# Industrious Selection: Explaining Five Revolutions and Two Divergences in Eurasian Economic History within a Unified Growth Framework

Chi Pui Ho

4 September 2016

# Industrious Selection: Explaining Five Revolutions and Two Divergences in Eurasian Economic History within a Unified Growth Framework[1*]

HO, CHI PUI

The University of Hong Kong

4 September, 2016

ABSTRACT

We develop a unified growth theory with Industrious Selection to explain the Five Revolutions in the development process (Agricultural Revolution, Structural Transformation, Industrial Revolution, Industrious Revolution, Demographic Revolution) and the Two Divergences in Eurasia (Little Divergence, Great Divergence) in AD0-AD2000. Industrious Selection refers to industrious (hardworking and cooperative) individuals gradually dominating the population composition through labor-leisure optimization and income effect on births. It raises working hours, improves production efficiency and accelerates development. The Black Death expedited Industrious Selection in late-Medieval Europe. Together with the population scale effect, the theory reconciles the British development process and Eurasian economic divergence during AD0-AD2000.

Keywords: Industrious Selection; Eurasian Economic History; Unified Growth Theory

JEL Codes: E1, N1, O5

[*] I wish to thank Yulei Luo, Joseph S.K. Wu, Stephen Y.W. Chiu, Chenggang Xu, Chi-Wa Yuen, Paul S.H. Lau and Fang Yang for helpful discussions, as well as seminar participants at the University of Hong Kong 2016. Financial support from the Hong Kong PhD Fellowship Scheme (PF11-08043) and Sir Edward Youde Memorial Fellowships (for Postgraduate Research Students 2013/14) are gratefully acknowledged.

*"Always there must have been, and always there must continue to be, a survival of the fittest … [A]mong the civilized human races, the equilibration becomes mainly direct".*
*(Herbert Spencer 1864, 468)*

*"[F]rom the war of nature, from famine and death, the most exalted object which we are capable of conceiving, namely, the production of the higher animals, directly follows."*
*(Charles Darwin 1876[1872], 429)*

# 1 INTRODUCTION

Ever since Adam Smith (1994[1776])'s inquiry into the nature and causes of the wealth of nations, how to account for the historical economic development and divergence across nations has always been at the center of the disciplines of politics and economics. This paper puts forward that *Industrious Selection*, a natural selection mechanism originating from human conscious optimization behavior, is a central component to reconcile Eurasian economic history within a unified growth framework.[2] In particular, we develop a unified growth theory with Industrious Selection to explain: (1) how an economy transits from its Malthusian stagnating state to one with sustainable growth, and to reconcile temporally developmental revolutions during the transition process: the Agricultural Revolution, Structural Transformation, the Industrial Revolution, the Industrious Revolution, and the Demographic Revolution; and (2) why there have been divergences in economic performance between Britain and Continental Europe, between the East and the West, and between the North and the South in Eurasia throughout history.

Our research contributes to the literature on unified growth theories. Unified growth theories aim to explain the transition of an economy from Malthusian stagnation, which characterizes most of human history, to one with sustainable growth, which has been observed in developed countries over the past 200 years. Most unified growth theories put emphasis on explaining long-run output and fertility behavior. Two pioneering works are Galor and Weil (2000) and Galor and Moav (2002)'s papers. Galor and Weil (2000) proposed that the inherent positive interaction between population size and technology level in the Malthusian era would accelerate technological progress and permit a takeoff to the Post-Malthusian era. The accelerated technological progress would also raise demand for human capital and ultimately trigger a fertility decline, opening up the Modern Growth era. Galor and Moav (2002) introduced household heterogeneity in preference with regard to child quality versus quantity. Households who care more about child quality would have an evolutionary advantage during the Malthusian era. On the eve of the Industrial Revolution, the composition of this type of households in the population would rise to a sufficiently high level to sustain the pace of technological progress.

A complete unified growth theory should be able to explain the development process from

[2] In this paper, the term "Eurasia" refers to Europe, Asia and Africa. The theory developed in this paper applies to these regions but not to the American landscapes. For the justification and construction of a unified growth theory for the Western Hemisphere (American UGT), see Ho (2016a).

both temporal and spatial perspectives. What are missing in the literature are: first, sequence of developmental revolutions taking place around when the economy breaks out of the Malthusian regime (the sequence is namely the Agricultural Revolution, Structural Transformation, Industrial Revolution, Industrious Revolution, and Demographic Revolution). This paper theorizes how these events are interrelated and sequenced. Second, seldom have unified growth theories been set up to analyze the world economies comparatively. This paper makes up for this aspect and uncovers the origin of economic divergences in Eurasia over the past two millennia.

In the first part of the paper (sections 4-5), we show how a typical nation goes through the *Five Revolutions* (the Agricultural Revolution, Structural Transformation, Industrial Revolution, Industrious Revolution, and Demographic Revolution) in its development process. We construct a unified growth model to grasp the stages of development. The distinctive feature of our model is population heterogeneity: there are two types of individuals – one possesses the "industrious trait", willing to supply more labor hours to the market (hardworking), and being better to solve coordination problems during the production process (cooperative). Assuming the "industrious trait" is perfectly inheritable from parents to children, through consciously working harder, the more industrious individuals earn higher incomes than the less industrious ones; through an income effect on the number of births, the more industrious individuals will have an evolutionary advantage and gradually dominate the population composition (we call this "Industrious Selection"). This will increase average working hours and production efficiency in the nation over time, and in turn expedite its growth and development.

In the early stages of development, population growth dissipates the slow technological progress and renders the economy in a Malthusian Trap. Production is concentrated in the agricultural sector to meet the food demand. Through learning-by-doing, this allows agricultural technological progress to speed up and the Agricultural Revolution to occur first. When agricultural productivity is high enough to feed the population, labor hours can be released from the agricultural sector and Structural Transformation takes place. Over time, intensified production comes along with accelerated productivity growth, triggering per capita income takeoff or the Industrial Revolution. The wage increase during the Industrial Revolution induces households to supply more labor hours and gives rise to the Industrious Revolution. The continuous technological improvement and structural transformation in favor of the manufacturing sector will ultimately raise relative food price (the relative cost of child-rearing), triggering a Demographic Revolution. Industrious Selection accelerates the above development process through evolutionary pressure, expediting the onset of the Five Revolutions. With Industrious Selection, an economy takes off earlier than one devoid of such pressure. We apply the model to simulate the British development process during AD0-AD2500, and illustrate the above mechanisms.

In the second part of the paper (section 6), we turn to the question of the causes of the relative rise and fall of nations. One crucial criticism of Galor and Weil (2000)'s paper is that, given the mechanism they proposed, Industrial Revolution should have first occurred in China, rather than in Britain, given its much larger population size throughout history (Clark 2014, 251). Mokyr (1999) surveyed geographical, historical, technological, social, institutional, political, demand and supply, and trade factors that narrated the causes of the British Industrial Revolution; however, there was no consensus on why the Industrial Revolution first took place in Britain. Our unified growth theory will hold these factors constant, and argue that population composition is key to this issue.[3] We put forward that, on the eve of the British Industrial Revolution, Britain (or Europe) possessed a higher proportion of industrious individuals in her population than China did, and was therefore blessed with higher working hours, production efficiency and faster technological progress. The critical event that gave rise to such a population structure was the Black Death during AD1346-AD1353.[4] The Black Death relatively wiped out the poorer population (that is, the less industrious individuals in our theory), effectively speeding up Industrious Selection in Britain (or Europe). The population composition that was more conducive to growth in Britain (or Europe) accounts for the origin of Little Divergence and Great Divergence (the *Two Divergences*) between the East and the West of Eurasia.

Industrious Selection, together with population scale effect, also explains the closing of the East-West per capita income gap since the late-twentieth century, as well as the evolution of within-Europe and North-South income differences in Eurasia. We conduct theory-based simulations to reconcile the divergence in economic performance among four nations/regions: Britain, Continental Europe, China and Africa over the past two millennia.[5]

We proceed as follows: The next section reviews the relevant literature. Section 3 describes the historical facts related to the Five Revolutions and Two Divergences. Section 4 presents the theoretical model. Section 5 applies the model to Britain and explains how the Five Revolutions arose during its development process. Section 6 extends our analysis to the other parts of Eurasia. We recalibrate the model with the Black Death shock to account for the divergent growth paths among Britain, Continental Europe, China and Africa over the past two millennia. Section 7 highlights some points for discussion. Section 8 concludes.

## 2 RELATED LITERATURE

Our work is related to five bodies of literature. The first set of literature is related to the Industrious Revolution. According to De Vries (1994, 249), "[t]he industrious revolution was a process of household-based resource reallocation that increased both the supply of marketed commodities and labor and the demand for market-supplied goods." In this paper, we focus on the "increased supply of labor" aspect of the Industrious Revolution. In Britain, the (average)

[3] We acknowledge the importance of the factors surveyed by Mokyr (1999) in explaining the British Industrial Revolution. The key insight of this paper is that population size and composition alone are sufficient to qualitatively replicate historical development and divergence patterns throughout Eurasian economic history (section 7.5). To make our model as simple as possible to bring out this insight, we ignore those factors surveyed by Mokyr (1999).

[4] We follow Benedictow (2004) to locate the Black Death in the years AD1346-AD1353. The Black Death arrived at the Golden Horde in AD1346 (60). By AD1353 it had reached most of the lands in Europe (xviii).

[5] In this paper, the term "Continental Europe" refers to the 11 Western European countries, except the United Kingdom, identified by Maddison (2008): Austria, Belgium, Denmark, Finland, France, Germany, Italy, Netherlands, Norway, Sweden and Switzerland. In comparison, the term "Europe" or "the West" refers to Britain and Continental Europe.

labor hours supply generally increased during the Modern Period (section 3.4). Clark (2007, 181) stated that, “work hours were very high in England by 1800 … What exactly the transition to longer work hours took place is hard to establish … It is clear that the transition in England had largely occurred before the onset of the Industrial Revolution. But work hours in medieval England were probably already high by forager standards”. Given such evidence and the proliferation of labor-leisure tradeoff theories in modern macroeconomics (Becker 1965; Kydland and Prescott 1982), it is perhaps surprising that little research has combined the two to explain the onset of the Industrious Revolution.[6] We will address this issue (sections 4 and 5).

The second set of literature is the unified growth theories. Unified growth theories explain how an economy evolves through a three-stage development process: from the Malthusian regime, through the Post-Malthusian regime, to the Modern Growth regime. The literature started with Galor and Weil (2000) and Galor and Moav (2002) (section 1), and has been extended along production and demography fronts. For the production side, Hansen and Prescott (2002), Doepke (2004), Strulik and Weisdorf (2008) and Lagerlöf (2010) investigated unified growth theories with dual sectors: as long as technological progress in the Solow (less land-intensive) sector is fast enough compared to the Malthus (more land-intensive) sector, an economy will eventually break through the stagnating equilibrium where per capita income growth is bounded by the land constraint. For the demography side, features such as child mortality (Lagerlöf 2003a), life expectancy (Cervellati and Sunde 2005), gender gap (Lagerlöf 2003b) and parental altruism (Soares 2005) have been added to the theories.[7] However, in this literature, there was neither consideration for households’ choice on leisure nor comparative analysis to reconcile divergent long-term growth experience across the globe.[8] We will fill these research gaps (sections 4 and 6).

The third body of literature is on how population size and composition affect growth (or income). For population size, Kremer (1993a) suggested that a larger population size drives faster productivity advancement. Whether productivity growth increases proportionately with population depends on whether the market size effect or the effort duplication effect dominates. For population composition, Kremer (1993b) proposed the O-ring production theory to explain income differences across countries: suppose production within a country can be broken down into complementary tasks, where workers’ quality cannot be substituted by quantity within each task. In equilibrium, assortative matching occurs: workers of similar quality are matched together in a country, and countries with better workers’ quality possess higher wages and incomes. Our paper will incorporate Kremer (1993a) and Kremer (1993b)’s formulations in a unified growth model, where population size and composition both affect productivity growth (section 4).

---

[6] One exception is Vollrath (2009)’s work. He proposed a unified growth theory where the Industrious Revolution is a consequence of manufacturing productivity growth.

[7] See Galor (2005, 2010) for surveys on unified growth theories.

[8] For leisure, one exception is Galindev (2011), who assumed leisure has to be in concert with children and goods to yield utility. In contrast to that approach, we model leisure as a component that directly enters household’s utility function (section 4). For divergence, Galor (2010, 3) stated that, the unified growth theory “implies that differences in the timing of the takeoff from stagnation to growth across countries contributed to the divergence in income per capita across the globe”. We will simulate this type of divergence dynamics (section 6).

The fourth body of literature is about structural transformation, which explains changes in production structures that accomplish growth and development. Kongsamut et al. (2001) proposed that, with a nonhomothetic household preference, neutral technological progress shifts production inputs away from a sector with lower income elasticity of demand through the income effect. Ngai and Pissarides (2007) posited that biased technological progress leads to sectoral shifts through the relative price effect. In Ho (2016b), population growth induces factor movements across sectors with different degrees of diminishing returns to labor. These papers assume homogenous households, and hold population growth rate exogenous to focus on different causes of structural transformation. In this paper, we relax these assumptions to examine how the above channels explain demographic-economic development within a model framework with heterogeneous population and endogenous fertility (section 5).[9]

The fifth body of literature employs theory-based simulations to shed light on the development and divergence issues. Related to our work, economists have employed this technique to replicate Galor and Weil (2000) and Galor and Moav (2002)'s three-stage development process (Lagerlöf 2006), to identify why Britain industrialized first (Voigtländer and Voth 2006), to trace out the causes of East-West Little Divergence (Voigtländer and Voth 2013a) and Great Divergence (Gollin et al. 2002, 2007) with different model frameworks. Broadberry (2015) put forward that the Black Death shock, together with the Industrious Revolution in the North Sea area, was one of the causes accounting for the Two Divergences.[10] In this paper, we take up the task of theorizing how the Black Death and labor-leisure tradeoff contributed to the developmental revolutions and economic divergences in Eurasia within a unified model framework (section 6).

## 3 HISTORICAL EVIDENCE

Sections 3.1-3.5 present historical evidence for the evolution of key economic and demographic variables related to the Five Revolutions during British development process.[11] Section 3.6 looks into the Little Divergence and Great Divergence issues.

### *3.1 Agricultural Revolution*

The timing of Agricultural Revolution in Britain is still a much debated topic. Earlier

[9] Another famous mechanism for structural transformation is the capital deepening effect (Acemoglu and Guerrieri 2008): capital deepening in the aggregate economy induces production factors to shift away from sectors with higher capital intensity. This effect does not appear in our theory because we abstract from capital accumulation (section 4).

[10] Broadberry (2015) stated that, there are two key shocks (the Black Death in the mid-fourteenth century and the discovery of new trade routes in the late-fifteenth century) and three key structural factors (the extend of sectoral diversification, the nature of state institutions, and the quality and quantity of labor) that account for divergences in Europe and Asia. Temin (2016, 38) also stated that the Black Death and the European discovery of America are the "big events of economic history".

[11] Britain is chosen among many developed countries because of the rich sources of historical data and estimates available. It was also the first industrializing country; Mokyr (1999, 127) dubbed it the "Holy Land of Industrialism".

views among economic historians dated the British Agricultural Revolution in the late-eighteenth and early-nineteenth centuries (Toynbee 1894, 27; Ernle 1936, 149; Overton 1996, 206), arguing for the rapid growth of land and labor productivity confluent with the British Industrial Revolution. In the recent decades, revisionist historians argued that most of the agricultural productivity growth had occurred by the mid-eighteenth century (Jones 1965; Kerridge 1967, 15; Allen 1999). For example, Allen (2004, 116) stated that, British "agriculture had already revolutionised itself between 1600 and 1750 … In that period, yields, output and labour productivity all increased sharply … The agricultural revolution did not run concurrently with the industrial revolution but rather preceded it".

Figure 1A depicts Allen (2000)'s estimates of agricultural output per worker in England during AD1300-AD1800, and Figure 1B depicts Clark (2002)'s estimates of agricultural productivity in England during AD1500-AD1912. In general agricultural productivity rose from AD1600 onwards, and came to a halt during the late-eighteenth century, and resumed its growth in the nineteenth century.

INSERT FIGURE 1 HERE

## *3.2 Structural Transformation*

This paper focuses on one aspect of structural transformation: the reallocation of labor hours between agricultural and manufacturing sectors. Figure 2 depicts Broadberry et al. (2013) and Clark (2010, 2013a)'s estimates of agricultural labor share in England during AD1381-AD1861. The former showed that agricultural-to-manufacturing transformation has occurred in Britain since the sixteenth century, while the latter indicated that this was the case only after the seventeenth century.

INSERT FIGURE 2 HERE

We will investigate how the income effect (Kongsamut et al. 2001), relative price effect, technology growth effect (Ngai and Pissarides 2007) and population growth effect (Ho 2016b) fostered structural transformation (and other development patterns) in a model with heterogeneous population and endogenous fertility.

## *3.3 Industrial Revolution*

The date of British Industrial Revolution is commonly set between AD1760 and AD1830 (Ashton 1948).[12] The period marked "[f]or the first time in history, the living standards of masses of ordinary people have begun to undergo sustained growth" (Lucas 2002, 109). While the magnitude of the rise in living standard is still being debated, the optimistic and pessimistic parties both agreed that the real wages showed sustainable increases by the AD1820s (Lindert and Williamson 1983; Feinstein 1998; Clark 2005). Figure 3A depicts Feinstein (1998) and Clark (2005)'s real wages estimates during AD1760-AD1870, with the indices being set to 100 in AD1860, to illustrate the above point. From Clark (2010)'s estimates, average per capita income growth rate was 0.29% per annum in AD1760-AD1830.

[12] AD1769 was a hallmark year for British industrialization. In that year three important machines were invented: the Spinning Jenny by James Hargreaves, the Water Frame by Richard Arkwright and the Steam Engine by James Watt.

INSERT FIGURE 3 HERE

One important aspect of the Industrial Revolution is the decisive rise in productivity growth rate that allowed for sustainable per capita income growth.[13] Figure 3B depicts Clark (2010)'s per capita income (solid line) and total factor productivity (dashed line) estimates in England from AD1200 to AD2000. "[T]he upturn in productivity growth rates can be located to the 1780s/1790s", where such growth rates "increased from close to zero to close to 1% per year … within 50 years of 1800 in England" (Clark 2014, 217, 220).

What was the engine of such productivity growth? North (1981, 162) stated that "[l]earning by doing can explain the technology developed during the Industrial Revolution". Similarly, Crafts (1995, 761) stated that during the British Industrial Revolution, "Arrow-like learning by doing was much more important relative to intentional, profit-seeking R&D than in today's world". Our theory predicts that, Industrious Selection and the increase in average working hours intensified production and accelerated learning-by-doing during the Industrial Revolution.

### *3.4 Industrious Revolution*

De Vries (2008, x) placed the Industrious Revolution in AD1650-AD1850. One important aspect of the Industrious Revolution was the increase in (average) labor hours supply (section 2). Figure 4 depicts Allen and Weisdorf (2011)'s annual working days per person estimates in Britain during AD1433-AD1870, and De Vries (2008)'s estimates of female labor-force participation rates in the United Kingdom during AD1955-AD1999. Both variables were generally increasing within their respective time frames, contributing to the increase in labor hours supply.

INSERT FIGURE 4 HERE

Given that most economic variables in Britain were in stasis before the eighteenth century, we hypothesize that the increase in labor hours supply before the eighteenth century occurred as a result of Industrious Selection (demographic selection pressure against the less industrious individuals), rather than as a response to economic signals. Thereafter further increase was mainly a reaction to the substantive wage increase since the Industrial Revolution.

### *3.5 Demographic Revolution*

Fertility declined in Britain during the nineteenth century. Figure 5 depicts the gross reproduction rate and net reproduction rate in England and Wales during AD1541-AD2008.[14] British fertility started its long-run decline in around AD1820.

INSERT FIGURE 5 HERE

---

[13] Before the AD1980s, economic historians tended to consider the British Industrial Revolution as a wide-spread phenomenon and the overall productivity growth rate was high (McCloskey 1981; Feinstein 1981). Crafts (1985), Crafts and Harley (1992), Harley (1999) made downward adjustments to the overall productivity growth rates and argued that the productivity growth was confined to some key manufacturing sectors and agriculture only. See Mokyr (1999) and Clark (2014a) for surveys on the British Industrial Revolution.

[14] Gross reproduction rate is defined as the average number of daughters that would be born to a woman. Net reproduction rate is defined as the average number of daughters that would be born to a woman and survive through her childbearing years.

In the current literature, there are at least five explanations for the fertility decline: decline in mortality (Notestein 1976[1945]), increase in relative child cost (Lindert 1980), increase in female wage (Becker 1991[1981], 140), child quality-quantity tradeoff (Becker 1960), and old-age security hypothesis (Caldwell 1976). The increase-in-relative-child-cost channel is potentially important to explain the British fertility decline during the early-nineteenth century. One key child cost is the food price, the "ultimate check to population" (Malthus 1826, 12).[15] Figure 6 depicts Broadberry et al. (2011)'s estimated price of agriculture goods relative to industry goods in Britain during AD1270-AD1870. In the early-nineteenth century there was a sharp rise in the relative agricultural price. We hypothesize that this raised the relative child cost and triggered the Demographic Revolution.

INSERT FIGURE 6 HERE

We deny mortality decline as a cause of fertility decline in the AD1820s. Figure 7A depicts Chesnais (1992)'s estimates of crude birth rate (solid line) and crude death rate (dashed line) in England and Wales during AD1735-AD1984.[16] Prior to the AD1820s, fertility and mortality were generally moving in opposite directions, rejecting mortality decline as a major cause of fertility decline.

INSERT FIGURE 7 HERE

We also disregard child education investment and the resulting quality-quantity tradeoff as key factors responsible for the British fertility decline in the early-nineteenth century (Galor and Weil 2000; Lagerlöf 2006). Figure 7B depicts Flora (1983)'s estimates of percentage of children aged 5 to 14 who enrolled in primary school in England and Wales during AD1855-AD1914. Although we do not have data for periods prior to AD1855, we conjecture that the enrolment rate had been staying below 10% throughout the first half of the nineteenth century. Hence increasing education investment was likely not to be the primary cause for the British fertility decline in the AD1820s.

### *3.6 Little Divergence and Great Divergence*

"Little Divergence" is the term used to describe the divergent economic performance occurring between northwest Europe and the rest of Europe, as well as between the northwest Europe and the East prior to AD1800. Allen (2001) showed in early Modern European real wages study that between AD1600 and AD1800, England's real wage rose slowly, while real wages of the other European countries declined or stagnated at best. Broadberry and Gupta (2006) found that during the same time frame, the northwest European countries enjoyed higher silver wages than did China and India, which witnessed stagnation similar to the southern, central and eastern parts of Europe.[17] In this paper, we prefer using per capita GDP to illustrate the Little

[15] Malthus (1826, 12) stated that, "[t]he ultimate check to population appears then to be a want of food, arising necessarily from the different ratios according to which population and food increase."

[16] Crude birth rate is defined as the number of births per 1,000 population. Crude death rate is defined as the number of deaths per 1,000 population.

[17] Allen (2001) and Broadberry and Gupta (2006) provided estimates for silver wages of building workers in leading European cities in Britain, Belgium, Netherlands, France, Spain, Italy, Germany, Austria and Poland during the early Modern Period.

Divergence. The left panel in Table 1 displays Maddison (2008)'s per capita GDP estimates for Britain, Continental Europe, China and Africa in AD1, 1000, 1500, 1600, 1700 and 1820: per capita GDP grew faster in Britain than in Continental Europe throughout AD1500-AD1820, while China and Africa were stagnating within the same time frame.

INSERT TABLE 1 HERE

"Great Divergence" refers to the differential growth among nations after AD1800. After AD1800 Western European countries and European offshoots grew sustainably, while other countries in the world either took off at later dates or stagnated. Figure 8 depicts per capita GDP growth paths for some representative countries (Britain, France, Spain, the United States, China, India and Niger) during AD1700-AD2008. European nations and the United States have displayed exponential growth since the nineteenth century, while China and India took off later during the twentieth century, and Niger is still stagnating today.

