# Degrees of Development –

## How Geographic Latitude Sets the Pace of Industrialization and Demographic Change

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**Abstract.** Successful economic development is usually characterized by two salient phenomena: industrialization and demographic transition. Chronologically both events happen so closely to each other that historians and economists alike suspect that they are interrelated. This paper develops a theory for their interaction with a special emphasis on the different pattern and pace of transition in cross-country comparison. For that purpose it rationalizes why a population grows at high rates at geographic locations of high extrinsic mortality. This mechanism is then used to explain why both demographic transition and structural change proceed at slower speed in countries of low absolute latitudes. It is also shown that at tropical locations the pace of transition can be so slow that it sometimes looks like as if societies got stuck in the midst of the process.

*Keywords:* Industrialization, Structural Change, Demographic Transition, Geography, Health, Cross-Country Divergence

*JEL:* J10, J13, O11, O12

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## 1. Introduction

Every economically developing society runs through two one-time transformations, an industrial revolution and a demographic transition. Although there are also important issues of timing – to which we turn later – the most salient observation is that both processes happen so closely to each other chronologically. Given the several thousand years since the great other one-time structural change, the Neolithic revolution, it is interesting to note that we have never observed a demographic transition, say, 500 years before industrialization or vice versa. Given the historically proximity, "our instincts suggest that there is some underlying connection between these events" (Clark, 2005).

Although the general pattern of demographic transition – according to which fertility follows a permanent decrease of mortality with delay so that population growth rises temporarily – is globally observed, the actual transition paths differ strikingly across countries. A study by Reher (2004) classifies the world's countries according to their onset of fertility decline into forerunners (on average around 1905), followers (between 1950 and 1960), trailers (1965-1975), and latecomers (after 1980). A general observation is that both pre-decline death rates and birth rates are lowest for forerunners, higher for followers and trailers, and highest for latecomers. Also, the average time gap between the onset of mortality decline and the onset of fertility decline was shortest for forerunners with about 5 to 10 years and longest for latecomers with about 40-45 years. The gap for followers and trailers lies in between. As a consequence of these differing speeds of reaction of fertility, population growth peaks at the lowest rate during transition for forerunners, at considerably higher rates for followers and trailers, and at the highest rate for latecomers.[1] Table 1 summarizes these results.

The group of forerunners contains almost exclusively European and North American countries located at high geographic latitudes with temperate climate. Followers and trailers (mostly Asian and South American countries) are less favorably located, on average just inside the tropics, while latecomers (mostly from Sub-Saharan Africa) are clearly tropically located at an average latitude of 13.8 degrees. Taken together the data suggests that the inverted u described by population growth during demographic transition is observed everywhere on the globe but

[1]Lee (2003) presents similar results. Among the forerunners there were also outliers where fertility moved first (e.g. France). Within the other groups, however, mortality has declined first in every instance (see also Kirk, 1996).

Table 1: Demographic Transition and Latitude

| | Forerunners | Followers | Trailers | Latecomers |
|---|---|---|---|---|
| Onset fertility decline | 1905 | 1950-60 | 1965-75 | 1980-2000 |
| Pre-decline birth rate | 3.3-3.5 | 3.6-4.0 | 4.1-4.4 | 4.6-4.7 |
| Pre-decline death rate | 2.2-2.5 | 2.6-2.9 | 2.7-3.0 | 3.3-3.4 |
| Gap mortality-fertility decline | 5-10 | 30 | 30 | 40-45 |
| Natural growth rates: peak | 1.2-1.3 | 2.6-2.7 | 2.6-2.7 | 2.7-2.9 |
| Percent countries | 17 | 12 | 33 | 38 |
| Average latitude | 47.8 | 20.8 | 21.6 | 13.8 |

Data from Reher (2004) and Masters and McMillan (2001).

the inverted u's of countries of low latitude are starting at higher rates, peaking at higher rates (and at later dates), and are lying everywhere above the inverted u's of countries of high latitude.

With respect to death rates it is no wonder that countries located at temperate zones perform better where, for example, extended periods of winter frost eliminate the prevalence of many pathogens and parasites (Masters and McMillan, 2001). It is, however, much less obvious and indeed somewhat puzzling from a biological viewpoint as well as from standard economic reasoning that human populations grow at higher rates when they are inhabiting unfavorable environments of high mortality.[2]

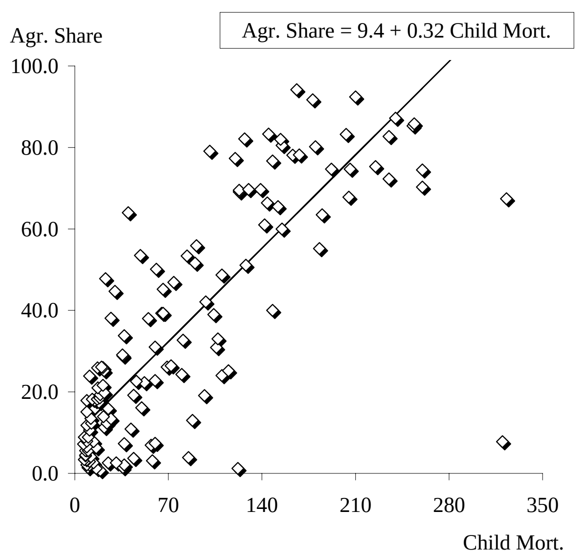
The present paper employs a theory developed in Strulik (2005, 2007) as an explanation for this phenomenon. A key element of the theory is a partition of child survival rates into extrinsic and intrinsic components. While the extrinsic part is exogenous to the individual parent the intrinsic part is individually controllable through expenditure on child nutrition and health. Extrinsic child survival rates are assumed to be determined by absolute geographic latitude and the state of economic development of a family's country or region of residence. The state of economic development is here summarized by average income per capita and subsumes factors like, for example, public health spending.[3]

The result that humans multiply at higher rates in environments of high mortality can be explained by a particular form of decreasing returns on child expenditure: An additional fraction of income spent on children is relatively ineffective in preventing death when the family lives in

[2]Throughout this paper we will use absolute latitude, in short just "latitude", measured in degrees as a catchall for a variety of geographic indicators like temperature, rainfall, and, in particular, the diversity of disease species.
[3]See Strulik (2005) for a detailed analysis of how latitude, income, and the interaction of both determine child survival probabilities. See Guegan et al. (2001) for evidence of a strong positive correlation between human fertility and the diversity of disease species.

a rich country at high geographic latitude where child survival rates are high anyway. On the other hand, it can "buy" a large improvement of survival chances when the family lives in an environment where extrinsic child survival rates are low. This fact creates a superproportional reaction of fertility to extrinsic mortality changes. Parents respond to an exogenous increase of the child survival rate with having less children not only because more children survive anyway but also because their individual income becomes less effective in preventing child death. Thus, parents in low mortality environments prefer small families whereas parents in high mortality environments prefer large ones.

Figure 1: Child Mortality Against Agricultural Employment Share




$R^2 = 0.73$. 133 observations from World Bank (2004) for year 1990. Agr. Share is agricultural share of employment (in per cent). Child Mort. is Under 5 Mortality Rate (per thousand born children). The regression excludes two outliers (visible in the figure): Niger (agricultural share stated as 7.4% in World Bank, 2004) and Bolivia (agricultural share stated as 1.3%).

Accepting the view of world-wide differing onsets and speeds of demographic transition the question occurs whether we cannot just have industrialization without demographic transition. Indeed, in some prominent economic articles like Hansen and Prescott (2002) industrialization is driven by TFP growth and capital accumulation and for industrialization to unfold a demographic transition is not really needed. An exogenous path of population growth is added to the model in order to produce more realistic time series. With contrast, another strand of literature, frequently addressed as unified growth theory (Galor, 2005), argues that industrialization and demographic transition are inevitably coupled together so that it is impossible to get just one phenomenon without the other.

Most articles concerned with unified growth theory conceptualize industrialization as take-off of growth rates of per capita income and factor productivity. Following this reasoning a one good model would be sufficient to explain the demo-economic transition and if a two-sector-one-good model is used this is mainly done in order to extract more realistic time paths from numerical representations of the model and not because it enhances our understanding of the growth process (Galor, 2005, p. 263).

