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ABSTRACT

Perhaps the most important change of the last century was the great expansion of life itself -- in the US alone, life expectancy increased from 48 to 78 years. Recent economic estimates confirm this claim, finding that the economic value of the gain in longevity was on par with the value of growth in material well-being, as measured by income per capita. However, ever since Malthus, economists have recognized that demographic changes are linked to economic behavior and vice versa. Put simply, living with others who live 78 years is different than living with others who live only 48 years, so that valuing the extra 30 years of life is not simply a matter of valuing the extra years a single individual lives. The magnitude by which such valuations differ is overstated when there are increasing returns to population and is understated under decreasing returns. Focusing on the gains in life expectancy in the United States from 1900 to 2000, we find that a significant part of the value of longer life may be affected by these general equilibrium demographic effects.

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I. INTRODUCTION

The 20th century witnessed tremendous advances in health, including the development of the germ theory of disease, the use antibiotics to treat infectious disease, and genetic testing for inherited conditions. Indeed, it seems hard to argue that any one change during this last century was more important than the expansion of life itself. Despite the large magnitude of these increases in life expectancy, relatively little effort has been made by economists to estimate the value of these increases, especially when compared to research efforts devoted to analyzing growth in per-capita income.

There is a growing consensus among economists that the total economic value of gains in longevity and health swamped the single accomplishments of some of the largest advances in the past hundred years, from such breakthroughs as railroads, aviation, and the internet. Indeed, a substantial amount of recent work indicates that the gain in human longevity is the most important economic advancement over the last century. For the US alone, Cutler and Richardson (1997), Nordhaus (2003), and Murphy and Topel (2006) all estimate that longevity gains have been on par in value to the gains in material well being from income growth as measured by traditional income account measures. For the world as whole, Becker, Philipson, and Soares (2005) argue that changes in inequality are greatly affected by incorporating longevity into national income accounting. This strand of work uses traditional microeconomic equilibrium methods to monetize the value of gains in longevity, in the sense that what is valued is a change in longevity itself, holding other factors constant (c.f. Usher (1973) and Rosen (1988)).

However, longevity affects the levels and growth of economic income and therefore ignoring these effects in the value of increased longevity may be misleading. There are several mechanisms by which longevity may affect income. The most direct is through population size—indeed, as fertility has been falling and longevity growing, the growth in longevity alone is an important source of the increased size of populations in many countries. And ever since the pioneering work of Malthus, economists and others have recognized the potential impact population size may have on income (Coale and Hoover, 1958; Kuznets, 1973; Boserup, 1981). Increased longevity may affect income through non population-based channels as well. For example, longer life may stimulate savings for old age (Lee, Mason, and Miller, 2000) or lead to increased human capital accumulation by lengthening the period over which returns to human capital investment accrue (Meltzer, 1992).

In this paper, we attempt to reconcile these separate strands of research efforts by incorporating the *external* effects of increased aggregate longevity into estimates of the value of gains in longevity. Our approach is in contrast with previous work assessing the value of growth in longevity which is *partial equilibrium* in nature, assuming non-existent the importance of demographic change in determining levels of income per capita. For example, aggregate improvements in longevity raise population size, which in turn impacts income levels, depending on whether there are decreasing or increasing returns to scale in population. Our main argument is that the wage effects induced by increased longevity may greatly alter estimates of the value of this increased longevity obtained from partial equilibrium approaches that ignore them. A fuller description of the value of mortality improvements incorporates not only the private valuation of improvements in survival but also the change in income that occurs as a result of population wide changes in longevity.

To illustrate this argument, consider the gains in survival that took place in the US in the last century—life expectancy rose nearly 30 years, from 48.2 years in 1900 to 77.6 years in 2000. Traditional methods of valuing these additional years of life would be based on the calibrated willingness-to-pay of an individual for the observed improvement in survival, holding all else constant. For example, we calibrate that for a hypothetical individual earning 1900 income per capita in every year of his life ($4,087 in 1996 dollars), he would be willing to spend nearly 43% of his annual income (or $1,752 annually) to face year 2000 cross-sectional survival compared to 1900 survival. However, this calibrated willingness-to-pay does not take into account the several ways in which increased aggregate longevity may affect annual income. For example, if the larger population increases (decreases) income per capita, the calibrated *social* value of the aggregate improvement in longevity would be higher (lower) than the calibrated *private* value. This is because living with others who live 78 years may be quite different than living with others who live only 48 years, so that privately valuing the extra 30 years of life is not simply a matter of valuing the extra years one lives. To the extent that these external effects of longevity on income are important, the true social value of improvements in longevity may depart widely from private valuations that ignore them.

We pursue five separate approaches to quantitatively examine how the value of improved longevity may be affected when the external effects of population-wide changes in mortality are accounted for. The main purpose of this analysis is not to advocate a particular size or sign of the external effect, but rather to illustrate the implications of alternative estimates of these effects for current methods of valuing aggregate improvements in longevity.

Our first two approaches focus on the effect of longer life expectancy on human capital investment and income, holding population constant. Longer life increases the return to investing in human capital at the individual level, which in turn leads to more education and higher annual earnings—the utility value of these additional earnings, of course, takes into account the utility and monetary costs required for the additional investment (e.g. postponing marriage, increasing foregone labor income, and so on). We discuss under what conditions this *internal* effect of improved longevity is captured by standard methods of valuing improvements in survival. Moreover, since the average level of human capital in an economy would be raised by population-wide reductions in mortality, there may be *external* effects of improved longevity on income as well. For example, individual productivity and earnings may depend on the human capital of others in the economy. Our first approach uses the calibrated external effects of education on income from Lucas (1988) along with the education effects of improved longevity from Acemoglu and Johnson (2006) to illustrate, for the 20th century US, the potential magnitudes of these internal and external effects of improved longevity on income. Our second approach uses estimates of the effect of life expectancy on growth from the cross-country growth literature. While some may argue that this literature often suffers from identification issues which render such estimates difficult to interpret, it serves as a useful initial benchmark to motivate our analysis.

Since the most direct effect of improved survival is a larger population, our last three approaches focus on the effects of population size on income per capita. In each of these instances, we calibrate the effect of a population increase that is consistent with how the US population would have evolved from 1900 to 2000 in the face of survival improvements alone—netting out the impact of immigration and under various assumptions on fertility behavior throughout the century, we estimate that these gains in longevity alone would have increased the counterfactual US population by almost 300 percent. The effect of this increase in population on per capita income naturally depends on whether there are increasing or decreasing returns to scale in population.

In the third approach, we calibrate the effect of increased population in a Malthusian regime, in which the presence of inelastically supplied inputs such as land imply that increases in population have negative effects on income by lowering the marginal product of labor. In this decreasing returns case, current methods of valuing improvements in aggregate longevity would overstate the social value, which incorporates the reduction in income associated with increased population. Our fourth approach calibrates a canonical endogenous growth model similar in spirit to work by Romer (1986; 1990) and Jones (1999). In this model, individual investments in R&D have economy-wide spillover effects that increase the productivity of other firms and generate increasing returns to population when firms are unable to fully capture the external effects of their R&D investments. Our fifth approach uses estimates from the growth literature to infer the empirical relationship between population and income. Again, while this literature may be inadequately identified at times, it does serve as a benchmark to frame our other estimates.

Our main finding is that, across all the approaches that we use, accounting for population-wide increases in survival has large effects on the estimated value of gains in US longevity. For example, we find that accounting for survival-induced increases in human capital investment and incomes increases the estimated value of gains in health by roughly 16-33%. Similarly, using the growth literature that examines the effects of increases in life expectancy and population on economic growth raises the estimated value of health gains by 150-250%. Importantly, not all of our approaches suggest that increases in population have a positive effect on the valuation of health gains. The Malthusian model, for example, predicts the value of 20th century health gains to be *negative*, because while increases in health are valued in and of themselves, the concomitant increase in population and its negative effects on income are much larger. In this light, an interesting implication of our findings is that the value of improved longevity in many developing countries—where Malthusian-like decreasing returns to population are perhaps more likely—may be overstated due to income-lowering effects of added population. A potentially relevant example of this is the increase in young-age mortality in Africa due to AIDS, which Young (2005) argues to have had substantial positive effects on income per capita among those surviving the epidemic.

The paper may be outlined as follows. Section II illustrates the bias in partial equilibrium estimates of the value of life and demonstrates how calibrated or empirical relationships between longevity and income can be incorporated to quantify its size and direction. Section III then develops the model in section II to obtain partial equilibrium estimates of the value of 20th century US health gains. Section IV discusses our efforts to quantify the differences between the general and partial equilibrium values. Lastly, Section V concludes and discusses future research.