INSERT FIGURE 8 HERE

After reviewing the historical evidence, we set up the theoretical model in the next section. In sections 5 and 6, we will calibrate the model and simulate the British development process and across-nation divergence pattern in Eurasia that we have documented in this section.

# 4 THE MODEL

Consider a closed overlapping generation economy which continues over infinite discrete time periods, indexed by $t$.[18] Households are heterogeneous, some of which are more hardworking (valuing less for leisure) and at the same time more cooperative (better at solving coordination problems during production process). We lump them together as the "industrious trait". The "industrious trait" is perfectly inherited across generations.[19] There are two sectors in the economy: the agricultural and manufacturing sectors; the former produces food for child-rearing while the latter produces manufacturing goods for adult consumption.

## *4.1 Households*

There are two types of identical households in the economy. Households are indexed by $i$, where $i = 1$ represents the "more industrious individuals", who possess the "industrious trait", and $i = 2$ represents the "less industrious individuals", who do not possess the "industrious trait".

[18] Our model is an extension of Strulik and Weisdorf (2008)'s one, by allowing for household heterogeneity, labor-leisure tradeoff, and coordination problems during the production process. Strulik and Weisdorf (2008) constructed a unified growth theory which could account for Four Revolutions (the Agricultural Revolution, the Industrial Revolution, Structural Transformation and the Demographic Revolution) during a country's development process.

[19] Clark (2008, 186) concluded from regression analysis that "in pre-industrial England economic success was highly hereditable, and that this was mainly because the children of the rich differed genetically or culturally from the general population". We hypothesize the "industrious trait" as one such "highly hereditable" genetic or cultural difference among different types of population. Relatedly, Clark (2013b, 2014b) argued that genetics (biological inheritance of abilities) is the main determinant of social position/economic success.

Let $L_t^1$ and $L_t^2$ be their respective adult population size at time $t$.

Households live for two consecutive time periods: childhood and adulthood. Each child has one parent. We assume a child will be of the same type as his/her parent (perfect inheritability of "industrious trait" from parent to children). Consider a generation-$t$ household. In the first period of his/her life (time $t-1$), as a child he/she does not work and earns no income. He/she consumes one unit of food which is paid for by his/her parent. In the second period of his/her life (time $t$), as an adult he/she is endowed with one unit of time, which is allocated over leisure and market work. He/she then spends the market wage income on manufacturing goods and child-rearing food. For simplicity, we assume that adults have no demand for food.[20]

The preference of a type-$i$, generation-$t$ household is defined over his/her consumption of manufacturing goods $m_t^i$, leisure $l_t^i$ and number of children $n_t^i$ in his/her adulthood (His/her childhood utility is normalized to zero). It is represented by the utility function:

(1) $$u_t^i = \frac{\left(m_t^i\right)^{1-\sigma}}{1-\sigma} + \varphi_i \log l_t^i + \gamma \log n_t^i \ ; \quad \sigma \in (0,1),\ \varphi_2 > \varphi_1 \geq 0,\ \gamma > 0\ ;\ i = 1,2.$$

The two types of households differ in the utility weight $\varphi_i$ they attach to leisure ("hardworkingness"): the more industrious individuals value less for leisure enjoyment, $\varphi_2 > \varphi_1 \geq 0$. The utility function features the "hierarchy of needs" (Strulik and Weisdorf 2008; Vollrath 2009): the parameter restriction $\sigma < 1$ ensures that the elasticity of marginal utility with respect to manufacturing goods is smaller than that with respect to number of children.[21] Intuitively, with such restriction, marginal utility from consuming more manufacturing goods diminishes at a slower rate than the marginal utility from having more children does. So when they become wealthier, households will spend higher fractions of income on manufacturing goods.[22] On the other hand, the parameter restriction $\sigma > 0$ ensures diminishing marginal utility from manufacturing goods consumption.

Continuing the choice problem for the type-$i$, generation-$t$ household, in childhood he/she makes no choice, but just eats and survives. In adulthood he/she faces a budget constraint. If the household supplies an amount of $(1-l_t^i)$ working hours to the market, he/she earns a wage income of $(1-l_t^i)w_t$, where $w_t$ is the wage per working hour at time $t$. The wage income is then divided between purchasing manufacturing goods and child-rearing food. Make the price of manufacturing goods the numéraire for all time periods, and let $p_t$ be the price of food relative to

---

[20] We might also think of this as children storing some of their food for adulthood. Letting adults demand food would not change the qualitative results.

[21] From (1), marginal utility with respect to manufacturing goods $m_t^i$ equals $\left(m_t^i\right)^{-\sigma}$.
Elasticity of marginal utility with respect to manufacturing goods equals $\left|\frac{m_t^i}{\left(m_t^i\right)^{-\sigma}} \cdot \frac{\partial\left(m_t^i\right)^{-\sigma}}{\partial m_t^i}\right| = \sigma < 1$.
Similarly, elasticity of marginal utility with respect to number of children equals 1.

[22] Using later equations/results (2) and (4), for a type-$i$, generation-$t$ household, fraction of income spent on food equals $\frac{p_t n_t^i}{m_t^i + p_t n_t^i} = \frac{\gamma\left(m_t^i\right)^{\sigma}}{m_t^i + \gamma\left(m_t^i\right)^{\sigma}} = \frac{\gamma}{\left(m_t^i\right)^{1-\sigma} + \gamma}$, which is decreasing in $m_t^i$ if and only if $\sigma < 1$. Therefore we restrict $\sigma < 1$ in (1) to match Engel's law (on individual level), which states that a household would spend a lesser fraction of income on food as his/her income rises. Note that we have used a result that manufacturing goods consumption increases with income. See Appendix 3 mechanism 1 for the proof.

manufacturing goods at time $t$. Hence $m_t^i$ and $p_t n_t^i$ are the expenditure spent on manufacturing goods and child-rearing food at time $t$ respectively. Formally, the budget constraint facing the type-$i$, generation-$t$ household in his/her adulthood is:

(2) $$m_t^i + p_t n_t^i = \left(1 - l_t^i\right) w_t \ ; \ i = 1,2.$$

This type-$i$, generation-$t$ household maximizes the utility function (1) subject to the budget constraint (2). This is a concave programming problem subject to a convex budget set and an interior solution is guaranteed. His/her optimal decisions concerning the amount of manufacturing goods to consume $m_t^i$, leisure $l_t^i$ and number of births $n_t^i$ are related by the following two equations:

(3) $$l_t^i = \frac{\varphi_i \left(m_t^i\right)^\sigma}{w_t} \ ; \ i = 1,2 \ ;$$

(4) $$n_t^i = \frac{\gamma \left(m_t^i\right)^\sigma}{p_t} \ ; \ i = 1,2.$$

In equilibrium, the more industrious individuals will supply more hours to market work and earn higher wage incomes than the less industrious ones. Since manufacturing goods and children are both normal goods, the more industrious individuals will consume more manufacturing goods and give more births too. These are summarized in the following proposition:

**Proposition 1: (Household maximization)** **For** $\boldsymbol{\sigma} > 0$ **,** $\boldsymbol{\varphi_2} > \boldsymbol{\varphi_1} \geq \mathbf{0}$ **,** $\boldsymbol{\gamma} > 0$ => $\boldsymbol{m_t^1} > \boldsymbol{m_t^2}$**,** $\boldsymbol{n_t^1} > \boldsymbol{n_t^2}$**, and** $\boldsymbol{l_t^1} < \boldsymbol{l_t^2}$ **for all** $\boldsymbol{t}$**.**

*Proof:* See Appendix 1.

Note from (3) and (4) that both types of households will reduce their leisure enjoyment when market wage rises. Also, they both give less birth when relative food price increases.

## *4.2 Demographic dynamics and Industrious Selection*

Adult populations of the two types of individuals evolve according to:

(5) $$L_{t+1}^1 = n_t^1 L_t^1 \ \text{; and}$$

(6) $$L_{t+1}^2 = n_t^2 L_t^2 \ ,$$

where the initial adult populations of the two types of individuals, $L_1^1$ and $L_1^2$, are taken as given. The total adult population and the gross population growth rate are defined as:

(7) $$L_t \equiv L_t^1 + L_t^2 \ \text{; and}$$

(8) $$1 + g_t^{pop} \equiv \frac{L_{t+1} + L_{t+1} n_{t+1}}{L_t + L_t n_t} \ .$$

Note that $L_t n_t$ represents the number of children in the economy at time $t$.

The aggregate working hours supplied by households, $H_t$, are the sum of working hours supplied by the two types of individuals:

(9) $$H_t = (1 - l_t^1) L_t^1 + (1 - l_t^2) L_t^2 \ .$$

The average leisure and average fertility rate are the population-weighted averages of their counterparts from the two types of individuals:

(10) $$l_t = \frac{L_t^1 l_t^1 + L_t^2 l_t^2}{L_t} \ ;$$

(11) $$n_t = \frac{L_t^1 n_t^1 + L_t^2 n_t^2}{L_t} \ .$$

The above two equations, together with proposition 1, imply that, ceteris paribus, when the proportion of the more industrious individuals (type 1) in population rises, average leisure decreases and average fertility rate increases.

From proposition 1 and population evolution equations (5)-(7), we have the following corollary:

**Corollary 1: (Industrious Selection) The more industrious individuals (type 1) have an evolutionary advantage in terms of population composition, that is, $\frac{L_t^1}{L_t}$ is increasing over time.**

*Proof:* See Appendix 1.

Corollary 1 states our important result of *Industrious Selection*: when individual preferences are characterized by the "hierarchy of needs" utility function (1) with $\sigma > 0$, through labor-leisure optimization the more industrious individuals will earn higher incomes; through income effect on number of births and perfect inheritability of "industrious trait", the more industrious individuals will possess an evolutionary advantage and gradually dominate the population composition.[23] Our theory yields a similar prediction as Darwin's (1958, 120), who stated that, "favourable variations would tend to be preserved, and unfavourable ones to be destroyed" in the struggle for life. Here, Industrious Selection destines that a certain variation of the human species (the more industrious individuals) to survive in the long run.[24] However, it is humans' conscious maximization activity, instead of "struggle for existence in relation to other organic beings or to external conditions" (Darwin 1876[1872], 69), that underlies natural selection in our model. The fittest of the human species is defined by fecundity, the ability to consciously raise the largest number of offspring. This opens up an additional channel of evolution in human society when compared to the animal kingdom.[25] [26]

[23] The prediction from Corollary 1 contrasts with Galor and Moav (2002). In their paper, population heterogeneity originates from individuals possessing different preference on child quality versus child quantity – "high quality" type attaches a higher utility weight to child quality than "high quantity" type does. Galor and Moav (2002) showed that, the "high quality" type has an evolutionary advantage over the "high quantity" type during the Malthusian era, and such an advantage is reversed after the Malthusian pressure relaxes. Their model predicts that the "high quantity" type will dominate the population composition in the long run. In contrast, in our model, the more industrious individuals always have an evolutionary advantage over the less industrious ones, and they will dominate the population composition in the long run.

[24] Clark (2007, 166) stated the emergence of "Modern Man" during the long Malthusian era:

> "*Work hours rose … societies [became] increasingly middle class in their orientation. Thrift, prudence, negotiation, and hard work were becoming values for communities that previously had been spendthrift, impulsive, violent, and leisure loving*".

In our theory, the "Modern Man" will be more industrious (hardworking and cooperative) than the primitive man.

[25] See Herbert Spencer's quote ahead of the Introduction. Relatedly, Becker (1991[1981], 136-137) stated that Darwin's theory loses relevance in human society if we do not take into account parents' conscious investment to increase representation of their children in the next generation. In Galor and Moav (2002), households consciously maximize their utility subject to a survival (subsistence consumption) constraint, which generates evolutionary pressure against individuals owing child quantity-biased preferences in the Malthusian era.

[26] We are aware of the potential conscious states in non-human animals (Boly et al. 2013). However, even this is the case, the channel through which conscious maximization activity generates evolutionary advantage through income effect on number of births is unique and

## 4.3 Production

There are two sectors producing final output in the economy: the agricultural (food) and manufacturing sectors. Labor hours are the sole input in the two sectors. Agricultural production is characterized by stronger diminishing returns to labor hours. Learning-by-doing is the sole engine of technological progress in the two sectors (Arrow 1962; Matsuyama 1992).[27]

### 4.3.1 The Agricultural sector

Agricultural output at time $t$, $Y_t^A$, is given by:

(12) $$Y_t^A = \mu E_t (A_t)^{\varepsilon} (H_t^A)^{\alpha} \ ; \ \mu > 0,\ \varepsilon \in (0,1),\ \alpha \in (0,1) \ ,$$

where $H_t^A$ is labor hours employed by the agricultural sector at time $t$, $E_t > 0$ and $A_t > 0$ are the levels of agricultural efficiency and technology at time $t$, both of which are determined endogenously. The assumption $\alpha \in (0,1)$ assures that agricultural production displays diminishing returns to labor hours.

Technological progress in the agricultural sector arises from learning-by-doing externality:

(13) $$A_{t+1} - A_t = Y_t^A = \mu E_t (A_t)^{\varepsilon} (H_t^A)^{\alpha},$$ where $A_1$ is taken as given.

Here, we assume that the agricultural technological progress has a simple one-to-one relationship with the level of agricultural output. The parameter restriction $\varepsilon \in (0,1)$ entails diminishing returns to learning-by-doing in the agricultural sector. Similar to Kremer (1993a), our learning-by-doing formulation implies that, ceteris paribus, technology growth rate rises with labor input (section 2); however, in our model technology progresses less than proportionately with labor input. This shows one of the channels through which population affects production and growth through a scale effect in our model.[28] [29]

Inspired by Kremer (1993b)'s work on the O-ring production theory (section 2), we hypothesize that the efficiency term $E_t$ takes the O-ring production form:

(14) $$E_t = \left(\prod_{j=1}^{L_t} q_j\right)^{\frac{1}{L_t}} \ ; \ q_j \in (0,1] \ .$$

where $L_t$ is the total adult population at time $t$, $q_j$ is a measure of how well an individual $j$ is at solving coordination problems during production process ("cooperativeness").[30] The more

significant to humans.

[27] As our focus is to explain the onset of the Five Revolutions and Two Divergences over the AD years rather than to explain growth today, we overpass R&D, and indeed focus on learning-by-doing as the sole engine of technological progress in this paper. R&D is an important ingredient to the study of modern economic growth. See Acemoglu (2009) and Aghion and Howitt (2009) for textbook treatments.

[28] Kremer (1993a, 690) and Jones (1995, 520) hypothesized that aggregate technological progress takes the form of $\dot{A} = gA^{\phi}p^{\psi}$, where $A$ is the technology level, $p$ is the population level (or R&D labors in Jones paper), $g$ is the research productivity, $\phi$ and $\psi$ are parameters. In case of $0 < \phi < 1$, $\psi > 0$, the formulation implies population scale effect on technological progress in the short run, but not in the long run. Our model differs from theirs by differentiating between different sectoral technological progresses and distinguishing efficiency and technology terms.

[29] In this paper, when we speak of population size having a "scale effect" on production and growth, we are referring to the population scale effect in the short run, but not in the long run when balanced growth path is attained (proposition 2).

[30] In Kremer (1993b, 571)'s original article, he hypothesized that the output rather than efficiency takes the O-ring production form: $Y = \left(\prod_{i=1}^{n} q_i\right)^{\psi}$, where $Y$ is output, $n$ is the number of tasks (or workers), $q_i$ is the skill of each worker, $\psi$ is a parameter between 0 and $\frac{1}{n}$. The crucial

industrious individuals are more cooperative and we assume $q_j$ to take the form of:

(15) $$q_j = \begin{cases} 1, & \text{if person } j \text{ is a type 1 (more industrious) individual} \\ v < 1, & \text{if person } j \text{ is a type 2 (less industrious) individual} \end{cases} .$$

Hence (14) can be simplified as $E_t = (1)^{\frac{L_t^1}{L_t}}(v)^{\frac{L_t^2}{L_t}} = (v)^{\frac{L_t^2}{L_t}}$. The higher the proportion of the more industrious individuals is, the more efficient the economy is in bringing its agricultural output towards its potential production level. To appreciate this, we consider two simple numerical illustrations. First, suppose each less industrious individual is half as skillful as the more industrious individual at solving coordination problems ($v = 0.5$). If, at time $t$, the population consists of only the more industrious type of individuals, the efficiency of the economy is $(1)^1 \cdot (0.5)^0 = 1$ and hence the agricultural production reaches its potential level: $Y_t^A = \mu(A_t)^\varepsilon (H_t^A)^\alpha$. On the other hand, if half of the population is made up of the less industrious individuals, the efficiency of the economy falls to $(1)^{0.5} \cdot (0.5)^{0.5} \approx 0.71$ and the agricultural production can only reach 0.71 of its potential level in this case. Obviously efficiency increases monotonically with the proportion of the more industrious individuals in the economy. This is how population affects production and growth through a composition effect in our model.

We adopt Weil (2013, 289)'s terminology that productivity is the multiple of efficiency and technology. We denote the term $E_t(A_t)^\varepsilon$ as agricultural productivity at time $t$. Hence the growth rate of agricultural productivity at time $t$ is:

(16) $$g_t^{EA} \equiv \frac{E_{t+1}(A_{t+1})^\varepsilon - E_t(A_t)^\varepsilon}{E_t(A_t)^\varepsilon} = v^{\left(\frac{L_{t+1}^2}{L_{t+1}} - \frac{L_t^2}{L_t}\right)} \left(\frac{A_{t+1}}{A_t}\right)^\varepsilon - 1 .$$

Agricultural productivity rises as agricultural technological progress occurs and as the proportion of the less industrious individuals in population diminishes.

### 4.3.2 The Manufacturing sector

We adopt similar production and technological progress formulations in the manufacturing sector. Manufacturing output at time $t$, $Y_t^M$, is given by:

(17) $$Y_t^M = \delta E_t (M_t)^\phi (H_t^M)^\lambda \;\; ; \; \delta > 0, \; \phi \in (0,1), \; \lambda \in (\alpha, 1] ,$$

where $H_t^M$ is the labor hours employed by the manufacturing sector at time $t$, $E_t$ and $M_t$ are the endogenously determined manufacturing efficiency and technology at time $t$. The assumption $\lambda \in (\alpha, 1]$ implies that manufacturing production also displays diminishing returns to labor hours, but to a lesser degree than agricultural production. For simplicity, we have assumed efficiency in the manufacturing sector to take the same form $E_t$ as it does in the agricultural sector (14)-(15). Hence we can interpret $E_t$ as an economy-wide efficiency term.

Technological progress in the manufacturing sector is again fueled by learning-by-doing externality:

---

feature of this production form is that "the cross derivative of output in the skill of different workers is positive". In other words, there are strong complementarities among workers' tasks. He employed the O-ring production function for output to explain income differences between rich and poor countries today (section 2). Kremer (1993b) implicitly assumed that workers flow freely across countries so that assortative matching occurs. In our model, workers stay in their own country throughout their lifetime, so that heterogeneity in workers' quality exists within a country. We think this fits well into the historical experience of most Eurasian countries.

(18) $M_{t+1} - M_t = Y_t^M = \delta E_t (M_t)^{\phi} (H_t^M)^{\lambda}$, where $M_1$ is taken as given.

There are diminishing returns to learning in the manufacturing sector ($\phi < 1$). Similar to (13), labor hours employed by the manufacturing sector exerts a scale effect on the sector's technological progress.

The manufacturing productivity at time $t$ is defined as $E_t(M_t)^{\phi}$, and the growth rate of manufacturing productivity at time $t$ is:

(19) $$g_t^{EM} \equiv \frac{E_{t+1}(M_{t+1})^{\phi} - E_t(M_t)^{\phi}}{E_t(M_t)^{\phi}} = v^{\left(\frac{L_{t+1}^2}{L_{t+1}} - \frac{L_t^2}{L_t}\right)} \left(\frac{M_{t+1}}{M_t}\right)^{\phi} - 1 \ .$$

Manufacturing productivity increases as manufacturing technological progress occurs and as the proportion of the less industrious individuals in population falls.

To recap: equations (13) and (18) show that population affects production and growth through two channels in our model: one is through the scale effect - a larger aggregate labor hours supply implies that either labor hours employed in the agricultural sector ($H_t^A$) or that in the manufacturing sector ($H_t^M$) increase. This will intensify production and speed up productivity growth in at least one of the sectors. The other channel is through the composition effect - a greater proportion of the more industrious individuals in population will alleviate coordination problems, and thereby improve production efficiency. With learning-by-doing externality, it accelerates productivity growth in both sectors.

#### 4.3.3 The Aggregate final output

The aggregate final output at time $t$, $Y_t$, is given by the sum of values of agricultural output at time $t$, $p_t Y_t^A$, and of manufacturing output at time $t$, $Y_t^M$:

(20) $$Y_t = p_t Y_t^A + Y_t^M \ .$$

Note that the price of manufacturing output is the numéraire in the economy, and $p_t$ is the relative food price at time $t$.

Per capita income at time $t$, $y_t$, is given by:

(21) $$y_t = \frac{Y_t}{L_t + L_t n_t} \ .$$

Per capita income growth rate at time $t$, $g_t^y$, is defined as:

(22) $$g_t^y \equiv \frac{y_{t+1} - y_t}{y_t} \ .$$

### *4.4 Market clearing and wage equalization*

To close our model, we impose three conditions.

#### 4.4.1 Labor market clearing

The first condition is labor market clearing. At each time $t$, the total labor hours employed by the two production sectors equal the aggregate working hours supplied by households:

(23) $$H_t^A + H_t^M = H_t \ .$$

#### 4.4.2 Food market clearing

The second condition is food market clearing. At each time $t$, the demand for food (for child-rearing purpose) equals the supply of food from the agricultural sector, meaning $n_t L_t =$

$\mu E_t(A_t)^{\varepsilon}(H_t^A)^{\alpha}$. We define $\theta_t$ to be the fraction of the economy's working hours devoted to agricultural production (agricultural labor hours share) at time $t$. Manipulating the food market equilibrium condition gives:

(24) $$\theta_t \equiv \frac{H_t^A}{H_t} = \frac{1}{1-l_t}\left[\frac{(L_t)^{1-\alpha} n_t}{\mu E_t(A_t)^{\varepsilon}}\right]^{\frac{1}{\alpha}} .$$

Agricultural labor hours share increases with the population size, average fertility rate and average leisure; it decreases with the economy-wide efficiency term and agricultural technology level.

Similarly, we define $\chi_t$ to be the fraction of the economy's working hours devoted to manufacturing production (manufacturing labor hours share) at time $t$. By (23):

(25) $$\chi_t \equiv \frac{H_t^M}{H_t} = 1 - \theta_t .$$

Manufacturing labor hours share rises if labor hours are released from the agricultural sector.

#### 4.4.3 Wage equalization

The third condition is wage equalization across the two production sectors. We make two assumptions: first, labor hours are completely divisible and are freely mobile across sectors. Second, labor hours are paid according to the average product in the two sectors.[31] At each time $t$, wage equalization implies:

(26) $$w_t = \frac{p_t Y_t^A}{H_t^A} = \frac{Y_t^M}{H_t^M} .$$

The first equality in (26) gives the wage determination equation:

(27) $$w_t = p_t \frac{[\mu E_t(A_t)^{\varepsilon}]^{\frac{1}{\alpha}}}{(n_t L_t)^{\frac{1-\alpha}{\alpha}}} .$$

The second equality in (26) gives the food price determination equation:

(28) $$p_t = \frac{\delta(M_t)^{\phi}}{\mu(A_t)^{\varepsilon}} \cdot \frac{(\theta_t L_t)^{1-\alpha}}{(\chi_t L_t)^{1-\lambda}} .$$

Note that by Walras' law, when all other markets are in equilibrium, the manufacturing goods market will also attain its equilibrium: $Y_t^M = L_t^1 m_t^1 + L_t^2 m_t^2$ .