The present paper contributes to a small literature arguing that a two-sector-*two*-good approach fundamentally improves our understanding of the world-wide differing patterns of demographic transition and industrialization. This is so because the two goods serve different *functions*. The main function of food is to fulfill the metabolic needs of adults and their offspring. Goods produced by the other sector, called industrial, manufacturing, or modern sector, cannot be used for nutrition. These goods satisfy less basic needs and are thus demanded relatively more when income is relatively high and nutritional needs are largely fulfilled. Industrialization is thus conceptualized as structural change from a society mainly based on the production of food towards a society where the bulk of GDP consists of non-food produced in a manufacturing (or modern) sector.[4]

Now suppose that food is produced according to a Malthusian-like production function with decreasing returns to labor input on limited land whereas manufactured goods are produced using capital and labor and a constant returns to scale technology. This implies that for societies at the beginning of the demographic transition where income is low and mortality and fertility are high most income is spend on food and most people are occupied with food production which in turn causes income per capita to be low because of decreasing returns in agriculture. In societies that managed a demo-economic transition, mortality and fertility are low, income per capita is high, the expenditure share for food is low, and most people are working outside of agriculture.

The implied close connection between demographic transition and industrialization is visualized in Figure 1. It shows for 133 countries (i.e. for those where the data is available from World Bank, 2004) child mortality against the employment share of agriculture. The forerunners of

[4]Related literature is discussed in Section 6.

demographic transition, located in temperate zones, have also experienced industrialization and are gathered around the origin with both agricultural shares and child mortality rates close to zero. The latecomers, located in tropical zones, are found in the upper right corner of the figure with yet high mortality rates (albeit lower than pre-transition levels) and agricultural employment shares around 70 percent. Followers and trailers are found at intermediate levels of mortality and employment shares.

The fact that, ceteris paribus, population growth is higher at low latitudes entails a geographic disadvantage for countries located in these regions. Potential economic growth through TFP growth is to a large extend "eaten up" by larger population growth and its implied rising food demand. A larger share of the population has to be allocated to agriculture, the sector with lower labor productivity. Less productivity implies less income per family and higher expenditure shares of food demand which feeds back negatively to the pace of industrialization and demographic transition.

In order to derive these chains of effects the paper is organized as follows. The next section states and solves the decision problem of households. Section 3 shows that the households' solution leads to an inverted-u shaped correlation between income and population growth and how geographic latitude contributes to the shape and location of the inverted-u. Section 4 integrates the households' decisions into a two-sector macro-economy and investigates its dynamic behavior analytically. Using a calibration of the model, Section 5 shows how geographic location affects the pace of industrialization and demographic transition. This paper does not claim a monocausal role for geography on development. It complements other approaches explaining the Great Divergence (Pomeranz, 2000) of income across countries by history and luck (summarized in different country specific shocks of TFP in the past). Section 6 thus investigates how much geography can contribute to explain the observed world income distribution. Differences to and similarities with related work are discussed in Section 7. Section 8 concludes.

## 2. The Decision Problem of Households

Life is assumed to be separable into the periods of childhood, (young) adulthood, and old age. All decisions are made by young adults who derive utility from consuming now and in old age, from having a family, and from child expenditure. Current consumption consists of food ($c_1$) and non-food ($c_2$). Consumption in old age ($c_3$) consists exclusively of non-food while child expenditure consists exclusively of food. Taking into account that children and the old are also consuming both goods would add more realism and improve the model's calibration. It would, however, not change the theory and thus this idea is not pursued for simplicity.

Adults are allowed to reproduce without matching. Of $n$ born children a fraction $\pi$ survive up to young adulthood. Survival during adulthood is assumed to be certain. To keep the analysis tractable $n$ is considered to be a continuous variable. Thus, the parent under investigation can be regarded as an economy's average adult who bears $n$ children, spends a fraction $h$ of his income on each child, and observes that a fraction $\pi$ of them survives the stage of childhood.

Child expenditure is partly motivated by the utility derived directly from it, i.e. for example, from the warm glow of giving (Andreoni, 1989) or from the preference for healthier, i.e. higher quality children (Becker, 1960). A second motive for child expenditure originates from the fact that parents do not aspire a certain number of births ($n$) but a certain family size ($\pi \cdot n$) and that they have have limited control over survival of their infants. In particular, we consider the following form of the child survival function.

$$\pi_t = \bar{\pi}_t + (1 - \bar{\pi}_t) \cdot \lambda \cdot h_t \ . \tag{1}$$

Survival probability in period $t$ consists of an extrinsic and an intrinsic part. The extrinsic part ($\bar{\pi}_t$) is taken as given by the individual parent. It depends on geographic location and the state of economic development (summarized by average income in the economy). The parameter $\lambda > 0$ measures effectivity of individual child expenditure in controlling survival. Strulik (2005, 2007) introduces (1) in greater detail and discusses the empirical evidence.[5] The crucial feature of the survival function is that the marginal effect of child expenditure, $(1 - \bar{\pi})\lambda$, is large at low extrinsic survival rates. In other words, individual expenditure is relative effective in improving child survival in poor economies and at unfavorable geographic locations with a high diversity of disease species. At favorable locations and at high incomes levels, i.e. when the extrinsic survival rate is anyway large, an additional fraction of income spent on child health and nutrition has relatively little effect on child survival. Thus, if it is nevertheless observed, it is mainly driven by the warm glow motive or child quality preferences.

[5]For the role of nutrition expenditure on child survival, see e.g. Dasgupta (1993, Ch. 4), Rice et al., 2000, Pelletier et al., 2003, Caulfield et al., 2004. See McKeown (1976) and Harris (2004) for the role of nutrition in the decline of mortality during England's demographic transition.

Summarizing, preferences are described by the following utility function.

$$\max u_t = \beta_1 \log(c_{1,t} - \bar{c}) + \beta_2 \log(c_{2,t}) + \beta_3 \log(c_{3,t+1}) + \beta_4 \log(\pi_t n_t) + \beta_5 \log(h_t) \ . \tag{2}$$

The Stone-Geary assumption for utility derived from $c_1$ makes the logarithmic form less restrictive than usually. It captures the empirical regularity (see, e.g., Atkeson and Ogaki, 1996) that the intertemporal elasticity of substitution is not tied to one but varies positively with income and food expenditure. The incidence of subsistence consumption, $\bar{c}$, causes parents to want to have larger families and to spent larger shares of income on industrial goods, savings, and children as income moves away from subsistence level. With further rising income, however, income shares converge towards constants.

The price of the agricultural good is normalized to one. Let $p$ denote the price of the industrial good, $y$ labor income measured in agricultural goods, and $r$ the interest rate. A young adult's budget constraint is then given by (3).

$$y_t = c_{1,t} + p_t c_{2,t} + p_{t+1} c_{3,t+1}/(1 + r_{t+1}) + n_t h_t y_t \ . \tag{3}$$

Maximizing (2) subject to (1) and (3) yields a unique interior solution.

$$c_{1,t} = \frac{\beta_1 y_t + (\beta_2 + \beta_3 + \beta_4)\bar{c}}{\phi} \tag{4a}$$

$$p_t c_{2,t} = \frac{\beta_2 (y_t - \bar{c})}{\phi} \tag{4b}$$

$$s_t = \frac{p_{t+1} c_{3,t+1}}{(1 + r_{t+1}) y_t} = \frac{\beta_3 (1 - \bar{c}/y_t)}{\phi} \tag{4c}$$

$$n_t = \frac{\beta_4 \beta_5 \lambda (1 - \bar{\pi}_t)(1 - \bar{c}/y_t)}{\phi(\beta_4 - \beta_5)\bar{\pi}_t} \tag{4d}$$

$$h_t = \frac{(\beta_4 - \beta_5)\bar{\pi}_t}{\beta_5 \lambda (1 - \bar{\pi}_t)} \ , \tag{4e}$$

where $\phi \equiv \sum_{i=1}^{4} \beta_i$, and $s_t$ defines the savings rate. Inspection of (4c) shows that the savings rate rises with income and approaches the constant $\beta_3/\phi$ as income goes to infinity.