II. PARTIAL vs GENERAL EQUILIBRIUM VALUATION OF LIFE

In order to illustrate how current methods of valuing population-wide changes in longevity are affected by the internal and external effects of such changes, we consider a *hypothetical life-cycle individual* (*HLCI*, c.f. Becker, Philipson, and Soares (2005)) born in calendar year *t* who faces cross-sectional survival (S_t) and lifetime net income given by:

$$Y(A(S_t), I_t, E_t) = A(S_t)y(I_t, E_t) \qquad (1)$$

where $A(S_t) = \sum_{a=0}^{\infty} \beta^a S_t(a)$ is the present value of an annuity paying one dollar per year given survival S_t and discount rate β, and $y(I_t,E_t)$ is annual net income which, for simplicity, is assumed to be constant over time and equal to its value in calendar year *t*.

Lifetime net income is defined as gross income minus all investment expenditures and is determined by three factors. The first is the period of time over which annual net income y is earned, captured by $A(S_t)$. The second is a set of "internal" behaviors denoted by I_t—namely behaviors chosen by the individual to maximize his utility. These behaviors may include decisions over one's own human capital investment, life cycle savings, and family formation, all of which are affected by life expectancy and likely chosen to maximize utility. Each of these investments may raise lifetime gross income, but presumably only at a cost, whether in foregone earnings, tuition, delayed marriage, etc. In theory, our concept of net income is intended to adjust for these costs. For example, consider an investment in education due to improved longevity that results in an increase in lifetime gross income of $500,000. If the cost of tuition and foregone earnings were $200,000, focusing on gross income alone would lead us to incorrectly calculate the effect of improved longevity on income to be \$500,000, rather than the \$300,000 that would obtain when investment costs are considered.

The third determinant of lifetime net income is a set of "external" behaviors denoted by E_t—namely outcomes (typically determined by others) that do not necessarily maximize utility but nonetheless are affected by survival. The total size of the population at various dates is the primary example we consider—it depends on the survival rates of all persons in the economy and does not necessarily maximize anyone's utility.[1] An individual's income might be affected by the number of persons alive because of (a) diminishing returns to labor arising from fixed inputs to production, e.g. land, (b) increases in the extent of the market which raise the returns to R&D, and (c) socially increasing returns to R&D arising from external effects of R&D on the productivity of other firms. An additional "external" effect of improved longevity may operate through spillovers in human capital. If aggregate improvements in longevity raise the average level of human capital (an internal effect) and individual productivity depends on the human capital of others (an external effect), population-wide changes in mortality would be expected to have both internal and external effects on income through a single channel alone, human capital. For convenience, we normalize the measurement of I_t and E_t so that they increase, rather than decrease, annual net income y.

The lifetime indirect utility of our *HLCI* born in calendar year t is:

$$V[Y(A(S_t),I_t,E_t),A(S_t)] \quad = \quad \max A(S_t)U(c_t) \quad s.t. \quad A(S_t)c_t = Y(A(S_t),I_t,E_t) \qquad (2)$$

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[1] For example, consider a birth cohort of size n_t born in year t that lives to age a with probability $S_t(a)$. The population size in any year t is then determined by $N_t = \sum_{k=-\infty}^{t} n_k S_k(t-k)$.

By having the same discount factor in both the preferences and the budget set, we are implicitly abstracting from life-cycle consumption profile decisions—cohort *t*'s decision, then, is only about the average amount to consume in every year c_t. Moreover, since our *HCLI* is assumed to derive utility only from consumption, the benefits and costs of human capital investment and other behaviors are fully captured in the maximized lifetime net income *Y*.

To illustrate how current methods of valuing population-wide changes in longevity are affected by the internal and external effects of such changes, we use the indirect utility to first calculate our *HLCI's* partial equilibrium (PE) willingness to pay, P_{PE}, for an increase in cross-sectional survival from *S* to *S'*. This willingness-to-pay holds constant the effects of survival on internal and external behaviors, implicitly assuming away (or approximating as zero) the effects on income of changes in own-investment and population size:

$$V[Y(A(S'), I, E) - P_{PE}, A(S')] = V[Y(A(S), I, E), A(S)] \qquad (3)$$

That is, P_{PE} is the amount our *HLCI* would be willing to pay to be just indifferent between the two survival prospects, *S* and *S'*, holding constant the internal and external behaviors.

The PE willingness-to-pay for an improvement in survival from S to S' can therefore be written as:

$$P_{PE} = P_{PE}(S, S', Y(A(S'), I, E), Y(A(S), I, E)) \qquad (4)$$

The PE willingness-to-pay does not account for the changes in the population, or changes in the individual's own behaviors, that result from the increased aggregate life expectancy—it does, however, account for the longer period over which the original annual income is now earned. For *small* changes in survival, the envelope theorem tells us that, even though the PE willingness to pay holds many things constant, it still captures the induced changes in any *internal* behavior I that already maximizes V for a given survival, because those induced changes have no utility value at the margin. Therefore, in the absence of any external effects, P_{PE} would be unaffected by small changes in survival. And in fact, since most estimates of the value of improvements in survival stem from the willingness-to-pay to avoid small changes in mortality risk, the expected magnitude of this internal effect is small or zero in these instances. However, while schooling, life cycle savings, and other personal decisions may well be optimally chosen by each individual, *for large changes in survival*, the utility value of new choices may not be zero. Therefore, when valuing large improvements in longevity, both the benefits and costs of these internal effects may be quite important. Moreover, even for small changes in survival, the envelope theorem does not apply to the effects of survival on population size and (other external behaviors) since there is no obvious reason why total population would maximize an individual's utility. For example, important activities like innovation have socially increasing returns.[2]

Given the various channels through which changes in survival may affect income, our *HLCI's* general equilibrium (GE) willingness-to-pay can be written as:

$$P_{GE} = P_{GE}(S, S', Y(A(S'), I', E'), Y(A(S), I, E)) \qquad (5)$$

The GE value of improved aggregate longevity accounts for the effect of mortality reductions on lifetime income. P_{GE} is determined by:

$$V[Y(A(S'), I', E') - P_{GE}, A(S')] = V[Y(A(S), I, E), A(S)] \qquad (6)$$

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[2] The envelope theorem does not apply when evaluating the effects of survival on outcomes other than utility, e.g. income inequality. In this case, even marginal changes in survival may have an impact, although behavior-induced effects on utility would be absent.

where *E'* reflects the effects of changes in survival on population and other external behaviors, and *I'* reflects the effects of changes in survival on internal behaviors. The GE willingness-to-pay for improved survival reflects the value of not only longer life, but of the potentially disproportionate change in net lifetime income that results from individual *and* aggregate increases in longevity. Specifically, the above expression illustrates that the GE value of improved longevity, which incorporates the income effect of improved health, differs from its PE counterpart by:

$$P_{GE} - P_{PE} = Y(A(S'), I', E') - Y(A(S'), I, E) = A(S')[y(I', E') - y(I, E)] \qquad (7)$$

The PE-GE difference, then, is the discounted change in net lifetime income holding survival fixed at its new value.[3] When changes in survival have no effect on the evolution of net annual incomes, the difference is zero.[4] Clearly then, the estimated magnitude of the PE-GE difference will depend heavily on estimates of how improvements in survival affect income per capita—either internally, through affecting incentives for investment, or externally, through affecting population size or the average level of human capital in the economy. The remainder of this paper illustrates the potential magnitude of this survival-induced income effect for several different scenarios, each of which can be usefully contrasted to the PE willingness-to-pay for improved survival which we turn to next.

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[3] A similar calculation can be made when determining the willingness to accept a survival change. For example, the PE willingness-to-accept satisfies $V[Y(A(S), I', E') + P_{PE, WTA}, A(S)] = V[Y(A(S'), I', E'), A(S')]$. The PE-GE difference is similarly $Y(A(S), I', E') - Y(A(S), I, E) = A(S)[y(I', E') - y(I, E)]$. The willingness-to-accept PE-GE difference therefore differs only by the annuity.

[4] In the absence of external effects, an upper bound of the PE-GE difference is the present value of the differences in *gross* annual incomes. Since the potential increases in income that result from survival improvements presumably come at a larger cost of investment, using net incomes which adjust for these costs would lower the computed difference.

