Does Mortality Decline Promote Economic Growth? *

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Abstract

This paper investigates the effects of declining mortality on economic growth in an endogenous fertility and human capital investment framework. The partial equilibrium model shows that as a result of an exogenous decline in infant and child mortality, parents produce fewer children and invest more resources in each child. This result depends on the crucial role of uncertainty about the number of surviving children that is present in a high mortality environment. By endogenizing mortality, the general equilibrium model demonstrates the existence of multiple equilibria: A "Malthusian" steady state, where the rate of population growth rises as income per capita rises, and a "developed economy" steady state, where the rate of population growth falls with the increases in income per capita. The developed economy steady state is characterized by higher levels of income per capita, human capital investment and a lower level of fertility compared to the Malthusian steady state. In a stochastic environment, depending on the nature of improvements in mortality, countries can be trapped around the Malthusian steady state or they can grow forever. The model is calibrated using historical and contemporary data on income and on survival probabilities from 26 countries. A survival function is estimated and then used to calibrate the model. In addition to the analytical solutions, this empirical exercise also shows that the model is consistent with the stylized facts of the development process.

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1 Introduction

"At a New Year's Eve Party, I asked our guests to name the major development of the 20th century. They had several excellent candidates, including the rise and fall of communism, the growth of democracy, and the advent of computers. But I believe none benefited the ordinary person more than the extending of life expectancy.......Falls in the mortality figures deserve to rank among the most significant events of the past century...."

Gary S. Becker (2000).

During the last century life expectancy at birth has doubled in most parts of the world. There is no doubt that increased life span has benefited the ordinary person immensely. But falling mortality also has important implications for the process of economic growth. Recently there has been an increase in the number of research studies that examine how reduced mortality affected economic decisions.[1] This paper focuses on two of these decisions, namely fertility and human capital investment, given the importance of these for economic growth and also given the fact that the most significant component of mortality decline has been reduction in infant and child deaths.

Higher life expectancy implies a higher rate of return on human capital investment and hence, declining child and youth mortality provides an important incentive to increase investment in the education of each child. Researchers have emphasized the role of human capital investment as the prime engine for economic growth but they have not rigorously investigated this channel, where declining mortality promotes growth by raising human capital investment.

The historical data of Europe and the post war data of developing countries show that mortality and fertility changed at about the same time, with mortality decline preceding the fertility decline. This, together with the fact that mortality and fertility rates jointly determine the growth rate of population, has led demographers to view the declines in these rates as components of a single "demographic transition." Figure 1 shows an illustrative picture of this transition. In the first phase of this transition, there is a decline in death rates due to better nutrition and public health measures. Declining mortality together with unchanged birth rates cause population growth to rise.[2] In the second phase, there is a

[1] See Sah (1991), Meltzer (1992), Ehrlich and Lui (1991), Wolpin (1997), Spatafora (1997), Eckstein et al. (1998), de la Croix and Licandro (1999), Chakraborty (2000), Kalemli-Ozcan and Weil (2000), Kalemli-Ozcan, Ryder and Weil (2000), Kalemli-Ozcan (2000a, 2000b).

[2] Fertility remains unchanged, at first, because of the lags and misperceptions. Fertility can also be increasing due to better health as Dyson and Murphy (1985) showed.

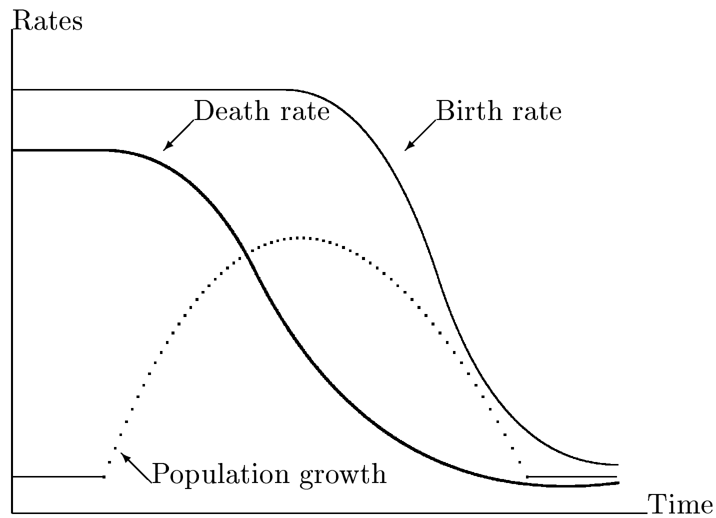

Figure 1: Demographic Transition

continuous decline in fertility rates which eventually surpasses the declining mortality rates and leads to a decline in the population growth rate.

The link between the demographic transition and economic growth has been explored in various studies, especially recently. In general, these studies attempt to present a unified model of industrialization and population dynamics.[3] Lucas (1998) states that the demographic transition and the industrial revolution are different aspects of a single economic event and industrial revolution is invariably associated with the reduction in fertility. He claims that it is hopeless to try to account for income growth since 1800 as a purely technological event. He argues what occured around 1800 that is new and that differentiates the modern age from all previous periods, is not technological change by itself but the fact that fertility increases no longer translated improvements in technology into increases in population. Therefore, understanding the causes of the fertility transition is crucial in terms of past, present and future economic growth.

The demographic transition literature posits that a necessary condition for fertility decline

[3]Galor and Weil's (2000) model is the first unified growth model, where the evolution of population growth, technological progress and output growth is consistent with the developments in the last several centuries. See also Kremer (1993), Lucas (1996, 1998), Hansen and Prescott (1998), Becker, Glaeser and Murphy (1999), Jones (1999), Tamura (1999).

is a reduction in infant and child mortality. The other explanations of the fertility transition include increased opportunity cost of children due to higher wages; the decline for the need of old-age support from children with the development of financial markets; quality-quantity trade off due to higher returns to education, which is caused by increased technological progress; and the development and dissemination of birth control methods. Which of these, including mortality decline, can explain a bigger fraction of the decline in fertility is still an open empirical question.

Existing growth models with endogenous fertility don't allow for mortality in general. The ones that allow mortality ignore the *uncertainty* about the number of surviving children that is present in a high mortality environment. The model here relies on individuals being prudent in the face of uncertainty (Kimball, 1990). If the marginal utility of a surviving child is convex in the number of survivors, then there will be a precautionary demand for children. As the mortality rate and thus uncertainty falls, this precautionary demand decreases and so does population growth. At the same time lower mortality increases a child's expected life span and hence the return to education, which encourages investment in the child's human capital. Thus, parents find it optimal to have fewer children and invest more resources in each one.

In a general equilibrium setup the combined result of these two effects enhances economic growth. By endogenizing mortality, the general equilibrium model demonstrates the existence of multiple equilibria: A Malthusian steady state, where the rate of population growth rises as income per capita rises, and a developed economy steady state, where the rate of population growth falls with the increases in income per capita. The developed economy steady state is characterized by higher levels of income per capita, human capital investment and a lower level of fertility compared to the Malthusian steady state. In a stochastic environment, depending on the nature of improvements in mortality, countries can be trapped around the Malthusian steady state or they can grow forever. The model is calibrated using historical and contemporary data on income and on survival probabilities from 26 countries A survival function is estimated and then used to calibrate the model. In addition to the analytical solutions, this empirical exercise also shows that the model is consistent with the stylized facts of the development process.