Food expenditure of a family is calculated as

$$e(y_t) = c_{1,t} + n_t h_t y_t = \frac{\beta_1 + \beta_4}{\phi} \cdot y + \frac{\beta_2 + \beta_3}{\phi} \cdot \bar{c}. \tag{5}$$

Observe that $e' > 0$ and $\partial(e(y_t)/y_t)/\partial y_t < 0$, i.e. food demand is rising with income but the income share spent on food is decreasing, which constitutes Engel's law.

As argued above the incidence of subsistence consumption causes a (temporary) positive income effect on fertility. When income rises above $\bar{c}$ current consumption becomes less essential and the desire to have children becomes more important for young adults.

$$\frac{\partial n_t}{\partial y_t} = \frac{\beta_4 \beta_5 \lambda (1-\bar{\pi}_t)\bar{c}}{\phi(\beta_4-\beta_5)\bar{\pi}_t y_t^2} > 0 \ . \tag{6}$$

The income elasticity of child demand, $(\partial n_t/\partial y_t) \cdot y_t/n_t = \bar{c}/(y_t - \bar{c})$, is infinite at subsistence level and decreases towards zero as income goes to infinity.

Improving child survival has a counterbalancing effect on fertility and a positive effect on child expenditure.

$$\frac{\partial n_t}{\partial \bar{\pi}_t} = -\frac{\beta_4 \beta_5 \lambda (1-\bar{c}/y_t)}{\phi(\beta_4-\beta_5)\bar{\pi}_t^2} < 0 \tag{7a}$$

$$\frac{\partial h_t}{\partial \bar{\pi}_t} = \frac{\beta_4-\beta_5}{\beta_5 \lambda (1-\bar{\pi}_t)^2} > 0. \tag{7b}$$

For an intuition of the mechanisms behind (7) it is helpful to consider the impact of an increase of extrinsic child survival ($\bar{\pi}$) on for child expenditure through the family-size motive (entering utility with weight $\beta_4$) and through the child quality motive (weight $\beta_5$ attached). Marginal returns ($\partial \pi/\partial h = [1-\bar{\pi}]\lambda$) are lower at higher $\bar{\pi}$ because child expenditure is less effective in preventing death under the improved general survival conditions. Furthermore, marginal utility from child expenditure driven by the wish for a large family ($\partial u/\partial \pi = \beta_4/\pi$) decreases when more children survive anyway. Parents react to this by having less children. Yet, with decreasing fertility the familiar quantity-quality trade-off becomes operative and parents want to spend more on each child according to the child quality-motive.[6]

## 3. Patterns of Development: Income Correlations

While extrinsic survival rates are exogenous to the single parent they are from macroeconomic viewpoint an endogenous function of average income per capita $\bar{y}$ and geographic latitude $\ell$ of the country or region under investigation. Specifically, the survival function is specified as in (8).

$$\bar{\pi} = \bar{\pi}(\bar{y}, \ell) \ , \quad \frac{\partial \bar{\pi}}{\partial \bar{y}} > 0, \quad \frac{\partial \bar{\pi}}{\partial \ell} > 0, \quad \lim_{\bar{y}\to\infty} \frac{\partial \bar{\pi}}{\partial \bar{y}} = 0, \quad \lim_{\bar{y}\to\infty} \bar{\pi} = a < 1 \ . \tag{8}$$

[6] Because the increase of $h$ has a positive feedback effect on family size we have to assume $\beta_4 > \beta_5$ for a consistent solution to exist. In other words, having a family must be more important than child expenditure. This parameter restriction is assumed to hold henceforth.

According to the empirical evidence the generally positive income effect on survival is largest at low levels and vanishes as income goes to infinity, i.e. the extrinsic survival rate approaches a constant smaller than one (see, e.g. Pritchett and Summers, 1996, Kalemli-Ozcan, 2002).

At any given income level some environments are less healthy than others. Simplifying and aggregating we represent this fact as a generally positive impact of latitude on extrinsic survival rates.[7] In particular, we say that country 1, situated at low latitude $\ell = \ell_1$, is unfavorably located relative to country 2 at high latitude, $\ell = \ell_2 > \ell_1$, because $\bar{\pi}(\bar{y}, \ell_1) < \bar{\pi}(\bar{y}, \ell_2)$ for any $\bar{y}$. Country- or region-specific survival rates are not needed in order to derive the proposed theory of industrialization and demographic transition in general, i.e. as global phenomena. They are, however, essential in explaining why both processes are initiated later and proceed at slower pace at unfavorable geographic locations.

Altogether there are four channels through which income affects population growth. Two direct effects operating through fertility and extrinsic survival rates and two indirect effects operating through the impact of extrinsic survival on fertility and on child expenditure and the feedback of the latter on total survival rates. In order to combine their joint impact we use homogeneity of households by setting $\bar{y} = y$ and differentiate the rate of population growth, given by $g_{L,t} := n_t(y_t, \bar{\pi}(y_t)) \cdot \pi(y_t) - 1$, with respect to $y$.

$$\frac{dg_{L,t}}{dy_t} = \frac{\partial n_t}{\partial y_t}\pi_t + \frac{\partial n_t}{\partial \bar{\pi}_t}\frac{\partial \bar{\pi}_t}{\partial y_t}\pi_t + \frac{\partial \pi_t}{\partial y_t} n_t \ . \tag{9}$$

The positive direct income effect on fertility is captured by the first term on the right hand side. The second term reflects the negative indirect effect on fertility though the quality-quantity substitution effect of (7). Mortality effects on population growth are summarized by the positive last term. More children survive because higher income improves extrinsic survival rates and because parents spend more income on child health and nutrition. Inserting (1), (4d), and (4e) and their respective derivatives into (9) the income effect can be expressed as

$$\frac{dg_{L,t}}{dy_t} = \left( \frac{\bar{c}}{y_t(y_t - \bar{c})} - \frac{1}{1 - \bar{\pi}_t}\frac{\partial \bar{\pi}_t}{\partial y_t} \right) n_t \pi_t \ . \tag{10}$$

Family size $(n_t \pi_t)$ is unambiguously positive so that the sign of (10) is determined by the expression in parentheses. This expression is independent from specific utility weights (the

[7] For empirical support see, for example, Bloom and Sachs (1998), McCarthy et al. (2000), Masters and McMillan (2001), Bloom et al. (2001), Conley et al. (2007). For simplicity we neglect a reversal of the survival effect at very high latitudes, i.e. in proximity to the poles.

$\beta$'s) and solely determined by the interplay of subsistence consumption and extrinsic survival rates. The first term is infinitely large at $\bar{c}$ and vanishes quickly with rising income. The second term is positive and particularly large at intermediate values of income when the income effect on survival ($\partial\bar{\pi}_t/\partial y_t$) is still large and amplified by a yet relatively low value of $(1 - \bar{\pi}_t)$. Eventually, the second term also vanishes because of the declining impact of income on extrinsic child survival. Summarizing, we observe an inverted u-shaped pattern of $g_L(y)$. When income is close to $\bar{c}$ the first term is dominating and $dg_L/dy > 0$. Yet, the subsistence effect vanishes quadratically and the second term, capturing the quantity-quality trade-off, becomes dominating so $dg_L/dy < 0$. With further rising income the second term also vanishes eventually and population growth becomes independent from income.