III. VALUING THE GAINS IN US LONGEVITY, 1900 – 2000: A PARTIAL EQUILIBRIUM CALIBRATION

We develop the infra-marginal framework described above to calibrate the PE value of improvements in US longevity from 1900-2000, a period over which life expectancy increased by nearly thirty years, from to 48.2 to 77.6. This offers us a quantitative benchmark with which to relate the income effects of increased aggregate longevity that we compute later. In the formulas above and below, the non-indexed variables correspond to year 1900 and the indexed ones to year 2000. Following our discussion and earlier work by Becker, Philipson, and Soares (2005), we value the observed improvement in longevity by considering a single *hypothetical life cycle individual* who faces 1900 cross-sectional survival and 1900 income per capita in every year of their life. We calibrate how much that individual would be willing to pay to face year 2000 cross-sectional survival and 1900 income per capita in every year of their life, instead.

We calibrate the PE value of life by parameterizing instantaneous utility according to:

$$U(c) = \frac{c^{1-1/\gamma}}{1-1/\gamma} + \alpha \qquad (8)$$

where γ is the intertemporal elasticity of substitution and α is a normalization factor that determines the level of annual consumption at which the individual is indifferent between being alive or dead.[5] Under the maintained parameter assumptions on utility, expressions

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[5] We assume the following parameter values: intertemporal elasticity of substitution, 1.25; normalization factor α, -16.2; interest rate, 0.03. See Becker, Philipson, and Soares (2005) for a detailed justification of these values.

(2) and (3) be can be solved to calculate the *annual* PE willingness to pay for an infra-marginal change in survival from S to S':[6]

$$p_{PE} = y(I,E) - \left[y(I,E)^{1-1/\gamma} \cdot \frac{A(S)}{A(S')} + \alpha \cdot (1-1/\gamma) \cdot \frac{A(S)-A(S')}{A(S')} \right]^{\frac{\gamma}{\gamma-1}} \qquad (9)$$

The corresponding *lifetime* PE willingness to pay, P_{PE}, is simply the discounted sum of the *annual* PE willingness to pay, p_{PE}:

$$P_{PE} = A(S')p_{PE}. \qquad (10)$$

To estimate S and S', we use US cross-sectional survival data from 1900 and 2000 obtained from the Berkeley Mortality Database, which contains historical life-tables published by the Office of the Actuary of the Social Security Administration. For simplicity, we assume that *net* income per capita in 1900, *y(I, E)*, equals actual income per capita in that year—that is, we implicitly assume investments in education and health to be zero in the initial period. For an individual earning 1900 income per capita for every year of their life—namely, $4,087 per year in 1996 dollars (Historical Statistics of the United States, 2003)—the calibrated willingness to pay for an improvement in survival from 1900 to 2000 levels is roughly $1,752 per year or $53,010 over a lifetime. As a share of 1900 income per capita, the PE value of these gains in longevity is nearly 43 percent. This is closely related to findings by Murphy and Topel (2006), who estimate the economic gains in health between 1900 and 2000 to be between 10 and 50 percent of annual GDP.

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[6] For more details, see Becker, Philipson, and Soares (2005) and Philipson and Jena (2005). These papers present valuation formulas based on a willingness-to-accept, whereas we calculate the willingness to pay.

IV. QUANTIFYING THE DIFFERENCES BETWEEN THE PE AND GE VALUES OF HEALTH

The size and direction of the PE-GE difference in valuing population-wide improvements in longevity are determined by the extent to which changes in survival affect annual income. Therefore, any conclusion of whether the PE-GE difference is of first- or second-order compared to PE valuations of improved longevity will rely heavily on empirical or calibrated estimates of how survival affects income, either directly or through changes in population size. We pursue five separate approaches to quantitatively examine how the value of improved longevity may be affected when the internal and external effects of population-wide changes in mortality are accounted for. *It is important to note that the main purpose of this analysis is not to advocate a particular size or sign of the external effect, but rather to illustrate the implications of alternative estimates of these effects for current methods of valuing aggregate improvements in longevity.*

A. Internal and external effects of life expectancy on human capital and income

Our first approach calculates the PE-GE difference by estimating how increases in life expectancy might affect human capital decisions and therefore income, holding population constant. Theoretically, increases in life expectancy should lead to increased investment in human capital, since the returns from investment can be enjoyed for longer periods of time. Our approach here mainly follows Lucas (1988), who examines the effect of human capital on output. Similar to the terminology in the previous section, in Lucas's model, human capital has both internal and external effects on output. The former is the effect of human capital on an individual's own productivity, which is taken into account in investment decisions, while the latter is the effect of the average level of human capital on output. Specifically, in Lucas' model, output Q is given by

$$Q = AK^{\beta}(hL)^{1-\beta}h_a^{\gamma} \qquad (11)$$

where A represents the level of technological progress, K is capital, and L is labor. h is the internal effect of human capital on output, and represents the direct effect of human capital on labor's productivity. h_a represents the average level of human capital in the society, and represents an external effect, since individuals do not take h_a into account when making investment decisions.

We use Lucas' model to quantify the magnitude of the external effect of survival on human capital and income as follows. From equation (11), the elasticity of output with respect to average human capital is simply γ. Lucas (1988) calibrates γ to be 0.417, so that a one percent increase in average human capital increases output by 0.417 percent. Next, we must find a way to convert increases in average schooling, which are easily observed, to increases in average human capital. To do this, we use the method employed by Bils and Klenow (2000), who add schooling into the Lucas model by calibrating the association between human capital and schooling s:

$$\ln h = \frac{\theta}{1-\psi}s^{1-\psi} \qquad (12)^{7}$$

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[7] Following Mincer (1974), Bils and Klenow also include terms for experience and experience squared. Although these terms include s (since all things equal, an additional year of schooling reduces experience by one year), we omit these terms to aid in tractability and to isolate the effect of schooling, apart from its effects on experience.

Bils and Klenow consider two sets of estimates: one where $\psi = 0.58$ and $\theta = 0.32$, as well as one where $\psi = 0.28$ and $\theta = 0.18$. The rationale for these two sets of estimates is driven primarily by the parameter ψ, which describes the degree of diminishing returns to schooling. Bils and Klenow find $\psi = 0.58$ to be an upper bound on the level of diminishing returns, while $\psi = 0.28$ is an extreme lower bound. Using the calibrated values of γ, ψ, and θ, it can be shown that a one year increase in average schooling increases output by $0.13s^{-0.58}$ to $0.42s^{-0.28}$, where s is the initial schooling level. Margo (1986) estimates that the average level of schooling in the US in 1900 was roughly 9 years.[8] Therefore, a one year increase in schooling increases output by 2.2-3.6%.

Calculating the increase in output due to the internal effects from increased human capital investments is more straightforward, as we simply use estimates from the returns to schooling literature. As an upper bound, Card (1995) estimates that a one year increase in schooling increases income by 13.2%, while as a lower bound, Angrist and Krueger (1992) estimate that a one year increase in schooling increases income by 5.9%. It is important to note that these returns to schooling do not net out the costs of education, so that our estimates of the internal effects are an upper bound.

Having calculated schooling's external and internal effects on income, all that remains is to calculate the actual increase in average schooling due to increases in survival. Despite a literature that has examined how specific health interventions have affected schooling[9], we are only aware of one paper by Acemoglu and Johnson (2006)

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[8] Margo (1986) estimates that between average schooling among whites was 9.5 years and average schooling among blacks was 6.4 years; we assume that blacks were 12% of the population to obtain a weighted average of 9.1 years.

[9] See Bleakley (2007) for a discussion of the effect of hookworm eradication on school attendance and Jayachandran and Lleras-Muney (2007) for a dicussion on the effect of maternal mortality declines on literacy rates.

that has explicitly examined the relationship between survival and average schooling. Using ordinary least squares, the authors find that a one percent increase in life expectancy increases schooling by 5 years. Using an instrumental variables approach to account for omitted variables that might affect schooling and life expectancy, the authors find that a 1 percent increase in life expectancy increases schooling by 0.014 years, although this result is statistically insignificant.[10]

Given the lack of literature that has empirically examined the effect between survival and schooling, Figure 1 examines how the GE/PE ratio may vary as a function of the increase in years of schooling. For example, if the observed increases in US life expectancy increased the average schooling level by 2 years, then our estimates suggest that the GE value of life would be 12-26% larger than the PE value of life due to the internal effects of education, 4-7% larger due to the external effects of education, and 16-33% larger due to the total effects of education. Again, it is important to note that the estimates of the internal and total effects are an upper bound, as they do not net out the costs of education.