## *4.5 Equilibrium price and quantities*

The first period of our model is indexed with $t = 1$, and the relevant initial conditions for the economy are given by $\{L_1^1, L_1^2, A_1, M_1\}$. The equilibrium for the economy constitutes sequences of household allocation $\{m_t^1, m_t^2, l_t^1, l_t^2, n_t^1, n_t^2\}_{t=1}^{\infty}$, production variables $\{Y_t^A, Y_t^M, Y_t, y_t\}_{t=1}^{\infty}$, economy-wide efficiency and sectoral technologies $\{E_t, A_{t+1}, M_{t+1}\}_{t=1}^{\infty}$, population variables $\{L_t, L_{t+1}^1, L_{t+1}^2, H_t, l_t, n_t\}_{t=1}^{\infty}$, sectoral inputs $\{H_t^A, H_t^M\}_{t=1}^{\infty}$, sectoral labor hours shares $\{\theta_t, \chi_t\}_{t=1}^{\infty}$, prices $\{w_t, p_t\}_{t=1}^{\infty}$, and growth rates $\left\{g_t^y, g_t^{pop}, g_t^{EA}, g_t^{EM}\right\}_{t=1}^{\infty}$ which satisfy:

(A) Household utility maximization: Given prices, $\left\{m_t^i, l_t^i, n_t^i\right\}$ maximize household utility function (1) subject to budget constraint (2) for both types $i = \{1,2\}$ at time $t$.

(B) Output production: Given efficiency, technology levels, labor hours input in each sector at

[31] This is a type of "share economy" (Drazen and Eckstei 1988, 437), where production incomes are divided among the working force.

time $t$, sectoral outputs $\{Y_t^A, Y_t^M\}$ are obtained by the sectoral production functions (12) and (17). The final output $\{Y_t\}$ is aggregated by (20), given prices. Per capita income $\{y_t\}$ is obtained from (21).

(C) Market clearing conditions: (23) for labor hours; (24) for agricultural goods.

(D) Wage equalization condition: Labor hours move across agricultural and manufacturing sectors until the average product of labor hours in the two sectors are equalized by (26).

(E) Sectoral labor hours shares definitions: (24) and (25).

(F) Population evolution: Population size and composition $\{L_t, L_{t+1}^1, L_{t+1}^2\}_{t=1}^{\infty}$ evolve according to (7), (5), (6), while aggregate working hours, average leisure and average fertility rate $\{H_t, l_t, n_t\}_{t=1}^{\infty}$ evolve according to (9), (10), (11).

(G) Economy-wide efficiency, agricultural and manufacturing technologies $\{E_t, A_{t+1}, M_{t+1}\}_{t=1}^{\infty}$ evolve according to (14)-(15), (13), (18).

(H) Growth rate definitions: (22) for per capita income growth rate, (8) for population growth rate, (16) and (19) for agricultural and manufacturing productivity growth rates.

The resulting system of equations from the above equilibrium conditions (A) to (H) is highly non-linear and is to be solved numerically.

# 5 SIMULATION: DEVELOPMENT AND THE FIVE REVOLUTIONS

## *5.1 Benchmark Simulation: Explaining the Five Revolutions*

In this section, we investigate the long-run development dynamics implied by the model. In particular we explain how Britain transits from its Malthusian state, through the endogenous occurrence of the Five Revolutions, to the Modern Growth state. We consider a model economy which starts in AD0 and ends in AD2500. Each model period corresponds to 20 years, which is about the length of one generation. Following history terminology, we denote "Ancient Period" as the period before AD450; "Medieval Period" as the period AD450-AD1500; "Modern Period" as the period after AD1500.[32]

Table 2 shows the numerical values of benchmark parameters and initial conditions we use in this section. We delay our discussion about parameter calibration to section 6.4.[33] The key to bear for the time being is that parameters in Table 2 allow the model to simulate the onset of British Industrial Revolution and Demographic Revolution in AD1780 and AD1820 respectively. See Table 3. For the occurrence of Industrial Revolution, our criterion is a model-simulated annual per capita income growth rate exceeding 0.29% (section 3.3). For the occurrence of Demographic Revolution, our criterion is the onset of long-run decline in model-simulated average fertility rate (section 3.5).

[32] The Medieval Period began with the fall of Rome in AD476. There have been various demarcations defining the start of the Modern Period: including the collapse of Byzantium in AD1453, the discovery of America by Christopher Columbus in AD1492, and the Renaissance.

[33] In section 6.4, we will calibrate an extended model with the Black Death, to match the timing of Industrial Revolutions and Demographic Revolutions in Britain, Continental Europe, China and Africa. Then we will apply most of the calibrated parameters back to this section, with some minor adjustments.

INSERT TABLE 2, TABLE 3 HERE

Figure 9 (solid lines) depicts the benchmark simulated development paths for (a) log of per capita income $\log y_t$; (b) average fertility rate $n_t$; (c) growth rate of agricultural productivity $g_t^{EA}$; (d) growth rate of manufacturing productivity $g_t^{EM}$; (e) average working hours $(1 - l_t)$; (f) agricultural labor hours share $\theta_t$; (g) relative food price $p_t$; and (h) proportion of the more industrious individuals in population $L_t^1/L_t$. Panels (a)-(c), (e)-(f) aim to display the Five Revolutions, while the others aid our explanation. From panels (a) and (b), the per capital income and population growth paths are consistent with the three-stage development process highlighted by Galor and Weil (2000) and Galor and Moav (2002).[34] The economy was initially in the Malthusian era (AD0-AD1780), when per capita income was stagnating and population grew gradually. Then the economy passed through the Post-Malthusian era (AD1780-AD1820), when per capita income growth and population growth accelerated. From AD1820 onwards, the economy has entered the Modern Growth era, which is featured by sustainable per capita income growth and declining population growth rate.

INSERT FIGURE 9 HERE

Based on Figure 9 (solid lines), we give an account of the British development process. Throughout the Ancient Period to the early Modern Period (AD0-AD1600), the economy was in a stasis state where most of the economic and demographic variables stayed at constant levels. This was because of the low starting levels of population, agricultural and manufacturing productivities, and hence sectoral outputs were small and learning-by-doing was slow (panels (c)-(d)). Population growth dissipated the slow overall productivity growth and so per capita income was confined at a low level (panel (a)). During this epoch, production was concentrated in the agricultural sector to meet the food demand (panel (f)), promoting relatively faster technological progress in agriculture; however (gradual) population growth continuously raised food demand, and guarded against the relative food price drop (panel (g)). The stability of the relative food price (relative cost of child-rearing) kept fertility and population growth rates at modest levels too (panel (b)). Though, one thing that kept on changing during the long Malthusian era was the population composition. By Corollary 1 Industrious Selection kept on relatively removing the less industrious individuals from the population (panel (h)), leading the way to the continuously increasing average working hours within this epoch (panel (e)).[35]

During the late-Malthusian era (AD1600-AD1780), Britain witnessed the unfolding of the *Agricultural Revolution.* Thanks to population growth, Industrious Selection and sectoral concentration in agriculture in earlier periods, the population size, the proportion of the more industrious individuals in population, as well as agricultural technology base had stockpiled to high enough levels. Through learning-by-doing, agricultural technological progress speeded up (panel (c)), to break through stasis and cause a drop in relative food price (panel (g)). This

[34] In the simulation, population growth rate follows qualitatively the same growth paths as average fertility rate, with the peak occurring in AD1820.

[35] Clark and Hamilton (2006) found that, during pre-industrial times, the richest testators left twice as many number of children as the poorest ones did in England. Their result is consistent with our theoretical prediction that the richer ones (the more industrious individuals) would be the more fertile ones in the economy.

reduced the relative cost of child-rearing and raised fertility (panel (b)). Since most of the agricultural productivity growth translated into increases in population growth rate, per capita income sat still at its low Malthusian level (panel (a)), complying with the "Iron Law of Wages" (Ricardo 1821).[36] On the other hand, agricultural productivity was high enough to feed the population in this era, so *Structural Transformation* occurred (equation (24)) and labor hours shifted to the manufacturing sector (panel (f)).[37] Yet manufacturing productivity growth was still slow (panel (d)).

Next Britain came to the Post-Malthusian era (AD1780-AD1820), which started with its Industrial Revolution. To facilitate our explanation, we highlight four internal adjustment mechanisms in the model:[38]

**[Mechanism 1: Income effect]** Ceteris paribus, when wage increases, individual households will raise the number of births and manufacturing goods consumption, as well as the portion of income spent on the latter. If this raises the relative aggregate demand for manufacturing goods, labor hours will shift from the agricultural sector (sector producing goods with higher elasticity of marginal utility) to the manufacturing sector (sector producing goods with lower elasticity of marginal utility).[39]

**[Mechanism 2: Relative price effect]** Ceteris paribus, if relative food price decreases, households will give more births. Labor hours will shift from the manufacturing sector (sector with relative price increase) to the agricultural sector (sector with relative price decrease).

**[Mechanism 3: Technology growth effect]** Ceteris paribus, agricultural technological progress will shift labor hours towards the agricultural sector, while manufacturing technological progress will do the opposite.

**[Mechanism 4: Population growth effect]** Ceteris paribus, an increase in aggregate labor hours supply will shift labor hours from the agricultural sector (sector with stronger diminishing returns to labor hours) to the manufacturing sector (sector with weaker diminishing returns to labor hours).

---

[36] Ricardo (1821, 87-88) stated that the reproductive response of labor to real wage changes would in turn keep real wage at around the long-run natural level:

> "*It is when the market price of labour exceeds its natural price, that the condition of the labourer is flourishing and happy, that he has it in his power to command a greater proportion of the necessaries and enjoyments of life, and therefore to rear a healthy and numerous family. When, however, by the encouragement which high wages give to the increase of population, the number of labourers is increased, wages again fall to their natural price, and indeed from a re-action sometimes fall below it.*"

[37] The simulated agricultural labor hours share began its long-run decline in AD1660.

[38] See Appendix 2 for mathematical proofs of the four mechanisms. Note that we disentangle relative price effect from relative marginal product effects (technology growth effect and population growth effect). This distinguishes from Ngai and Pissarides (2007) and Ho (2016b)'s works. See Ho (2016b) for more details on the relative price effect and relative marginal product effect.

[39] In our model, the direction of labor hours shift caused by the income effect is theoretically ambiguous. To be more precise, with a heterogeneous population, although Engel's law always holds on the individual level, it does not necessarily hold on the aggregate level. This is a more general result than Kongsamut et al. (2001)'s model with a homogeneous population. Numerically, given our parameter values and initial conditions, the simulation result shows that the income effect always induces an agricultural-to-manufacturing structural transformation throughout the British development process. See Appendix 2 Mechanism 2 for more details.

To summarize the four mechanisms, wage increase and relative food price drop will raise fertility. Wage increase, manufacturing productivity growth and aggregate labor hours (or population) growth will shift working hours to the manufacturing sector, while relative food price drop and agricultural productivity growth will do the opposite.

During the Post-Malthusian era, besides witnessing per capita income takeoff, Britain also experienced the Industrious Revolution, while the Agricultural Revolution and Structural Transformation were still underway. Thanks to Structural Transformation, manufacturing technological progress took off (panel (d)) and slowed down the pace of relative food price decline (panel (g)). Through a slower drop in the relative cost of child-rearing, rate of fertility increase decelerated (panel (b)). Some improvement in aggregate productivity could then translate into an increase in per capita income rather than an increase in population, and Britain broke away from the Malthusian Trap (panel (a)), marking the *Industrial Revolution*. Note that the real wage (not shown in Figure 9) also took off.[40] The wage improvement, together with manufacturing technological progress and population expansion, speeded up labor hours shift from the agricultural to the manufacturing sector [Mechanisms 1, 3, 4] (panel (f)), and Britain witnessed mass production of manufacturing goods.[41] The wage takeoff also raised the opportunity cost of leisure, and both types of households responded by supplying more labor hours to the market, triggering the *Industrious Revolution* (panel (e)); households in effect shifted their consumption in the form of leisure to consumption in the form of market-supplied goods.[42] Finally, through learning-by-doing, the aforementioned structural transformation and increase in aggregate labor hours supply further accelerated manufacturing technological progress, generating virtuous cycles of wage growth, structural transformation, labor hours supply increase and manufacturing productivity growth.

In AD1820, the *Demographic Revolution* set in and average fertility rate declined (panel (b)). Since then Britain has entered the Modern Growth era. What triggered the Demographic Revolution was the "ultimate check to population" (Malthus 1826): rise in relative food price (panel (g)). Since the late-Malthusian era, thanks to the labor hours shift towards manufacturing (panel (f)), learning-by-doing in the manufacturing sector had been relatively enhanced (panel (d)). The relatively mass production of manufacturing goods finally pushed up relative food price, reversing the heretofore relative price effect [Mechanism 2] and fertility trend in AD1820.[43]

---

[40] In our simulation, the real wages in terms of both food price and manufacturing goods price took off in around AD1780. This result conforms to Crafts and Mills (2009)'s finding that English real wages were stationary until the end of the eighteenth century. On the other hand, Møller and Sharp (2014) suggested that England might have escaped the Malthusian epoch in the mid-sixteenth century.

[41] The simulated relative food price was declining before AD1820, so the relative price effect, together with agricultural technology growth effect, exerted forces to push labor hours into the agricultural sector before AD1820 [Mechanisms 2, 3].

[42] While being able to explain the Industrious Revolution since the eighteenth century, our model cannot replicate the large increase in working hours during AD1536-AD1578 as shown in Figure 4. The increase in working hours within this time frame was likely caused by the abolishment of 49 holy days in England during AD1536, as a consequence of the Protestant Reformation (De Vries 2008, 88). The abolishment relaxed the maximum working days constraint and the households responded by supplying more labor hours to the market during the sixteenth century.

[43] Broadberry et al. (2015, 193-194) stated that, relative agricultural price rose strongly than ever

During the Modern Growth era (after AD1820), the continuous fertility decline added impetus to the aforementioned virtuous cycles.[44] It further boosted per capita income and wage growth. In terms of structural transformation, the relative price effect now pushed labor hours towards the manufacturing sector. Also, the boosted wage further incentivized households to work more, become richer and spend increasing portions of their income on manufacturing goods. This further promoted production and learning-by-doing in the manufacturing sector. The (enhanced) virtuous cycles allowed Britain to achieve sustainable per capita income growth in the nineteenth and twentieth centuries.

However, the diminishing returns to learning-by-doing destined productivity growth to slow down in the Modern Growth era. Since there exist a lower limit to agricultural labor hours share and an upper limit to working hours supplied per household, the productivity growth originating from structural transformation and increasing average working hours channels will eventually be exhausted. Ultimately, the British economy will converge to a balanced growth path, which is characterized by proposition 2:

**Proposition 2: (Balanced growth path) The balanced growth path (BGP) is defined as a steady state in the economy where the growth rates, sectoral labor hours shares and average working hours are constant, and population composition is dominated by type 1 individuals. Define the value of variable $Z$ in BGP as $(Z)^* \equiv \lim_{t\to\infty} Z_t$, and the growth rate of variable $Z$ in BGP as $(g^Z)^* \equiv \lim_{t\to\infty} \frac{Z_{t+1}-Z_t}{Z_t}$. Given $\alpha+\varepsilon \neq 1$, $\phi \neq 1$, we have**

**(a)** $(E)^* = 1$ .

**(b)** $(g^Z)^* = 0$, $Z = \{m^i, l^i, L^i, m, l, L, A, M, Y^A, Y^M, Y, y, \theta, \chi, w, p\}$, $i = \{1, 2\}$ .

*Proof:* See Appendix 1.

In the balanced growth path, agricultural and manufacturing productions achieve their potential levels. All individual and aggregate variables converge to constant values.[45]

## *5.2 Industrious Selection as development accelerator*

The importance of incorporating Industrious Selection in our model is two-fold. First, it accelerates the development process. Second, such an accelerator property offers an explanation to the historical divergence pattern in Eurasia. We will investigate the second issue in section 6. For the first issue, we perform a counterfactual exercise to examine the accelerator property. Figure 9 (dashed lines) depicts the simulation result by adopting all parameters and initial conditions stated in Table 2, except re-setting $\varphi_2 = 1.3$. When compared to the benchmark

before in the early-nineteenth century. The reasons were that food remained expensive while the price of manufactured goods fell dramatically due to mechanized production methods.

[44] After AD1820, the continuous fertility decline, that originated from the faster manufacturing technological progress, and agricultural-to-manufacturing labor hours shift maintained the rising trend of relative food price (panel (g)). The relative food price rise in turn lowered average fertility [Mechanism 2].

[45] Standing in the twenty-first century, we say "growth is sustainable" in the sense that there is still a long time before per capita income growth would decline to its zero balanced growth path level. From Figure 9 panels (c) and (d), sectoral productivity growth would be still underway by AD2500, while in the balanced growth path these rates would converge to zero (proposition 2). Hence the model economy does not come close to the balanced growth path by AD2500.

economy (solid lines), the population in the counterfactual economy was more homogeneous in the sense that people were "hardworking-alike". Although the population as a whole was more hardworking, the counterfactual economy took off 400 years later than the benchmark economy did (AD2180 versus AD1780)!

The key to the counterfactual economy's later takeoff is that Industrious Selection was weakened when compared to the benchmark economy. In both cases, economy-wide coordination problems were resolved gradually through evolutionary pressure across generations to relatively eliminate the less industrious type of individuals from the population. However, in the counterfactual economy, such evolutionary pressure was weakened because the more industrious individuals had less comparative advantage in gaining composition supremacy during population evolution (panel (h)). Hence the coordination problems became more persistent across generations, and cursed the counterfactual economy with a lagged development towards economic takeoff. In case we set $\varphi_2 = 1.01$, where the Industrious Selection pressure was effectively removed, the economy did not take off before AD2500 (not shown in Figure 9).[46]

Figure 9 also shows that, once the counterfactual economy took off, its per capita income grew at a faster rate than that previously enjoyed by the benchmark economy (panel (a)). Hence our model has the implication that, whether the correlation between population heterogeneity and economic growth is positive depends on the stage of development (whether the economy has taken off from the Malthusian regime). The reason why the counterfactual economy enjoyed a faster economic growth despite its greater population heterogeneity (panel (h)) in around AD2200 is that its population size had stockpiled to a high enough level to permit faster technological progresses in the two sectors (panels (c)-(d)); greater population heterogeneity by itself did not cause faster economic growth.[47]

One last point worth mentioning in our benchmark economy is that, a high proportion of the more industrious individuals in population and a high agricultural technology level are both pre-conditions for the Industrial Revolution to occur. Only when we have sufficiently high efficiency and technology levels in the agricultural sector to produce enough food for the nation, can we release labor hours out of the agricultural to the manufacturing sector, and set stage for manufacturing technological progress that brings along the Industrial Revolution. So what is crucial for a nation's economic takeoff is not just its technology, but also its population.[48]

---

[46] See Appendix 3A for other sensitivity tests related to variation in parameters or initial values in the benchmark model.

[47] In contrast, Ashraf and Galor (2013) put forward that the low (genetic) diversity of native American populations and high diversity of African populations have been detrimental to development, while the intermediate levels of diversity of European and Asian populations have been conducive to development.

[48] North (1981, ch.12) argued that it was the better specified property rights, which increased market size and brought about a more efficient economic organization in Britain, that facilitated the British Industrial Revolution. We agree that institution is also a necessary condition for the Industrial Revolution to occur; but it is not a sufficient condition as demonstrated by Netherlands, which also possessed a well-defined system of property rights, that its Industrial Revolution did not occur before the AD1860s (Mokyr 1999, 2000).

# 6 BLACK DEATH AND THE TWO DIVERGENCES

In this section we investigate the causes of the wealth of nations. From sections 6.1 to 6.5, we focus on exploring the divergence in economic performance among three nations/regions: Britain, Continental Europe and China throughout the history. Denote Britain and Continental Europe as "the West" countries, and China as "the East" country. We will argue, in section 6.1, that the Black Death in late-Medieval Europe was a key event in economic history that contributed to the East-West and within-Europe divergence in the Modern Period. Sections 6.2 and 6.3 further elaborate on this issue. Sections 6.4 and 6.5 are for calibration and simulation. In section 6.6 we add Africa into the picture.

## *6.1 The questions and Black-Death-Origin hypothesis*

Borrowing Clark (2007, 1)'s opening paragraph in *A Farewell to Alms*: "The basic outline of world economic history is surprisingly simple. Indeed it can be summarized in one diagram": Figure 10. It depicts the evolution of log of per capita GDP in Britain, Continental Europe, and China from AD1-AD2008 (we leave Africa for section 6.6).

INSERT FIGURE 10 HERE

Observing Figure 10, the questions pertaining to the Two Divergences in Eurasia include:

**[Question 1: Little Divergence within Europe]** Why was British income level above its Continental European competitors by AD1800?

**[Question 2: Little Divergence between the East and the West]** Why were Britain and Continental Europe's incomes above China's by AD1800?

**[Question 3: Timing of Industrial Revolution]** Why did the Industrial Revolution occur first in Britain, then in Continental Europe, and lastly in China?

**[Question 4: Great Divergence between the East and the West]** Why was there a large per capita income gap between the East and the West during the nineteenth and twentieth centuries?

**[Question 5: British Relative Economic Decline]** Why was there a British relative economic decline in terms of per capita income growth rate when compared to Continental Europe during the late-nineteenth and twentieth centuries?

**[Question 6: Chinese Growth Miracle]** Why is China's economy catching up with the West at a fast rate today?

The particularly challenging question is [Question 3]. To put up the question more saliently, why did the Industrial Revolution take place first in Britain rather than in China (Needham 1969, Lin 1995)? Throughout most of the history China had a larger population size than Britain and a comparable technology level. Figure 11 depicts the relative population sizes and relative technology levels in Britain and China (as well as in Continental Europe and Africa) in AD0 and AD1500.[49] Take AD0 Britain and AD0 China to make a comparison, AD0 China had 74.5 times

[49] Comin et al. (2010, 77) provided historical estimates of average overall technology adoption in Western Europe, China, Indian and Arab. In constructing Figure 11, we assume Britain and Continental Europe shared the same level of technologies, and proxy African technology level to be the same as that in Arab in AD0 and AD1500. On the other hand, we calculate the AD0 and AD1500 relative populations in the four nations/regions based on the AD1 and AD1500 population

more population and about 4% higher technology level than AD0 Britain, why did the Industrial Revolution first occur in the World's Edge with such a tiny population at the outset? Why Britain industrialized first was not coincidental. Any theory aiming to explain the British Industrial Revolution should reconcile it from both the temporal and spatial perspectives. For the temporal dimension, we have shown that the Industrial Revolution emerged as an endogenous event in the British development process in section 5. For the spatial dimension, the British Industrial Revolution should be viewed as part of the inquiry into the causes of the Two Divergences.

INSERT FIGURE 11 HERE

We put forward that the Black Death was the origin of Eurasian divergences. In a nutshell, as depicted in Figure 12, the Black Death brought two developmental impacts to Britain (or Europe). The first was promoting Industrious Selection by wiping out the less industrious population, raising average working hours, economy-wide efficiency and accelerating development (section 5.2). The second was the depopulation that reduced production input, and through slower learning-by-doing it decelerated growth. The dominance and long-run implication of the first impact explains Britain's (or Europe's) developmental lead over China in the post-Black Death era. The more severe Black Death impact on Britain than in Continental Europe also accounts for Britain's pre-industrial wealth supremacy and earlier industrialization. Eventually in the late-nineteenth and twentieth centuries the population size factor dictated, explaining Britain's relative decline and China's growth miracle.

INSERT FIGURE 12 HERE

## *6.2 The Black Death – Historical Perspective*

The Black Death (AD1346-AD1353) has been one of the most severe epidemics outbreaks that have occurred in human history. It ravaged Europe, North Africa, Asia Minor and the Middle East in the mid-fourteenth century. In Europe, it was estimated that between 25% and 60% of the population were killed during the first few years of outbreak.[50]

The outbreak of the Black Death has been considered by some historians as "a turning point in history" (Bowsky 1971). It marked the time division between the High Middle Ages and the late-Medieval Period. Although the Black Death brought along with it mourning pain and deaths in Europe, it also brought forward charming economic and social changes that prepare the European societies to move on to the Modern Period. First, depopulation created labor scarcity and boosted workers' wages, shifting the balance of power from employers to employees, and from landlords to peasants (Phelps Brown and Hopkins 1962; Penn and Dyer 1990; Roseberry 1991, 25). Second, the plagues accelerated the changes in consumption pattern: there were dietary improvements; households shifted their consumption from food to manufacturing goods (Dyer 1988; 1998, 174-175; Voigtländer and Voth 2013a). Third, the increase in labor wages

data from Table 1 in this paper.