Geographic latitude shifts the inverted u-curve for population growth. For any given income level the *partial* effect of extrinsic child survival on population growth is negative and using (4d) and (7a) we obtain

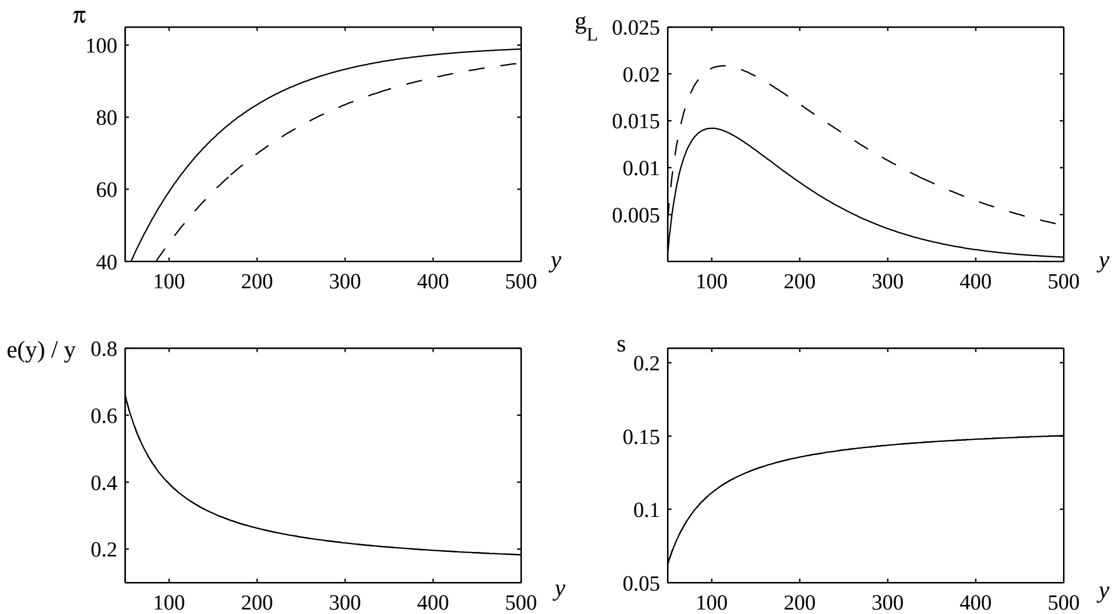
$$\frac{\partial g_L}{\partial \bar{\ell}} = -\frac{n\mu\pi}{1-\mu\bar{\pi}} \cdot \frac{\partial \bar{\pi}}{\partial \ell} < 0. \tag{11}$$

Of two otherwise identical countries or regions, population grows at higher rate for any given level of income in the one of lower latitude.

For a calibration of the model we transform generational growth rates into annual ones. Annual population growth is given by $\gamma_L \equiv (1 + g_L)^{1/\psi} - 1$ where $\psi$ is defined by the length of young adulthood. According to various other numerical experiments we set $\psi$ to the length of the fecundity period estimated to be 25 years. The functional form for (8) is taken from Kalemli-Ozcan's (2002) empirical work as $\bar{\pi} = a \cdot (1 - e^{-b \cdot y})$ implying exponentially declining child mortality at rate $b$.

For the calibration of preference parameters we normalize $\beta_2 = 1$ and set the remaining $\beta$'s such that the household behavior for high income values (for income to infinity) mimics stylized behavior in a fully developed country, i.e. households save (invest) 16 percent of income, spend 12 percent of income per child, spend 13 percent altogether on food, and have 1.05 children (i.e. 2.1 per couple). This renders $\beta_1 = 0.0056$, $\beta_3 = 0.225$, $\beta_4 = 0.177$, $\beta_5 = 0.124$. We calibrate $\lambda$ such that all children survive when income goes to infinity, implying $\lambda = 8.33$. The parameters $a$, $b$ and $\bar{c}$ are calibrated such that the generated inverted u approximates the historical path of the demographic transition in England. The peak of population growth is assumed at a growth rate of 1.4 percent when child survival rates are about 60 percent. Afterwards child survival improves rapidly and converges to 1.[8] At the peak of population growth an adult has 2.4 children, i.e. 4.8 children per couple of adults. This yields $a = 0.7$, $b = 0.0015$, and $\bar{c} = 182$. After deriving the data implied by the model income per capita at the peak of population growth is normalized to 100 for better comparison with real data (in Section 5).

Figure 2: Patterns of Development I: Income Correlations




Parameter values: $\beta_1 = 0.0056$, $\beta_2 = 1$, $\beta_3 = 0.225$, $\beta_4 = 0.177$, $\beta_5 = 0.124$, $\lambda = 8.33$, $\bar{c} = 80$, $a = 0.7$, and $b = 0.0015$ (solid lines) and 0.001 (dashed lines).

Solid lines in Figure 2 show the resulting correlations of variables with income for the benchmark case. With rising income first mortality and then fertility decreases implying an inverted u-shaped pattern of population growth. Food expenditure shares fall monotonously with rising income and savings rates increase. The upper left panel shows the resulting overall income survival according to (1). Dotted lines represent income correlations generated when households with identical preferences are populating an unfavorable geographic location. For that purpose parameter $b$ in the child survival function has been reduced from 0.0015 to 0.001. Population growth is higher at the unfavorable location for all income levels (although country-specific growth rates converge for $y \to \bar{c}$ and $y \to \infty$).

[8]Note that $\pi$ is the probability to survive up to adulthood. According to the data from the Human Mortality Database the survival probability up to age 20 in England and Wales in 1870 was about 0.65 (www.mortality.org). The model thus underpredicts survival somewhat. This could, in principle, be corrected at the expense of overpredicting population growth. For population growth data see Mitchell (1998).

The shift of the population growth curve reflects the above explained effect of extrinsic child survival on fertility. In favorable environments the contribution of child expenditure to survival (the $\beta_4$ component of utility) is less important because nutrition expenditure is relatively ineffective in reducing child mortality. Parents equating the relatively high marginal costs of having another surviving child with marginal utility from family size decide to have relatively few children. Consequently, the "warm glow" contribution (the $\beta_5$ component of utility) has a more pronounced influence. In other words, the quality-quantity trade-off is stronger. Parents in favorable locations have fewer children on each of which they spend more income. This is also visible by the coincidence of solid and dotted line in the lower left panel. Geographic location, i.e. the extrinsic survival rate, does not affect a household's expenditure share for food implying that the expenditure share of food per child is higher for lower fertility rates, i.e. at high latitudes.

## 4. Firms and Macroeconomic Dynamics

The Encyclopedia Britannica (2005) defines the industrial revolution as "the process of change from an agrarian, handicraft economy to one dominated by industry and machine manufacture." We will use a strict mapping of this definition into economic terms and consider a two-sector economy in which land and labor are essential for agriculture and physical capital and labor are essential for modern (industrial) production. The agricultural sector produces food $Y_1$ using labor $L_1$ and land $X$ and a Cobb-Douglas technology.

$$Y_{1,t} = A_{1,t} L_{1,t}^{\alpha} X^{1-\alpha}. \tag{12}$$

Arable land is of limited supply and henceforth normalized to one. Because labor is then the only variable factor of production, agriculture displays the Malthusian feature of decreasing returns to scale. This, however, does not necessarily imply stagnation because general productivity $A_{1,t}$ is allowed to grow at a positive rate $g_{A_1}$, which can be thought of as labor-augmenting as well as land-augmenting technological progress.

The industrial sector produces all other goods, summarized in $Y_{2,t}$, using labor $L_{2,t}$ and capital $K_t$ and a Cobb-Douglas technology with constant returns to scale.

$$Y_{2,t} = (A_{2,t} L_{2,t})^{\epsilon} K_t^{1-\epsilon}. \tag{13}$$

Again, general productivity is allowed to grow at a positive rate, $g_{A_2}$.[9]

All land rents are assumed to go to farm workers so that wages in agriculture are given by the average product of labor. Workers in the industrial sector are paid according to their marginal product. Thus, a young adult who supplies one unit of labor receives income

$$y_t = \frac{Y_{1,t}}{L_{1,t}} = p_t \cdot \epsilon \cdot \frac{Y_{2,t}}{L_{2,t}} = p_t \cdot \epsilon \cdot y_{2,t}. \tag{14}$$

A key variable of structural change is the share of labor allocated to agriculture denoted by $\theta_t \equiv L_{1,t}/L_t$. Given full employment this implies that a labor share $1 - \theta_t$ is allocated to the modern sector. Aggregate food demand of the $L_t$ families populating the economy is $e(y_t) \cdot L_t$ and thus the food market equilibrium fulfils

$$e(y_t) = \frac{Y_{1,t}}{L_t} = \frac{Y_{1,t}}{L_{1,t}} \frac{L_{1,t}}{L_t} = y_t \cdot \theta \quad \Rightarrow \quad \theta(y_t) = \frac{e(y_t)}{y_t}. \tag{15}$$

This establishes a one-to-one correspondence between Engel's law and structural change, $\theta' = \partial(e(y_t)/y_t)/\partial y_t < 0$. If the income share of food decreases by $x$ percent so does the labor share in agriculture.