To obtain a better sense of the potential magnitude of the effect of education, it is useful to consider several alternative scenarios. First note that the average years of schooling increased from 9 to 11 years between 1900 and 2000.[11] As an upper bound, then, assuming that all of this increase in schooling were due to increases in survival alone, this would imply that the GE value of life were 16-33% larger than the PE value of

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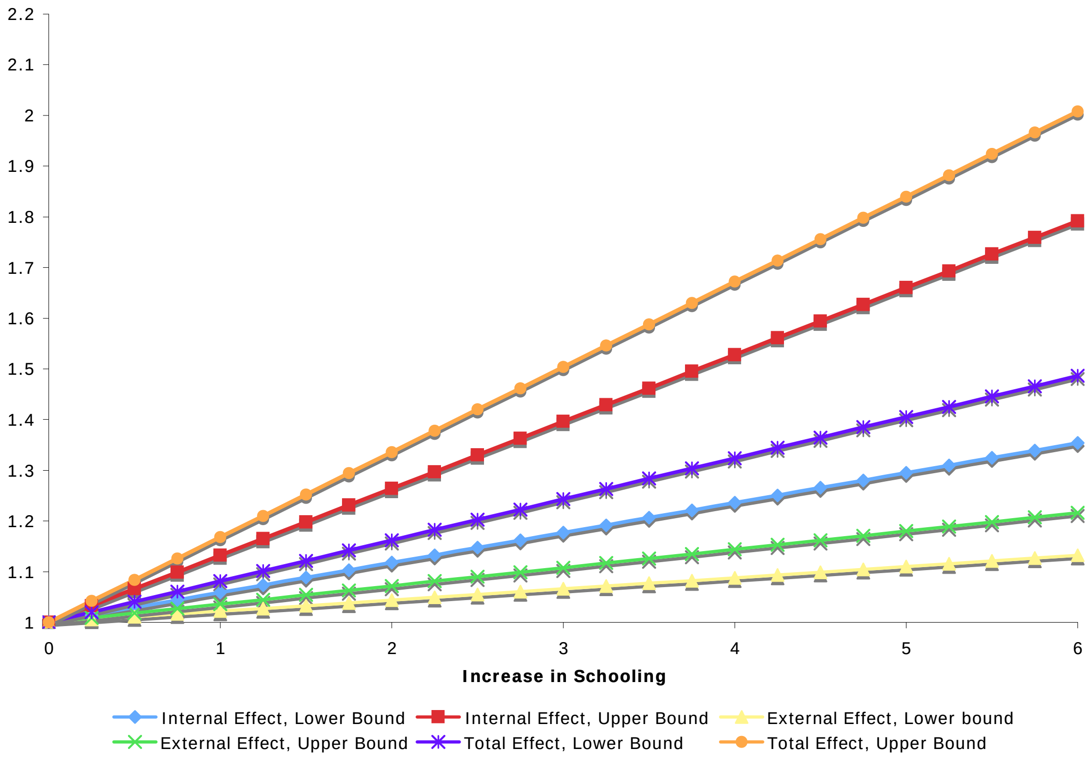
[10] It is important to note that their instrumental variable approach primarily uses variations in infant and early childhood mortality to identify the effects of life expectancy on schooling. Increases in US life expectancy in the latter half of the 20th century were driven primarily by increases in adulthood survival, which may have very different effects on human capital investment.

[11] Estimates of average schooling in 1900 come from Margo (1986). Estimates of average schooling in 2000 come from the census.

life. In addition, it is also useful to consider the effects implied by the estimates of Acemoglu and Johnson (2006). Their OLS estimate suggests that the 62% increase in US life expectancy between 1900 and 2000 would have increased schooling by roughly three years, while the IV estimate suggests that schooling would have increased by 0.9 years. Therefore, under the OLS estimates, our analysis suggests that the GE value of life is 18-40% higher than the PE value of life due to internal effects, 7-11% higher due to external effects, and 24-50% larger due to the total effects of education. Even with the smaller IV estimate, our results suggest that the GE value of life is 5-12% higher due to the internal effects of education, 2-3% higher due to the external effects of education, and 7-15% higher due to the total effects of education.

FIGURE 1 – GE/PE Difference due to Changes in Education: United States, 1900-2000



Source: Authors' calculations.

B. Cross-country estimates of the effect of life expectancy on income

This section complements the previous one by calculating the PE-GE difference from estimates of the effect of life expectancy on income derived from the empirical growth literature. The literature we consider includes cross-country regressions of log per-capita income on log life expectancy and other variables and typically estimates equations of the form:

$$g = \gamma_{LE} * \ln\left(LE\right) + X\beta + \varepsilon \qquad (13)$$

where g is the average annual growth rate across the time period considered (e.g. 1960 to 1990) and LE is the life expectancy in the initial period (e.g. 1960). As discussed, improvements in life expectancy may affect income per capita through both larger population sizes and increased incentives for physical or human capital accumulation. In empirical specifications that control for population, we interpret the estimated coefficient on log life expectancy as reflecting the impact of increased incentives for capital accumulation alone. In these instances, the coefficient presumably captures both the internal effect of life expectancy on human capital and its associated earnings, as well as the external effect of human capital on the productivity and earnings of others. While identifying the causal effect of life expectancy on growth is a natural problem faced in this literature, we use these estimates mainly as a benchmark to compare our earlier calibrated estimates.

To calculate the counterfactual increase in per-capita income associated with a given percentage change in life expectancy, we conservatively assume that changes in life expectancy affect GDP growth for the length of the cross section used in a particular study and have no effects after that time. Thus, γ_{LE} multiplied by the cross-section length is the elasticity of final income with respect to life expectancy. For example, Barro (1996) estimates that γ_{LE} equals 0.042; a 1% increase in life expectancy increases annual GDP by 0.042%. Since Barro uses a 10 year cross section, the elasticity over that period is $10 \cdot 0.42 = 0.42$; a 1% increase in life expectancy therefore increases per-capita GDP by 0.42%. Given that life expectancy increased by 61% between 1900 and 2000 (from 48 to 78 years), the counterfactual percentage increase in annual income owing to life expectancy would be $61*0.42 = 25.6\%$. Since the PE willingness to pay for the observed improvement in survival is 43% of initial income, the GE value would be roughly 60% higher, i.e. (0.43 + 0.26)/0.43 = 0.60. Put differently, our interpretation of Barro's *LE* coefficient implies that the observed increase in US life expectancy from 1900 to 2000 would have raised annual income by $1,045 from $4,078 annually (1900 income in 1996 dollars) to $5,123. Since this additional income comprises the increase in the value of life due to general equilibrium effects, this particular estimate therefore suggests that the traditional calibrated value of improvements in 20th century US survival—$1,752 annually—would *understate* the true value by 60% (($1,752 + $1,045)/$1,752)).

Table 1 repeats this calculation for several values of γ_{LE} from the growth literature. In general, there appears to be little consensus on the precise effect of life expectancy on GDP. Moreover, while the income elasticity (as defined) varies widely, from -0.025 to 1.575, most studies find that increases in life expectancy lead to increases in income per capita.

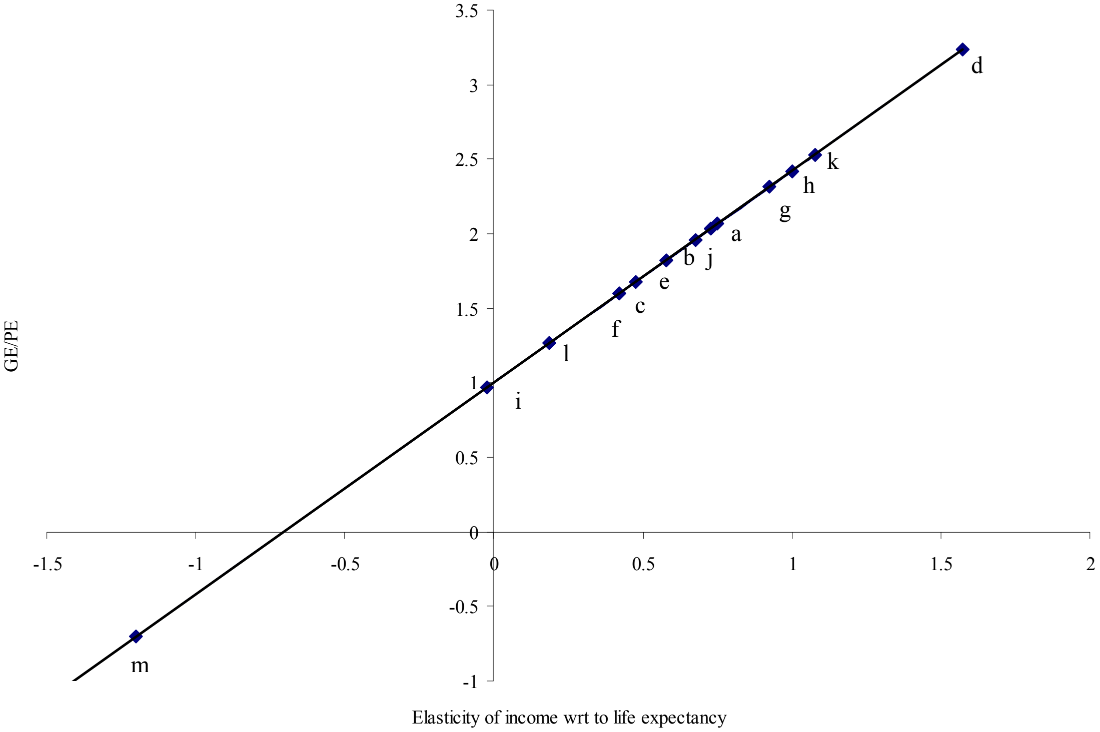
TABLE 1—Calibrated Effect of Increased US Life Expectancy on Income, 1900-2000