[50] Gottfried (1983, xiii) stated that, "The Black Death … devastated the Western world from 1347 to 1351, killing 25%-50% of Europe's population and causing or accelerating marked political, economic, social, and cultural changes". Ziegler (1997[1969], 185) accepted that "a third of the population died of the Black Death". Benedictow (2004, 383) estimated an average death toll of 60% in Europe between AD1346-AD1353. Over a longer time horizon, Herlihy (1997, 17) stated that European population had been reduced by about two-thirds by the AD1420s.

encouraged innovations in labor-saving technologies, such as the replacement of grain farming by animal husbandry, and the adoption of water mills (Gottfried 1983, 138; Barbier 2011, 199). Other aspects such as culture, education, medical science, architecture, religion, art, and even marriage patterns were also influenced by the Black Death (Herlihy 1997, ch.3; Ziegler 1997[1969], ch.16-17; Voigtländer and Voth 2013b). As summarized by Benedictow (2004, 393):

> "*By creating a great deficit of labour [the Black Death] speeded up economic, technological, social and administrative modernization … It also hastened the breakdown of feudal economic structures and mentalities and the rise of a prevailing dynamic capitalist market economy and concomitant innovative and dynamic attitudes and mentalities*."

Complementing Benedictow's claim, we posit that, it was the Black Death that triggered a sweeping change in the overall population's quality: "Survival of the Industrious" (hardworking and cooperative people).[51] This in turn cultivated technological and economic development in Europe. The Black Death is hence "a turning point in history" in the sense that it accelerated development process in the West relative to the East, resulting in the Western countries dominating the world in terms of their economic powers in the following few centuries.

Our theoretical argument will rely on the assumption that the poor people were more vulnerable to the Black Death than the rich people did (section 6.3). Benedictow (2004, 262, 266) stated two reasons why this was true: "Firstly, poor people lived in far more unhygienic environments … which increased their exposure to rat fleas; secondly, in pre-plague society, many poor and destitute people may have had their physiological resistance to disease (immunity) significantly impaired or weakened by long-term undernutrition or malnutrition"; data indicated that "the mortality among the poor and destitute was 5-6 percentage points higher than the mortality among the better-off social classes". Similarly, Herlihy (1997, 55-56) noted that medieval observers generally agreed that the poor were "much more susceptible" to plague inflection than the rich. Some even claimed that "the Black Death of 1348 wiped out the poor completely."[52] Byrne (2012, 243, 288) also stated that: "Plague epidemics seemed to begin among the poor and to strike them the hardest … As the 14th century produced one more plague outbreak after another, authorities came to conclude a direct correlation between poverty and the disease."

## *6.3 Unified Growth Theory with Black Death Shock: Explaining the Two Divergences*

In this subsection, we incorporate the Black Death shock in our unified growth model (section 4) and explain how the Black Death gave rise to the Two Divergences in Eurasia. We assume that the Black Death was more deadly to the poorer individuals than to the richer individuals (see section 6.2 for evidence). In our model, from proposition 1, the less industrious

[51] See Charles Darwin's quote ahead of the Introduction.
[52] The difference in mortality rates between the rich and the poor depends on how the rich and the poor were defined. But their qualitative implications are the same: the poor were more susceptible to the Black Death than the rich.

(type 2) individuals would be the poorer group and so more susceptible to the Black Death.

**[Unified growth model with Black Death shock]**

- We model the Black Death as an exogenous decrease in population.
- When the Black Death shock arrives, the population reduction starts within the type 2 individuals group.
- Only when 99% of type 2 individuals are exhausted, will there be loss of type 1 individuals as a result of the plague.

Why was the Black Death the origin of the East-West divergence? The outbreak of the Black Death (AD1346-AD1353), and possibly with the plague recurrences continuing into the mid-seventeenth century, brought two favorable effects to Britain and Continental Europe.[53] The first was the direct impact on per capita income during the plague years. Depopulation caused labor scarcity and pushed up wages, also the surviving population was more industrious as a whole and the average working hours increased.[54] The rises in wages and working hours boosted per capita income in the West during the plague years.[55]

The second favorable effect of the plagues was to expedite Industrious Selection during the plague years. The plagues provided developmental impetuses by relatively eliminating the portion of population with traits unfavorable for economic growth (the less industrious individuals, who were less hardworking and cooperative), raising working hours, production efficiency and accelerating development. This effect dominated the population scale effect on production and growth, so that Britain and Continental Europe enjoyed faster economic progress than China during the plague years (Figure 12).[56]

The second favorable effect also explains why Britain and Continental Europe could sustain higher per capita income levels than China even after the Black Death (and plague recurrences) faded away. By the time the Black Death (and plague recurrences) reached an end, Britain and Continental Europe had acquired population compositions that were more conducive to production and growth. Hence over the Modern Period the Little Divergence, Industrial Revolution and Great Divergence worked in Britain and Continental Europe's favor over China.[57]

---

[53] In Britain and Continental Europe, the plagues have repeatedly returned: in AD1361-AD1362, the plague killed 10%-20% of people; from AD1369-AD1480 the plagues recurred every 5-12 years, killing 5%-15% of the population; further outbreaks occurred in Britain in AD1499, AD1509-AD1510, AD1516-AD1517, AD1527-AD1530, AD1544-AD1546, AD1557-AD1559, AD1587-AD1588, AD1592-AD1593, AD1596-AD1598, AD1603-AD1604, AD1624-AD1626, AD1638-AD1639, AD1643-AD1644, AD1657-AD1659, AD1665-AD1666 (Gottfried 1983, ch.7; Slack 1985, 58).

[54] The rise in working hours is consistent with Hatcher (1994, 28)'s view that, "[i]t is far more likely that although labourers and smallholders were refusing to accept all the work they were offered they were on average spending more time, not less, in employment than their predecessors had been able to". Similarly, Epstein (2000, 57) stated that, "the Black Death reduced the proportion of un- or under-employed in the population and increased labour participation".

[55] The wage increase together with "Survival of the Industrious" might also answer Clark (2007, 181)'s question on why England had high working hours by AD1800 (section 2).

[56] Broadberry et al. (2015, Table 10.02) provided per capita GDP estimates in England, Netherlands, Italy, Spain and China in AD1400. The former three countries had overtaken China by AD1400.

[57] China's per capita GDP relative to Western Europe's had been continuously declining from

On the issue of within-Europe divergence prior to the late-nineteenth century, why did Britain have an edge over its Continental European competitors? The Black Death is again the key. Table 4 shows the population estimates of Britain (England and Wales) and other parts of Europe in AD1300 and AD1400. Britain suffered more from the Black Death in terms of the depopulation percentage when compared to other parts of Europe. There was a population loss of $1-\frac{3{,}000}{5{,}750}\approx 48\%$ in Britain compared to $1-\frac{64{,}950}{88{,}450}\approx 27\%$ in other parts of Europe during AD1300-AD1400. We assume the 27% death rate in other parts of Europe applied to Continental Europe being defined in this paper. The more deadly plagues in Britain than in Continental Europe relatively accelerated Industrious Selection in the former. By the same mechanism described in the previous paragraphs, this led Britain to enjoy a superior pre-industrial per capita income growth path and an earlier industrialization than Continental Europe.

INSERT TABLE 4 HERE

## 6.4 *Calibration*

Next, we calibrate the unified growth model with Black Death shock. Similar to section 5, we consider a model economy which starts in AD0 and ends in AD2500. Each model period corresponds to 20 years. Table 5 shows the numerical values of (baseline) parameters and initial conditions we use in this section.

INSERT TABLE 5 HERE

For the sectoral production functions, we follow Strulik and Weisdorf (2008) in setting $\mu=0.5,\ \alpha=0.8,\ \phi=0.3,\ \lambda=0.931.$[58] We let $\sigma=0.01$ to approximate quasi-linear utility function. Such a small $\sigma$ value ensures that Industrious Selection progresses at a slow pace without demographic shocks (Corollary 1).[59] Next, we set parameter values that allow the model to simulate the timings of Industrial Revolutions and Demographic Revolutions as listed in Table 6.[60] For Britain, we set $\varphi_1=1.05,\ \varphi_2=1.65,\ \gamma=4.95,\ \varepsilon=0.456,\ \delta=2,\ v=0.3225,$ $A_1=11.95$ and $M_1=150$. To fit into AD0 technology comparison in Figure 11, for Continental Europe, we set $A_1$ and $M_1$ to take the same values as those in Britain. For China, we set $A_1$ and $M_1$ at $\frac{1}{0.96}$ times those in Britain. To fit into AD0 population comparison, we set initial Chinese type 1 and type 2 population to be $0.003$ and $0.007$ respectively, and divide them by $74.5$ and $3.35$ respectively to obtain the British and Continental European AD0 counterparts.

---

77.5% in AD1500 to the all-time low 7.3% in AD1973, rebounding rapidly thereafter (Brandt et al. 2014, Table 1).

58 In Strulik and Weisdorf (2008)'s paper, they set $\lambda=0.95$. We adjust $\lambda$ to a slightly smaller value in this paper for a purely technical reason: to guarantee Matlab to solve for real solution paths throughout the simulation periods.

59 Note that when $\sigma=0$, Industrious Selection will be shut down because the more industrious individuals will choose the same number of births as the less industrious ones.

60 Our calibration relies on manually adjusting parameters in Table 5 to match the timing constraints in Table 6, rather than on micro-evidence from consumption/production data in specific (short) time periods. Another constraint we face is that Matlab cannot always solve for real solution paths, given the complexity of the equilibrium equation system.

INSERT TABLE 6 HERE

We explain our timing choices in Table 6. Maddison (2008) provided per capita income estimates in Western Europe on a yearly basis since AD1870, when sustainable growth occurred. We take AD1860 as the onset year of the Industrial Revolution in Continental Europe. From Maddison (2008), China and Africa have undergone sustainable per capita income growth on yearly basis since AD1950 and AD1994 respectively. We take AD1960 and AD2000 as the years of Industrial Revolutions in the two nations/regions respectively. Chesnais (1992, 133) showed that fertility transition (birth rate dropping from 30 per 1,000 to 20 per 1,000) occurred in Sweden, Switzerland, Belgium, Demark, Norway, Netherlands, Germany, Austria and Finland within AD1880 to AD1920. We take AD1900 as the year of Demographic Revolution in Continental Europe. For China, we take AD1980 as the time of Chinese Demographic Revolution.[61] For Africa, Maddison (2008) showed that African population growth rate stayed fairly stable within AD1990-AD2008, and it dropped in AD2009. We simply presume AD2020 as the year when Africa will go through its Demographic Revolution.

For calibrating the effects of the Black Death on European populations, we assume for simplicity that all such effects were concentrated in one model period: AD1340-AD1359. We adjust the mortality rates for type 1 and type 2 individuals during AD1340-AD1359 in the model to match the aggregate death rates during the fourteenth century implied by Table 4. In Britain, under our model simulation, in the period prior to the Black Death (AD1320-AD1339) there would be 52% of type 1 individuals and 48% of type 2 individuals within the population. We set the Black Death to kill off 0.9% of type 1 individuals and 99% of type 2 individuals, to yield $1-[0.52\times(1-0.009)+0.48\times(1-0.99)]\approx 48\%$ aggregate death rate during the model period AD1340-AD1359, to match what we computed in section 6.3.[62] Similarly, in Continental Europe, by AD1340 the model simulates 53% of type 1 individuals and 47% of type 2 individuals within the population. We set zero mortality rate for type 1 individuals and 57% mortality rate for type 2 individuals to yield $1-[0.53\times(1-0)+0.47\times(1-0.57)]\approx 27\%$ aggregate death rate during the model period AD1340-AD1359, to match our computed value in section 6.3.

We make a note for the calibration in section 5.1. We did not have Black Death shock there. So in that section we adjust $\varphi_1 = 1,\ \sigma = 0.02296$ so that Britain would industrialize in AD1780, and British Demographic Revolution would occur in AD1820.

### *6.5 Simulation: Eurasian Economic History*

We employ the calibrated model to simulate the divergences among Britain, Continental Europe and China in AD0-AD2500. Figure 13 depicts the development paths for the same set of variables we considered in Figure 9; the solid lines are for Britain, while the dashed and dotted lines are for Continental Europe and China respectively. In panel (a), we replicate the patterns

[61] The total fertility rate in China fell from 5.7 per woman in AD1970 to 2.8 per woman in AD1979. By international standard China had by and large completed the fertility transition, in the absence of the one-child policy, by the late-AD1970s (Wang and Mason 2008, 138).

[62] We use the formula:

$$\text{Aggregate death rate} = 1-\begin{bmatrix} Type1\ pop.\%\ \times(1-Type1\ mortality\ rate) \\ +\ Type2\ pop.\%\ \times(1-Type2\ mortality\ rate)\end{bmatrix}.$$

pertaining to the Two Divergences we highlighted in [Question 1]-[Question 6] (or Figure 10) in section 6.1.

INSERT FIGURE 13 HERE

We can understand basic Eurasian economic history from analyzing Figure 13 (and Figure 14 to follow). The population scale effect and the population composition effect will be crucial to explain the relative rise and fall of nations. Prior to the Black Death, all the three nations/regions were stuck in low-income Malthusian Traps (panel (a)). The slow technological progresses impeded significant advancements in per capita income. In fact, thanks to its initial larger population size and more advanced technology levels, China had an advantage over Britain and Continental Europe in terms of production and technological progress prior to the Black Death, making it the wealthiest nation in most of the time prior to AD1340 (however, the differences in wealth prior to AD1340 are too small to be observed in Figure 13, panel (a)).

The outbreak of the *Black Death* during the mid-fourteenth century was the "turning point in history" when the West made significant economic progress relative to the East. In addition to the current literature, we argue that it was the "Survival of the Industrious" (relative depopulation of the less industrious individuals) that led to the rise of Europe, especially Britain, in the early Modern Period.[63] The immediate impact of the Black Death was raising wage and average working hours (panel (e)), leading to higher per capita incomes in Britain and Continental Europe (panel (a)). Within AD1340-AD1800, Britain and Continental Europe also benefited from possessing higher proportions of the more industrious individuals in population (panel (h)), and therefore they enjoyed higher production efficiencies and faster technological progresses than China did (panel (c) and (d)). Although the Iron Law of Wages was still operative in early Modern Europe, such faster technological progresses allowed Britain and Continental Europe to sit at the high-income Malthusian Traps when compared to China's low-income one (panel (a)). Hence the *Little Divergence* between the East and the West emerged. The above discussion answers [Question 2] in section 6.1.

Next, for the British exceptionalism, the origin was the stronger Black Death impact on the British population composition than on Continental Europe's, while there was no Black Death in China. Such an order of impact relatively expedited Industrious Selection in Britain than in Continental Europe, in Continental Europe than in China. Hence after the Black Death Britain possessed the highest proportion of industrious individuals in population among the three nations/regions.[64] This gave Britain an upper hand in terms of production and growth, and it turned into the richest country during the Little Divergence era. As observed from panels (a) to (f) in Figure 13, Britain underwent the Five Revolutions at earlier dates than Continental Europe

[63] Various hypotheses have been proposed to explain the Little Divergence, including institutional difference (North and Thomas 1973), geography (Diamond 1997), access to Atlantic trade (Acemoglu et al. 2005), advanced skill formation (Baten and van Zanden 2008), European Marriage Pattern (Voigtlander and Voth 2009, 2013b), disease spread through trade and war (Voigtlander and Voth 2009, 2013a, 2013c).

[64] Allen and Weisdorf (2011, Table 2) and Malanima (2011, Table A1.3) provided annual working days per person estimates in Britain and in Italy respectively. Throughout AD1433-AD1800, Britain's working days rose from 165 to 320-343; throughout AD1450-AD1800, Italy's working days rose from 136 to 210. British labor worked more days per year than Italian labor in the post-Black Death era.

and China did. Britain industrialized in AD1780, breaking away from its Malthusian Trap and further exaggerating the within-Europe and Anglo-Chinese per capita income gaps in the early-nineteenth century. These answer [Question 1] and [Question 3] in section 6.1.

Following Britain, Continental Europe took off in AD1860. In the century that follows, Britain and Continental Europe's per capita income kept on growing while China was still stagnating, leading to the *Great Divergence* between the East and the West.[65] Since the late-nineteenth century, there has been a relative economic decline in Britain when compared to Continental Europe - per capita income grew faster in Continental Europe than in Britain (panel (a)). This was because the scale effect on production and growth originating from the larger population size in Continental Europe dominated the population composition effect. The above answers [Question 4] and [Question 5] in section 6.1.[66]

For China, in AD1960, the country finally accumulated enough agricultural and manufacturing technologies, as well as a sufficiently high proportion of the more industrious individuals in population that permitted its takeoff from the Malthusian regime. Similar to Continental Europe's case during the British relative economic decline, China has benefited from its large population size and has enjoyed fast per capita income growth since its takeoff, rapidly narrowing the Great Divergence gap between the East and the West. This answers [Question 6] in section 6.1.[67] Our model predicts that the fast per capita income growth in China today is sustainable, and China will overtake Britain and Continental Europe eventually. The East will ultimately regain its economic supremacy over the West due to its larger production scale.[68]

### *6.6 Adding Africa into the picture*

In this subsection, we add Africa into the picture of Eurasian economic history. The main

[65] Before the emergence of the Great Divergence literature (Pomeranz 2000; Galor and Mountford 2006, 2008), growth economists mainly focused on modeling mechanisms of modern economic growth (Solow 1956; Romer 1986; Lucas 1988; Romer 1990; Aghion and Howitt 1992; Jones 1995), or on tracing growth determinants from empirical analysis (Barro 1991; Mankiw et al. 1992; Young 1995; Hall and Jones 1999; Acemoglu et al. 2001).

[66] See Broadberry and Crafts (2003) and Crafts (2012) for other explanations for the British relative economic decline. The former stated that the inability to transfer labor out of the agricultural sector, poor at implementing mass production methods in British manufacturing, prevalence of principal-agent problems in British companies, and government's overemphasis on maintaining employment levels hampered Britain's productivity growth relative to the Continental European countries during AD1950-AD1979. The latter argued that weak competition, inadequate management and dysfunctional industrial relations were responsible for the British relative decline from the AD1870s to AD1970s.

[67] Pomeranz (2000) offered a geographic explanation for the origin of the Great Divergence between the East and the West. He stated that the British coal deposits and Europe's access to overseas colonies were responsible for Britain and Europe's head start in industrialization. On the other hand, Brandt et al. (2014) attributed China's relative economic decline in the nineteenth century to the political-economic system that protected the interests of the elites who resisted reforms and changes. Only in the late-twentieth century were the institutional barriers obstructing prosperity and growth overcome and led to China's current economic boom.

[68] Xu (2011) analyzed China's contemporary spectacular growth performance through its institution - the regionally decentralized authoritarian (RDA) regime. The RDA regime allied China's central-local incentives towards economic growth through the personnel control system, and facilitated regional competition and reform experiments. However the intrinsic deficiencies of the RDA regime (multi-task problems, law enforcement, firm independence) might place obstacles to China's future development.

question we address is:

**[Question 7: African Stagnation]** Why is Africa still (nearly) stagnating today?

From Figure 10, African economic growth has picked up since the late-twentieth century, but at a slower pace when compared to China's. Maddison (2008) provided the annual per capita GDP growth rates for 53 individual (or pairs of) African countries in AD1990-AD2008, and 18 of them were suffering from zero or even negative growth rates. Most of these countries make up the bottom layer of the Great Divergence pattern (such as the Niger plot in Figure 8).

To answer [Question 7] using our unified growth model, we redo the simulation exercise using all the calibrated parameters from Table 5, while changing the initial conditions on population and technologies based on Figure 11 (See Table 7).

INSERT TABLE 7 HERE

Figure 14 depicts the simulated African development paths (dotted-dashed lines) when compared to China's (dotted line).[69] From panel (a) African per capita income has been stagnating since AD0. Such stagnation came to an end at the turn of the twenty-first century.

INSERT FIGURE 14 HERE

Since Africa and China had similar technology levels in AD0 and similar population composition evolution paths (panel (b)), the divergence in per capita income growth paths between Africa and China must have come from the long-run accumulated scale effect originating from the difference in AD0 population sizes. Such a cumulative scale effect over two thousand years since AD0 resulted in the African economy taking off nearly half a century later than China's did. Africa is crossing the borderline between Malthusian and Post-Malthusian regime today, and it will go through its Demographic Revolution in the near future (AD2020).

Combining the per capita income panels from Figures 13 and 14, we obtain the evolution pattern of the North (Britain, Continental Europe) – South (China, Africa) income difference depicted in Figure 8 or 10. This completes our understanding on basic Eurasian economic history.

# 7 DISCUSSION

## *7.1 Historical shocks and Development/Divergence*

The central theme of this paper is the construction of a unified growth theory with Industrious Selection to reconcile the stages of development (Five Revolutions), patterns of East-West divergence (pre-Industrial Little Divergence, Great Divergence and Chinese Growth Miracle), North-South divergence (African Stagnation) and within-Europe divergence (pre-Industrial Little Divergence, British Industrial Revolution and British Relative Economic Decline). Given the initial population and technology conditions in AD0, with one observable exogenous shock (the Black Death), our theory endogenously reconciles development and divergence among Eurasian nations/regions in the next two millennia (AD0-AD2000).

[69] The dotted lines depicting China in Figure 14 are exactly the same as the dotted lines depicting China in Figure 13.

We agree with Broadberry (2015) and Temin (2016) that the Black Death and discovery of new trade routes are key (demographic- and geographic-) shocks in economic history. Historical shocks are perhaps the first important elements in explaining issues relating to long-run development and divergence. To make a comparison, most socio-political-economic structures are endogenous (just think of the number of sociologists, political scientists and economists explaining structural phenomena in their fields). Attributing cross-country divergences to socio-political-economic structures begs the question on why socio-political-economic structures differed across nations at the outset, and motivates us to trace for even earlier shocks for explanation.[70] In this paper, we focus on the Black Death shock and let all other things endogenously determined in our theory. Note that we are not saying that socio-political-economic structures are not important, as they will shape the impact of historical shocks. The bottom-line is that we should take shocks and structures together in explaining economic history. For example, we relate the Black Death shock with economic structures (overall preference evolution and coordination problems) through a biological channel (Industrious Selection) to reconcile Eurasian economic history.[71]

Historical shocks and the fostered structures are inseparable components that explain current development and divergence. This applies not only to the economic front, but also to the demographic front. For example, in Figure 13 panel (h), even though the populations in the three nations/regions started with the same overall preference in AD0, the Black Death shock and long-run economic development had made them diverge by AD2000. This poses a challenge to the fundamental assumption of identical aggregate preference across nations, which is often used in economic models, in accounting for international income/demographic differences today (Barro and Sala-i-Martin 1992; Manuelli and Seshadri 2009).[72]

## *7.2 Human trait evolution and Economic development*

Our theory argues for the importance of Industrious Selection in rendering evolutionary advantage to the relatively industrious population in development process (Corollary 1). More generally, our theory relies on the income effect on number of births to confer an evolutionary advantage on a certain portion of the population, whose intrinsic trait will determine overall preference or technology evolution in the economy in the long run. This type of mechanism may

---

[70] For example, Kremer (1993a, 709) mentioned the “melting of the polar ice caps at the end of the ice age, around 10,000 B.C., and the consequent flooding of land bridges” as another geographic shock event that shaped technological development in the Old World, Americas, mainland Australia, Tasmania, and Flinders Island before AD1500.

[71] Borrowing Morris (2010, 557)’s words:

> “*The West rules because of geography. Biology tells us why humans push social development upward; sociology tells us how they do this (except when they don't); and geography tells us why the West, rather than some other region, has for the last two hundred years dominated the globe. Biology and sociology provide universal laws, applying to all humans in all times and places; geography explains differences.*”

[72] Related to our argument, Nunn and Wantchekon (2011) found that historical transatlantic and Indian Ocean slave trades reduce trust within African societies today. Galor and Özak (2015) noted that historical return to agricultural investment affects a country’s rate of time preference today. Becker et al. (2015) found that the length of time elapsed since two populations shared common ancestors predicts how similar two countries’ risk preferences are today.

shed light on constructing new theories to explain the long-run declines in interest rate, violence and the rise of literacy throughout human history (Clark 2007, ch.9). As most economic and demographic variables were static over the long Malthusian era, it is hard not to suspect human trait evolution to be the main cause driving all those long-run rising and declining trends.