The rest of the paper is structured as follows. Section 2 presents the historical and the contemporary data and summarizes the empirical evidence and the related literature. Section 3 solves the partial equilibrium model. Section 4 introduces the general equilibrium model and presents a non-linear estimation for the survival function, which is used to calibrate the model. Conclusions are presented in Section 5.

2 Evidence and Related Literature

2.1 Historical Data and Empirical Evidence

The first panel of Figure 2 shows the survival function for Sweden. Although the likelihood of survival for all ages increased tremendously between 1780 and 1985, the most significant reduction in mortality was realized at infancy and childhood. In 1780, a newborn Swedish child had a 60% chance of living to age 20. By 1930 this figure had risen to 90%. The second panel of Figure 2 shows probabilities of dying based on the age-specific death rates. These mortality changes in Sweden resemble those of other developed countries in the nineteenth century. Over the past few decades, infant and child mortality also fell dramatically in less developed regions of the world. In these regions life expectancy at birth rose from approximately 40 years in 1950 to 63 years in 1990.[4]

Some researchers have argued that since most of the mortality decline has occurred in infancy a decline in mortality should not matter for the human capital investment decision, which comes later in life. In fact, the mortality changes around ages 10-15 are also pretty large. In Sweden around 1800, 5200 children die between ages 10 and 15 out of 100000 birth, whereas around 1930 this number becomes 400. This represents a 92% decline in the probability of a child at age 10 dying before age 15.

Birth rates also show a sharp decline. During the nineteenth century in the developed world the total fertility rate (TFR) declined from 5 children to 2.5 children. In Western European countries fertility decline began by the end of nineteenth century and was completed by World War II. In the developing world, however, the fertility transition started around the 1950s and TFR declined from 6 children to 3 children over the past forty years.[5]

The hump-shaped pattern of population growth, which arises due the fact that mortality decline precedes the fertility decline, is evident in the historical data for Western European

[4]The survival function shows the probability that a person will be alive at a given age. Life expectancy at birth is the area under the survival function. The probability of dying at an age is the chance of a person exactly that age dying before reaching the next age group. Swedish data is from Keyfitz and Flieger (1968, 1990) and late developed country (LDC) data is from United Nations (1998).

[5]Developed countries data is from Livi-Bacci (1997) and LDC data is from United Nations (1998).

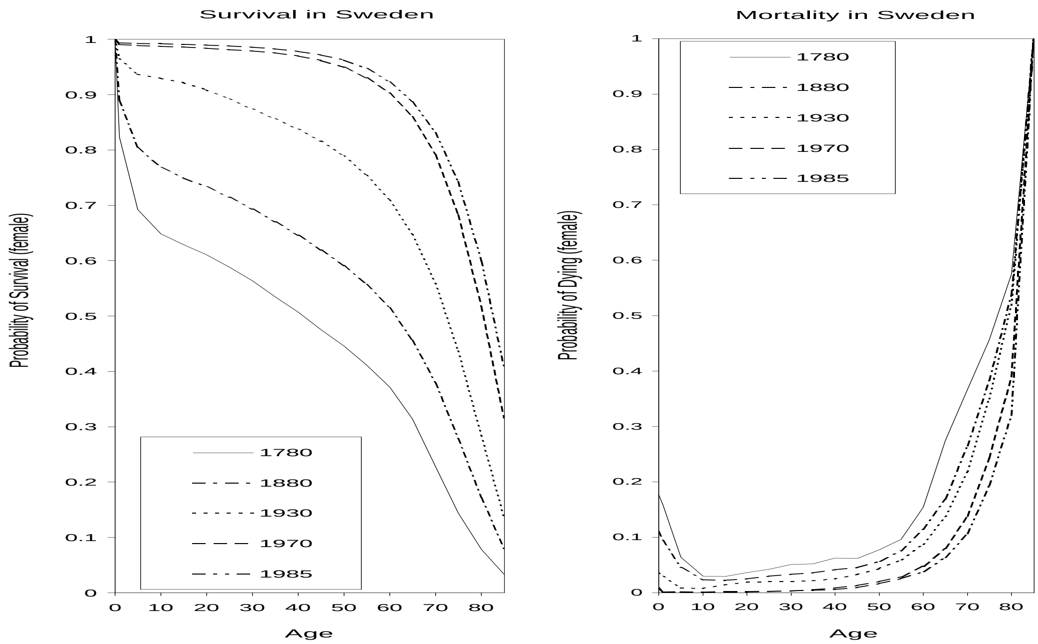

Figure 2: Survival and Mortality in Sweden

countries as shown in the first panel of Figure 3. In the second panel of Figure 3 the same pattern is given for the LDCs.[6]

The huge increase in educational attainment can be seen in data from both developed and developing countries. For example, the average number of years of schooling in England rose from 2.3 for the cohorts born between 1801 and 1805 to 9.1 for the cohorts born between 1897 and 1906. It rose even further to 14 for the 1974-1992 cohorts. In LDCs, gross secondary school enrollment increased from 17.1% in 1960 to 46.9% in 1990.[7]

What about the empirical evidence?[8] Eckstein et al. (1998), in a study of Swedish fertility

[6]The countries are Austria, Belgium, Denmark, Finland, France, Germany, Italy, Netherlands, Norway, Sweden, Switzerland, UK. This data is from Maddison (1995). The less developed countries are all countries of Africa, Latin America, and Asia (excluding Japan). This data is from United Nations (1998). The first two observations which are marked differently are from Maddison (1995).

[7]For England data is from Matthews, Feinstein, and Odling-Smee (1982), table E.1. For 1974-1992 see Maddison (1995). For LDCs data is from World Bank (1999).

[8]There may be two different strategies at work that generate the fertility response to reduced mortality and it is hard to distinguish them empirically. First, the "replacement strategy," is the response of fertility to experienced deaths, where parents replace deceased children before the end of their reproductive life. Second, the "insurance strategy," or hoarding, is the response of fertility to expected deaths, where parents bear more children than their optimal number of survivors. If parents follow a replacement strategy, they can produce

