royal Society fellows, constructed using the period mortality rates depicted in Figure 6. The thick solid line shows period e_{40} for all English men and women, based on mortality rates provided by Wrigley et al. (1997). The dashed line shows period e_{40} for males in the British peerage based on cohort mortality rates presented by Hollingsworth (1964) transformed into period rates. Male and female e_{40} were roughly the same in the Hollingsworth data.

Figure 10: 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 11: Views of the historical record and causality