To prepare dynamic analysis we rewrite $Y_{1,t}/L_{1,t}$ as

$$y_t = A_{1,t} \theta(y_t)^{\alpha-1} L_t^{\alpha-1}. \tag{16}$$

The number of workers, i.e. this period's young adults, is determined by last period's survival rates and the number of last period's young adults and their fertility rates and child expenditure, which were themselves determined by last period's income. Thus the four channels that tie population growth to income explained in connection with (9) and (10) link generational work forces, $L_{t+1} = [g_L(y_t) - 1]L_t$, and their income levels $y_t$ and $y_{t+1}$. To see the latter clearly we define a measure of labor productivity $x \equiv A_1/L^{1-\alpha}$, and rewrite (16) as a two-dimensional dynamical system.

$$y_{t+1} \cdot \theta(y_{t+1})^{1-\alpha} - (1 + g_{A_1}) \left[1 + g_L(y_t)\right]^{\alpha-1} x_t = 0 \tag{17a}$$

$$x_{t+1} = (1 + g_{A_1})(1 + g_L(y_t))^{\alpha-1} x_t \ . \tag{17b}$$

[9] At some cost of tractability we could alternatively assume that technological growth is (partly) endogenously explained by child expenditure as in Strulik (2004). For simplicity, I follow here the majority of related literature on structural change and impose exogenous technological progress.

An equilibrium of stagnation requires $g_L(y) = g_L{}^* = (1 + g_{A_1})^{1/(1-\alpha)} - 1$. Without technological progress in agriculture the equilibrium always exists and is observed together with a constant population. Generally, the equilibrium displays the Malthusian property that higher technological progress enables higher population growth but does not trigger any successful demo-economic development. Temporarily, technological progress yields higher income, which rises fertility (given that income was sufficiently close to subsistence level), which rises next period's labor force ,which depresses income because of decreasing returns to scale until technological progress is counter-balanced by population growth.

Sufficiently strong progress in agriculture, however, eliminates the equilibrium. This is the case when the equilibrium rate of population growth that would offset the positive impact of technological progress on income becomes so high that it is no longer supported by household preferences, i.e., graphically, when the peak of population growth along the inverted-u of demographic transition falls short of $g_L{}^*$. The Appendix contains a proof of existence and local stability of the equilibrium of stagnation.

Theories about structural change can be classified by whether the change is caused by an agricultural push or an industrial pull of workers out of the traditional sector (Matsuyama, 2005). According to the agricultural push hypothesis the industrial revolution has been triggered by a series of innovations in agricultural technology. Johnson (2002), for example, supports the push argument with the estimate that the direct labor input to produce a ton of grain – while staying almost constant for a long time in history – declined by 70 percent in the 19th century. In the present model, agricultural push is the driving mechanism and structural change is initiated when technological progress in agriculture changes from a small rate fulfilling $g_{A_1} < (1 + \max g_L(y))^{1-\alpha} - 1$ to a sufficiently high rate, $g_{A_1} > (1 + \max g_L(y))^{1-\alpha} - 1$, which eliminates the Malthusian equilibrium.

When the equilibrium of stagnation ceases to exist labor income starts to grow perpetually at a positive rate so that the country under investigation undergoes an industrial revolution and a demographic transition, following the paths displayed in Figure 2. With perpetually rising income, survival probability $\bar{\pi}$ converges towards its upper bound $a$. Population growth first increases when the subsistence effect is dominating and, after the quality-quantity effect becomes dominating, decreases with growing income and thus over time. In the long run $gL$ approaches a constant $\bar{g_L}$.

Along the adjustment path food demand is perpetually increasing but its share in total expenditure is decreasing, see (5). Engel's law translates one to one to structural change implying a re-allocation of labor from agriculture to the modern sector, see (15). In the long-run, $\theta$ approaches a low constant from above. From $g_\theta = 0$ we conclude $g_{L_1} = g_{L_2} = g_L$. Furthermore, as income moves away from subsistence level, concerns about future consumption become more important, and the savings rate increases and approaches a constant from below. Taken together the economy approaches a balanced growth path on which population growth, sectoral employment shares, and the savings rate are constant.

## 5. Patterns of Demo-economic Development around the Globe

Consider two otherwise similar stagnant economies at different geographic location. We expect that an increase of the rate of productivity growth is more likely to initiate a demographic transition for the favorably located economy because it displays the lower maximum rate of population growth (recall Figure 2). Also, if a demographic transition is indeed triggered in both economies, we expect that it will take longer for the less favorably located economy where high population growth offsets large parts of the potential impact of productivity growth on growth of income per capita and therewith on the speed of industrialization.

In this section we use the calibrated model to explore how geographic latitude (extrinsic survival rates) shapes the pattern and sets the pace of industrialization and demographic change. In particular we investigate how well the geographic channel established by the present model explains the Great Divergence, i.e. the observable increasing variance of income per capita across the globe. For the following numerical experiments we assume $\alpha = \epsilon = 0.6$, i.e. a capital share of 40 percent in manufacturing and set $g_{A_1} = 0.22$ percent before the onset of demographic transition, which allows for modest population growth at a rate of 0.6 percent and leads to stagnation in the Malthusian equilibrium.[10]

The numerical experiment investigates a set of countries which are identical to the benchmark country (England) in every aspect except latitude (extrinsic survival). Since this is certainly not true, the task cannot be to let the model redraw an as exact as possible evolution of the world

[10]A capital share for manufacturing of 0.4 is standard in numerical calibrations of the neoclassical growth model. The value for $\alpha$, the labor share in agriculture, of 0.6 lies between the value used in similar studies of industrialization in a two-sector model. Voigtlaender and Voth (2006) use a value of 0.4, Gollin et al. (2007) use a value of 0.7 for a traditional technology in agriculture.

income distribution. Instead, the task is to investigate how much of the variation of income across countries can be attributed to the established channel of geographic location.

At a unique point of time a demographic transition and industrialization are initiated by a jump of $g_{A_1}$ to 1.3 percent annually. For better comparison with real data I begin with one run of the benchmark country (defined by $b = 0.0015$, see Figure 2) and normalize time such that this country reaches the peak of population growth in 1870, which was historically true for England (see Mitchell, 1998). From the time series for $y$ and $\theta$ we can infer the time series of GDP per capita, denoted by $z$.

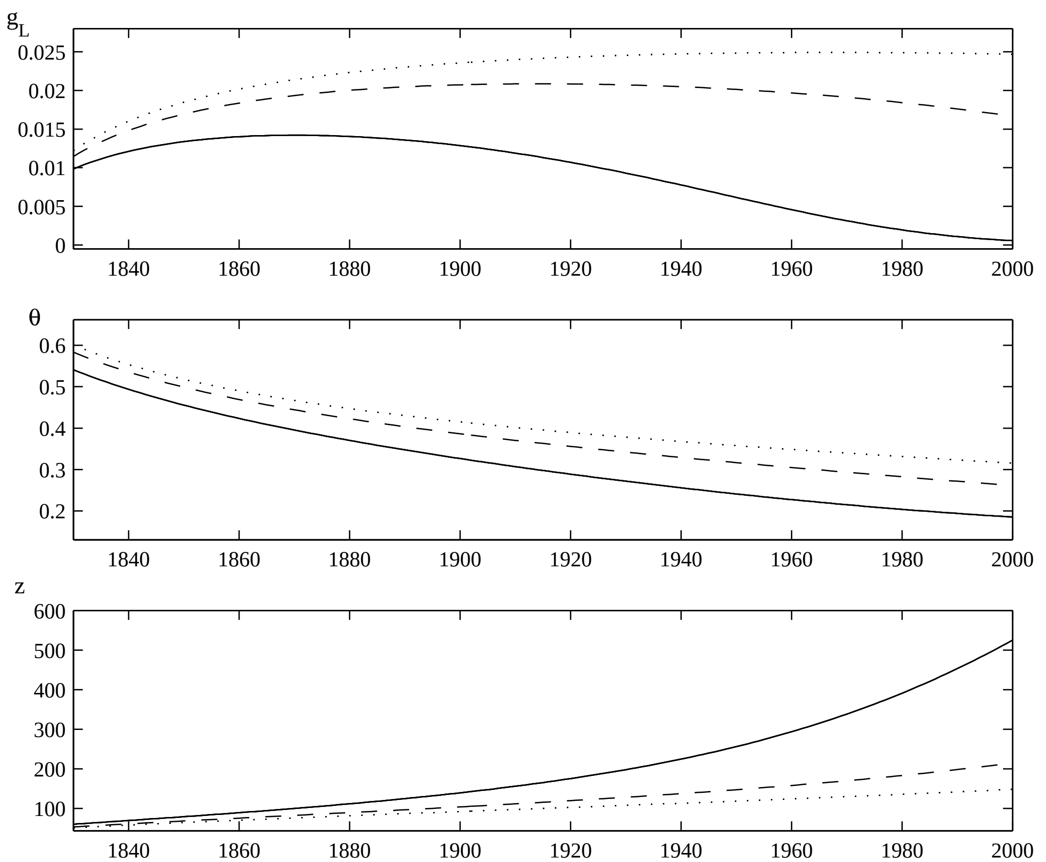
$$z = \frac{Y_{1,t} + p_t Y_{2,t}}{L_t} = y_t \cdot \theta_t + p_t \cdot y_{2,t} \cdot (1 - \theta_t) = [\theta_t + (1 - \theta_t)/\epsilon] \cdot y_t.$$