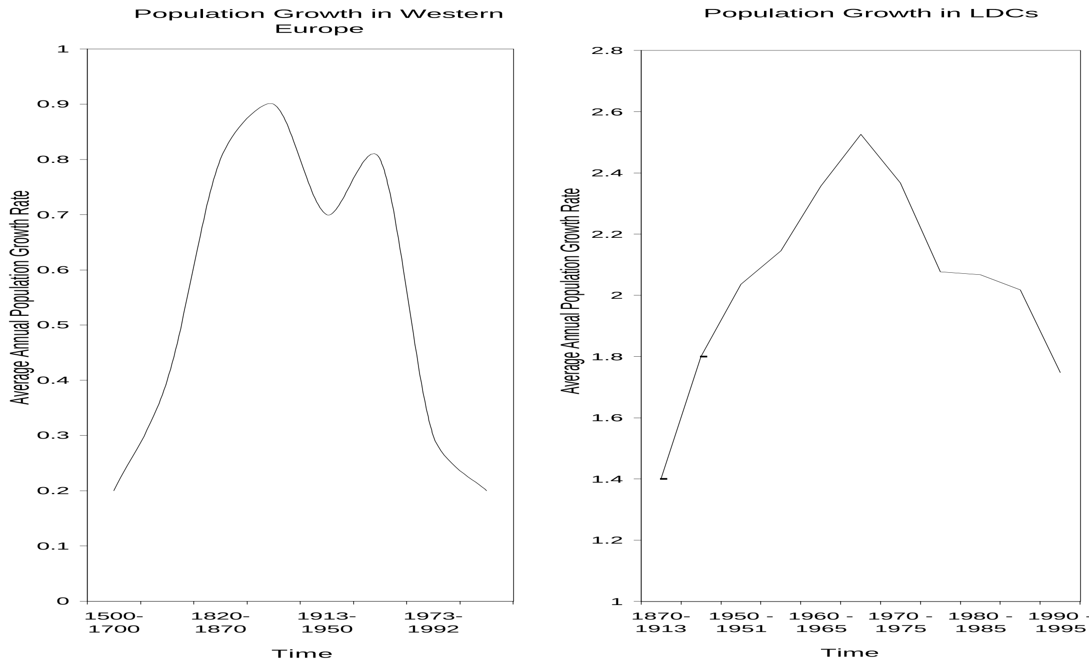

Figure 3: Population Growth

dynamics, show that the reduction in infant and child mortality is the most important factor explaining the fertility decline, while increases in the real wage can explain less than one-third of the fertility decline. Galloway et al. (1998), in a study of Europe, conclude that despite all the accompanying structural changes in economies, the very long-term decline in fertility is due to a very long-term decline in mortality.[9] For the developing countries some studies, like Bulatao (1985), find that the statistically significant threshold of life expectancy that, when attained, induce couples to limit their fertility is 50-60 years.[10]

their target number of survivors with no error and a change in child mortality will have no effect on the population growth rate. However, in the empirical studies using micro data, the estimated replacement effect is always smaller than 0.5 and generally it is around 0.2. But only a replacement effect of 1 means a fully working replacement strategy. (See Schultz (1997) for a summary of relevant empirical studies.)

[9]France is the only exception in this general picture of Europe, where fertility decline began early in the nineteenth century before the mortality had declined. See also Coale (1986) and Preston (1978b) for Europe.

[10]In general, fertility responds to the mortality decline with a lag. The main reason for this lag is that it takes parents some time to recognize that mortality has fallen. Thus, in some of the developing countries fertility decline cannot be seen yet even though mortality has declined. Montgomery (1998) develops a model of Bayesian learning to explore the lags and misperceptions of mortality change.

2.2 Related Theoretical Literature

The earliest theoretical formulation, known as the "target fertility model", implies that in order to have N surviving children, N/q children must be borne if the survival rate is q. However, this framework ignores the fact that children are economic goods and hence they are costly.[11] If a budget constrained is included then an increase in the survival rate reduces the number of births only if demand for children is inelastic with respect to the cost of a child. Thus, it could be optimal to have fewer births at a positive mortality rate than at a zero mortality rate. Indeed, Becker and Barro (1988) include mortality in their basic model of fertility and show that the decline in mortality lowers the cost of raising a survivor and thus increases the demand for surviving children. This implies that births rise in response to a decline in mortality, which is not consistent with the data. Sah (1991) develops a stochastic discrete time model where he shows that the number of children produced by a couple declines as the mortality rate declines. This is the first theoretical paper that investigates this causal relationship in an uncertain environment.[12]

There have been numerous papers on the relationship between fertility and education, after the introduction of the quality-quantity tradeoff idea by Becker and Lewis (1973). The main idea is that with increased returns to human capital parents value quality more than quantity. Note that in this literature it is not the mortality decline but rather increases in wages or technological advancement that causes returns to education to increase.

There has not been much work linking mortality to investments in education. Some researchers investigate the direct effect of mortality on education. Ram and Schultz (1979) argue that improvements in mortality have been an important incentive to increase investment in education, and the post war experience of India is consistent with this incentive. Preston (1980) calculates the degree to which reductions in mortality raise the rate of return to investments in education but concludes that the mortality effect on returns is not large enough to cause an enrollment increase. Meltzer (1992) extends Preston's data and argues that mortality-induced increases in returns could explain large movements in enrollment. In a recent paper, Kalemli-Ozcan, Ryder and Weil (2000), calibrating their model by using

[11] Schultz (1969), O'Hara (1975) and Ben-Porath (1976) were among the first attempts to analyze the relationship between mortality and fertility in such a framework. O'Hara and Ben-Porath also tried to incorporate a budget constraint into their analysis.

[12] Wolpin (1997), extending the Sah model, presents discrete time static and dynamic models of fertility decision in an uncertain environment and provides empirical evidence. Dalko (1992) extends the Sah model to endogenize the survival probability.

returns to schooling estimates, show that mortality decline produces significant increases in schooling.[13]

Three papers have incorporated the effect of changes in life expectancy on fertility and human capital investment into general equilibrium models. Uncertainty regarding the survival of children, however, is not part of any of these three models. Ehrlich and Lui (1991) model the effect of changing mortality in an OLG setup. They show that without old-age support motivation for having children, pure altruism is not enough to have a mortality effect on the optimal amount of human capital investment and therefore on growth. Meltzer (1992) extends Becker, Murphy and Tamura's (1990) model of human capital, fertility and growth by introducing a relationship between adult mortality and education. In his setup, as the longevity of parents increases, their investment in the human capital of their children increases because parents have a longer adult life during which they can invest more.[14] The third paper is by Spatafora (1997). He develops a general equilibrium growth model, also under certainty, where education, fertility, and mortality are endogenously determined.

Eswaran (1998) develops the only general equilibrium model under uncertainty with the old-age support motive for having children. Extending the Sah setup, he models demographic transition but does not deal with human capital investment. Barro and Sala-i-Martin (1995) also develop a continuous time general equilibrium model with endogenous fertility and exogenous mortality but no human capital investment and no uncertainty. Jones (1999) develops a similar growth model that generates the demographic transition. Lastly, Tamura (1999) incorporates human capital accumulation into the Jones (1999) model to match the economic history of the past several millennia.

3 The Model

Consider an OLG model, where individuals within a generation have identical preferences. Members of generation t live for two periods: in the first period of life, $(t-1)$, individuals consume a fraction of their parent's unit time endowment. In the beginning of the second period of life, (t), individuals make a one-time fertility decision. This choice is a static fertility

[13] See also de la Croix and Licandro (1999).

[14] One can also introduce child mortality as an exogenous parameter by assuming certainty, as Meltzer did, into the Becker, Murphy and Tamura's (1990) setup. This would yield no effect of mortality on human capital investment and a positive effect of it on fertility.

decision in an uncertain environment.

The preferences of the altruistic member of generation t are defined over today's consumption, C_t, and the future income of the survivors, $N_t w_{t+1} h_{t+1}$, where N_t is the number of survivors, w_{t+1} is the future wage of a survivor per unit of human capital and h_{t+1} is the human capital of a survivor. E_t denotes expectation as of time (t). We can write the utility function for a member of generation t as[15]

$$U_t^t = \gamma ln\Big[C_t^t\Big] + (1-\gamma)E_t\Big\{ln\Big[N_t w_{t+1} h_{t+1}\Big]\Big\}. \tag{1}$$

Human capital production is given by

$$h_{t+1} = e_t^{\beta} h_t, \qquad 0 < \beta < 1, \tag{2}$$

where e_t is the education level of a child and h_t is the level of parental human capital. This human capital production function implies that the child's level of human capital is increasing and strictly concave in the education of the child.