Within a country we have shown that Industrious Selection accelerates development (section 5.2). The crucial assumption to achieve this result is that the more industrious population, who enjoys an evolutionary advantage, also inherits traits which are more conducive to economic growth. In this paper we modeled "hardworkingness" and "cooperativeness" as one pair of such traits. This is not the only trait pair that is conducive to economic growth. For example, we may model the more hardworking individuals to be better entrepreneurship innovators (Schumpeter 1934), more willing to embark on education and training (Mincer 1958), more capable to deal with disequilibria associated with economic growth (Schultz 1975), better at redesigning institutions that solve coordination failures and facilitate market integration (Epstein 2000, ch.1), more likely to learn and adopt new innovations (Spolaore and Wacziarg 2009), and so forth. These can also generate the accelerator property.

What our theory emphasizes is the "supply side" of human trait evolution; the "demand side" may be just as significant. Due to geographic or political reasons, some traits might be rewarded, incentivizing people to preserve them. From a historical perspective, one trait that might have been important to development during the Modern Period was shipbuilding trait. Take Portugal and China in the fifteenth century as examples. For Portugal, there was a "strategic benefit in being located on the South Atlantic coast of Europe near to the exit of the Mediterranean" (Maddison 2001, 57). The demand for Portuguese deep-sea fishing and African slavery trade might have incentivized people there to reward shipbuilding trait. Conversely, although China was leading the Europeans in terms of shipbuilding techniques by the early-fifteenth century, Ming dynasty's "increasing concern to defend the new northern capital [Beijing] against potential invasion form Mongolia or Manchuria" led it to abandon the ocean diplomacy; fleets and sea-going junks were reduced or prohibited (Maddison 2007, 163). It is no surprise under these circumstances that the shipbuilding trait hardly got an evolutionary advantage in China than in Portugal, or more generally, in the Atlantic European nations.[73] This might explain why Atlantic European nations dominated the oceans in the age of imperialism, despite their inferior shipbuilding technology at the outset.[74]

Across country we have shown how the Black Death gave rise to the European exceptionalism by speeding up Industrious Selection. In comparison Africa has been stagnating partly because the slow evolutionary nature of population composition has maintained the

[73] In the late-fifteenth century, the Chinese emperor ordered to retrieve the documents concerning Zheng He's treasure voyages (AD1405-AD1433) from the War Office. However, the officer extracted the documents, and burned them, describing the contents as "deceitful exaggerations of bizarre things far removed from the testimony of people's ears and eyes" (Duyvendak 1939, 395-396).

[74] For example, Maddison (2001, 76, 92) also mentioned that the Netherlands has "occupied a flat amphibious terrain where the relationship between land and water was very close", and that in Britain "the strategic advantages of being an island were intelligently exploited. The British merchant fleet was greatly expanded".

economy-wide coordination problems across generations (section 6). This provides an explanation in additional to the institutional arguments (North and Thomas 1973; Acemoglu and Robinson 2012) for why some countries failed to take advantage of trade and investment to promote their economic growth. Even when there are no institutional barriers to trade and investment, slow population evolution can contribute to the persistence of large income gaps between rich and poor countries.

The development policy implication from our theory is straightforward: to promote the shift of population structure to one that is more conducive to growth. Although decimating the less conducive population can theoretically do the job, genocide policy is immoral and objectionable. Rather, we can promote Industrious Selection by raising fertility of the more industrious individuals, or doing the opposite for the less industrious ones.[75] [76] Alternatively, we can trace out and relieve the underlying causes of coordination problems within the society, thereby improving production efficiency of the economy. Lastly, brain-draining industrious individuals from abroad is also an option in an open-economy setting.[77]

### *7.3 Sensitivity test*

One sensitivity test we wish to highlight is the robustness of our results to the variation in pre-Black Death population estimates in Britain (Table 4). There has been a wide range of such estimates in the literature. Table 8 shows some of them.

INSERT TABLE 8 HERE

Applying our calibrated model from section 6, Broadberry et al. (2011), Campbell (1991) and Clark (2007)'s population estimates give us the same qualitative results as shown in Figure 13. However, using Russell (1966)'s population estimate, the model predicts counterfactually that Britain would industrialize later than Continental Europe. This is because Russell (1966)'s estimate implies Continental Europe suffered from a higher aggregate death rate than Britain in the fourteenth century, which in turn implies that Industrious Selection would work in Continental Europe's rather than in Britain's favor.[78]

What is required for our Industrious Selection model to reconcile the Little Divergence within Europe is a higher Black Death rate in Britain than in Continental Europe. One caveat in Table 4 is that Continental Europe might have suffered from a higher Black Death toll rate but its population recovered at a faster pace than Britain. The latter might be caused by the emergence

[75] For example, observing from Figure 14, Africa could never overtake China in terms of per capita income. However, if we allow Africa to adopt an "evolution policy" such that the reproductive preference of the more industrious individuals was to be exogenously raised by 10% starting from AD2000, then Africa could catch up with China by AD2200. Equivalently, we can exogenously hamper population growth of the less industrious individuals, say, to reduce by 10% their reproductive preference starting from AD2000. This can achieve qualitatively the same result. See Appendix 3B for more details.

[76] In reality, conditional transfers based on industrious behavior might be considered. For example, Progresa, a Mexican poverty program in AD1998-AD2000, promised educational grants to eligible poor mothers with children who attended 85% of school days (Schultz 2004).

[77] See Gibson and McKenzie (2011) and Docquier and Rapoport (2012) for surveys on Brain Drain.

[78] See Appendix 3C for sensitivity tests pertaining to variation in values of population estimates in Britain and Continental Europe during the Black Death era.

of the European Marriage Pattern (EMP) (Hajnal 1965), which kept total fertility rate low, in Britain relative to in Continental Europe.[79] If this is the case, then Industrious Selection would work in favor of Continental Europe.

On the other hand, in sections 6.4-6.5 we treated Continental Europe as one unified economic unit throughout the analysis. By doing so we implicitly assigned a greater population scale effect advantage on growth to Continental Europe than to Britain. In reality, Continental Europe has been a region characterized by its high political fragmentation since the fall of the Western Roman Empire in AD476. No single European nation could restore the large scale of unification that the Roman Empire once did. If we take this fact into account, our theory would predict even a greater within-Europe Little Divergence prior to AD1800 and later industrialization dates for the Continental European nations. A similar argument holds for Africa in section 6.6.

## *7.4 Demographic-economic paradox*

Our theory also provides an explanation for the demographic-economic paradox. The paradox states that the positive correlation between income and fertility within a nation (measured on individual level) turns negative across nations (measured on aggregate levels). The within-nation positive correlation originates from the income effect on number of births. Since number of children is a normal good, individuals with higher incomes choose to form larger families. The across-nation negative correlation arises because different countries are in different stages of development. Some variables other than per capita income affect fertility in magnitudes dominating over the income effect on number of births. In our model, one such factor is the relative food price. Take Britain and China from our simulation as an example. Observing from Figure 13 panel (g) that, since China was lagging behind Britain in terms of development process, the fast relative food price drop in China occurred in the twentieth century, two centuries later than the British one. This means, in the twentieth century, when Britain has entered the Modern Growth era and fertility declined, China had just entered its late-Malthusian or Post-Malthusian era in which fertility rose. This gave rise to the negative income-fertility correlation (measured on aggregate levels) between Britain and China in that century. Note that our simulation always generates a positive within-nation income-fertility relationship (from proposition 1). Therefore our model reconciles the demographic-economic paradox between developed countries (e.g. Britain) and developing countries (e.g. China) in the twentieth century.

## *7.5 Limitations*

We have abstracted the role of land from our model. For example, we did not capture the fact that China possessed a larger territory than Britain throughout history. The main reason is

[79] There were four features of EMP (Alter and Clark 2010, 48): (1) Late first marriage for women, typically at age 24-26; (2) High fertility rate within marriage; (3) A significant portion of women (10-25%) never married; (4) Low illegitimacy rates. In particular, (1), (3) and (4) helped to keep average birth rates in northwest Europe low during the pre-industrial era. De Moor and Van Zanden (2010) hypothesized that the increased access to employment for women after the Black Death set in motion for the EMP, in particular in the North Sea area relative to the Southern Europe. See Dennison and Ogilvie (2014) for a scrutiny of the effect of EMP on economic growth.

for simplicity: the salient point of this paper is the interdependency between population and relative rise/fall of nations; our argument, that population size and composition are key to understanding development and divergence, is readily generalized into a theory with land size.[80] Also, similar to other unified growth models (Strulik and Weisdorf 2008, 2014), ours loses predictive power once a country enters the Modern Growth era. For example, from Clark (2010)'s estimates, per capita income in Britain rose by a factor of 8.3 from AD1780 to AD1995. However, our simulation in section 6 only predicts a factor of 3.1 from AD1780 to AD2000. The reason is that learning-by-doing is the sole engine of growth in our model. In reality, science-based innovation becomes a more important engine of growth when a country enters the more advanced stages of development.[81] Since the late-nineteenth century there has been a proliferation of science-based innovations in the West, transforming the Western societies into knowledge-based economies and high-energy civilizations (Mokyr 1998; Vaclav 2005). Ignoring innovation in our model results in underestimating economic growth in Britain and Continental Europe since the late-nineteenth century.[82]

Last but not least, as the focus of this paper is to reconcile the emergence of the Five Revolutions and the Two Divergences in Eurasia, we have also abstracted away elements such as physical and human capital accumulation, trade and technology diffusion, institutional changes, and so forth, that we think are of second order importance. These "omitted variables" are likely to be significant in explaining growth experience in specific nations/regions within narrower time horizons; for example, phases of convergence and divergence in Modern Europe (Fouquet and Broadberry 2015), growth acceleration during the Modern Growth era. Understanding these phenomena would bring additional insights to developing and developed countries nowadays. To conclude, while this paper has provided a unified growth theory to account for the relative rise and fall of nations/regions in Eurasia over the past two millennia, we still demand further research efforts in order to understand development and divergence in other time- and spatial-specific contexts.

## 8 CONCLUSION

This paper presents a unified growth theory with Industrious Selection to explore development and divergence in Eurasia in the past two millennia. We first investigate the development process that a nation goes through. A nation first experiences Malthusian stagnation because population growth dissipates slow technological progress. As a result of conscious

[80] There is a technical issue with including land. We have tried to include land in the production functions (12) and (17), and capture the difference in land size between Britain and China. Theoretically lowering the coordination efficiency parameter $v$ could replicate our qualitative results in section 6. However, Matlab is unable to solve for real solution paths in low $v$ cases. Not to be burdened by the technical issue which brings only marginal contribution to this paper, we ignore the role of land in our model.

[81] Acemoglu et al. (2006) proposed that the importance of innovation relative to imitation as a source of productivity growth rises as an economy moves closer to the world technology frontier.

[82] See Ho (2016c)'s unified growth model which incorporates innovations since the Second Industrial Revolution (AD1870-AD1914) to reconcile French development process.

labor-leisure optimization and income effect on the number of births, the more industrious individuals, who are more hardworking and cooperative, have an evolutionary advantage over the less industrious ones and they gradually dominate the population composition (*Industrious Selection*). Over time, this raises working hours, improves production efficiency and accelerates technological progress. Concentration on agricultural production during the Malthusian era has blessed the agricultural sector with faster productivity growth, leading to the Agricultural Revolution. Once agricultural productivity is high enough to feed the population, Structural Transformation occurs and labor hours shift to the manufacturing sector. The manufacturing technological progress is relatively promoted, decelerating relative food price drop as well as fertility increase. This ultimately pulls the economy out of the Malthusian Trap, marking the Industrial Revolution. From then on the nation enters the Post-Malthusian era, when sustainable per capita income growth starts. The Industrious Revolution also takes place as households supply more labor hours in response to the substantive increase in market wages since the Industrial Revolution. The continuous structural transformation and the fast productivity growth in the manufacturing sector will eventually lead to a drop in relative manufacturing prices. Households will prefer to expand their consumption of cheaper manufacturing goods to giving birth to children, triggering the Demographic Revolution. Then the nation will enter the Modern Growth era, which is characterized by long-run fertility decline.

This paper then investigates the causes of divergence in the wealth of nations, in particular among Britain, Continental Europe, China and Africa, over the past two millennia. Population size (Kremer 1993a; Galor and Weil 2000) and its composition (Kremer 1993b; Galor and Moav 2002) are key to understanding this issue. Our theory puts forward that the Black Death in late-Medieval Europe was more fatal to the less industrious individuals, expedited Industrious Selection and hence the onset of the Five Revolutions in Europe. The Black Death toll rate was higher in Britain than in Continental Europe, and in Continental Europe than in China/Africa. Such an order of severity meant that the respective populations became conducive to growth in the same order, and resulted in the same wealth ordering in the Little Divergence and Great Divergence eras. However, ultimately the population size will become the dominant factor in determining the growth of a nation. Therefore, we observe the British economic decline relative to Continental Europe during the late-nineteenth and twentieth centuries. In the same vein, our theory predicts that China will embrace fast and sustainable growth in the twenty-first century and ultimately catch up with the European nations. Lastly, Africa, being constrained by its population size and composition, has just crossed the borderline of Malthusian stagnation today.

Our unified growth theory (two-type household – two-sector production model with Black Death shock) simulates long-run development paths that are broadly consistent with British historical experience and the relative rise and fall of Eurasian economies (Britain, Continental Europe, China, Africa) in the past two millennia (Clark 2007; Maddison 2008; Broadberry 2015). In particular, our simulations reconcile the timings of Industrial and Demographic Revolutions in the four nations/regions, and replicate the emergence of East-West, North-South and within-Europe divergences throughout the Eurasian economic history.

Industrious Selection points to an additional channel that generates natural selection pressure in human society when compared to the animal world (Darwin 1876[1872]): it is not just the most adaptable humans that survive, but also the ones that are most industrious. Reward lies ahead of diligence and cooperativeness, which gives individuals (or nations) superiority in terms of wealth and offspring dominance. We, humans, consciously interact with other humans, the society, the institutions, the economy, the environment, and more factors. We do so not just to endeavor for survival, but also to strive for material or normative goals subject to constraints related to the above factors. How humans' survival and maximization activities interact with biological-demographic and socio-political-economic elements, and shape past and modern economic growth in different landscapes, will always be an exciting question, and future inquiries into this issue will surely enrich our understanding of the nature and causes of the wealth of nations.

## Appendix 1: Proofs

**Proposition 1**

*Proof:* Use (3) and (4) to rewrite (2) as

(A.1) $$m_t^i + \gamma\left(m_t^i\right)^\sigma = w_t - \varphi_i\left(m_t^i\right)^\sigma,\ i = 1, 2.$$

Since $\sigma > 0$ and $\varphi_2 > \varphi_1 \geq 0$ we must have $m_t^1 > m_t^2$. From (4), this implies $n_t^1 > n_t^2$. Finally using the results $m_t^1 > m_t^2$ and $n_t^1 > n_t^2$ in the budget constraint (2), we must have $l_t^1 < l_t^2$.

**Corollary 1**

*Proof:* $\frac{L_{t+1}^1}{L_{t+1}} = \frac{n_t^1 L_t^1}{n_t^1 L_t^1 + n_t^2 L_t^2} = \frac{L_t^1}{L_t^1 + \frac{n_t^2}{n_t^1} L_t^2} > \frac{L_t^1}{L_t^1 + L_t^2} = \frac{L_t^1}{L_t}$ .

The first equality follows from (5), (6) and (7). The third inequality follows from proposition 1 that $n_t^1 > n_t^2$.

**Proposition 2**

*Proof:* Part (a): By the definition of BGP, $\frac{(L^2)^*}{(L)^*} = 0$. By $E_t = (v)^{\frac{L_t^2}{L_t}}$ we have $(E)^* = 1$.

Part (b): By the definition of BGP, $\left(g^\theta\right)^* = (g^\chi)^* = (g^l)^* = 0$. Note $l_t = (1)l^1 + (0)l^2$ in BGP, so $(l)^* = l^1$ is constant.

Constant adult population growth rate means adult population grows at $(g^L)^*$ in BGP. Hence by $1 + g_t^L = \frac{L_t n_t}{L_t}$, in BGP $(n)^* = 1 + (g^L)^*$.

Rewrite (13) as $g_t^A \equiv \frac{A_{t+1} - A_t}{A_t} = \frac{\mu[\theta_t(1-l_t)L_t]^\alpha v^{(\frac{L_t^2}{L_t})}}{(A_t)^{1-\varepsilon}}$ (Note $H_t^A = \theta_t H_t = \theta_t(1 - l_t)L_t$). In BGP $1 = \left(\frac{A_{t+1}}{A_t}\right)^{1-\varepsilon}\left(\frac{L_{t+1}}{L_t}\right)^{-\alpha}$.

By (24), in BGP $1 = \left(\frac{L_{t+1}}{L_t}\right)^{1-\alpha}\left(\frac{A_{t+1}}{A_t}\right)^{-\varepsilon}$. Combine the above two BGP equations, we obtain $(g^A)^* = (g^L)^*$. Plug back to the first BGP equation, $[1 + (g^L)^*]^\alpha = [1 + (g^L)^*]^{1-\varepsilon}$. Given

$\alpha \neq 1-\varepsilon$, we have $(g^L)^* = 0$. Hence $(g^A)^* = 0$ too.
Next $(n)^* = 1 + (g^L)^* = 1$.

By (18), $g_t^M \equiv \frac{M_{t+1}-M_t}{M_t} = \frac{\delta[\chi_t(1-l_t)L_t]^{\lambda} v^{(\frac{L_t^2}{L_t})}}{(M_t)^{1-\phi}}$. In BGP $\left(\frac{M_{t+1}}{M_t}\right)^{1-\phi} = \left(\frac{L_{t+1}}{L_t}\right)^{\lambda}$. Since $(g^L)^* = 0$, given $\phi \neq 1$,we have $(g^M)^* = 0$.

Define average manufacturing consumption $m_t \equiv \frac{L_t^1 m_t^1 + L_t^2 m_t^2}{L_t}$. Combine manufacturing goods market equilibrium condition $Y_t^M = m_t L_t$, (17) and (25) to yield $(1-l_t)\chi_t = \left[\frac{m_t L_t^{1-\lambda}}{\delta v^{(\frac{L_t^2}{L_t})}(M_t)^{\phi}}\right]^{\frac{1}{\lambda}}$. In BGP $1 = \left[\frac{m_{t+1}}{m_t}\left(\frac{L_{t+1}}{L_t}\right)^{1-\lambda}\left(\frac{M_{t+1}}{M_t}\right)^{-\phi}\right]^{\frac{1}{\lambda}}$. By $(g^L)^* = (g^M)^* = 0$, we have $(g^m)^* = 0$.
Given type 1 individuals are the asymptotically dominant type in the population, from $n_t \equiv \frac{L_t^1 n_t^1 + L_t^2 n_t^2}{L_t}$ and $m_t \equiv \frac{L_t^1 m_t^1 + L_t^2 m_t^2}{L_t}$, we get $(n^1)^* = (n)^*$ and $(m^1)^* = (m)^*$. Therefore $\left(g^{n^1}\right)^* = \left(g^{m^1}\right)^* = 0$ .By $n_t^1 = 1 + g_t^{L^1}$, in BGP we have $\left(g^{L^1}\right)^* = 0$.

From (4), $n_t^1 = \frac{\gamma(m_t^1)^{\sigma}}{p_t}$. Since in BGP $(n^1)^*$ and $(m^1)^*$ are constants, we have $(g^p)^* = 0$.
From (12), $Y_t^A = \mu E_t (A_t)^{\varepsilon}(\theta_t)^{\alpha}(1-l_t)^{\alpha}(L_t)^{\alpha}$. In BGP $(E)^*$, $(A)^*$, $(\theta)^*$, $(l)^*$ and $(L)^*$ are constants, hence $\left(g^{Y^A}\right)^* = 0$. Similarly we have $\left(g^{Y^M}\right)^* = 0$.

By (20) and $\left(g^{Y^A}\right)^* = \left(g^{Y^M}\right)^* = (g^p)^* = 0$, we have $(g^Y)^* = 0$.

By (21) and $(g^Y)^* = (g^L)^* = 0$, we get $(g^y)^* = 0$.

By (21), (20) and (26), $y_t = \frac{Y_t}{L_t + L_t n_t} = \frac{Y_t}{L_t(1+n_t)} = \frac{p_t Y_t^A + Y_t^M}{(1+n_t)L_t} = \frac{1}{1+n_t}\left(\frac{p_t Y_t^A}{H_t^A}\cdot\frac{H_t^A}{L_t} + \frac{Y_t^M}{H_t^M}\cdot\frac{H_t^M}{L_t}\right) = \frac{1}{1+n_t}\left(w_t\frac{H_t^A}{L_t} + w_t\frac{H_t^M}{L_t}\right) = \frac{w_t(1-l_t)}{1+n_t}$. Since $(g^y)^* = (g^l)^* = (g^n)^* = 0$, we obtain $(g^w)^* = 0$.

From (3), $l_t^1 = \frac{\varphi_i(m_t^1)^{\sigma}}{w_t}$. Since in BGP $(w)^*$ and $(m^1)^*$ are constants, we have $\left(g^{l^1}\right)^* = 0$.

Apply (A.1) in Appendix 1 to type-2 individuals, since $(g^w)^* = 0$, we have $\left(g^{m^2}\right)^* = 0$. Then by (3) and (4) we also have $\left(g^{l^2}\right)^* = \left(g^{n^2}\right)^* = 0$.
By $n_t^2 = 1 + g_t^{L^2}$, in BGP we have $\left(g^{L^2}\right)^* = 0$.

## Appendix 2: Adjustment mechanisms in the model

**[Mechanism 1: Income effect]**[83]

[83] To be more precise, in our model with heterogeneous households, mechanism 1 should be called the "wage effect" instead of the "income effect".

*Mechanism:* $w_t \uparrow$ => $n_t \uparrow,\ m_t \uparrow,\ l_t?(\downarrow),\ \theta_t?(\downarrow)$

*Explanation*: This operates through the household optimization channel. Number of children and manufacturing goods are both normal goods in household's utility function. Holding relative food price constant, a rise in wage will relax the households' budget constraint, and induce them to spend more on both goods. Although Engel's law holds on the individual level, it does not necessarily hold on the aggregate level (that all individual fractions increase does not imply aggregate fraction has to increase as well).

*Proof:* Consider an increase in $w_t$, by (A.1) from Appendix 1 we have:

$$\frac{\partial m_t^i}{\partial w_t} = \frac{1}{(\gamma+\varphi_i)\sigma\left(m_t^i\right)^{\sigma-1}+1} > 0,\ i = 1,2\ .$$

Hence $m_t \equiv \frac{L_t^1 m_t^1 + L_t^2 m_t^2}{L_t}$ also increases.

Using (2), (4), for a type-$i$, generation-$t$ household, fraction of income spent on food equals $\frac{p_t n_t^i}{m_t^i + p_t n_t^i} = \frac{\gamma\left(m_t^i\right)^{\sigma}}{m_t^i+\gamma\left(m_t^i\right)^{\sigma}} = \frac{\gamma}{\left(m_t^i\right)^{1-\sigma}+\gamma}$, which is decreasing in $m_t^i$ if and only if $\sigma < 1$. Since we have proved above that an increase in $w_t$ raises $m_t^i$, the fraction of income spent on food for this household also decreases with wage (Engel's law on individual level).

Holding $p_t$ constant, by (4) $n_t^i$ moves in the same direction as $m_t^i$ and increases. Therefore $n_t \equiv \frac{L_t^1 n_t^1 + L_t^2 n_t^2}{L_t}$ also increases. By (3)

$$\frac{\partial l_t^i}{\partial w_t} = \left[\frac{\sigma\varphi_i\left(m_t^i\right)^{\sigma-1}}{w_t\left[(\gamma+\varphi_i)\sigma\left(m_t^i\right)^{\sigma-1}+1\right]} - \frac{\varphi_i\left(m_t^i\right)^{\sigma}}{(w_t)^2}\right]$$

with sign indeterminate. From our simulation in section 5, this sign was found to be always negative in Britain throughout AD0-AD2500.