I normalize GDP of the obtained time series by dividing through $z(1870)$ of the benchmark country and multiplying by 100. The value of $g_{A_1}$ of 1.3 has been chosen such that GDP per capita for the benchmark country in 1990 is approximately fivefold the GDP of 1870 as it has been observed for England (see Maddison, 2001).

The values of $g_{A_1}$ and $\alpha$ imply that the equilibrium of stagnation would be where the annual growth rate of population equals 3.3 percent and I assume that preferences and geographic parameters are such that this equilibrium exists nowhere on the globe. The numerical experiment thus starts out with the assumption that industrialization and demographic change are *initiated* at the same time everywhere around the globe. Again, this was certainly not true historically. The experiment will thus "only" demonstrate how much of the income differences across countries can be explained by the fact that industrialization and demographic transition proceed at a slower pace at low latitudes. This way, the present study compliments otherwise similar experiments that focus on world-wide differing onset of industrialization by assuming an unequal distribution of luck across countries (see Lucas, 2000, Gollin et al., 2007).

Finally, we are left with one degree of freedom, the rate of productivity growth in manufacturing. Because of the agricultural push mechanism, productivity in manufacturing does not affect industrialization and demo-economic change. Yet, it affects prices of industrial goods and real income. Given the mixed empirical evidence on whether productivity grows at higher rates in agriculture or manufacturing and the implicit hypothesis of any one-sector growth model that production of every good is subject to the same rate of TFP growth, we employ the "natural" assumption $g_{A_1} = g_{A_2}$. Equality of sectoral TFP rates has the convenient side-effect that prices of industrial goods vary only moderately along the transition path and are almost constant in the long-run, which accords well with the empirical evidence.[11]

Figure 3: Patterns of Development II: Time Paths




For $g_{A_1} = g_{A_2} = 0.013$, and $\alpha = \epsilon = 0.6$. All other parameters as for Figure 2 (i.e. $b = 0.0015$ for solid and $b = 0.001$ for dashed paths).

Figure 3 shows time paths of population growth, labor share in agriculture, per capita output of agriculture, and GDP per capita induced by the TFP push in agriculture. The evolution of the benchmark country is reflected by solid lines. Higher income through higher agricultural productivity entails lower child mortality, higher relative demand for industrial goods, and the wish for a larger family. It initiates the first phase of demo-economic transition, which is remarkably short. Fertility rises only very moderately initially and begins to decline 5 years after the onset of mortality decline. The observable increase of population growth is thus – according

[11]If population growth converges to zero in the long-run, the assumption of identical TFP growth rates across sectors implies constant relative prices along the balanced growth path. Positive population grows translates into moderately falling relative prices for industrial goods because of decreasing returns to scale in agriculture.

with the empirical evidence for the Western world – mainly driven by falling mortality caused by rising income and increasing expenditure on child nutrition and health. After about 40 years the effect from falling fertility overcompensates the mortality effect and population growth begins to decline. After about 180 years the transition is completed and population growth stabilizes at its low pre-transition rate of 0.2 percent and employment in agriculture settles down at its minimum.

Dashed lines represent demo-economic development of an otherwise equal but less favorably located country, characterized by $b = 0.001$ The lower value of $b$ implies that both mortality and fertility are higher at the pre-transition Malthusian equilibrium (which supports population growth of 0.6 percent). Given the comparative advantage of child-bearing, the positive income effect on net fertility is higher at the unfavorable location. It takes now 12 years until fertility begins to decline and – since child survival rates improve less quickly – 90 years until population growth begins to decline. Furthermore, population growth peaks at a higher rate so that the demographic transition is still under way after 200 years.

Higher population growth depresses economic growth through decreasing returns to scale in agriculture, which feeds back to slower demographic change. Slower growing income also delays structural change. For example, agricultural employment shares of 40 (30) percent are reached by the favorably located country in 45 (90) years after the onset of industrialization and by the less favorably located country after 70 (140) years implying a delay of industrialization by two generations. Summarizing, the less favorably located country shows characteristics of a typical "follower" of the demographic transition: high pre-transition birth and death rates, delayed fertility transition, and high peak of population growth.

A further reduction of $b$ to 0.00075 produces the case of a "latecomer". Dotted lines in Figure 3 show that the time path for population growth is – given a time window of 150 years – indistinguishable from a stalled demographic transition. But there exists no equilibrium of stagnation for this value of $b$. We can analytically verify that also the latecomer will finish a demographic transition eventually. Thus, a discussion of whether the apparently not progressing demo-economic situation in some Sub-Saharan African countries is appropriately described as stabilization at a low-level equilibrium could be misleading. A disequilibrium could equally well characterize a process with no visible movement within a reasonable time frame. High population growth absorbs to a large extent the power of productivity growth and the country does not even double income in a century where the forerunner quintuples its income. Slow income growth leads to slow industrialization which is delayed by about 75 years, i.e. three generations, for the latecomer.[12]

The next numerical experiment helps to check the model's power in explaining the Great Divergence. For that purpose we consider an artificial world consisting of 100 countries which are identical except of their geographic latitude, i.e. extrinsic survival probability. Country specific extrinsic survival is determined by country specific $b \in [0.0016, 0.0005]$. For simplicity, we consider an equal distribution of countries around (latitudes of) the globe, where $b = 0.0005$ is assigned to the country of lowest extrinsic survival rate and $b = 0.0016$ to the country with best survival conditions. All countries are specified as for Figure 3, in particular all face at the same time the same increase of TFP towards 1.3 percent annually. After having collected the time series data from the simulations I divide each time series of GDP by the leader's GDP and multiply it by 100.

