Trade, Technology, and the Great Divergence

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Abstract

Why did North-South divergence occur so dramatically during the era of late 19th Century globalisation, rather than at the outset of the Industrial Revolution? How were some countries able to reverse this trend during the globalization of the late 20th Century? To answer these questions, this paper develops a trade-and-growth model that captures the key features of the Industrial Revolution and Great Divergence between an industrializing "North" and a potentially lagging "South." The model includes both endogenous biased technological change and intercontinental trade. An Industrial Revolution begins as a sequence of unskilled-labor-intensive innovations which initially incite fertility increases and limit human capital formation in both the North and the South. We show that the subsequent co-evolution of trade and technological growth can create a delayed, but inevitable divergence in living standards — the South increasingly specializes in production that worsens its terms of trade and spurs even greater fertility increases and educational declines. Adding technological diffusion from North to South can mitigate and even reverse divergence, spurring a reversal of fortune for the South.

Keywords: Industrial Revolution, unified growth theory, endogenous growth, demography, fertility, education, skill premium, North-South model

JEL Codes: O, F, N

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1. Introduction

The last two centuries have witnessed dramatic changes in the global distribution of income. At the dawn of the Industrial Revolution, gaps in living standards between the richest and poorest economies of the world were roughly in the range 2 to 1. With industrialization came both income and population growth in a few core countries. But massive divergence in living standards across the globe did not emerge right away. It was not seen until the latter half of the 19th century, the time when the first great era of globalization started to take shape (see Figure 1). Today the gap in material living standards between the richest and poorest economies of the world is of the order of 30 or 40 to 1, in large part due to the events of the 19th century. And yet today, as the world experiences a second era of globalization, a few formerly developing countries in the "South" are on the path towards convergence with the "North" and global inequality is starting to abate.

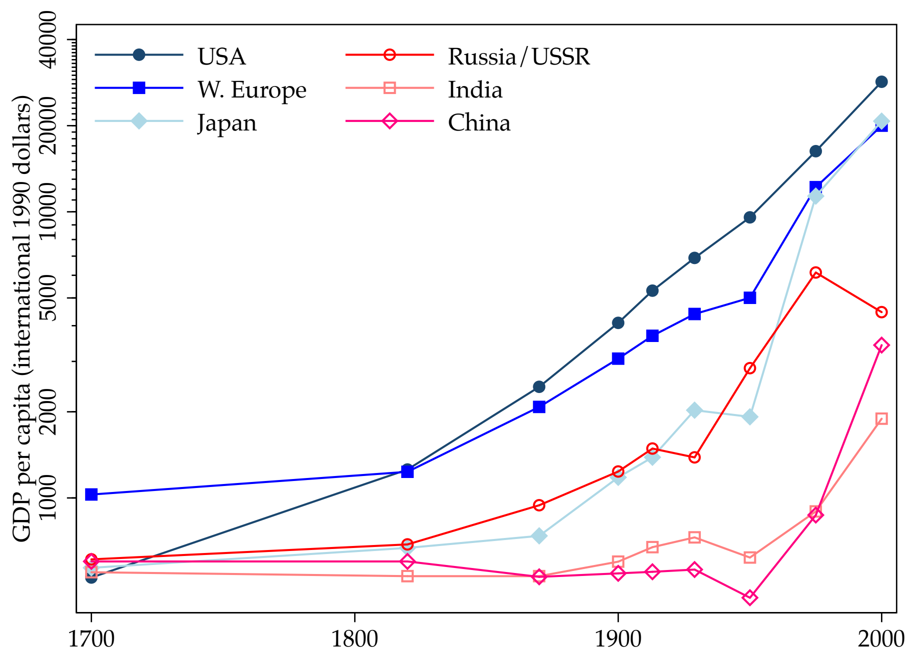
It seems to us an interesting coincidence that the unprecedented growth in 19th century inter-continental commerce (conceivably creating a powerful force for convergence by inducing countries to exploit their comparative advantages) coincided so precisely with an unprecedented divergence in living standards across the world. Why did incomes diverge just as the world became flatter? And why are some poor countries today able to replace divergence with convergence, in the midst of a second era of globalization?