Households choose the number of children, n_t, and the optimal amount of education to give to each child, e_t, where each child's survival is uncertain. These choices are subject to a constraint on the total amount of time, which is unity. Assuming a fixed time cost, $v \in (0,1)$, for every child, the time left for the household after the child-bearing cost is incurred, is $1 - vn_t$. This remaining time is divided between work to earn a wage income and educational investment. Therefore, the budget constraint is

$$w_t h_t(1-(v+e_t)n_t) = C_t. \tag{3}$$

Notice that there can be two different scenarios regarding the educational investment. Education may be provided before or after the uncertainty about mortality is realized. If parents give education to every newborn child before the uncertainty about the survival is realized, each child will have a fixed cost and an education cost regardless of whether he or she dies. This paper investigates this ex-ante case. If education is given to each survivor after the uncertainty is realized then each child has a fixed cost but only survivors have an

[15]The log form of the utility function is chosen for two purposes: to have convex marginal utility in the number of survivors and to balance out the income and substitution effects on fertility. The analysis was also carried out using a CRRA form of utility function. The qualitative results remain unchanged.

education cost. In this case, the only difference will be in the budget constraint of equation 3, which can be written as $w_t h_t(1 - vn_t - e_t N_t) = C_t$.[16]

With uncertainty, N_t, the number of survivors, will be a random variable drawn from a binomial distribution. Thus, the probability that N_t out of n_t children will survive is (suppressing the time sub-script t),

$$f(N; n, q) = \binom{n}{N} q^N (1-q)^{n-N} \qquad N = 0, 1, \ldots, n. \tag{4}$$

Members of generation t choose the number of children, and the optimal amount of education to provide in order to maximize their expected utility as of time (t),

$$E_t^t(U_t^t) = \sum_{N_t=0}^{n_t} \left\{ \gamma ln \left[C_t^t \right] + (1-\gamma) ln \left[N_t w_{t+1} h_{t+1} \right] \right\} f(N_t; n_t, q). \tag{5}$$

This formulation implies that the number of children born and the number of surviving children are represented as nonnegative integers, which is a discrete representation.

I use the Delta Method to approximate the utility around the mean and the variance of the binomial distribution. This approach allows us to incorporate the variance, which is nothing but the risk effect, in a tractable way. By using the Delta Method and taking expectations, we can rewrite the maximization of expected utility as,[17]

$$\{n_t, e_t\} = argmax \left\{ \gamma ln \left[w_t h_t (1 - (v + e_t) n_t) \right] + (1-\gamma) ln \left[n_t q w_{t+1} h_{t+1} \right] - \frac{(1-\gamma)(1-q)}{2 n_t q} \right\}, \tag{6}$$

subject to: $(n_t, e_t) \geq 0$.

The first order condition with respect to e_t is,

$$e_t = \frac{\beta(1-\gamma)}{(\beta(1-\gamma) + \gamma)} \frac{(1 - vn_t)}{n_t}. \tag{7}$$

The first order condition with respect to n_t is non-linear due to the expected utility maximization,

[16] This ex-post case is considered in Kalemli-Ozcan (2000a), which shows an exogenous mortality decline causes educational investment to increase even if parents invest in education after the uncertainty about mortality is resolved.

[17] See Appendix A for details.

$$\frac{-\gamma(v+e_t)}{1-(v+e_t)n_t}+\frac{(1-\gamma)}{n_t}+\frac{(1-\gamma)(1-q)}{2qn_t^2}=0. \tag{8}$$

Due to uncertainty, parents engage in a self-insurance strategy and overshoot their desired fertility. This "insurance effect" is nothing but the risk effect that is incorporated through the variance of the binomial distribution, which affects the optimization with respect to n_t, and hence the comparative statics. Thus,

Proposition 1: *An exogenous increase in the survival probability (a decline in mortality), causes parents to decrease their precautionary demand for children. Thus, they choose to have fewer children and provide them with more education.*

$$\begin{aligned}\frac{dn_t^*}{dq} &< 0,\ \forall q,\\ \frac{de_t^*}{dq} &> 0,\ \forall q.\end{aligned} \tag{9}$$

Proof: See Appendix B.[18]

What about the effect of increased survival on the population growth rate? The population growth rate can be written as,

$$\frac{L_{t+1}}{L_t}-1=E_t(N_t^*)-1=n_t^*q-1, \tag{10}$$

where L_t is the size of the population at time t.[19]

The model also generates the stylized fact of the demographic transition, that is, popu-

[18]Note that $\frac{dn}{dq}=\frac{\partial n}{\partial(uncertainty)}\frac{\partial(uncertainty)}{\partial q}$. Uncertainty comes from the variance but high mortality does not necessarily mean high variance. So the second partial does not have to be negative for all the values of the survival probability, q. For given number of children the expected number of survivors (mean of the binomial distribution) always increases with a rise in the survival probability but the variance of the binomial rises or falls according to the value of the survival probability. If the survival probability is bigger than 1/2 the variance falls with a rise in the survival probability. But due to the Delta Method approximation the second partial is negative for all the values of q. This is consistent with the data. We don't see mortality rates that are higher than 50% in the data for historical populations. Thus, the survival probability we observe in the data is always higher than 1/2. This implies an increase in the survival probability will always lower the variance in the data. Therefore showing the negativeness of the total derivative in proposition 3 implies that the first partial is positive as it should be since this represents the precautionary demand.

[19]Note that due to the law of large numbers there is no aggregate uncertainty even though there is individual uncertainty, and hence the population growth rate is $E_t(N_t)-1$.

lation growth is a hump-shaped function of the survival probability.[20]

Proposition 2: *At low levels of survival (q near 0) an increase in the survival probability unambiguously raises the population growth rate, while at high levels of survival (q near 1) an increase in the survival probability causes the population growth rate to decline if the returns to education are high enough (β near 1).*

$$\begin{aligned} \frac{dE_t(N_t^*)}{dq} &> 0 \quad \text{if } q = 0, \\ \frac{dE_t(N_t^*)}{dq} &< 0 \quad \text{if } q = 1 \text{ and } \beta = 1, \end{aligned} \tag{11}$$

$$\frac{d^2 E_t(N_t^*)}{dq^2} < 0, \ \forall \ q.$$

Proof: See Appendix B.

When the survival probability is low, the population growth rate increases with the increases in the survival rate due to the increase in the number of expected survivors. When the survival probability is high, although the population growth rate may increase due to the increased number of survivors, the negative response of fertility can offset this effect, depending on the degree of concavity of the human capital production function. Most of the quality-quantity trade off literature assumed a linear human capital production function, meaning $\beta = 1$. Also Parente and Prescott (1999) argue that when β is close to 1 the differences in the time allocated to human capital investment lead to large differences in the steady state levels of income per capita, which are consistent with the data. Therefore, as evidence suggests, population growth is a concave function of the survival probability, for any q, and if β is close to 1 it is a hump-shaped function. This is shown in Figure 4.[21]

As a result, the partial equilibrium setup establishes the link from mortality to fertility and to human capital investment. This setup is enough to show the positive effect of mortality decline on economic growth in a general equilibrium framework. The higher human capital investment and the lower population growth will enhance economic growth.

[20] The same model is solved under certainty (meaning the number of survivors are given by the expected number of survivors, $N_t = E_t(N_t) = n_t q$) in Kalemli-Ozcan (2000b), which shows an exogenous increase in the survival probability has no effect on either fertility or human capital investment and has a positive effect on the rate of population growth.

[21] Note that $\beta = 1$ is the sufficient condition. See Appendix B for the necessary condition.