		Log Life-Expectancy Coefficient in Growth Regressions	Length of Cross Section (years)	Elasticity of Final Annual Income with Respect to Life Expectancy	Control for Population?
(a)	Barro (1996)	0.042	10	0.42	No
(b)	Barro and Lee (1994)	0.073	10	0.73	No
(c)	Barro and Sala-i-Martin (1995)	0.058	10	0.58	No
(d)	Bloom, Canning, and Malaney (2000)	0.063	25	1.575	Yes
(e)	Bloom and Malaney (1998)	0.027	25	0.675	Yes
(f)	Bloom et al. (1999)	0.019	25	0.475	Yes
(g)	Bloom and Sachs (1998)	0.037	25	0.925	Yes
(h)	Bloom and Williamson (1998)	0.04	25	1.00	Yes
(i)	Casselli et al. (1996)	-0.001	25	-0.025	No
(j)	Gallup and Sachs (2000)	0.03	25	0.75	No
(k)	Hamoudi and Sachs (1999)	0.072	15	1.08	Yes
(l)	Sachs and Warner (1997)	0.0075	25	0.1875	Yes
(m)	Acemoglu and Johnson (2006)	-0.03	40	-1.2	

Source: Authors' calculations based on each of the studies listed.

Given the PE value of improved US survival from 1900 to 2000 and the percentage increase in life expectancy, we can examine how the relative PE-GE difference (i.e. P_{GE}/P_{PE}) depends on the elasticity of income with respect to population size. Figure 2 displays this linear relationship and illustrates where, along this curve, the above elasticities lie. Note that when the elasticity of income with respect to population is zero, P_{GE}/P_{PE} is unity.

FIGURE 2—PE-GE Difference in the Value of Survival Gains: United States, 1900-2000



Source: Authors' calculations. Estimates of the elasticity of income with respect to life-expectancy for various studies are included.: (a) Barro (1996); (b) Barro and Lee (1994); (c) Barro and Sala-i-Martin (1995); (d) Bloom, Canning, and Malaney (2000); (e) Bloom and Malaney (1998); (f) Bloom et al. (1999); (g) Bloom and Sachs (1998); (h) Bloom and Williamson (1998); (i) Caselli et al. (1996); (j) Gallup and Sachs (2000); (k) Hamoudi and Sachs (1999) (l) Sachs and Warner (1997) (m) Acemoglu and Johnson (2006)

Several points stand out in Figure 2. First, the calibrated PE-GE difference in the value of life from 1900 to 2000 is potentially large, with the most extreme estimate suggesting a GE value of improved survival more than three times as large as the corresponding PE value. This estimate implies that the increase in annual income attributable to the observed improvement in longevity is more than two times as large as the willingness to pay for the improvement in survival alone. Second, the calibrated effects predicted by the studies surveyed show no clear consensus.[12] Estimates of the bias range from being slightly negative to two to three times as high as the PE value of life. Indeed, at the extreme, Acemoglu and Johnson (2006) find that the GE value of life is *negative*; in other words, the decreases in income from longer life expectancy outweigh the value of gains in health. Despite the variation in these effects, it appears that the majority of the studies predict GE values on the order of 1.5 to 2.5 times the PE value of life.

C. Survival and population size: The United States 1900-2000

The remaining sections examine the effects of changes in population on income by computing the elasticity of income per capita with respect to population size under various scenarios. In order to apply these findings to our earlier PE valuation of improved US longevity, we first must determine the percentage change in the US population that can be attributed solely to observed changes in mortality risk. This percentage change can then be multiplied by the elasticity of income with respect to population size in each of the scenarios we consider.

Estimating the change in the US population due solely to changes in longevity requires that we net out the effects of immigration. While the Census provides data on the number of immigrants entering the country, this data is not sufficient, since we must net out not only the presence of immigrants themselves, but also the presence of their

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[12] This lack of consensus is in part due to differences in the estimated effects of life expectancy on average, annual GDP growth, β. It is also due to variation across studies in the length of time considered. For example, consider two studies that estimate an elasticity of average, annual growth with respect to life expectancy of 1. If Study 1 spans a ten-year period, while Study 2 spans a twenty-year period, the calibrated effect on final annual income will be twice as large in the second study, simply because the growth in income is observed to occur over a longer period of time.

descendents. Thus, to estimate the change in US population due solely to changes in longevity, we perform a simple simulation. Our first step is to take the 1900 US population and divide it into single-year age groups.[13] Letting $N_{i,t}$ represent the number of persons age i at time t, and $S_{i,t}$ the one-year survival probability for persons of age i at time t, we then have that

$$N_{i+1,t+1} = S_{i,t} N_{i,t} \qquad (14)$$

while the number of births is simply

$$B_{t+1} = \sum_{i} N_{i,t} f_{i,t} * 0.5 \qquad (15)$$

where $f_{i,t}$ is the fertility rate among women of age i at time t. Because we do not have data on the gender distribution of the US population at earlier years, we assume an even male-to-female sex ratio; thus, we multiply the fertility ratio by one-half. Equations (14) and (15) therefore allow us to simulate the evolution of the US population over time under alternative survival probabilities. These expressions raise an important implication of the effects of survival improvements on population size—holding improvements in life expectancy constant, reductions in mortality that occur at child-bearing ages will naturally increase population by more than mortality reductions at later ages. This is because total fertility rises with the population of childbearing age women. Therefore, the effect of changes in survival on population size may be very different depending on the age at which those changes in mortality occur.

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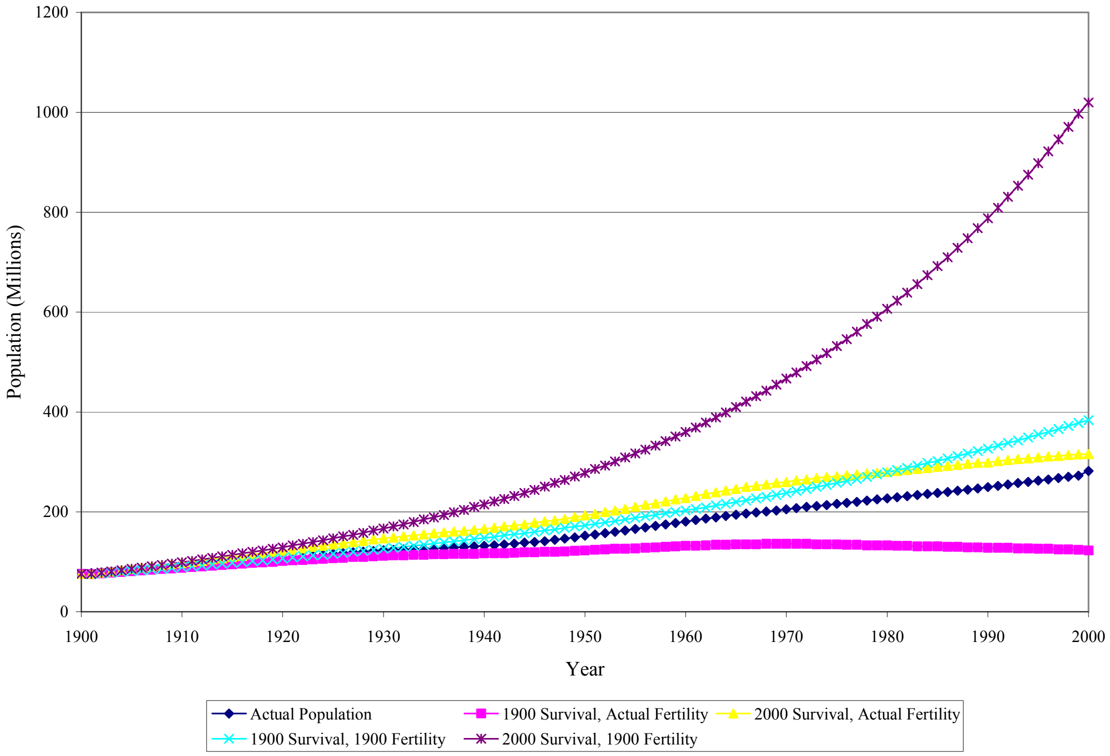
[13] The single-year age distribution of the 1900 US population is taken from the Berkeley Mortality Database.