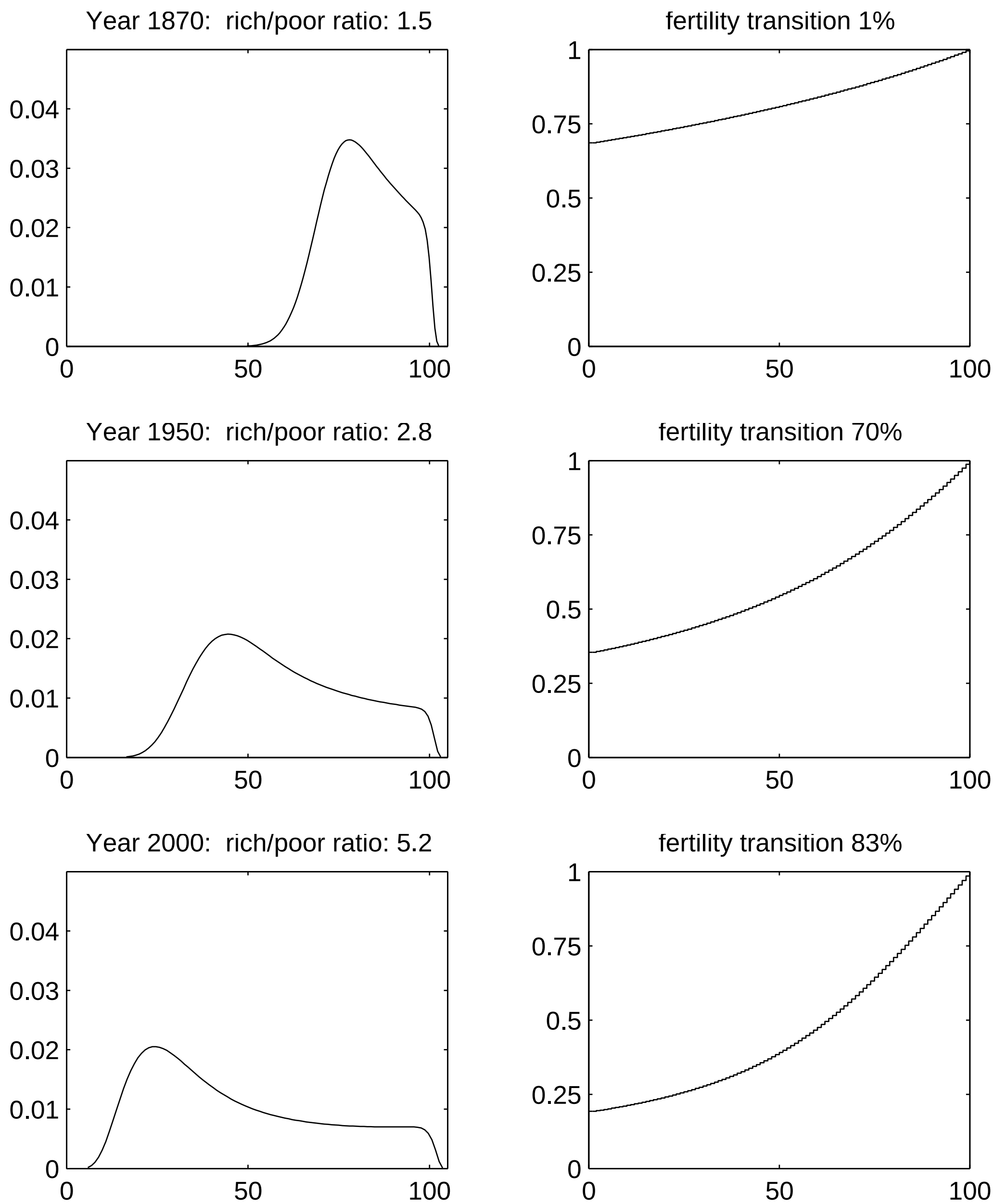
Figure 4 shows three snapshots of the evolution of the word income distribution. The right panels show the empirical cumulated distribution function of GDP per capita and the left panels show the estimated kernel density. I have also counted for each date how many countries have already entered the second phase of demographic transition (where population growth rates are decreasing) and calculated the ratio of GDP for the richest and poorest country of the sample.[13]

At the time when the first country enters its second phase of demographic transition (i.e. in 1870) income is comparatively equally distributed around the globe; the richest country produces 1.5 times the GDP of the poorest country. By 1900, 40% of the countries have initiated their demographic transition, and the rich-poor ratio increased to 1.8 (not shown). In 1950, at the time when followers and trailers enter the second second phase of demographic transition, the majority of countries has less than half the income of the leader. By the year 2000 all countries have initiated the fertility decline but population growth is not yet falling in 17% of the countries. The rich/poor ratio has risen to 5.2 and the density function has become skewed to the left. In the upper half of the distribution income is almost uniformly distributed. This subset of the

[12]See Bloom et al. (2003) and Graham and Temple (2006) for an empirical discussion of poverty traps and multiple equilibria. Bloom et al. conclude that the probability of being in a low-level equilibrium is high for countries at the equator but falls with economic latitude; the high-level equilibrium, however, is independent of geography. It is straightforward to see that this result could also be used as supportive evidence for the current model, where low-latitude countries show inferior performance during transition but all countries converge towards the same balanced growth path.

[13]The complete evolution from 1820 to 2050 on a year to year basis can be downloaded as a movie-file from the author's webpage.

Figure 4: Evolution of the World Income Distribution




Simulation for 100 countries with alternative $b$'s equally distributed in $[.0005, .0016]$. All other parameters as for Figure 2 and Figure 3. The abscissa is indexed by GDP relative to the leader country. The kernel is univariate Gaussian. The *rich/poor ratio* is the GDP ratio between the richest and poorest country; *fertility transition* counts the share of countries that have entered the second phase of demographic transition (characterized by decreasing population growth).

distribution comprises all countries that are developing along (or close to) the balanced growth path yet without catching up to the leader (the model supports only catch up in growth rates but not in levels). In the lower half we find all countries which have not yet managed a successful transition.

Figure 5: World Income Distribution: Evolution of the Log Standard Deviation

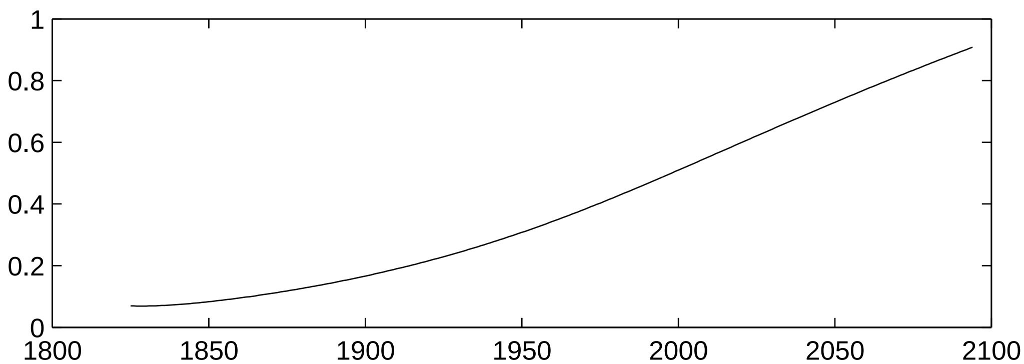



Figure 5 shows how the log standard deviation of income evolves as time proceeds, another indicator of the Great Divergence. It corresponds remarkably well to the left arm of the log standard deviation obtained by Lucas' (2000) experiment. Only here, the result is less optimistic. There is no right arm indicating world-wide convergence of income per capita levels. The present model shares this result with Gollin et al.'s (2007) experiment who also obtain convergence of growth rates but not of levels of income for forerunners and latecomers of the industrial revolution.

Overall, the model tends to overpredict slightly the world-wide speed of demographic transition and to underpredict largely the resulting divergence of income levels (the actual rich-poor ratio was 5:1 in 1870, 15:1 in 1950 and 18:1 in 2000, see Galor, 2005). The model also underpredicts the speed of industrialization for the leader (and other forerunners) and overpredicts the speed for latecomers. Some explanation for these shortcomings could be based on neglected non-linearities. Obviously, the countries of the world are not equally distributed around the globe, the density of countries is higher at low latitudes. For example, 38% of the countries of the world belong to Reher's set of latecomers, on average close to equator, but only 17% of countries belong to the on average temperately located forerunners. Another non-linearity not considered is that extrinsic survival may not be a continuous function of latitude. Instead, there is probably a jump of mortality (and fall of extrinsic survival) at the latitudes where countries becomes lacking of winter frost and where they become tropical and subject to the ambient temperature needed for elsewhere not present pathogenes (Guegan, et al., 2001).

On, the other hand it has already been said, that the model does not claim monocausality. In this respect it is interesting to note that simulation gets the *degree* of the increase of the income wedge about right. The model predicts that from 1870 to 2000 the income wedge increases by factor 3.4 (i.e. 5.2/1.5). Actually it was 3.6 (i.e. 18/5). It is thus mainly the *initial* variance of cross-country income that is underpredicted by the model. In an otherwise similar numerical exercise Gollin et al. (2007) investigate how the unequal distribution of initial endowments of technology can explain the differing onset of industrialization across countries. Both approaches to the Great Divergence, one focussing on initial endowment and onset, the other on geographic location and duration, are thus nicely complementing each other. One advantage of the current approach is that it locates the winners and losers of the income race. The losers are to be found in the tropical zones.