Globalization is a multidimensional phenomenon. In this paper, we focus on two dimensions that seem particularly relevant to the international distribution of income: lower trade barriers and the faster diffusion of knowledge between countries. Economic theory is ambiguous about whether the former, in particular, promotes convergence or divergence between rich and poor countries. Standard neoclassical models may lean toward the former, but models with increasing returns, externalities, or path dependence, can favor the latter. Can a unified model be found which can helps explain the very different experiences of the first and second eras of globalization?

The main goal of this paper is to present a unified growth model where both pro- and anti-convergence forces are potentially present, but where their relative strengths are generally state- and history-dependent. We argue that historical trade and technological growth patterns *jointly* sowed the seeds of divergence, contributing enormously to today's great wealth disparities, while they are now operating so as to mitigate these disparities.

Some important "stylized facts" from economic history motivate our search for a new theory. One concerns the nature of industrialization itself — technological change was unskilled-labor-intensive during the early Industrial Revolution but became relatively

Figure 1: *Real GDP per capita in six economies since 1700*



Source: Maddison (2010).

skill-intensive during the late 19th century. For example, the cotton textile industry, which along with metallurgy was at the heart of the early Industrial Revolution, was able to employ large numbers of unskilled and uneducated workers, thus diminishing the relative demand for skilled labor and education (Galor 2005; Clark 2007; de Pleijt and Weisdorf forthcoming). By the 1850's, however, two major changes had occurred — technological growth became much more widespread, and it became far more skill-using (Mokyr 2002).

Another factor of great importance was the rising role of international trade in the world economy. Inter-continental commerce between "western" economies and the rest of the world (which we will mildly mislabel as "North-South" trade, in the language of these models) grew dramatically in the second half of the 19th century. By the 1840s steam ships were faster and more reliable than sailing ships, but their high coal consumption limited how much cargo they could transport; consequently only very light and valuable freight was shipped (O'Rourke and Williamson 1999). But by 1870 a number of innovations had dramatically reduced the cost of steam ocean transport, and real ocean freight rates fell by nearly 35% between 1870 and 1910 (Clark and Feenstra 2003). By 1900 the economic centers of the "South" such as Alexandria, Bombay, and Shanghai were fully integrated into the British economy, both in terms of transport costs and capital markets (Clark 2007).

Thus, while the British economy remained relatively closed during the first stages of the Industrial Revolution (1750–1850), it became dramatically more open during the latter stages of industrialization (1850–1910).

Modeling Trade and Divergence We develop a two-region model with several key features mimicking these historical realities. The first key feature of the model is that we endogenize the extent and direction of bias of technological change in both regions. Technologies are sector specific, and sectors have different degrees of skill intensity. Following the endogenous growth literature, we allow potential innovators in the North (and, in some cases, in the South) to observe factor use in different sectors, and tailor their research efforts towards particular sectors. Thus the scope and direction of innovation will depend on each region's factor endowments and hence on its demography.

The second key feature is that we endogenize demography itself. More specifically, we allow households to make education and fertility decisions based on market wages for skilled and unskilled labor, as in other endogenous demography and unified growth theories in which households face a quality-quantity tradeoff with respect to their children. When the premium for skilled labor rises, families will tend to have fewer but better educated children.

The final feature is that we allow for time-varying trade costs between the North and the South. During the initial stages of industrialization, our "baseline case" assumes that trade is not possible due to prohibitively high transport costs. However, these costs exogenously decrease over time; at a certain point trade becomes feasible, at which time the South exchanges unskilled-labor-intensive products for the North's skill-intensive products. It is at this stage that development paths begin to markedly diverge — the North's specialization in skilled production produces a demographic transition, while the South's specialization in unskilled production generates unskilled-labor-intensive technological growth but also more population.