Figure 3 depicts how the total US population would have evolved under several counterfactual scenarios, all of which are net of the large migration into the US that characterized much of the last century.

FIGURE 3—THE POPULATION EFFECTS OF CHANGES IN SURVIVAL FROM 1900 TO 2000



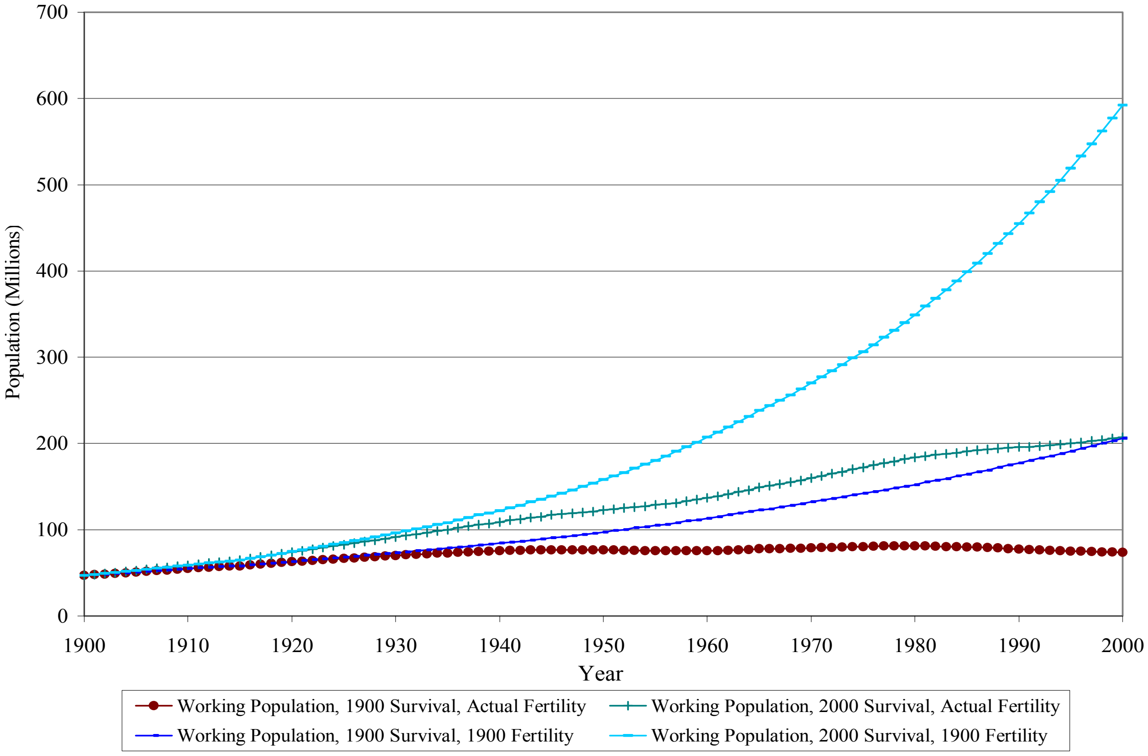
Source: Authors' calculations.

The lowermost curve of Figure 1 depicts the evolution of the US population over time if survival and fertility rates had remained at their 1900 values. In 1900, the US population was 76.1 million persons, and life expectancy was 48 years. With no changes in survival and fertility, the US population would have increased to 336 million by 2000, a percentage gain of 445%. While this number seems large and indeed is greater than the actual US population in 2000, it is important to keep in mind that death *and* fertility rates were higher in 1900, and have fallen over time. To calculate the increase in population due to changes in survival alone, we calculate the change in US population that would have occurred had the survival probabilities in 2000 been in effect in 1900 and fertility rates remained at their 1900 values. The resulting evolution of the US population is the topmost curve in Figure 1, and suggests that the US population would have grown to 1.03 billion by 2000. Our calculations therefore suggest that the US population would have increased by 307% if persons living in the 20th century had enjoyed year 2000 survival.

Rather than hold fertility rates constant from 1900 onwards, an alternative approach would be to allow them to follow their empirically observed time-series. Figure 1 shows how the US population would have evolved if survival were held fixed at 1900 levels and fertility was at its observed rate in each year. The assumptions imply that the US population would have grown to 105 million in 2000. This number is markedly smaller than the population we estimated under constant 1900 fertility, and reflects the fact that fertility rates generally declined over the past century. If survival were held constant at its 2000 levels, the US population would have increased to 316 million by 2000. These calculations suggest that the US population would have increased by 301% if every cohort from 1900 onwards experienced year 2000 survival. Thus, whether or not we allow fertility to change, our estimates suggest that increased survival would have increased the total US population by roughly 300%.

Since the age structure of the population may be relevant as well—for example, through its effect on dependency ratios within a country—Figure 4 simulates the evolution of the US *working-age population* under various survival and fertility probabilities.

FIGURE 4— THE WORKING AGE POPULATION EFFECTS OF CHANGES IN SURVIVAL FROM 1900 TO 2000



Source: Authors' calculations.

In 1900, there were 46.8 million working age persons in the United States. If survival and fertility rates had remained at their 1900 values, this number would have increased to 206 million by 2000. However, if survival and fertility rates in 1900 had been characterized by their 2000 values, there would have been 592 million working age persons in 2000. Thus, the increased survival probabilities would have increased the working age population by 287%. We also consider the case where fertility rates are allowed to follow their observed time series. In this case, the working age population would have increased to 73.7 million in 2000, under the 1900 survival probabilities and to 207 million, under the 2000 survival probabilities. Therefore, whether or not we allow fertility rates to change, our estimates suggest that the US working age population would have been roughly 280% higher under the year 2000 survival probabilities.

D. Effect of population on income: A simple Malthusian model

Given the counterfactual increase in population attributable solely to improvements in 20th century US survival, we can compare the PE value of this improved longevity to GE values which incorporate the potential income effects of this increase in population size. In this and the following section, we calibrate the effect of survival-induced increases in population size on income per capita. This section considers the implications of a simple Malthusian model, in which labor and capital are the two inputs to production and capital is fixed. This may be particularly relevant for agrarian economies in which income is most heavily derived from the use of fixed capital inputs such as land.

Suppose, then, that capital is inelastically supplied, that survival does not affect the fraction of the population that is employed, and that aggregate production is Cobb-Douglas with labor share 0.70.[14] In this case, the elasticity of income per capita with respect to population is -0.30 because the marginal product of labor is proportional to the

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[14] The second assumption may be unwarranted if changes in survival alter the demographic composition of the population (e.g. by increasing the fraction of elderly through improvements in end-of-life care) so that labor supply is not raised proportionately with population.

labor force raised to the -0.30 power. If the PE willingness-to-pay for the observed improvement in longevity is 43% of income, the roughly 300% increase in population would imply that P_{PE} is *overstated* by a factor of 0.9/0.43 or 210%. Put differently, given an annual income per capita in 1900 of \$4,087, a 300% increase in population would reduce income \$3,678 to \$409 annually in this model. Since the GE value of improved longevity incorporates this income reduction, the GE willingness-to-pay would actually be *negative*—approximately -\$1,926 (= \$1,752 - \$3,678)—so that individuals would be worse off with the improvement in longevity. The large negative magnitude of the measured PE-GE difference would be entirely due to the reduction in income that the large population increase produces. This has the interesting implication that the value of improved longevity in many developing countries—where Malthusian-like decreasing returns to population are more likely to occur—may be partially offset by the income-lowering effects of added population.

E. Effect of population on income: An increasing returns model

The previous section illustrated how decreasing returns to population size could significantly lower the value of improvements in longevity compared to traditional measures. This section develops and calibrates a simple endogenous growth model which has the potential to deliver the opposite effect of population size on income. This model is closely related to earlier models of Romer (1986; 1990; 1994) and Jones (1999).

The basic framework of the model is as follows. Let R&D capital X be accumulated at constant cost, which we normalize to one, and depreciate at rate δ_x. In reality, R&D

capital serves a variety of purposes, but we focus on just one of those – the enhancement of productivity in the business sector. Generally, R&D may enhance productivity in the household sector as well, e.g. through dishwashing machines, microwaves, etc. While a fuller notion of the sectors in which R&D may enhance productivity is important, for simplicity, we focus our attention on the business sector.