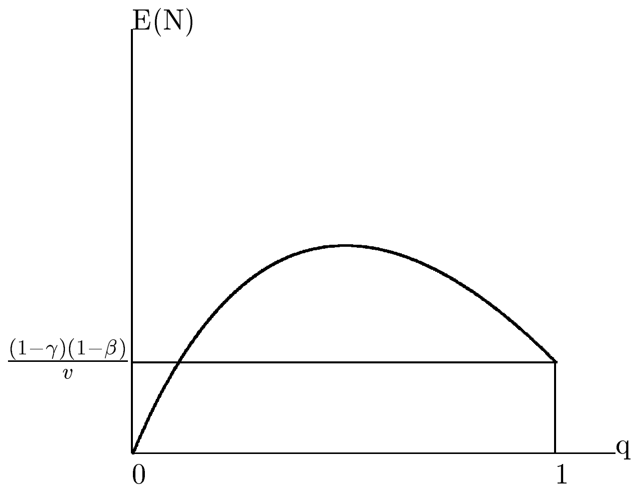

Figure 4: Population Growth and Survival Probability

4 General Equilibrium Analysis

The partial equilibrium setup establishes the link from mortality to fertility and to human capital investment in a stochastic framework. What are the dynamic implications of these links for economic growth? The answer to this question is important since ultimately we want to look at the larger picture in order to understand the importance of the mortality decline in the development process. To be able to perform this kind of general equilibrium exercise survival probability should be endogenous, namely a function of income per capita.

Until now, the survival probability has been assumed exogenous. But both time-series and cross-sectional empirical studies have found that as income per capita in a country rises, mortality rates tend to fall. Based on this evidence, q is assumed to be a concave function of income per capita.

$$q_t \equiv f(y_t), \tag{12}$$

$$f_y(y_t) > 0 \ , \ f_{yy}(y_t) < 0.$$

This concave relation between the survival probability and income per capita results in a hump-shaped relation between the population growth rate and income per capita, as given in Figure 5, since the population growth rate is a hump-shaped function of the survival

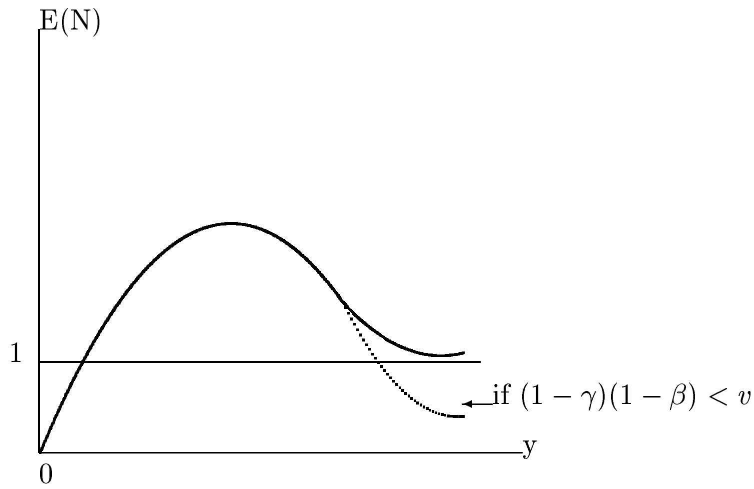

Figure 5: Population Growth and Income per Capita

probability as shown under the partial equilibrium setup.[22] Now we should analyze the determinants of income.

4.1 Production of Final Output

We suppose that production occurs according to a constant returns to scale neoclassical production technology. Thus the output produced at time (t), Y_t is

$$Y_t = AH_t^{\alpha}X^{1-\alpha}, \qquad 0 < \alpha < 1, \tag{13}$$

where H_t is the aggregate amount of human capital at time (t) and X is the fixed amount of land. A is a fixed productivity parameter. Output per worker at time (t), y_t can be written as

$$y_t = Ah_t^{\alpha}x_t^{1-\alpha} \equiv y(h_t, x_t), \tag{14}$$

[22] In Figure 5, having the expected number of survivors below 1 depends on the parameter values, specifically $v > (1-\gamma)(1-\beta)$. This is consistent with the current evidence of Europe (Bongaarts (1999)). This restriction says that for a fixed rate of return on education, if parents care about their own consumption a lot so that children become very costly, then they prefer to have less children in order to increase their own consumption. If this inequality holds with equality, the expected number of survivors asymptotes to 1 with very high income per capita, implying a population growth rate of zero.

where $h_t = H_t/L_t$ is the human capital per worker (or the number of efficiency units per worker) and $x_t = X/L_t$ is the resources per worker at time (t).

4.2 The Evolution of Income per Capita

Substituting equations 7 and 8 and equation 10 into the one-period iterated form of equation 14, y_{t+1} can be written as a function of y_t,

$$y_{t+1} = \left[\frac{\beta(1-\gamma)}{\gamma+\beta(1-\gamma)}\right]^{\beta\alpha} (y_t)(q_t)^{\alpha-1}(1-vn_t)^{\alpha(1-\beta)-1}. \tag{15}$$

Equation 15 can also be written as,

$$\frac{y_{t+1}}{y_t} = e_t^{\beta\alpha} E_t(N_t)^{\alpha-1}. \tag{16}$$

where the positive effect of human capital investment and the negative effect of population growth (due to high fertility) on income per capita growth is clear.

Therefore, the hump-shaped pattern of the population growth as a function of income per capita, as given in Figure 5, results in the dynamics for income per capita given in Figure 6. There are two steady states: A stable Malthusian steady state (denoted as y_m), and an unstable developed economy steady state (denoted as y_g), at or above which persistent growth is achieved, depending on the parameter values. Thus, at low levels of income per capita (either side of y_m), the survival chances are low, so increases in the survival probability lead to increases in population growth. This effect would dilute the resources, resulting in lower income per capita. This is the Malthusian trap. At high levels of income per capita (above y_g), the survival chances are high, so further increases in the survival probability causes population growth to decline. This, together with high levels of human capital investment and lower fertility, as a result of increased survival, leads to higher income per capita and, therefore to persistent growth.[23] In a stochastic world a country can end up anywhere depending on the nature of mortality improvements, which in turn will effect the rate of population growth. Depending on having zero or negative population growth one can stay at the developed steady state or can grow forever.

[23] Notice that having persistent growth depends on having the expected number of survivors in Figure 5 below 1. If this number asymptotes to 1 with very high income per capita, this corresponds in ending up on the 45^0 degree line in Figure 6.

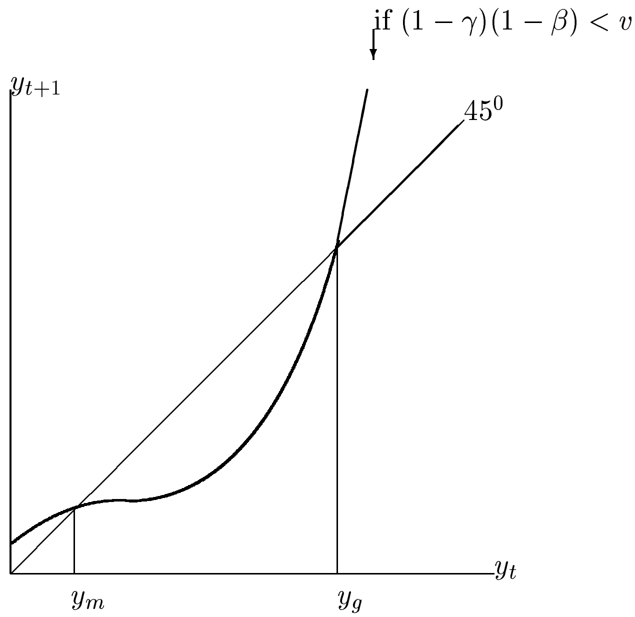

Figure 6: Evolution of Income per Capita

4.3 Estimating the Survival Function

In order to calibrate the model we need to estimate the survival probability as a function of income per capita. We use mortality and income per capita data from 26 countries between 1900 and 1990.[24] Both developed and developing countries are included in the sample. Each of the three dependent variables, q_1, q_5, q_{15}, which are the probabilities of surviving to ages 1, 5 and 15 respectively, is estimated as a function of income per capita. Hence, the following concave functional form is estimated cross-sectionally for each of these q's and for four different years, namely 1900, 1930, 1960 and 1990.[25]