By goods market equilibrium conditions and (4):

$$\frac{Y_t^M}{p_t Y_t^A} = \frac{L_t^1 m_t^1 + L_t^2 m_t^2}{p_t\left(L_t^1 n_t^1 + L_t^2 n_t^2\right)} = \frac{L_t^1 m_t^1 + L_t^2 m_t^2}{\gamma\left[L_t^1\left(m_t^1\right)^{\sigma} + L_t^2\left(m_t^2\right)^{\sigma}\right]}\ .$$

Taking total derivative of the above expression with respect to $w_t$:

$$\frac{\partial\left(\frac{Y_t^M}{p_t Y_t^A}\right)}{\partial w_t} = \frac{\partial\left(\frac{Y_t^M}{p_t Y_t^A}\right)}{\partial m_t^1}\frac{\partial m_t^1}{\partial w_t} + \frac{\partial\left(\frac{Y_t^M}{p_t Y_t^A}\right)}{\partial m_t^2}\frac{\partial m_t^2}{\partial w_t}$$

$$= \frac{\left[L_t^1\left(m_t^1\right)^{\sigma}+L_t^2\left(m_t^2\right)^{\sigma}\right]^{-2}}{\gamma\left[(\gamma+\varphi_1)\sigma\left(m_t^1\right)^{\sigma-1}+1\right]}\{[L_t^1(m_t^1)^{\sigma} + L_t^2(m_t^2)^{\sigma}]L_t^1 - (L_t^1 m_t^1 + L_t^2 m_t^2)\sigma(m_t^1)^{\sigma-1}L_t^1\}$$

$$+ \frac{\left[L_t^1\left(m_t^1\right)^{\sigma}+L_t^2\left(m_t^2\right)^{\sigma}\right]^{-2}}{\gamma\left[(\gamma+\varphi_2)\sigma\left(m_t^2\right)^{\sigma-1}+1\right]}\{[L_t^1(m_t^1)^{\sigma} + L_t^2(m_t^2)^{\sigma}]L_t^2 - (L_t^1 m_t^1 + L_t^2 m_t^2)\sigma(m_t^2)^{\sigma-1}L_t^2\}$$

with sign indeterminate. From our simulation in section 5, this sign was found to be always positive in Britain throughout AD0-AD2500. Since $\frac{Y_t^M}{p_t Y_t^A} = \frac{\delta E_t(M_t)^{\phi}[(1-\theta_t)H_t]^{\lambda}}{\mu E_t(A_t)^{\varepsilon}[(\theta_t)H_t]^{\alpha}}$, holding $p_t,\ A_t,\ M_t,\ H_t$ constant, an increase in $w_t$ reduces $\theta_t$ (Engel's law on aggregate level).

**[Mechanism 2: Relative price effect]**

*Mechanism:* $p_t \downarrow$ => $n_t \uparrow,\ m_t$ constant, $l_t$ constant, $\theta_t \uparrow$

*Explanation:* This operates through the household optimization channel. A drop in relative food price reduces child-rearing cost. Holding wage constant, the households devote the additional purchasing power on raising more children.[84] A greater agricultural labor hours share is required to meet the higher food demand.

*Proof:* Holding $w_t$ constant, when $p_t$ decreases, by (A.1) $m_t^i$ stayed constant for all $i$. By (4) $n_t^i$ increases for all $i$. It follows immediately that $n_t \equiv \frac{L_t^1 n_t^1 + L_t^2 n_t^2}{L_t}$ increases and $m_t \equiv \frac{L_t^1 m_t^1 + L_t^2 m_t^2}{L_t}$ remains constant. By (3) $l_t^i$ also remains constant for all $i$ and so does $l_t$.

From goods market equilibrium conditions $Y_t^A = n_t L_t$ and $Y_t^M = m_t L_t$, $\frac{Y_t^A}{Y_t^M}$ increases. Holding $A_t$, $M_t$, $H_t$ constant, from (12) and (17) $\theta_t$ increases.

**[Mechanism 3: Technology growth effect]**

*Mechanism:* $A_t \uparrow$ => $\theta_t \uparrow$ ; $M_t \uparrow$ => $\theta_t \downarrow$

*Explanation:* This operates through the wage parity channel. Without loss of generality, consider the case of agricultural technological progress. It exerts an upward pressure on agricultural wage. Hence labor hours shift to the agricultural sector to keep wage parity between the two sectors. Similar reasoning applies to manufacturing technological progress.

*Proof:* Use (12), (17), (23) to rewrite (26) as

$$w_t = p_t \mu E_t (A_t)^{\varepsilon} (H_t^A)^{\alpha-1} = \delta E_t (M_t)^{\phi} (H_t - H_t^A)^{\lambda-1} \ .$$

Rewrite using the definition of $\theta_t$ from (24):

(A.2) $$p_t \mu E_t (A_t)^{\varepsilon} (H_t)^{\alpha-\lambda} (\theta_t)^{\alpha-1} = \delta E_t (M_t)^{\phi} (1-\theta_t)^{\lambda-1} \ .$$

Holding $p_t$, $E_t$, $M_t$, $H_t$ constant, taking total derivative of (A.2) with respect to $A_t$:

$$\frac{\partial \theta_t}{\partial A_t} = \frac{\varepsilon p_t \mu E_t (A_t)^{\varepsilon-1} (H_t)^{\alpha-\lambda} (\theta_t)^{\alpha-1}}{p_t \mu E_t (A_t)^{\varepsilon} (H_t)^{\alpha-\lambda} (1-\alpha)(\theta_t)^{\alpha-2} + \delta E_t (M_t)^{\phi} (1-\lambda)(1-\theta_t)^{\lambda-2}} > 0 \quad \text{, given } \alpha, \lambda < 1.$$

Holding $p_t$, $E_t$, $A_t$, $H_t$ constant, taking total derivative of (A.2) with respect to $M_t$:

$$\frac{\partial \theta_t}{\partial M_t} = -\frac{\phi \delta E_t (M_t)^{\phi-1} (1-\theta_t)^{\lambda-1}}{p_t \mu E_t (A_t)^{\varepsilon} (H_t)^{\alpha-\lambda} (1-\alpha)(\theta_t)^{\alpha-2} + \delta E_t (M_t)^{\phi} (1-\lambda)(1-\theta_t)^{\lambda-2}} < 0 \quad \text{, given } \alpha, \lambda < 1.$$

**[Mechanism 4: Population growth effect]**[85]

*Mechanism:* $H_t \uparrow$ => $\theta_t \downarrow$

*Explanation*: This operates through the wage parity channel. Agricultural production is characterized by stronger diminishing returns to labor hours. Ceteris paribus, an increase in aggregate labor hours supply exerts a greater downward pressure on agricultural wage. This induces a shift of labor hours from the agricultural to the manufacturing sector, to maintain wage parity between the two sectors.

*Proof:* Holding $p_t$, $E_t$, $A_t$, $M_t$ constant, taking total derivative of (A.2) with respect to $H_t$:

---

[84] A relative food price drop has no effect on individual household's manufacturing goods consumption in our model. The reason is that the substitution effect on manufacturing goods consumption is exactly offset by a relaxation on the household's budget constraint.

[85] To be more precise, in our model with labor-leisure choice, mechanism 4 should be called the "labor hours growth effect" instead of the "population growth effect".

$$\frac{\partial \theta_t}{\partial H_t} = \frac{(\alpha - \lambda) p_t \mu E_t(A_t)^{\varepsilon}(H_t)^{\alpha-\lambda-1}(\theta_t)^{\alpha-1}}{p_t \mu E_t(A_t)^{\varepsilon}(H_t)^{\alpha-\lambda}(1-\alpha)(\theta_t)^{\alpha-2} + \delta E_t(M_t)^{\phi}(1-\lambda)(1-\theta_t)^{\lambda-2}} < 0 \quad \text{, given } \alpha < \lambda \leq 1.$$

## Appendix 3: Sensitivity Tests

### A) Sensitivity tests on the benchmark model

We perform sensitivity tests on the benchmark model (section 4, Table 2). Table A.1 summarizes the scenarios and test results. In each scenario one parameter is raised by 10% above its benchmark value (except parameters with extreme benchmark values $\sigma$, $\lambda$). The last two columns in Table A.1 show how the timings of British Industrial Revolution and Demographic Revolution are affected in each scenario. In general the timings of the two revolutions are sensitive to the changes in the production function parameters ($\mu$, $\varepsilon$, $\alpha$, $\delta$, $\phi$, $\lambda$).

INSERT TABLE A.1 HERE

### B) African "evolution policy"

We investigate the impact of two "evolution policies" in Africa. We extend the benchmark model to allow for difference in reproductive preference between the two types of individuals. In particular, type 1 and type 2 individuals possess the following modified utility function:

(1') $$u_t^i = \frac{(m_t^i)^{1-\sigma}}{1-\sigma} + \varphi_i \log l_t^i + \gamma_i \log n_t^i \;\; ; \quad \sigma \in (0,1), \; \varphi_2 > \varphi_1 \geq 0, \; \gamma_i > 0 \;\; ; i = 1,2 \;\; ,$$

where $\gamma_1$ is not necessarily equal to $\gamma_2$. In terms of the resulting system of equilibrium equations, the only change to the benchmark model is that equation (4) becomes:

(4') $$n_t^i = \frac{\gamma_i (m_t^i)^{\sigma}}{p_t} \;\; ; \; i = 1,2.$$

We adopt baseline parameters and initial values in section 6, Table 7, with $\gamma_1 = \gamma_2 = 4.95$ at the outset.

In the first policy P1, suppose the African government encourages the more industrious individuals to give more birth. Consider this to raise the reproductive preference of the more industrious individuals exogenously by 10% above the initial value starting from AD2000:

- Policy P1: $\gamma_1 = 4.95 \times 1.1$ since AD2000.

Figure A.1 depicts per capita income growth path of Africa under Policy P1 (dotted-dashed line) when compared to that of China without such a policy (dotted line). Although Africa was poorer than China in AD2000, with policy P1 it would catch up with China by the end of the twenty-second century.

INSERT FIGURE A.1 HERE

Another African evolution policy with similar effect is to discourage the less industrious individuals to give birth. In Figure A.2 we consider a policy P2 that hampers the reproductive preference of the less industrious individuals exogenously by 10% starting from AD2000:

- Policy P2: $\gamma_2 = 4.95 \times 0.9$ since AD2000.

The African economy under policy P2 (dotted-dashed line) would catch up with the Chinese economy without such a policy (dotted line) by the mid-twenty-third century.

INSERT FIGURE A.2 HERE

## C) Robustness checks to variation in population estimates

We consider the effects of variation in population estimates on the timings of Industrial Revolutions and Demographic Revolutions in Britain and Continental Europe. We adopt baseline parameters and initial values in section 6, Table 5. Table A.2 summarizes the scenarios and test results.

INSERT TABLE A.2 HERE

In scenarios 18, 19 and 20, we employ the pre-Black Death England population estimates from Clark (2007), Broadberry et al. (2011) and Russell (1966) in Table 8, and AD1400 England and Wales population from Table 4, to calculate the implied aggregate death rate in Britain during the fourteenth century. In scenarios 21 and 22 the implied aggregate death rates in Continental Europe are respectively the lower and upper bounds of European death rates we mentioned in section 6.2.

Then we use the implied aggregate death rates to recalibrate the type-specific mortality rates during the fourteenth century in different scenarios. For example, in scenario 18, given the England population estimates of 6 million (Table A.2) and 3 million (Table 4) before and after the Black Death, the implied aggregate death rate in the fourteenth century Britain is $1-\frac{3{,}000}{6{,}000}=50\%$. From section 6.4 our model simulates 52% of type 1 individuals and 48% of type 2 individuals in Britain prior to the Black Death, we recalibrate the type 1 and type 2 mortality rates to be 5% and 99% respectively to match the 50% aggregate death rate in Britain $\{1-[0.52\times(1-5\%)+0.48\times(1-99\%)]\approx 50\%\}$. Table A.3 shows the implied aggregate death rates and the recalibrated type-specific mortality rates for the other scenarios.

INSERT TABLE A.3 HERE

The last four columns in Table A.2 show the test results. We focus on the resulting timings of Industrial Revolutions in Britain and in Continental Europe. In general, when the Black Death aggregate death rate was higher in Britain than in Continental Europe, our model predicts that the Little Divergence and the timing of Industrial Revolution would work in Britain's favor (scenarios 18,19 and 21). Otherwise, the opposite would be true (scenarios 20 and 22).

## REFERENCE

**Acemoglu, Daron. 2009.** *Introduction to Modern Economic Growth.* Princeton, New Jersey: Princeton University Press.

**Acemoglu, Daron, and Veronica Guerrieri. 2008.** Capital Deepening and Non-balanced Economic Growth. *Journal of Political Economy* 116(3):467-498.

**Acemoglu, Daron, Philippe Aghion, and Fabrizio Zilibotti. 2006.** Distance to Frontier, Selection, and Economic Growth. *Journal of the European Economic Association* 4(1):37-74.

**Acemoglu, Daron, and James A. Robinson. 2012.** *Why Nations Fail: The Origins of Power, Prosperity, and Poverty.* New York: Crown Publishers.

**Acemoglu, Daron, Simon Johnson, and James A. Robinson. 2001.** The Colonial Origins of Comparative Development: An Empirical Investigation. *American Economic Review* 91(5):1369-1401.

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

**Aghion, Philippe, and Peter Howitt. 1992.** A Model of Growth through Creative Destruction. *Econometrica* 60(2):323-351.

**Aghion, Philippe, and Peter Howitt. 2009.** *The Economics of Growth.* Cambridge, Massachusetts: MIT Press.

**Allen, Robert C. 1999.** Tracking the Agricultural Revolution in England. *The Economic History Review* 52(2):209-235.

**Allen, Robert C. 2000.** Economic structure and agricultural productivity in Europe, 1300-1800. *European Review of Economic History* 3:1-25.

**Allen, Robert C. 2001.** The great divergence in European prices and wages from the Middle Ages to the First World War. *Explorations in Economic History* 38(4):411-447.

**Allen, Robert C. 2004.** Agriculture during the industrial revolution, 1700-1850. In *The Cambridge Economic History of Modern Britain, Volume 1*, edited by Roderick Floud and Paul A. Johnson, 96-116. Cambridge: Cambridge University Press.

**Allen, Robert C, and Jacob Louis Weisdorf. 2011.** Was there an 'industrious revolution' before the industrial revolution? An empirical exercise for England, c.1300-1830. *The Economic History Review* 64(3):715-729.

**Alter, George, and Gregory Clark. 2010.** The demographic transition and human capital. In *The Cambridge Economic History of Modern Europe, Volume 1*, edited by Stephen Broadberry and Kevin H. O'Rourke, 43-69. New York: Cambridge University Press.

**Arrow, Kenneth J. 1962.** The Economic Implications of Learning by Doing. *Review of Economic Studies* 29(3):155-173.

**Ashraf, Quamrul, and Oded Galor. 2013.** The Out-of-Africa Hypothesis, Human Genetic Diversity, and Comparative Economic Development. *The American Economic Review* 103(1):1-46.

**Ashton, Thomas Southcliffe. 1948.** *The Industrial Revolution (1760–1830).* London: Oxford University Press.

**Barbier, Edward B. 2011.** *Scarcity and Frontiers: How Economies Have Developed Through Natural Resource Exploitation*. Cambridge: Cambridge University Press.

**Barro, Robert J. 1991.** Economic Growth in a Cross Section of Countries. *The Quarterly Journal of Economics* 106(2):407-443.

**Barro, Robert J, and Xavier Sala-i-Martin. 1992.** Convergence. *Journal of Political Economy* 100(2): 223-251.

**Baten, Joerg, and Jan Luiten van Zanden. 2008.** Book production and the onset of modern economic growth. *Journal of Economic Growth* 13(3):217-235.

**Becker, Anke, Benjamin Enke, and Armin Falk. 2015.** The Ancient Origins of Cross-Country Heterogeneity in Risk Preferences. Working Paper. May 6.

**Becker, Gary S. 1960.** An Economic Analysis of Fertility In D*emographic and Economic Change* *in Developed Countries* edited by Universities-National Bureau, 209-240. Princeton, New Jersey: Princeton University Press.

**Becker, Gary S. 1965.** A Theory of the Allocation of Time. *The Economic Journal* 75:493-517.

**Becker, Gary S. 1991.** *A Treatise on the Family*. Cambridge, Massachusetts: Harvard University Press.

**Benedictow, Ole Jørgen. 2004.** *The Black Death, 1346-1353: The Complete History*. Woodbridge, Suffolk, UK: The Boydell Press.

**Blanchard, Ian. 1978.** Labour productivity and work psychology in the English mining industry, 1400-1600. *Economic History Review* 31(1):1-24.

**Boly, Melanie, Anil K. Seth, Melanie Wilke, Paul Ingmundson, Bernard Baars, Steven Laureys, David B. Edelman, and Naotsugu Tsuchiya. 2013.** Consciousness in humans and non-human animals: recent advances and future directions. *Frontiers in psychology*, 4:625. http://doi.org/10.3389/fpsyg.2013.00625 (Accessed April 1, 2016)

**Bowsky, Willam M. 1971.** *The Black Death: A Turning Point in History?* New York: Holt, Rinehart and Winston.

**Broadberry, Stephen. 2015.** Accounting For The Great Divergence. LSE Working Paper, July 13.

**Broadberry, Stephen, and Nicholas Crafts. 2003.** UK productivity performance from 1950 to 1979: a restatement of the Broadberry-Crafts view. *The Economic History Review* 56(4):718-735.

**Broadberry, Stephen, and Bishnupriya Gupta. 2006.** The early modern great divergence: wages, prices and economic development in Europe and Asia, 1500-1800. *The Economic History Review* 59(1):2-31.

**Broadberry, Stephen, Bruce M.S. Campbell, and Bas van Leeuwen. 2013.** When did Britain industrialise? The sectoral distribution of the labour force and labour productivity in Britain, 1381–1851. *Explorations in Economic History* 50(1):16-27.

**Broadberry, Stephen, Bruce M.S. Campbell, Alexander Klein, Mark Overton, and Bas van Leeuwen. 2011.** British Economic Growth, 1270-1870: An Output-based Approach. Unpublished manuscript, December 18.

**Broadberry, Stephen, Bruce M.S. Campbell, Alexander Klein, Mark Overton, and Bas van Leeuwen. 2015.** *British Economic Growth, 1270-1870.* Cambridge: Cambridge University Press.

**Brandt, Loren, Debin Ma and Thomas G Rawski. 2014.** From Divergence to Convergence: Reevaluating the History Behind China's Economic Boom. *Journal of Economic Literature* 52(1):45-123.

**Byrne, Jposeh P. 2012.** *Encyclopedia of the Black Death.* Santa Barbara, California: ABC-CLIO.

**Campbell, Bruce M.S. 1991.** *Before the Black Death: Studies in the "crisis" of the Early Fourteenth Century*. Manchester: Manchester University Press.

**Caldwell, John C. 1976.** Toward a restatement of demographic transition theory. *Population and Development Review* 2:321-366.

**Cervellati, Matteo, and Uwe Sunde. 2005.** Human capital, life expectancy, and the process of development. *American Economic Review* 95(5):1653-1672.

**Chesnais, Jean Claude. 1992.** *The Demographic Transition: Stages, Patterns, and Economic Implications: a longitudinal study of sixty-seven countries covering the period 1720-1984*. Oxford: Clarendon Press.

**Clark, Gregory. 2002.** The Agricultural Revolution and the Industrial Revolution: England, 1500-1912. Working Paper, University of California, Davis. June.

**Clark, Gregory. 2005.** The Condition of the Working-Class in England, 1209-2004. *Journal of Political Economy* 113(6):1307-1340.

**Clark, Gregory. 2007.** *A Farewell to Alms: A Brief Economic History of the World.* Princeton, New Jersey: Princeton University Press.

**Clark, Gregory. 2008.** In defense of the Malthusian interpretation of history. *European Review of Economic History* 12:175-199.

**Clark, Gregory. 2010.** The Macroeconomic Aggregates for England, 1209-1869. *Research in Economic History* 27: 51-140.

**Clark, Gregory. 2013a.** 1381 and the Malthusian Delusion. *Explorations in Economic History* 50(1):4-15.

**Clark, Gregory. 2013b.** Surnames and a Theory of Social Mobility. Working Paper, University of California, Davis. March 25.

**Clark, Gregory. 2014a.** The Industrial Revolution. In *Handbook of Economic Growth, Vol. 2A*, edited by Philippe Aghion and Steven N. Durlauf, 217-262. Amsterdam: Elsevier.

**Clark, Gregory. 2014b.** *The son also rises: surnames and the history of social mobility.* Princeton, New Jersey: Princeton University Press.

**Clark, Gregory, and Gillian Hamilton. 2006.** Survival of the Richest: The Malthusian Mechanism in Pre-Industrial England. *The Journal of Economic History* 66(3):707-736.

**Clark, Gregory, and Ysbrand Van Der Werf. 1998.** Work in Progress? The Industrious Revolution. *The Journal of Economic History* 58(3):830-843.

**Comin, Diego,William Easterly and Eric Gong. 2010.** Was the Wealth of Nations Determined in 1000 B.C.? *American Economic Journal: Macroeconomics* 2(3):65-97.

**Crafts, Nicholas F.R. 1985.** *British Economic Growth during the Industrial Revolution.* Oxford: Clarendon Press.

**Crafts, Nicholas F.R. 1995.** Exogenous or endogenous growth? The Industrial revolution reconsidered. *Journal of Economic History* 55(4):745-772.

**Crafts, Nicholas F.R. 2012.** British relative economic decline revisited: The role of competition. *Explorations in Economic History* 49(1):17-29.

**Crafts, Nicholas F.R., and C.K. Harley. 1992.** Output Growth and the British Industrial Revolution: A Restatement of the Crafts-Harley View. *The Economic History Review* 45(4):703-730.

**Crafts, Nicholas F.R., and Terence C. Mills. 1992.** From Malthus to Solow: How Did the Malthusian Economy Really Evolve? *Journal of Macroeconomics* 31(1):68-93.

**Darwin, Charles. 1876.** *The Origin of Species, 6th Edition*. London: John Murray.

**Darwin, Charles. 1958.** *The Autobiography of Charles Darwin 1809-1882*, edited by Nora Barlow. London: Collins.

**De Moor, Tine, and Jan Luiten Van Zanden. 2010.** Girl power: the European marriage pattern and labour markets in the North Sea region in the late medieval and early modern period. *Economic History Review* 63(1):1-33.

**Dennison, Tracy, and Sheilagh Ogilvie. 2014.** Does the European Marriage Pattern Explain

Economic Growth? *The Journal of Economic History* 74(3):651-693.

**De Vries, Jan. 1994.** The Industrial Revolution and the Industrious Revolution. *The Journal of Economic History* 54(2):249-270.

**De Vries, Jan. 2008.** *The Industrious Revolution: Consumer Behavior and the Household Economy, 1650 to the Present*. Cambridge: Cambridge University Press.

**Diamond, Jared. 1997.** *Guns, Germs, and Steel: The Fates of Human Society*. New York: W.W. Norton & Co.

**Docquier, Frederic, and Hillel Rapoport. 2012.** Globalization, Brain Drain, and Development. *Journal of Economic Literature* 50(3):681-730.

**Doepke, Matthias. 2004.** Accounting for Fertility Decline during the Transition to Growth. *Journal of Economic Growth* 9(3):347-383.

**Drazen, Allan, and Zvi Eckstein. 1988.** On the organization of rural markets and the process of development. *The American Economic Review* 78(3):431-443.

**Duyvendak, J.J.L. 1939.** The True Dates of the Chinese Maritime Expeditions in the Early Fifteenth Century. *T'oung Pao, Second Series* 34(5):341-413.

**Dyer, Christopher. 1988.** Changes in Diet in the Late Middle Ages: The Case of Harvest Workers. *The Agricultural History Review* 36(1):21-37.

**Dyer, Christopher. 1998.** *Standards of Living in the Later Middle Ages: Social change in England c. 1200-1520, revised edition*. Cambridge: Cambridge University Press.