Analytically, aggregate GDP is assumed to be a function of R&D capital X, physical capital K, and labor L. The partial derivative of the aggregate production function with respect to X represents the social returns to R&D capital, which diminish because, among other things, researchers undertake the most promising projects first, and less promising research projects later. Although total human capital and its relationship to the production of R&D are likely to be important in any story of increasing returns, we omit it from this analysis for sake of simplicity.

The owners of R&D capital enjoy only a fraction θ of the social returns to R&D. Following Romer (1986; 1990; 1994), we model this situation by distinguishing between two forms of R&D capital in the production function facing a representative producer: his own R&D capital X and the average R&D capital of other producers $\overline{X}$. In its Cobb-Douglas form, the production function facing a representative producer is:

$$B\overline{X}^{(1-\theta)\gamma} X^{\theta\gamma} K^{\alpha} L^{1-\alpha-\theta\gamma} \qquad (16)$$

which has constant returns from the representative producer's point of view, because he takes the average amount of R&D capital of others as given. From the point of view of society, however, there are increasing returns arising from R&D due to its non-rival and only partially excludable nature. B is the productivity of firms for a given amount of capital, labor, own R&D capital, and average R&D capital of other firms. National income (gross of depreciation) is divided among the factors in shares $\theta\gamma$, α, and $1-\theta\gamma-\alpha$.

Labor is inelastically supplied. Since physical and R&D capital are supplied at constant cost, the long run average amounts of those capital stocks are determined by the following standard optimality conditions:

$$\rho = \theta\gamma B \overline{X}^{\gamma-1} \overline{K}^{\alpha} \overline{L}^{1-\alpha-\theta\gamma} - \delta_X = \alpha B \overline{X}^{\gamma} \overline{K}^{\alpha-1} \overline{L}^{1-\alpha-\theta\gamma} - \delta_K \tag{17}$$

where ρ is the rate of time preference and δ_k is the rate of physical capital depreciation. The middle term is the marginal private product of R&D capital, and the last term is the marginal (social and private) product of physical capital (both net of depreciation). The relevant marginal product of R&D capital is the private marginal product (i.e., holding constant the average R&D capital of other producers), but (after differentiating) we have evaluated the marginal products at an aggregately consistent allocation $X = \overline{X}$. Let lower case letters denote amounts measured per unit of labor. In terms of amounts per unit labor, the steady state conditions are:

$$\rho = \theta\gamma B \overline{x}^{\gamma-1} \overline{k}^{\alpha} \overline{L}^{(1-\theta)\gamma} - \delta_x = \alpha B \overline{x}^{\gamma} \overline{k}^{\alpha-1} \overline{L}^{(1-\theta)\gamma} - \delta_k \tag{18}$$

The two factor equilibrium conditions imply long run quantities of R&D and physical capital as a function of the amount of labor. These long run quantities can be plugged into the production function to calculate long run output per worker as a function of the total amount of labor and the other parameters. In particular, *per capita* output increases with the aggregate amount of labor as long as the social returns to R&D exceed the private returns ($\theta < 1$). The elasticity is:

$$\frac{d \ln y}{d \ln \overline{L}} = \frac{1-\theta}{\theta} \frac{\theta\gamma}{1-\alpha-(\theta\gamma/\theta)} \tag{19}$$

As in the models of Romer (1986) and others, our model has socially increasing returns to all factors including labor as the inelastically supplied factor, which means that large economies can produce more per capita than small economies. In this case, the source of socially increasing returns is the external effect of one firm's R&D on another's productivity. Given the magnitude of the private returns to R&D, $(1-\theta)$ is a measure of the amount by which social returns exceed private returns and thereby the amount by which social returns are increasing.

When appropriation is full and $\theta = 1$, the elasticity of income with respect to population is zero, while it is positive when $\theta < 1$. If output exhibited socially constant returns to scale, we would obtain the standard result that the long-run level of output per capita would not depend on population. However, when there are socially increasing returns $(1-\theta>0)$, the *elasticity* of output with respect to population is positive. Intuitively, increases in labor are met with long-run increases in all factors that would normally leave per-capita output unchanged, were it not for the additional, external effect on aggregate R&D capital that an individual firm takes as given and that ultimately raises per-capita output.

Calibrating the elasticity of income with respect to population

In addition to the qualitative predictions above, Equation (19) demonstrates that calibrating the elasticity of income with respect to population requires only three types of data: information on the gap between social and private returns (θ), and the shares of R&D and physical capital in national income ($\theta\gamma$ and α). Historically, labor and capital income shares are found to be roughly 70% and 30%, respectively. These shares do not distinguish factors according to their use in R&D vs. non-R&D activities; we assume that labor and capital shares are the same in the R&D and non-R&D sectors. For example, if R&D expenditure were 5% of value-added, then $\theta\gamma$ would be 0.05 and (assuming capital intensity to be the same in R&D and non-R&D sectors) α would be 30% of 0.95 (= 0.285). The output elasticity would therefore be $[(1-\theta)/\theta][0.05/(0.715-(0.05/\theta))]$. If $\theta = 0.5$, then the output elasticity would be 0.08.

Figure 5 illustrates this calculation more generally for various shares of R&D in national income. Historically, R&D expenditures have ranged between 1.36% and 2.88% of GDP (Shackelford, 2002).[15] Therefore, our calculations consider the cases where $\theta\gamma$ adopts these extremes, as well as the case where $\theta\gamma$ adopts the average between 1953 and 2002 (2.45%). For each of the three shares considered, a single curve in Figure 3 depicts the relationship between the elasticity of per-capita income with respect to population and the gap between private and social returns to R&D.

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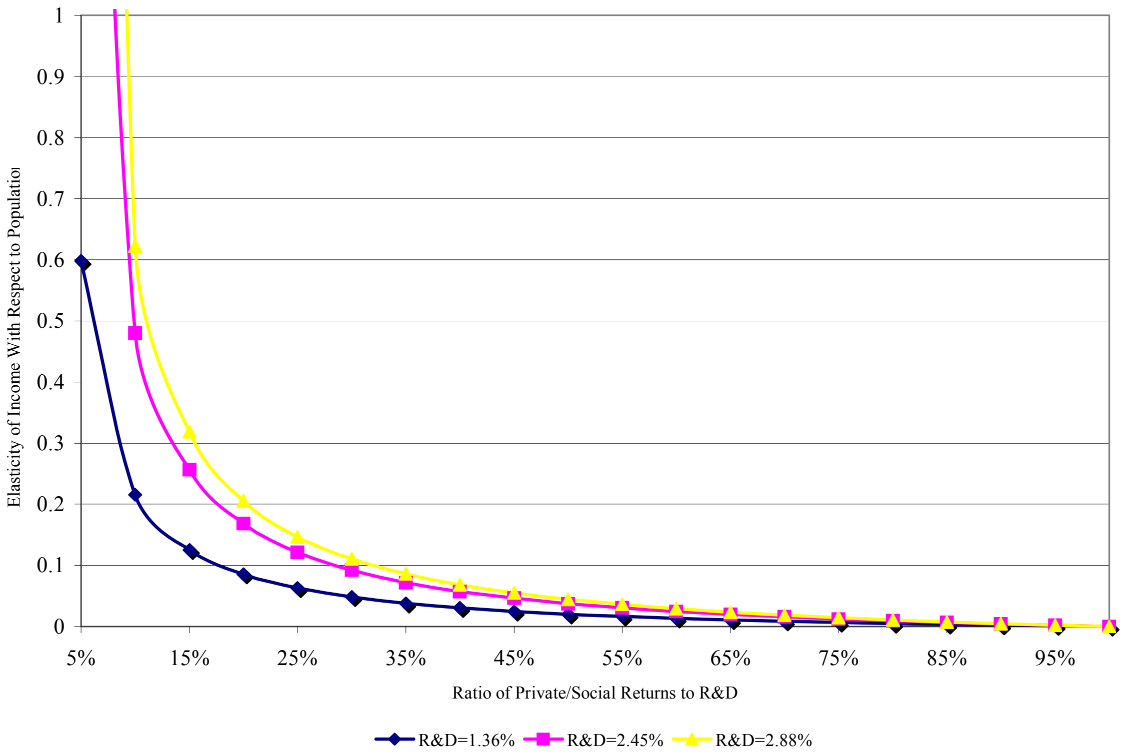
[15] R&D accounted for 1.36% of GDP in 1953 and 2.88% of GDP in 1964. Since 1995, the ratio of R&D expenditures to GDP has experienced an upward trend, and currently R&D accounts for roughly 2.8% of GDP.