[24] This data set is in the process of being updated to more years and countries. Income per capita is from Maddison (1995) and in 1990 Geary-Khamis dollars. The mortality (survival) data is from various sources: Barro and Lee (1994), Colin Clark (1970), Flora (1987), Keyfitz and Flieger (1968, 1990), Haines (1994), Keyfitz, Preston and Schoen (1972) and United Nations Demographic Yearbook from various years. The countries that are included: Egypt, US, Chile, India, Japan, Belgium, Denmark, France, Netherlands, Sweden, UK, Czechoslovakia, Hungary, Ireland, Spain, Finland, Australia, Italy, New Zealand, Norway, Greece, Bulgaria, Yugoslavia, Mexico, Venezuela and China. The data is available upon request from the author.

[25] Note that the aim of this estimation is only to show the robustness of the concavity assumption of q_t as a function of y_t. I am not trying to estimate any structural relationship since an identification problem then arrives due to the mutual dependence of q_t and y_t. For such an analysis one needs to use IV estimation.

Table 1: Estimation of the Survival Probability (Age 1)
Functional form : $q_{1t} = a_0(1 - exp(-a_1 y_t))$

Dependent variable	$q_1 1900$	$q_1 1930$	$q_1 1960$	$q_1 1990$
Observations:	18	24	26	23
a_0	0.852	0.897	0.957	0.986
	(0.013)	(0.012)	(0.007)	(0.002)
a_1	0.275	0.241	0.361	0.0
	(0.049)	(0.032)	(0.043)	–

Note: Standard errors are in parentheses. q_{1t} is the survival probability to age 1. y_t is income per capita. Each column shows the estimation of the given functional form for q_1 for four different years; 1900, 1930, 1960, 1990.

$$q_t = a_0(1 - exp(-a_1 y_t)). \tag{17}$$

All coefficients are found to be significant, as shown in Tables 1, 2 and 3. The first column of Table 1 shows the cross-sectional estimation for the dependent variable $q_1 1900$, which is the survival probability to age 1 for the year 1900, as a function of income per capita. The other columns reports the same estimation for q_1 for the years 1930, 1960 and 1990. Tables 2 and 3 do the same exercise for ages 5 and 15 respectively.

Figure 7 shows the fitted values for each year from the estimations of q_5 that are given in Table 2. This parallel upward shifts in child survival over time is consistent with the Preston (1978a, 1980) evidence that there is an upward shift in the relationship between life expectancy and income per capita in time, meaning this relation becomes more and more independent of the level of income per capita.

4.4 Calibrating the Model

The model is calibrated using the estimated survival function for q_5, as given in Table 2 and Figure 7. The purpose of this exercise is to show that the model is consistent with the stylized facts of the data.

The first set of results of this calibration exercise are given in Figure 8, which shows the

Table 2: Estimation of the Survival Probability (Age 5)
Functional form : $q_{5t} = a_0(1 - exp(-a_1 y_t))$

Dependent variable	$q_5 1900$	$q_5 1930$	$q_5 1960$	$q_5 1990$
Observations:	18	24	26	23
a_0	0.796	0.869	0.947	0.983
	(0.024)	(0.020)	(0.009)	(0.002)
a_1	0.168	0.155	0.265	0.0
	(0.033)	(0.022)	(0.028)	–

Note: Standard errors are in parentheses. q_{5t} is the survival probability to age 5. y_t is income per capita. Each column shows the estimation of the given functional form for q_5 for four different years; 1900, 1930, 1960, 1990.

Table 3: Estimation of the Survival Probability (Age 15)
Functional form : $q_{15t} = a_0(1 - exp(-a_1 y_t))$

Dependent variable	$q_{15} 1900$	$q_{15} 1930$	$q_{15} 1960$	$q_{15} 1990$
Observations:	18	24	26	23
a_0	0.781	0.858	0.940	0.980
	(0.027)	(0.022)	(0.010)	(0.0020
a_1	0.138	0.135	0.247	0.0
	(0.024)	(0.020)	(0.027)	–

Note: Standard errors are in parentheses. q_{15t} is the survival probability to age 15. y_t is income per capita. Each column shows the estimation of the given functional form for q_{15} for four different years; 1900, 1930, 1960, 1990.

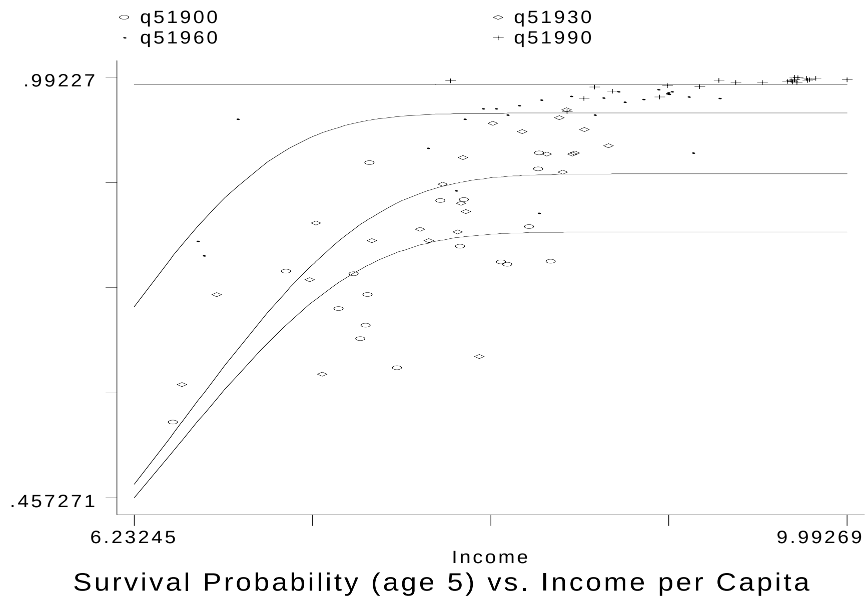

Figure 7: Estimation of the Survival Probability

expected number of survivors as a function of income per capita.[26] This is basically the calibration of the closed form solution for population growth from the partial equilibrium model using the estimated survival functions for age 5 for the years 1900, 1930, 1960 and 1990. For all of the four years there is a hump-shaped relationship between population growth and income per capita since β is chosen to be high.[27] These results are fully consistent with the evidence and the model. Figure 5 shows that having the expected number of survivors below 1, when q goes to 1 or alternatively when income per capita is high, depends on the parameter values such as, $v > (1-\gamma)(1-\beta)$. The parameter values here are chosen such that this inequality can hold. Thus, the expected number of survivors is below 1 for the years 1960 and 1990. But for the years 1900 and 1930 it is above 1. The reason is that for those years q doesn't asymptote to 1, as shown in Figure 7.