**Epstein, Stephan R. 2000.** *Freedom and Growth: The Rise of States and Markets in Europe, 1300-1750.* London: Routledge.

**Ernle, Lord. 1936.** *English farming: past and present.* London: Longmans, Green & Co.

**Feinstein, Charles H. 1981.** Capital accumulation and the Industrial Revolution. In *The Economic History of Britain Since 1700, vol. 1,* edited by Roderick Floud and Donald Nansen McCloskey, 128-142. Cambridge: Cambridge University Press.

**Feinstein, Charles H. 1998.** Pessimism Perpetuated: Real Wages and the Standard of Living in Britain during and after the Industrial Revolution. *Journal of Economic History* 58(3):625-658.

**Flora, Peter, Jens Alber, Richard Eichenberg, Jürgen Kohl, Franz Kraus, Winfried Pfenning, and Kurt Seebohm. 1983.** *State, Economy, and Society in Western Europe 1815-1975, volume 1.* Chicago: St. James Press.

**Fouquet, Roger, and Stephen Broadberry. 2015.** Seven Centuries of Economic Growth and Decline. *Journal of Economic Perspectives* 29(4):227-244.

**Galindev, Ragchaasuren. 2011.** Leisure goods, education attainment and fertility choice. *Journal of Economic Growth* 16:157-181.

**Galor, Oded. 2005.** From Stagnation to Growth: Unified Growth Theory. In *Handbook of Economic Growth, Vol. 1A*, edited by Philippe Aghion and Steven N. Durlauf, 171-293. Amsterdam: Elsevier.

**Galor, Oded. 2010.** Comparative economic development: Insights from unified growth theory. *International Economic Review* 51(1):1-44.

**Galor, Oded, and Omer Moav. 2002.** Natural selection and the origin of economic growth. *Quarterly Journal of Economics* 117:1133-1191.

**Galor, Oded, and Andrew Mountford. 2006.** Trade and the Great Divergence: The Family

Connection. *The American Economic Review* 96(2):299-303.

**Galor, Oded, and Andrew Mountford. 2008.** Trading Population for Productivity: Theory and Evidence. *Review of Economic Studies* 75(4):1143-1179.

**Galor, Oded, and Ömer Özak. 2015.** The Agricultural Origins of Time Preference. CESIFO Working Paper No. 5211. February.

**Galor, Oded, and David Nathan Weil. 1996.** The Gender Gap, Fertility, and Growth. *American Economic Review* 86(3):374-387.

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

**Gibson, John, and David McKenzie. 2011.** Eight Questions about Brain Drain. *Journal of Economic Perspectives* 25(3):107-128.

**Gollin, Douglas, Stephen L. Parente, and Richard Rogerson. 2002.** The role of agriculture in development. *The American Economic Review* 92(2):160-164.

**Gollin, Douglas, Stephen L. Parente, and Richard Rogerson. 2007.** The food problem and the evolution of international income levels. *Journal of Monetary Economics* 54(4):1230-1255.

**Gottfried, Robert Steven, 1983.** *The Black Death: Natural and Human Disaster in Medieval Europe*. New York: The Free Press.

**Hajnal, John. 1965.** European Marriage Patterns in Perspective. In *Population in History: Essays in Historical Demography*, edited by David Victor Glass and David Edward Charles Eversley, 101-143. London: Edward Arnold.

**Hall, Robert E., and Charles Irving Jones. 1999.** Why do some countries produce so much more output per worker than others? *Quarterly Journal of Economics* 114(1):83-116.

**Hansen, Gary D., and Edward C. Prescott. 2002.** Malthus to Solow. *The American Economic Review* 92(4):1205-1217.

**Harley, C. Knick, 1999.** Reassessing the Industrial Revolution: A Macro View. In *The British Industrial Revolution : An Economic Perspective, 2nd edition*, edited Joel Mokyr, 160-205. Boulder, Colorado: Westview Press.

**Hatcher, John. 1994.** England in the Aftermath of the Black Death. *Past & Present* 144:3-35.

**Herlihy, David. 1997.** *The Black Death and the Transformation of the West*, edited by Samuel Kline Cohn. Cambridge, Massachusetts: Harvard University Press.

**Ho, Chi Pui. 2016a.** GeoPopulation-Institution Hypothesis: Reconciling American Development Process and Reversal of Fortune within a Unified Growth Framework. In: *A Four-part treatise on the subject of Population and the Rise of Nations*. PhD diss., The University of Hong Kong.

**Ho, Chi Pui. 2016b.** Population Growth and Structural Transformation. In: *A Four-part treatise on the subject of Population and the Rise of Nations*. PhD diss., The University of Hong Kong.

**Ho, Chi Pui. 2016c.** Rise of Women in Unified Growth Theory: French Development Process and Policy Implications. In: *A Four-part treatise on the subject of Population and the Rise of Nations*. PhD diss., The University of Hong Kong.

**Jones, Eric Lionel. 1965.** Agriculture and economic growth in England, 1650-1750: agricultural change. *Journal of Economic History* 25:1-18.

**Jones, Charles Irving. 1995.** Time series tests of endogenous growth models. *The Quarterly*

*Journal of Economics* 110(2):495-525.

**Kerridge, Eric. 1967.** The Agricultural Revolution. London: George Allen & Unwin.

**Kongsamut, Piyabha, Sergio Rebelo, and Danyang Xie. 2001.** Beyond Balanced Growth. *Review of Economic Studies* 68(4):869-882.

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

**Kremer, Michael R. 1993b.** The o-ring theory of economic development. *Quarterly Journal of Economics* 108(3):551-575.

**Kydland, Finn E, and Edward C. Prescott. 1982.** Time to Build and Aggregate Fluctuations. *Econometrica* 50(6): 1345-1370.

**Lagerlöf, Nils-petter. 2003a.** From Malthus to modern growth: Can epidemics explain the three regimes? *International Economic Review* 44(2):755-777.

**Lagerlöf, Nils-petter. 2003b.** Gender equality and long-run growth. *Journal of Economic Growth* 8: 403-426.

**Lagerlöf, Nils-petter. 2006.** The Galor-Weil model revisited: A quantitative exercise. *Review of Economic Dynamics* 9:116-142.

**Lagerlöf, Nils-petter. 2010.** From Malthusian war to Solovian peace. *Review of Economic Dynamics* 13(3):616-636.

**Lin, Justin Yifu. 1995.** The Needham Puzzle: Why the Industrial Revolution Did Not Originate in China. *Economic Development and Cultural Change* 43(2): 269-292.

**Lindert, Peter H. 1980.** Child Costs and Economic Development. In *Population and Economic Change in Developing Countries*, edited by Richard A. Easterlin. Chicago: University of Chicago Press.

**Linder, Peter H, and Jeffrey G. Williamson. 1983.** English Workers' Living Standards during the Industrial Revolution: A New Look. *Economic History Review* 36(1): 1-25.

**Lucas, Robert E. 1988.** On the mechanics of economic development. *Journal of Monetary Economics* 22(1):3-42.

**Lucas, Robert E. 2002.** The Industrial Revolution: Past and Future. *Lectures on economic growth.* Cambridge, Massachusetts: Harvard University Press.

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

**Maddison, Angus. 2007.** *Contours of the World Economy 1-2030 AD: Essays in Macro-Economic History.* Oxford: Oxford University Press.

**Maddison, Angus. 2008.** Statistics on World Population, GDP and Per Capita GDP, 1-2008 AD. http://www.ggdc.net/maddison/oriindex.htm (Accessed April 1, 2016).

**Malthus, Thomas Robert. 1826.** *An essay on the principle of population, 6th edition*. London: John Murray.

**Mankiw, N. Gregory, David Romer, and David Nathan Weil. 1992.** A Contribution to the Empirics of Economic Growth. *The Quarterly Journal of Economics* 107(2):407-437.

**Manuelli, Rodolfo E., and Ananth Seshadri. 2009.** Explaining International Fertility Differences. *The Quarterly Journal of Economics* 124(2): 771-807.

**Matsuyama, Kiminori. 1992.** Agricultural Productivity, Comparative Advantage, and Economic Growth. *Journal of Economic Theory* 58(2): 317-334.

**McCloskey, Donald Nansen. 1981.** The Industrial Revolution 1780-1860: A Survey. In *The Economic History of Britain Since 1700, vol. 1*, edited by Roderick Floud and Donald Nansen McCloskey, 103-127. Cambridge: Cambridge University Press.

**Mincer, Jacob. 1958.** Investment in Human Capital and Personal Income Distribution. *Journal of Political Economy* 66(4): 281-302.

**Mitchell, Brian R. 1988.** *British Historical Statistics*. Cambridge: Cambridge University Press.

**Mokyr, Joel. 1998.** The Second Industrial Revolution, 1870-1914. http://faculty.wcas.northwestern.edu/~jmokyr/castronovo.pdf (Accessed April 1, 2016).

**Mokyr, Joel. 1999.** Editor's Introduction. In *The British Industrial Revolution : An Economic Perspective, 2nd edition*, edited Joel Mokyr, 1-127. Boulder, Colorado: Westview Press.

**Mokyr, Joel. 2000.** The Industrial Revolution and the Netherlands: Why did it not happen? *De Economists* 148(4): 503-520.

**Møller, Niels Framroze, and Paul Sharp. 2014.** Malthus in cointegration space: evidence of a post-Malthusian pre-industrial England. *Journal of Economic Growth* 19:105-140.

**Morris, Ian. 2010.** Why the West rules-- for now: the patterns of history, and what they reveal about the future. New York : Farrar, Straus and Giroux.

**Needham, Joseph. 1969.** *The grand titration: science and society in East and West*. London: George Allen & Unwin.

**Ngai, L. Rachel, and Christopher A. Pissarides. 2007.** Structural Change in a Multisector Model of Growth. *American Economic Review* 97(1): 429-443.

**North, Douglass C. 1981.** *Structure and Change in Economic History*. New York: W.W. Norton & Co.

**North, Douglass C., and Robert Paul Thomas. 1973.** *The Rise of the Western World: A New Economic History*. Cambridge: Cambridge University Press.

**Notestein, Frank W. 1976[1945].** Population—The Long View. In *Food for the World*, edited by Theodore W. Schultz, 36–57. New York: Arno Press.

**Nunn, Nathan, and Leonard Wantchekon. 2011.** The Slave Trade and the Origins of Mistrust in Africa. *American Economic Review* 101(7): 3221-3252.

**Office of National Statistics, UK.** http://www.ons.gov.uk (Accessed April 1, 2016).

**Overton, Mark. 1996.** *Agricultural Revolution in England: The Transformation of the Agrarian Economy 1500-1850*. Cambridge: Cambridge University Press.

**Pamuk, Sevket. 2007.** The Black Death and the Origins of the 'Great Divergence' across Europe, 1300–1600. *European Review of Economic History* 11(3):289–317.

**Penn, Simon A.C., and Christopher Dyer. 1990.** Wages and Earnings in Late Medieval England: Evidence from the Enforcement of the Labour Laws. *The Economic History Review* 43(3): 356-376.

**Pomeranz, Kenneth. 2000.** *The Great Divergence: China, Europe, and the Making of the Modern World Economy*. Princeton, New Jersey: Princeton University Press.

**Phelps Brown, E.H., and Sheila V. Hopkins. 1956.** Seven Centuries of the Prices of Consumables, Compared with Builders' Wage- Rates. *Economica*, 23(92): 296-314.

**Ricardo, David. 1821.** *On the Principles of Political Economy, and Taxation. 3rd ed.* London: John Murray.

**Romer, Paul Michael. 1986.** Increasing returns and long-run growth. *The Journal of Political Economy* 94(5):1002–1037.

**Romer, Paul Michael. 1990.** Endogenous technological change. *The Journal of Political Economy* 98(5):71–102.

**Roseberry, William. 1991.** Potatoes, Sacks, and Enclosures in Early Modern England. In *Golden Ages, Dark Ages: Imagining the Past in Anthropology and History*, edited by Jay O'Brien and William Roseberry, 19-47. Oxford: University of California Press.

**Russell, Josiah C., 1966.** The Preplague Population of England. *Journal of British Studies* 5(2): 1-21.

**Schultz, T. Paul. 2004.** School subsidies for the poor: evaluating the Mexican Progresa poverty program. *Journal of Development Economics* 74(1): 199– 250.

**Schultz, Theodore W. 1975.** The value of the ability to deal with disequilibria. *Journal of Economic Literature* 13(3): 827-846.

**Schumpeter, Joseph A. 1934.** The Theory of Economic Development: an inquiry into profits, capital, credit, interest, and the business cycle. Cambridge, Massachusetts: Harvard University Press.

**Slack, Paul. 1985.** *The Impact of Plague in Tudor and Stuart England*. London: Routledge and Kegan Paul.

**Smith, Adam. 1994[1776].** *An Inquiry into the Nature and Causes of the Wealth of Nations*, edited by Edwin Cannan. New York: Modern Library.

**Soares, Rodrigo R. 2005.** Mortality reductions, educational attainment, and fertility choice. *American Economic Review* 95(3): 580-601.

**Solow, Robert M. 1956.** A contribution to the theory of economic growth. *The Quarterly Journal of Economics* 70(1): 65–94.

**Spencer, Herbert. 1864.** The Principles of Biology. London: Williams and Norgate.

**Spolaore, Enrico, and Romain Wacziarg. 2009.** The Diffusion of Development. *The Quarterly Journal of Economics* 124(2):469-529.

**Strulik, Holger, and Jacob Weisdorf. 2008.** Population, food, and knowledge: a simple unified growth theory. *Journal of Economic Growth* 13:195-216.

**Strulik, Holger, and Jacob Weisdorf. 2014.** How child costs and survival shaped the industrial revolution and the demographic transition. *Macroeconomic Dynamics* 18(1):114–144.

**Temin, Peter. 2016.** Economic History and Economic Development: New Economic History in Retrospect and Prospect. In *Handbook of Cliometrics*, edited by Claude Diebolt and Michael Haupert, 33-51. New York: Springer.

**Toynbee, Arnold. 1894.** *Lectures on the industrial revolution of the 18th century in England popular addresses, notes, and other fragments.4th Edition.* London: Longmans, Green & Co.

**Vaclav, Smil. 2005.** *Creating the Twentieth Century: Technical Innovations of 1867-1914 and Their Lasting Impact.* New York: Oxford University Press.

**Voigtländer, Nico, and Hans-Joachim Voth. 2006.** Why England? Demographic factors, structural change and physical capital accumulation during the Industrial Revolution. *Journal of Economic Growth* 11(4):319-361.

**Voigtländer, Nico, and Hans-Joachim Voth. 2009.** Malthusian Dynamism and the Rise of

Europe: Make War, Not Love. *American Economic Review* 99(2): 248-54.

**Voigtländer, Nico, and Hans-Joachim Voth. 2013a.** The Three Horsemen of Riches: Plague, War, and Urbanization in Early Modern Europe. *The Review of Economic Studies* 80(2):774-811.

**Voigtländer, Nico, and Hans-Joachim Voth. 2013b.** How the West "Invented" Fertility Restriction. *The American Economic Review* 103(6): 2227-2264.

**Voigtländer, Nico, and Hans-Joachim Voth. 2013c.** Gifts of Mars: Warfare and Europe's Early Rise to Riches. *The Journal of Economic Perspectives* 27(4): 165-186.

**Vollrath, Dietrich. 2009.** The dual economy in long-run development. *Journal of Economic Growth* 14(4):287–312.

**Voth, Hans-Joachim. 2001.** The longest years: new estimates of labor input in England, 1760-1830. *Journal of Economic History* 61(4): 1065-1082.

**Wang, Feng, and Andrew Mason. 2008.** Demographic Factor in China's Transition. In *China's Great Economic Transformation*, edited by Loren Brandt and Thomas G. Rawski, 136-166. New York: Cambridge University Press.

**Weil, David N. 2013.** *Economic Growth, 3rd Edition.* Boston: Pearson.

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

**Xu, Chenggang. 2011.** The Fundamental Institutions of China's Reforms and Development. *Journal of Economic Literature* 49(4):1076–1151.

**Young, Alwyn. 1995.** The Tyranny of Numbers: Confronting the Statistical Realities of the East Asian Growth Experience. *The Quarterly Journal of Economics* 110(3): 641-680.

**Ziegler, Philip. 1997[1969].** *The Black Death.* Stroud, Gloucestershire: Sutton Publishing.

**TABLE 1**

***The Little Divergence - Britain, Continental Europe, China and Africa***

**per capita GDP (AD1990 international dollars)**

| *Year* | *Britain* | *Continental Europe* | *China* | *Africa* |
|---|---|---|---|---|
| 1 | 400 | 608 | 450 | 472 |
| 1000 | 400 | 427 | 466 | 425 |
| 1500 | 714 | 805 | 600 | 414 |
| 1600 | 974 | 898 | 600 | 422 |
| 1700 | 1,250 | 996 | 600 | 421 |
| 1820 | 1,706 | 1,127 | 600 | 420 |

**Population ('000)**

| *Year* | *Britain* | *Continental Europe* | *China* | *Africa* |
|---|---|---|---|---|
| 1 | 800 | 17,800 | 59,600 | 17,000 |
| 1000 | 2,000 | 17,700 | 59,000 | 32,300 |
| 1500 | 3,942 | 44,250 | 103,000 | 46,610 |
| 1600 | 6,170 | 56,410 | 160,000 | 55,320 |
| 1700 | 8,565 | 60,231 | 138,000 | 61,080 |
| 1820 | 21,239 | 93,320 | 381,000 | 74,236 |

Source: Maddison (2008).

-------------------------------------

**TABLE 2**

***Benchmark parameter values, to explain the Five Revolutions***

| | Interpretation | Value |
|---|---|---|
| *Parameters* | | |
| $\varphi_1$ | Utility weight attached to leisure for type 1 individuals | 1 |
| $\varphi_2$ | Utility weight attached to leisure for type 2 individuals | 1.65 |
| $\gamma$ | Utility weight attached to number of children | 4.95 |
| $\sigma$ | Elasticity of marginal utility with respect to $m_t^i$ | 0.02296 |
| $\mu$ | Agricultural production function parameter | 0.5 |
| $\varepsilon$ | Diminishing returns to agricultural learning-by-doing | 0.456 |
| $\alpha$ | Diminishing returns to labor hours in agricultural production | 0.8 |
| $\delta$ | Manufacturing production function parameter | 2 |
| $\phi$ | Diminishing returns to manufacturing learning-by-doing | 0.3 |
| $\lambda$ | Diminishing returns to labor hours in manufacturing production | 0.931 |
| $\upsilon$ | Coordination efficiency parameter for type 2 individuals | 0.3225 |
| *Initial values* | | |
| $L_1^1$ | Initial adult population of type 1 individuals | $\frac{0.003}{74.5}$ |
| $L_1^2$ | Initial adult population of type 2 individuals | $\frac{0.007}{74.5}$ |
| $A_1$ | Initial agricultural technology level | 11.95 |
| $M_1$ | Initial manufacturing technology level | 150 |

**TABLE 3**

***Timing of Industrial Revolution and Demographic Revolution, Benchmark model***

| ***Country/Region*** | ***Year of Industrial Revolution**** | ***Year of Demographic Revolution***** |
|---|---|---|
| Britain | 1780 | 1820 |
| Counterfactual economy | 2180 | 2200 |

* Criterion for Industrial Revolution: simulated annual per capital income growth rate > 0.29% (see section 3.3)

** Criteria for Demographic Revolution: simulated average fertility rate starting long-run decline (see section 3.5)

------------------------------------

**TABLE 4**

***Population estimates of Britain and other parts of Europe* ('000), AD1300-AD1400**

| | *1300* | *1400* |
|---|---|---|
| England and Wales | 5,750 | 3,000 |
| Total Europe | 94,200 | 67,950 |
| Other parts of Europe (Total Europe excluding Britain) | 88,450 | 64,950 |

Source: Pamuk (2007) Table 1.

**TABLE 5**

***Baseline parameter values in unified growth model with Black Death shock, to explain the Two Divergences***

| | Interpretation | Value | | |
|---|---|---|---|---|
| *Parameters* | | | | |
| $\varphi_1$ | Utility weight attached to leisure for type 1 individuals | 1.05 | | |
| $\varphi_2$ | Utility weight attached to leisure for type 2 individuals | 1.65 | | |
| $\gamma$ | Utility weight attached to number of children | 4.95 | | |
| $\sigma$ | Elasticity of marginal utility with respect to $m_t^i$ | 0.01 | | |
| $\mu$ | Agricultural production function parameter | 0.5 | | |
| $\varepsilon$ | Diminishing returns to agricultural learning-by-doing | 0.456 | | |
| $\alpha$ | Diminishing returns to labor hours in agricultural production | 0.8 | | |
| $\delta$ | Manufacturing production function parameter | 2 | | |
| $\phi$ | Diminishing returns to manufacturing learning-by-doing | 0.3 | | |
| $\lambda$ | Diminishing returns to labor hours in manufacturing production | 0.931 | | |
| $\upsilon$ | Coordination efficiency parameter for type 2 individuals | 0.3225 | | |
| *Initial values* | | Britain | Continental Europe | China |
| $L_1^1$ | Initial adult population of type 1 individuals | $\frac{0.003}{74.5}$ | $\frac{0.003}{3.35}$ | 0.003 |
| $L_1^2$ | Initial adult population of type 2 individuals | $\frac{0.007}{74.5}$ | $\frac{0.007}{3.35}$ | 0.007 |
| $A_1$ | Initial agricultural technology level | 11.95 | 11.95 | $\frac{11.95}{0.96}$ |
| $M_1$ | Initial manufacturing technology level | 150 | 150 | $\frac{150}{0.96}$ |

*The Black Death at AD1340-AD1359 period*

Britain – killed 0.9% of type 1 individuals and 99% of type 2 individuals

Continental Europe – killed 57% of type 2 individuals

China – no Black Death

**TABLE 6**

***Timing of Industrial Revolution and Demographic Revolution, Unified growth model with Black Death shock***

| ***Country/Region*** | ***Year of Industrial Revolution**** | ***Year of Demographic Revolution***** |
|---|---|---|
| Britain | 1780 | 1820 |
| Continental Europe | 1860 | 1900 |
| China | 1960 | 1980 |
| Africa | 2000 | 2020 |

* Criterion for Industrial Revolution: simulated annual per capital income growth rate > 0.29% (see section 3.3)

** Criterion for Demographic Revolution: simulated average fertility rate starting long-run decline (see section 3.5)

-------------------------------------

**TABLE 7**

***Baseline parameter values, to explain the African Stagnation***

| | | Interpretation | Value |
|---|---|---|---|
| *Parameters* | | $\varphi_1,\ \varphi_2,\ \gamma,\ \sigma,\ \mu,\ \varepsilon,\ \alpha,\ \delta,\ \phi,\ \lambda,\ v$ | Same as those in Table 5 |
| *Initial values* | | | |
| | $L_1^1$ | Initial adult population of type 1 individuals | $\frac{0.003}{3.51}$ |
| | $L_1^2$ | Initial adult population of type 2 individuals | $\frac{0.007}{3.51}$ |
| | $A_1$ | Initial agricultural technology level | $\frac{11.95}{0.96}$ |
| | $M_1$ | Initial manufacturing technology level | $\frac{150}{0.96}$ |
| *The Black Death at AD1340-AD1359 period* | | | |
| | Africa – no Black Death | | |

**TABLE 8**

***Independent estimates for population in England before the Black Death***

| *Year* | *Population (in millions)* | *Source* |
|---|---|---|
| 1300 | 5.75 | Pamuk (2007, 294) |
| 1310 | >6 | Campbell (1991, 49) |
| 1316 | 6 | Clark (2007, 30) |
| 1347 | 3.7 | Russell (1966, 16) |
| 1348 | 4.81 | Broadberry et al (2011, Appendix 50) |