FIGURE 5—Calibrated Elasticity of Income per Capita with Respect to Population



Source: Authors' calculations.

As Figure 5 illustrates, the elasticity of per-capita income with respect to population falls sharply with θ, the ratio of the private to social returns to R&D, and indeed, comes close to zero once the ratio of private to social returns reaches 50%. Moreover, for larger values of θ, the elasticity of per-capita income with respect to population is fairly insensitive to the ratio of R&D expenditures to GDP, θγ. However, for smaller values of θ, the elasticity varies significantly with R&D expenditures. For example, suppose that the ratio of private to social returns to R&D is 5%. In that case, if R&D expenditures are 1.36% of GDP, the elasticity of per-capita income with respect to population is 0.6. However, the calibrated elasticity increases to 4.3 if R&D accounts for 2.88% of GDP.

Figure 5 therefore suggests that the most important determinant of the elasticity of per-capita income with respect to population is θ, the ratio of the private to social returns to R&D. Table 2 presents the results of several studies examining social and private returns to R&D across various industries.

TABLE 2—Estimated Ratio of Private to Social Returns to R&D

Study	Private Return (%)	Social Return (%)	Ratio (θ)
Mansfield et al. (1977)	25.0	56.0	44.6
Bernstein and Nadiri (1988)	13.5	30.2	44.7
Bernstein and Nadiri (1989)	7	14	50
Bernstein and Nadiri (1991)	22.5	28.5	78.9
Bernstein (1994)	16.6	99.2	18.0

Source: Authors' calculations. Pleasee also see Jones and Williams' (1998) Table I for a comparable list of studies). Each study examined the returns among several industries; the values shown are the median social and private returns.

Overall, Table 2 illustrates that for the studies surveyed, the ratio of social to private returns is around 50%. Assuming that θ adopts its lowest reported value in Table 2 (18%), an upper bound for the elasticity of per capita income with respect to population ranges from 0.09 to 0.24, depending on the ratio of R&D expenditures to GDP—for the average share of R&D to GDP from 1953 to 2002, this would imply an elasticity of 0.20. If θ is equal to 50%, the elasticity ranges from 0.02 to 0.05, with an elasticity of 0.04 at the average share of R&D to GDP. Therefore, we assume that the elasticity of income with respect to population falls in the range of 0.04 to 0.20.

The income elasticities calibrated from this model imply that the roughly 300% counterfactual increase in US working-age population from 1900 to 2000 would have increased annual income by 12 to 60 percent, from \$4,078 annually (1900 income in 1996 dollars) to between \$4,567 and \$6,524 annually. Recall that this additional income comprises the increase in the value of life due to general equilibrium effects. This particular model therefore suggests that the calibrated value of improvements in 20th century survival—\$1,752 annually—would *understate* the true value by as little as 28% ((\$1,752 + \$490)/\$1,752)) and as much as 140% ((\$1,752 + \$2,252)/\$1,752)).

F. Cross-country estimates of the effect of population on income

The previous model-based approaches to determining the elasticity of income with respect to population can be usefully contrasted to similar estimates from the growth literature. This literature typically estimates cross-country regressions in which the average annual growth in per-capita income depends on, among other things, the average annual growth in working-age and total population over a period of time, e.g. 30 years. We interpret these empirical specifications as first-difference regressions in log levels which allow us to infer the elasticity of income with respect to population over a 30-year time frame. To the extent that such estimated effects of population on income are due to changes in internal behaviors, the estimated elasticities will be too high since they do not account for the costs of changing behaviors. Similarly, to the extent that the estimated elasticities reflect effects of population on income that are external to any decisions made by individuals regarding investments in human capital, marriage, etc., they will not overstate the net income effects.

Table 3 presents the elasticity of income with respect to population for several representative studies in the growth literature. As before, we use these estimates only as benchmarks for our analysis given the natural issues of identification associated with growth regressions.

TABLE 3—Elasticity of Income With Respect to Population

Study	Elasticity of income w.r.t. total population	Elasticity of income w.r.t. working-age population	% Change in income given counterfactual increase in both US populations
Bloom, Canning, and Malaney (2000)	-0.3	0.75	120
Bloom and Malaney (1998)	0.44	-0.54	19.2
Bloom and Sachs(1998)	0.01	0.25	73
Bloom and Williamson (1998)	0.03	0.46	138
Hamoudi and Sachs (1999)	-0.31	0.95	173
Average	-0.13	0.37	65

Source: Authors' calculations from each of the studies listed and calculated counterfactual increases in US populations.

Table 3 illustrates the positive correlation between the size of the working age population and income per capita. For 4 out of the 5 studies considered, the impact of population size on income per capita is positive. Across all studies, the average elasticity is 0.37. This figure is only slightly larger than the elasticities predicted by our endogenous growth model—recall that as an upper bound, the calibrated elasticity of income per capita with respect to population is 0.20 and as a lower bound, 0.04. Put differently, for the estimated population effects to be consistent with our model, the gap between private and social returns (θ) would have to be around 12 to 15 percent, which is slightly below the lowest level of appropriation reported in Table 1. The effects of total population on income are much more varied, with two studies reporting a negative effect, and one reporting a larger effect. Overall, the mean elasticity of income with respect to total population, holding working age population constant, is -0.13.

Given the estimated elasticities of income with respect to total and working age population, we can calculate the PE-GE difference implied by these estimates. For example, consider the mean elasticities of income with respect to total and working age population, which are -0.13 and 0.37, respectively. Given that total and working age population increased by 300% and 280%, this implies that the overall effect on income is 300·(-0.13) + 280·(0.37) = 65%. Thus, when evaluated at the mean elasticities, the growth literature suggests that changes in longevity and their associated effects on population would have increased income by 65%. This implies an increase in annual income of $2,641 from $4,087 to $6,728 and therefore a PE-GE difference of roughly 150% (($1,752 + $2,641)/$1,752). Recall that our calibrated endogenous growth model suggested that difference between 28% and 140%, so the difference suggested by the growth literature is in the upper bound of this range. Table 3 reports similar calculations for each of the studies listed. Not surprisingly, given the wide range of reported elasticities, there is similar variation in the calibrated effects on income. At the low end, Bloom and Malaney (1998) find that increases in population would have decreased incomes by 19%, while at the high end, Hamoudi and Sachs (1999) find that population would have increased income by 173%. Thus, the growth literature reviewed here suggests that the PE-GE difference is anywhere between the broad range of 56% and 636%.

V. CONCLUDING REMARKS

Perhaps the most important change of the last century was the great expansion of life itself. In fact, recent estimates for the US have demonstrated that the value of gains in longevity have nearly equaled gains in all other material well-being. While these estimates are large by any means, they have typically ignored the important demographic and economic consequences such aggregate changes in longevity can induce. For example, a variety of previous literatures have shown that life expectancy affects individual behavior and that population or scale matters for economic performance. The purpose of our paper is to illustrate the implications of these previous results for valuing the enormous gains in life that took place in the last century, and to make a first attempt at quantifying some of them.

The basic intuition behind our analysis is straightforward. Living to the age of 78 rather than 48 is not just a 30 year extension in life, but also affects *how well one lives* their first 48 years as well as their last 30. The reason is that living with others who live 78 years is different than living with others who live only 48. We begin to quantify the total value of life extension by focusing on two reasons why this might be true: own human capital accumulation and total population. The value of these responses may be on the same order of magnitude – perhaps even larger – than the value of extra lifetime itself.

One reason to calculate the benefits of life extension is for the purpose of a cost-benefit analysis of medical research (Murphy and Topel, 2006). However, a cost-benefit analysis that includes the value of the indirect effects of life extension may implicitly propose oblique solutions to problems that could be solved more directly. Suppose, for example, that life extension raises the corporate capital stock, and that the social value of the corporate capital stock exceeds its private value as a consequence of corporate taxation. Then, life extension would have the beneficial side effect of raising the corporate capital stock, but to use this as an argument for medical research amounts to arguing that lives should be extended in order to alleviate damage done by the corporate tax system. Obviously, the more direct solution to that damage is to fix the corporate tax code itself. This is one important reason that we have focused on a particular category of the external effects of life expectancy: those associated with population. Extending lives may well be one of the best and most direct ways of increasing the population.

Theory and empirical studies have cited both beneficial and deleterious effects of population. One conclusion of our paper is that it matters exactly how beneficial or deleterious population may be, because even minor effects in either direction may have a big impact on the estimated value of life. However, given the observation that much of R&D has a social return that exceeds its private return, and given that so many people have chosen big cities as their place to live and work, we suspect that the beneficial effects of population are the dominant ones. In this case, the general equilibrium value of life may be as much as 2.5 times the partial equilibrium value.

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