It is also straightforward to solve equation 15 as a calibration exercise, which results in the multiple equilibrium dynamics given in Figure 9. Using the estimated survival function

[26] Log of income per capita is used in Figures 7 and 8. The y-axis in Figure 8 is L_{t+1}/L_t. Thus to find the population growth rate, one has to subtract 1 from this axis.

[27] The parameters are $v_1 = 0.1, \beta = 0.9, \gamma = 0.5$.

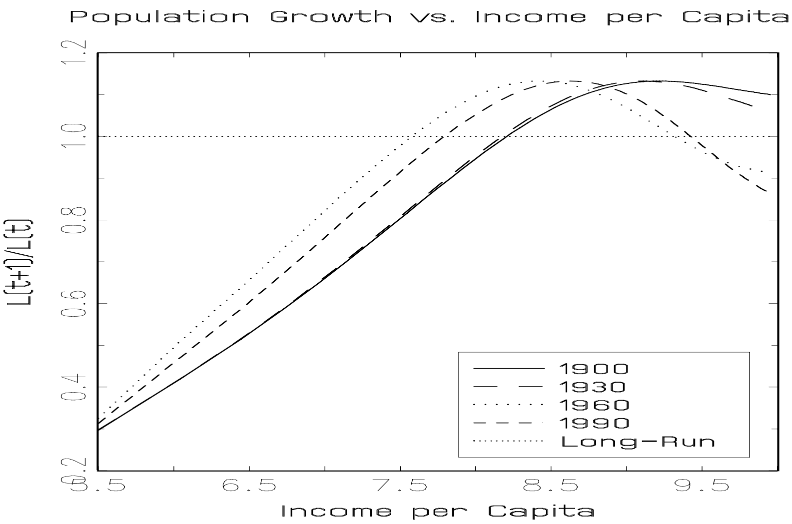

Figure 8: Calibration of Population Growth

for age 5 and for year 1960 from the third column of Table 2 and a high value for β, the two steady states are shown. If a low value of β were used, the developed economy steady state would disappear since the negative effect of higher income per capita on population growth would disappear in such a case.[28] Thus population growth always increases and dilute resources. Thus, in this case we will only have the Malthusian steady state.

Notice that there is neither exogenous nor endogenous technological progress in this setup. Thus, there is no source of steady state growth. Although including technological progress is a straightforward extension, it is not necessary since mortality decline does all the work. Nevertheless, if one includes endogenous technological progress, an exogenous decline in mortality can serve as the basis for a unified growth model that describes the complete transition from a Malthusian world to the modern growth era. A discussion of this is given in Galor and Weil (1999). After an initial decline in mortality, population growth rises without the fertility response (as shown here). But the effect of lower mortality in raising the human capital investment is present and this lead to higher technological progress, since technical change

[28]The parameter values are $v = 0.1, \alpha = 0.3, \beta = 0.9, \gamma = 0.5$.

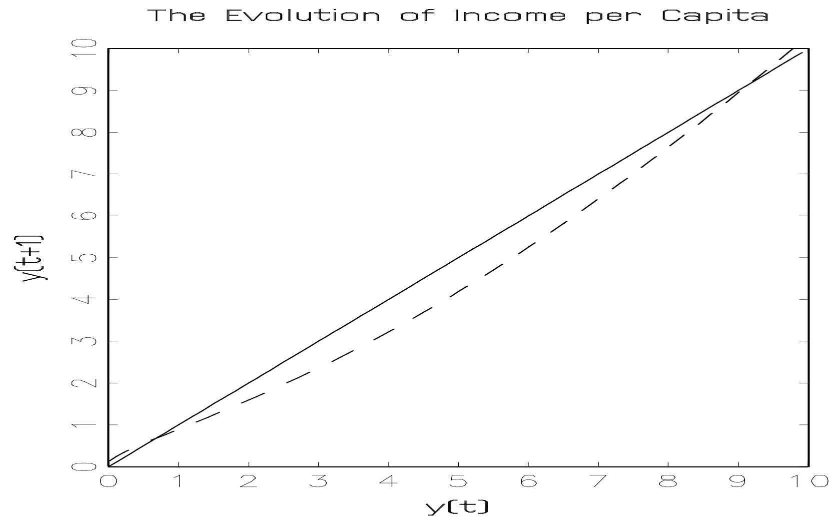

Figure 9: Calibration of Dynamics

is a function of education, therefore, higher income further lowers mortality. Then fertility response comes into play and population growth falls together with more human capital investment. As a result, a decline in mortality not only causes the steady state growth rate to increase through technological progress, but also can transfer an economy from a Malthusian steady state to a developed economy steady state.

5 Conclusion

Over the last decade there has been extensive research on the determinants of economic growth. Empirical studies have found three determinants that are robust to different specifications. These are; the positive effect of human capital investment; the negative effect of fertility (and/or population growth); and the positive effect of life expectancy (or health proxies) on the rate of economic growth (Barro, 1997; Knowles and Owen, 1995). Unfortunately, researchers have not provided direct evidence regarding the mechanism through which higher life expectancy promotes growth.

Given these empirical findings one such mechanism could be mortality decline working through the channels of education and fertility to enhance economic growth. Here, the fertility channel is based on individuals being prudent, which causes a precautionary demand for children. As the mortality rate and thus uncertainty falls, this precautionary demand decreases, and so does population growth. Education channel is based on the fact that higher expected life span implies higher returns to education. Thus, parents will choose to move along a quality-quantity frontier, having fewer children and investing more in each child.

In addition to these micro foundations, this paper also provides an aggregate framework to investigate whether or not mortality decline promotes growth. By endogenizing mortality, the general equilibrium model demonstrates the existence of multiple equilibria: A Malthusian steady state, where the rate of population growth rises as income per capita rises, and a developed economy steady state, where the rate of population growth falls with the increases in income per capita. In a stochastic environment, depending on the nature of improvements in mortality, countries can be trapped around the Malthusian steady state or they can grow forever. Calibration exercises show that the general equilibrium model is consistent with the stylized facts of the development process. Recently there has been numerous research studies, which attempt to present a unified model of industrialization and population dynamics, as described in the introduction. However, mortality is not incorporated into these models. The model of this paper generates the facts of the demographic transition by including mortality. Population growth is a hump-shaped function of income per capita, which implies the existence of multiple equilibria.

This paper also has some important policy implications. Reducing infant and child mortality will lead a reduction in fertility and an increase in schooling. Although demographic transition is complete in most parts of the world, there are still high fertility countries, especially in Africa. Some researchers find evidence that child mortality have declined in recent decades in some countries of Africa and those countries began their demographic transition. But currently the spreading AIDS epidemic threatens this progress and fertility starts to increase and schooling levels starts to decrease in the face of increased child mortality (Ainsworth et al., 1998).