---------------------------------------

**TABLE A.1**

***Sensitivity tests to variation in benchmark parameters and initial values***

| *Scenario* | *Change from benchmark model* | *Year of Industrial Revolution* | *Year of Demographic Revolution* |
|---|---|---|---|
| 0 | Benchmark | 1780 | 1820 |
| 1 | $\varphi_1$=1*1.1 | 1880 | 1900 |
| 2 | $\varphi_2$=1.65*1.1 | 1680 | 1720 |
| 3 | $\gamma$=4.95*1.1 | 1480 | 1500 |
| 4 | $\sigma$=0.02296+0.02 | 1620 | 1660 |
| 5 | $\mu$=0.5*1.1 | 1380 | 1400 |
| 6 | $\varepsilon$=0.456*1.1 | 1260 | Nil |
| 7 | $\alpha$=0.8*1.1 | Nil | Nil |
| 8 | $\delta$=2*1.1 | 2280 | 2320 |
| 9 | $\phi$=0.3*1.1 | Nil | Nil |
| 10 | $\lambda$=0.931+0.02 | 1420 | 1460 |
| 11 | $\nu$=0.3225*1.1 | 1760 | 1780 |
| 12 | $L_1^1=\frac{0.003}{74.5}$*1.1 | 1760 | 1800 |
| 13 | $L_1^2=\frac{0.007}{74.5}$*1.1 | 1820 | 1860 |
| 14 | $A_1$=11.95*1.1 | 1640 | 1680 |
| 15 | $M_1$=150*1.1 | 1920 | 1960 |
| 16 | Initial type 1 proportion = 0.3*1.1 | 1740 | 1780 |

**TABLE A.2**

***Sensitivity tests to variation in population estimates in Britain and Continental Europe***

| | | *Britain* | | *Continental Europe* | |
|---|---|---|---|---|---|
| *Scenario* | *Change from baseline model* | *Industrial Revolution* | *Demographic Revolution* | *Industrial Revolution* | *Demographic Revolution* |
| 17 | Baseline | 1780 | 1820 | 1860 | 1900 |
| 18 | pre-Black Death, England population = 6m. | 1780 | 1820 | 1860 | 1900 |
| 19 | pre-Black Death, England population = 4.81m. | 1840 | 1880 | 1860 | 1900 |
| 20 | pre-Black Death, England population = 3.7m. | 1980 | 2000 | 1860 | 1900 |
| 21 | Continental Europe death rate = 25% in AD1341-AD1360 | 1780 | 1820 | 1880 | 1900 |
| 22 | Continental Europe death rate = 60% in AD1341-AD1360 | 1780 | 1820 | 1760 | 1800 |

---------------------------------------------

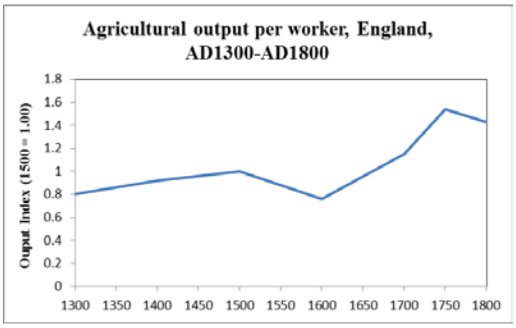
**TABLE A.3**

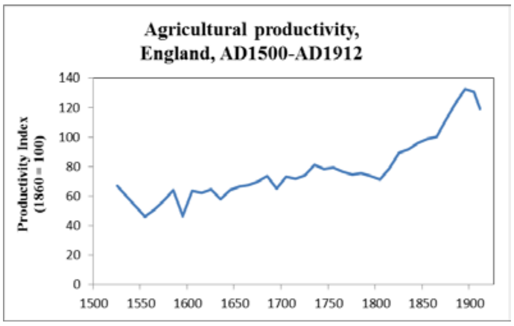
***Implied aggregate death rates and type-specific mortality rates from Table A.2***

| | | *Britain* | | *Continental Europe* | |
|---|---|---|---|---|---|
| *Scenario* | *Implied aggregate death rates in the fourteenth century* | *Type 1 mortality rates* | *Type 2 mortality rates* | *Type 1 mortality rates* | *Type 2 mortality rates* |
| 17 | Baseline: 48% | 0.9% | 99% | 0% | 57% |
| 18 | Britain: 50% | 5% | 99% | - | - |
| 19 | Britain: 38% | 0% | 79% | - | - |
| 20 | Britain: 19% | 0% | 40% | - | - |
| 21 | Continental Europe: 25% | - | - | 0% | 53% |
| 22 | Continental Europe: 60% | - | - | 25% | 99% |

Note: Aggregate death rate = 1- $\begin{bmatrix} Type1\ pop.\% \times (1 - Type1\ mortality\ rate) \\ + Type2\ pop.\% \times (1 - Type2\ mortality\ rate) \end{bmatrix}$

**FIGURE 1A** **FIGURE 1B**

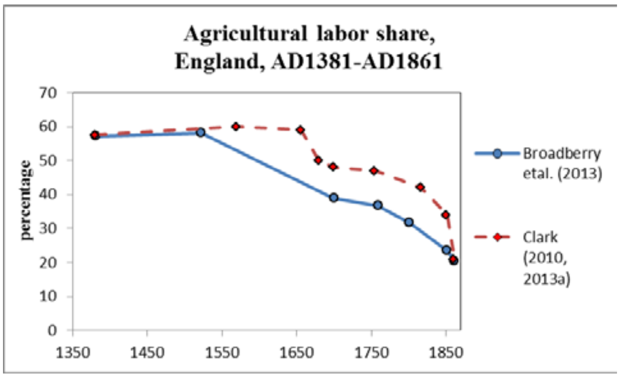



Note: (Left) Agricultural output per worker (1500=1.00), England, AD1300-AD1800. Source: Allen (2000) Table 8. (Right) Agricultural productivity index (1860=100), England, AD1500-AD1912. Source: Clark (2002) Table 5.

--------------------------------------

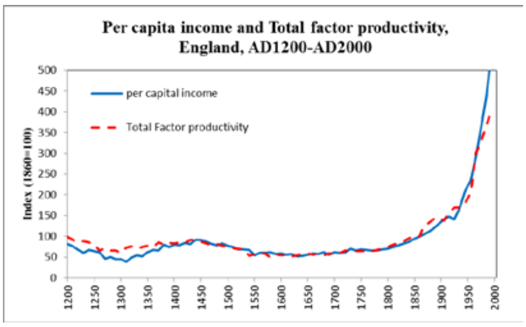
**FIGURE 2**




Note: Agricultural labor share, England, AD1381-AD1861. Solid (blue) line: Broadberry et al. (2013) estimates. Dotted (red) line: Clark (2010, 2013a) estimates. Sources: Broadberry et al. (2013a) Table 9; Clark (2013) Table 2, section 7 for AD1381-AD1660 data; Clark (2010) for AD1680-AD1851 data.

--------------------------------------

**FIGURE 3A** **FIGURE 3B**

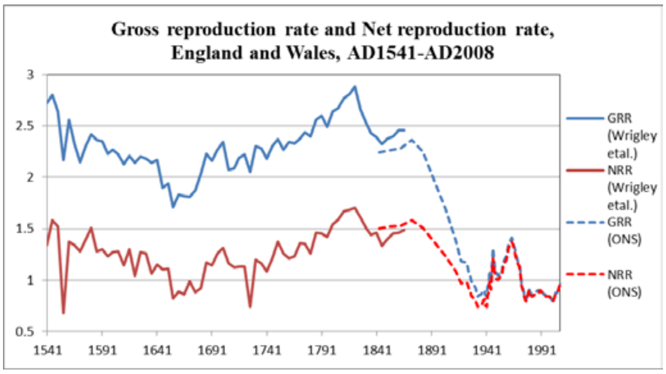

Note: (Left) Real wages (1860=100), England, AD1760-AD1870. Sources: Feinstein (1998) Appendix Table 1, Average Full-Employment Real Earnings. Clark (2005) Table A2, Craftsmen's Real Wage. (Right) Solid (blue) line: Per capita income (1860=100), England, AD1200-AD2000. Dotted (red) line: Total factor productivity (1860=100), England, AD1200-AD2000. Sources: Clark (2010) Tables 28, 33-34.

**FIGURE 4**


Note: Solid (blue) line: Annual working days, Britain, AD1433-AD1870. Dashed (red) line: Female labor-force participation rates in U.K., AD1955-AD1999. Sources: annual working days from Allen and Weisdorf (2011) Table 2, which in turn based on Blanchard (1978), Clark & van der Werf (1998) Table 1 (we obtain AD1867-AD1870 data here), Voth (2011) Table 7; female labor-force participation rate from de Vries (2008) Table 6.1.

-------------------------------------

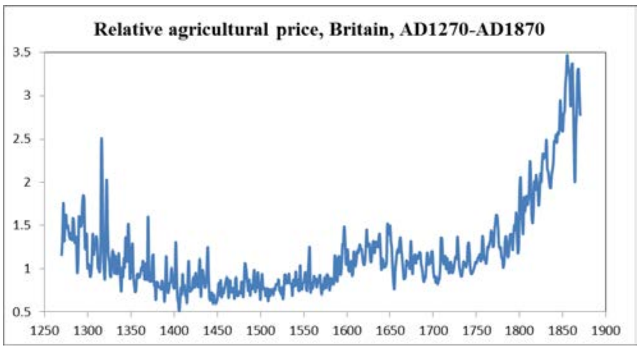
**FIGURE 5**




Note: Gross reproduction rate and Net reproduction rate, England and Wales, AD1541-AD2008. Source: Wrigley et al. (1997) Table A9.1 for AD1541-AD1866 data (solid lines). Office of National Statistics, U.K. for AD1941-AD2008 data (dotted lines).

-------------------------------------

**FIGURE 6**




Note: Relative agricultural price, Britain, AD1270-AD1870. Source: Broadberry et al. (2011) Agriculture price index divided by Industry price index.

**FIGURE 7A**

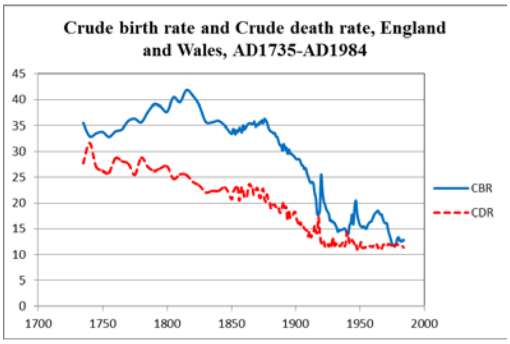
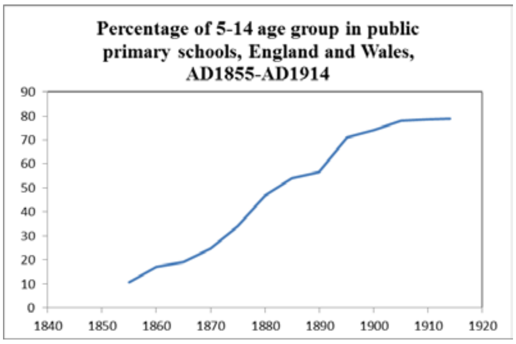


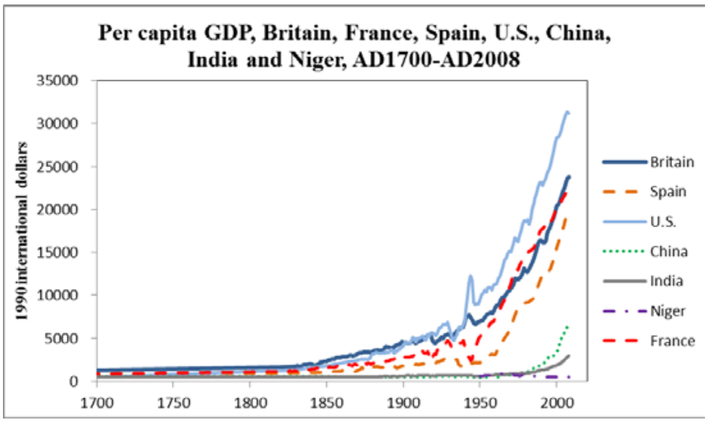

**FIGURE 7B**




Note: (Left) Crude birth rate and Crude death rate, England and Wales, AD1735-AD1984. Source: Chesnais (1992), Appendix 1 for CBR, Appendix 3 for CDR. (Right) Percentage of 5-14 age group in public primary schools, England and Wales, AD1855-AD1914. Source: Flora et al. (1983, 624-625).

--------------------------------------

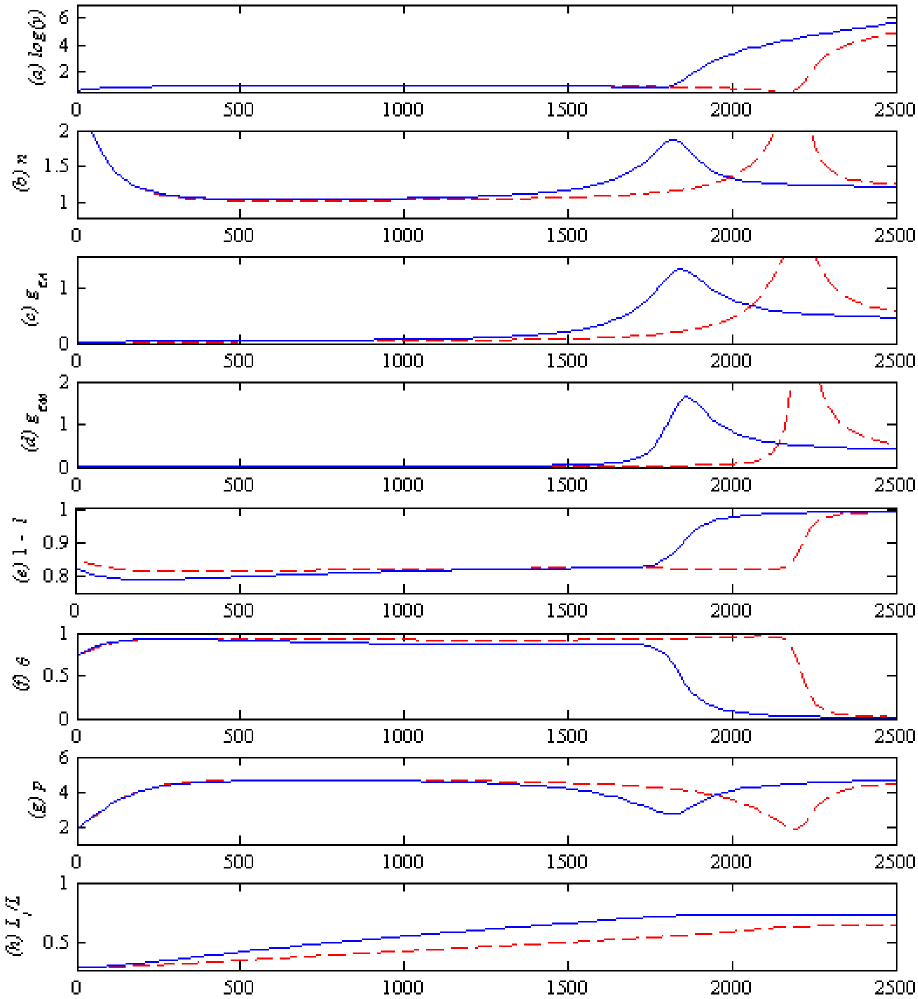
**FIGURE 8**




Note: Per capita GDP in Britain (blue solid line), France (red dashed line), Spain (orange dashed line), United States (light blue solid line), China (green dotted line), India (grey solid line) and Niger (purple dotted-dashed line) in AD1990 international dollars, AD1700-AD2008. Source: Maddison (2008).

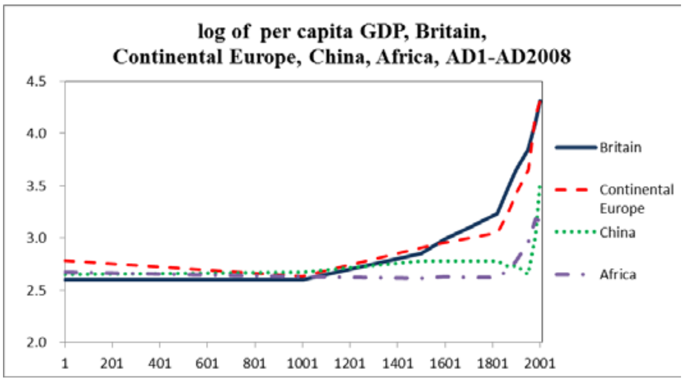
**FIGURE 9**

**Development dynamics and the Five Revolutions, Britain, AD0-AD2500**




Note: Solid (blue) lines: the benchmark economy. Dashed (red) lines: the counterfactual economy, $\varphi_2 = 1.3$, otherwise benchmark parameters from Table 2. Panels (a) to (f) show log of per capita income, average fertility rate, growth rate of agricultural productivity, growth rate of manufacturing productivity, average working hours, agricultural labor hours share, relative food price, and proportion of the more industrious individuals in population.

**FIGURE 10**




Note: log of per capita GDP in Britain (blue solid line), Continental Europe (red dashed line), China (green dotted line), and Africa (purple dotted-dashed line), AD1700-AD2008. Source: Maddison (2008).

--------------------------------------

**FIGURE 11A**

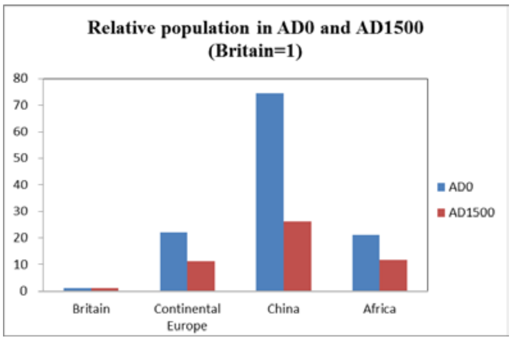
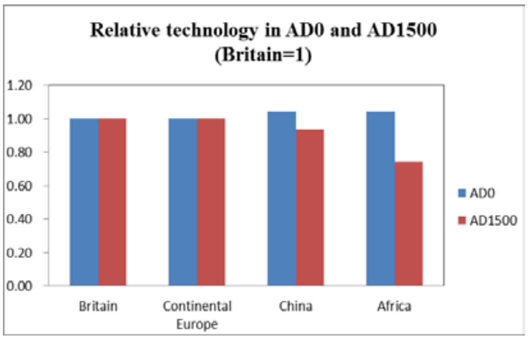



**FIGURE 11B**




Note: Comparison of population sizes and technology levels among Britain, Continental Europe, China and Africa in AD0 and AD1500 (Britain levels = 1). Sources: Maddison (2008), Comin et al. (2010).

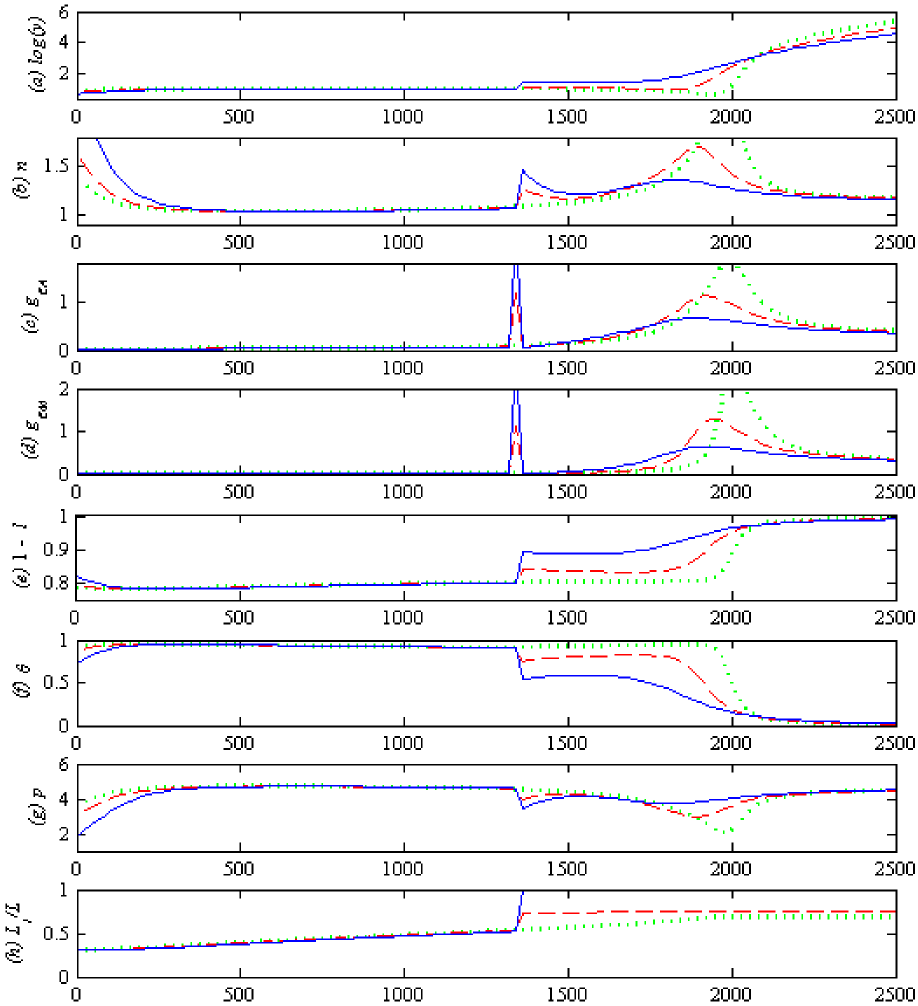
--------------------------------------

**FIGURE 12**

***Developmental impact of the Black Death***

**FIGURE 13**

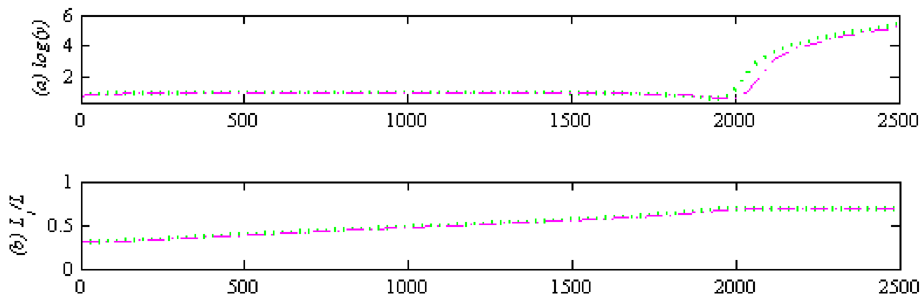
**The Black Death and the Two Divergences, Eurasia, AD0-AD2500**




Note: Solid (blue) lines: British economy. Dashed (red) lines: Continental European economy. Dotted (green) lines: Chinese economy. Parameters from Table 5. Panels (a) to (f) show log of per capita income, average fertility rate, growth rate of agricultural productivity, growth rate of manufacturing productivity, average working hours, agricultural labor hours share, relative food price, and proportion of the more industrious individuals in population.

**FIGURE 14**

**The African stagnation, AD0-AD2500**

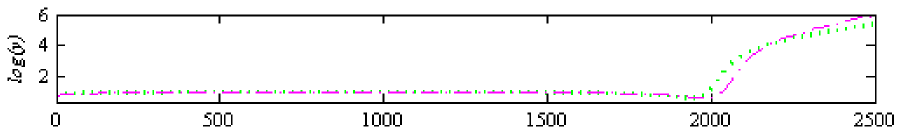



Note: Dotted-dashed (purple) lines: African economy. Dotted (green) lines: Chinese economy. Parameters from Tables 5 and 7. Panels (a) and (b) show log of per capita income, and proportion of the more industrious individuals in population.

-------------------------------------

**FIGURE A.1**

**African evolution policy P1**

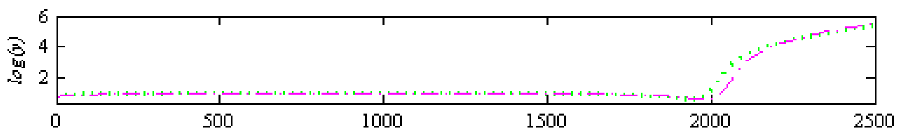



Note: Dotted-dashed (purple) line: African economy with evolution policy P1. Dotted (green) line: Chinese economy. Parameters from Tables 5 and 7. The panel shows log of per capita income evolution.

-------------------------------------

**FIGURE A.2**

**African evolution policy P2**




Note: Dotted-dashed (purple) line: African economy with evolution policy P2. Dotted (green) line: Chinese economy. Parameters from Tables 5 and 7. The panel shows log of per capita income evolution.