## 6. Related Literature

The literature on unified growth theory and two-sector growth models to which this article contributes has by now become quite large. It is summarized by Galor (2005) and Temple (2005), respectively. Quantitative studies of the industrial revolution understood as structural change are also provided by Harley and Crafts (2000), Stokey (2001), and Voigtlaender and Voth (2006). These studies mainly focus on a very detailed modelling of industrialization in Britain. An interaction of structural change with demographic variables is either not considered or fertility and mortality are not endogenously explained.[14]

The present paper shares with Kögel and Prskawetz (2001), Galor and Mountford (2006), Galor et al. (2006), and Gollin et al. (2002, 2007) the emphasis of an agricultural sector producing a good that serves a particular function, i.e. nutrition. Oded Galor and his coauthors are also contributing to an explanation of the role of geography for the Great Divergence. They propose two different channels, inequality of landownership (Galor et al. 2006) and specialization

[14]Simulation exercises on the economic take-off in the 19th century taking endogenous mortality into account but neglecting structural change are presented by Lagerlöf (2003a,b), Cervelatti and Sunde (2005), and Strulik (2007). Galor and Moav (2005) distinguish also between extrinsic and intrinsic mortality. Intrinsic mortality, however, is subject to evolutionary dynamics and not controlled by nutrition expenditure as in the present paper.

in international trade (Galor and Mountford, 2006), and are thus complementing the disease environment–mortality channel of the present paper.[15]

The present paper could possibly be seen as a refinement and extension of Kögel and Prskawetz's (2001) approach. Food demand is central in their model and industrialization is initiated through an agricultural push, i.e. an exogenous increase of agricultural productivity growth. Productivity growth in manufacturing is driven by endogenous technological progress.[16] In the simple version higher productivity growth leads to higher population growth and there is no demographic transition. The extended version integrates an exogenous decrease of mortality leading to lower fertility based on the precautionary child bearing motive (see Kalemli-Ozcan, 2002, Doepke, 2005). The present model differs in that it investigates endogenous mortality and the role of nutrition and thus by proposing an alternative channel through which mortality affects fertility. Also, Kögel and Prskawetz are not attempting to calibrate their model with real data and are not concerned with world-wide differing patterns of development and the Great Divergence.

The work of Gollin et al. (2002, 2007) shares with the present approach – besides a similar two-sector setup – a calibration with data from the British industrialization and a quantitative exploration of the Great Divergence. The demographic transition and the feedback of population growth to the "food problem" and the speed of industrial transition, however, are not playing a role in their model. Instead, they study a more detailed production side of the economy and ask (in the spirit of Hansen and Prescott, 2002) when the agricultural sector switches to a superior technology. This depends, ceteris paribus, on the initial endowment of technology, which differs across countries. The model could be thus understood as an economic foundation of Lucas' (2000) purely mechanical approach to the dynamics of the world income distribution. Both are emphasizing the role of luck (good initial conditions) on the onset of industrialization whereas the present paper emphasizes the role of geographic location on its pace.

[15] Acemoglu et al. (2001) and Olsson and Hibbs (2005) propose alternative theories on geography's impact on economic performance that are not based on industrialization and demographic change. Landes (1998) and Bloom and Sachs (1998) provide a less formal discussion of the different channels through which climate and geography impact on economic development.

[16] Weisdorf and Strulik (2007) consider endogenous technological progress in both sectors and derive a new channel through which sectoral development drives fertility, the price of food. Geography, mortality, and the world income distribution, however, are not (yet) addressed.

## 7. Final Remarks

This article has offered a theory that explains why fertility and population growth are higher at geographically unfavorable (tropical) locations and how high population growth slows down the pace of economic development and structural change. From a world-wide perspective it contributes to the emerging literature that tries to explain the Great Divergence, i.e. the increasing wedge between rich and poor countries observable since the early and relatively quick industrialization of "forerunner" countries.

While complementing theories generally focus on the role of initial conditions on the onset of industrialization and demographic change the focus here was on the role of geographic location on the duration of these transitions. A crude test of whether it was sheer luck of drawing good initial conditions or whether some (temperate located) countries are luckier than others (tropical located ones) could be to observe whether income is distributed independently from geographic location around the globe. But then, of course, it could be (and is) argued that geography matters *indirectly* for the distribution of growth promoting and growth inhibiting initial endowments, for example via its impact on institutions at colonial times.

The important role of initial conditions on successful development has already been sufficiently acknowledged during the discussion of results. Yet, there exists a mainly empirically lead debate on whether there is a separate role of geography at all, i.e. irrespective of its indirect impact on initial conditions. The current model supports such a direct influence. In fact, since the diversity of the disease environment depends on ambient temperature rather than on country borders (as institutions do), an empirical test of the model with country data is probably misleading.

Recently, Nordhaus (2006) has compiled a data set for economic activities on a fine longitude-latitude grid of the globe and has provided evidence that can be interpreted as largely supportive of the present model. Investigating the association between temperature and output per capita per grid cell, he finds that the highest output is reached at temperatures between 7 and 14$°C$ and is then steeply decreasing by factor 100 from the peak to the regions of highest temperature. Two thirds of this gradient turn out to be independent from country-specific factors. Once the grid data are available on a time series basis, an interesting task for future research will be a more thorough test of geography's impact on the pace of economic and demographic development.

## Appendix: Equilibrium of Stagnation

There exist at most two equilibria $g_L^*$. This follows from the hump-shaped structure of $g_L(y)$. Let the first one where the correlation between $g_L$ and $y$ is positive be denoted by $y^*$ and the let the other one (where $\partial g_L/\partial y < 0$) be denoted by $\tilde{y}$. We ignore the degenerate case of a unique equilibrium at $g_L^* = \max g_L(y)$. Using implicit differentiation we obtain the following elements of the Jacobian matrix $J$ of system (17) evaluated at an equilibrium.

$$\frac{\partial y_{t+1}}{\partial y_t} = -\frac{(1-\alpha)x}{(1+g_L)\left[\theta^{1-\alpha} + (1-\alpha)\theta^{-\alpha} \cdot \theta' \cdot y\right]} \cdot \frac{\partial g_L}{\partial y} \equiv J_1 \tag{A.1}$$

$$\frac{\partial y_{t+1}}{\partial x_t} = \frac{1}{\theta^{1-\alpha} + (1-\alpha)\theta^{-\alpha} \cdot \theta' \cdot y} \equiv J_2 \tag{A.2}$$

$$\frac{\partial x_{t+1}}{\partial y_t} = -(1-\alpha)x(1+g_L)^{-1} \cdot \frac{\partial g_L}{\partial y} \equiv J_3 \tag{A.3}$$

$$\frac{\partial x_{t+1}}{\partial x_t} = 1. \tag{A.4}$$

Conclude from (15)

$$\theta' = \frac{e'y - e}{y^2} = \frac{e'}{y} - \frac{\theta}{y} \quad \Rightarrow \quad \frac{1}{J_2} = \alpha\theta^{1-\alpha} + (1-\alpha)e'\theta^{-\alpha} > 0$$

so that $J_2$ is always positive. Conclude by the same token that $J_1 < 0$ if $\partial g_L/\partial y > 0$ and $J_1 \geq 0$ otherwise.

Local stability requires that both eigenvalues are smaller than one in absolute terms implying $|1+J_1| < (1+J_1) - J_2 J_3$. Because $J_2 > 0$, this necessarily requires $J_3 < 0$ and thus $\partial g_L/\partial y > 0$. Conclude from this that the equilibrium at $\tilde{y}$ is never stable. Because $\partial g_L/\partial y > 0$ the sufficient condition that renders $y^*$ stable is given by $J_2 J_2 < 2 + 2J_1$ or after inserting the elements from (A.1) – (A.4) and equilibrium $x$ obtained from (17):

$$1 + (1-\alpha)\frac{\partial\theta}{\partial y}\frac{y}{\theta} > \frac{(1-\alpha)}{2}\frac{\partial(1+g_L)}{\partial y}\frac{y}{1+g_L}.$$

Thus, the equilibrium $y^*$ is locally stable if the income elasticity of the gross rate of population growth is not too large. Numerical investigation reveals that the condition is not at all restrictive. If the Malthusian equilibrium $y^*$ exists, it is locally stable for any reasonable parameterization of the model.

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