Appendix A

The Delta Method tells us to take the expectations after a Taylor series approximation of the utility around the mean of the distribution. I am going to do a third degree approximation since higher order terms after third degree does not matter. Thus,

$$U_t(N_t) \cong U(n_tq) + (N_t - n_tq)U_N(n_tq) + \frac{(N_t - n_tq)^2}{2!}U_{NN}(n_tq) + \frac{(N_t - n_tq)^3}{3!}U_{NNN}(n_tq) + \ldots.. \tag{18}$$

From log utility it is straight forward to calculate the above partial derivatives, hence,

$$\begin{aligned} \frac{\partial U_t}{\partial N_t} &= U_N = \frac{(1-\gamma)}{N_t}, \\ \frac{\partial^2 U_t}{\partial N_t^2} &= U_{NN} = -\frac{(1-\gamma)}{N_t^2}. \end{aligned} \tag{19}$$

Substituting equation 19 in equation 18 and taking the expectations implies

$$E_t(U_t) = U_t(n_tq) + 0 - \frac{(1-\gamma)}{2(n_tq)^2}n_tq(1-q) + 0 + \ldots.. \tag{20}$$

The second term is zero since $E(N - nq) = 0$. The third term is the variance, which is $E(N - nq)^2 = \sigma^2 = nq(1-q)$. The fourth term is zero since it is the third central moment. Let μ denotes the mean (nq) and σ^2 denotes the variance $(nq(1-q))$. Also let $E(N-\mu)^3$ denotes the third central moment. The moment generating function can be written as $\mu'(t) = (\mu + \sigma^2(t))\mu$. So, $\mu'(0)$ gives the mean, and $\mu''(0) - (\mu'(0))^2$ gives the variance. And $\mu'''(0) - 3\mu\mu''(0) + 3\mu^3 - \mu^3$ gives the third central moment, which is zero.

Therefore, after substituting the budget constraint in the log utility function, the equation 20 can be written as

$$E_t(U_t) = \gamma ln\Big[w_th_t(1-(v+e_t)n_t)\Big] + (1-\gamma)ln\Big[n_tqw_{t+1}h_{t+1}\Big] - \frac{(1-\gamma)(1-q)}{2n_tq}. \tag{21}$$

Appendix B

Proof of Proposition 1:

Multiplying everywhere in the equation 8 by n_t^2 and substituting e_t from equation 7 gives

$$G(n_t, q) = \frac{-n_t(vn_t\gamma + \beta(1-\gamma))}{1 - vn_t} + (1-\gamma)n_t + \frac{(1-\gamma)(1-q)}{2q} = 0, \tag{22}$$

which defines n_t^* implicitly. Thus, suppressing $*$ and t subscript for convenience and using subscripts for partial derivatives from now on

$$\frac{dn}{dq} = -\frac{G_g}{G_n}. \tag{23}$$

Equation 22 can also be written as

$$\frac{(1-\gamma)(1-q)}{2q} = \frac{n(vn\gamma + \beta(1-\gamma))}{1 - vn} - (1-\gamma)n. \tag{24}$$

Thus, LHS of the equation 24 is only a function of q and RHS of it is only a function of n. Hence,

$$\begin{aligned} LHS_q(q) &= G_g, \\ RHS_n(n) &= -G_n. \end{aligned} \tag{25}$$

Given $0 < q \leq 1$, it is easy to show that $LHS(q)$ is always negative

$$\begin{aligned} LHS_q(q) &= -\frac{(1-\gamma)}{2q^2} < 0 \ \forall q, \\ LHS_q q(q) &= \frac{(1-\gamma)}{q^3} > 0 \ \forall q, \\ lim_{q \to 0} LHS(q) &\to +\infty, \\ lim_{q \to 1} LHS(q) &= 0. \end{aligned} \tag{26}$$

Thus equation 26 implies

$$G_q < 0 \ \forall q. \tag{27}$$

The budget constraint in the equation 3 implies that $0 \leq n \leq \frac{1}{v}$. Then it is easy to show that $RHS(n)$ is always positive for the range of n that is relevant for finding an optimum. $RHS(n)$ can be written as

$$RHS(n) = \frac{n(vn - (1-\gamma)(1-\beta))}{(1-vn)}. \tag{28}$$

Taking the derivative with respect to n gives

$$RHS_n(n) = \frac{vn(2-vn) - (1-\gamma)(1-\beta)}{(1-vn)^2}. \tag{29}$$

To determine the sign of equation 29, one has to evaluate the following:

$$\begin{aligned} lim_{n\to 0} RHS_n(n) &= -(1-\gamma)(1-\beta) < 0, \\ lim_{n\to 1/v} RHS_n(n) &\to +\infty, \\ RHS_{nn}(n) &= \frac{2v(\gamma + \beta(1-\gamma))}{(1-vn)^3} > 0 \ \forall n, \\ lim_{n\to 0} RHS(n) &= 0. \\ lim_{n\to 1/v} RHS(n) &\to +\infty. \end{aligned} \tag{30}$$

Thus equation 30 implies[29]

$$-G_n > 0 \ \forall n. \tag{31}$$

Therefore equations 27 and 31 together with the equation 23 imply

$$\frac{dn^*}{dq} < 0, \tag{32}$$

which is the proof of the first part of Proposition 3.

The proof of the second part is straightforward.

$$\frac{de^*}{dq} = -\frac{\beta(1-\gamma)}{(\beta(1-\gamma)+\gamma)(n^*)^2}\frac{dn^*}{dq} > 0. \tag{33}$$

[29]Note that $\forall n$ here describes the range of n's such that there can be a solution to the optimization problem.

Proof of Proposition 2:

Substituting $n_t = E(N_t)/q$ and the optimal e_t from equation 7 into the equation 8 gives

$$\widetilde{G}(E(N), q) = -2vE(N)^2 + 2q(1-\beta)(1-\gamma)E(N) + (1-\gamma)(1-q)(q - vE(N)) = 0, \quad (34)$$

which defines $E(N)$ implicitly, thus,

$$\frac{dE(N)}{dq} = -\frac{\widetilde{G}_q}{\widetilde{G}_{E(N)}}. \quad (35)$$

Evaluating this with implicit function theorem gives

$$\frac{dE(N)}{dq} = \frac{(1-\gamma)[2(1-\beta)E(N) + vE(N) + 1 - 2q]}{4vE(N) - (1-\gamma)[2(1-\beta)q - (1-q)v]}. \quad (36)$$

When $q \to 0$, $E(N) \to 0$ and $n \to 1/v$. Equation 36 is unambiguously positive

$$\frac{dE(N)}{dq} = \frac{1}{v} > 0 \text{ if } q \to 0. \quad (37)$$

When $q \to 1$, $E(N) \to n$ and $n \to (1-\gamma)(1-\beta)/v$. Equation 36 is ambiguous in sign

$$\frac{dE(N)}{dq} = \frac{(1-\gamma)[2(1-\beta)n + vn - 1]}{4vn - 2(1-\gamma)(1-\beta)} < 0 \text{ if } q \to 1 \text{ and } \beta \to 1. \quad (38)$$

Substituting $n = (1-\gamma)(1-\beta)/v$, when $q \to 1$, gives the necessary condition for 38,

$$\frac{(1-\gamma)(1-\beta)}{v} < \frac{1}{2(1-\beta) + v}. \quad (39)$$

If $\beta \to 1$, the condition in equation 39 is satisfied. If $n < 1$ when $q \to 1$, meaning $v > (1-\gamma)(1-\beta)$, another sufficient condition is $2(1-\beta) + v < 1$.

Proof of Concavity:

Showing $\frac{d^2E_t(N_t^*)}{dq^2} < 0$ is straightforward. This can be written as

$$\frac{d^2E_t(N_t^*)}{dq^2} = \frac{G_{nn}(G_q)^2 q}{(-G_n)^3} + \frac{qG_{qq}}{-G_n} + \frac{2G_q}{-G_n}. \quad (40)$$

But $qG_{qq} = -2G_q$, thus this implies

$$\frac{d^2 E_t(N_t^*)}{dq^2} = \frac{G_{nn}(G_q)^2 q}{(-G_n)^3} < 0 \ \forall q. \tag{41}$$

Equation 41 holds given the fact that $-G_n > 0$ and $-G_{nn} > 0$.

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