We simulate this model to demonstrate a number of key historical interactions between the Northern and Southern economies. We first present the results for a baseline case which we suggest roughly captures the dynamics for the period from 1700 to the early 1900s. Because of the great abundance of unskilled labor in the world, innovators everywhere first develop unskilled-labor intensive technologies. Early industrialization is thus characterized by unskilled-labor-intensive technological growth and population growth *both* in the North and the South; living standards slightly converge during this period. Once trade becomes possible, however, the North starts specializing in skill-intensive innovation and production. This induces a demographic transition of falling

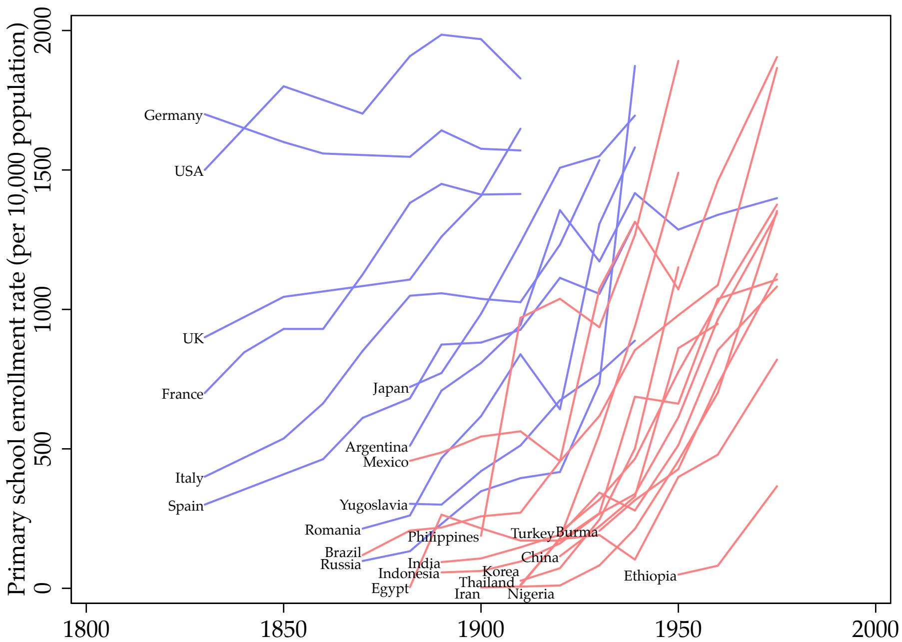
fertility and rising education rates in the North, while the South specializes in unskilled-labor-intensive production, inducing both unskilled-labor-intensive technological growth and further population growth (Figures 2 and 3). This population divergence fosters a deterioration in the South's terms of trade, forcing the South to produce more and more primary commodities and generating even more fertility increases (Figure 4). Thus the South's static gains from trade become a dynamic impediment to prosperity, and living standards between the two regions diverge dramatically.

We also simulate an alternative scenario more reminiscent of the mid- and later- 20th century, and perhaps the 21st also. In this case, we assume for illustration, and as a polar extreme, that the South does not invent its own technologies but instead costlessly adopts, i.e., imports, technologies developed by the North. We show that in this case trade and technological change can still interact so as to generate some divergence early on. This occurs because skill-oriented technologies developed in the North are somewhat "inappropriate" in the South, given endowment differences. But we also show that this divergence must eventually give way to convergence. This is because trade-induced skilled specialization in the North generates a deep pool of skill-intensive technologies from which even the South, with its relatively low endowment of skilled workers, can benefit in the end. That is, what is in the short run "inappropriate" (for a low-skill, high-fertility South) may in the long run benefit living standards (by eventually leading the South down a high-skill, low-fertility path).

Alternative Stories of Divergence We argue that analyzing the interactions between the North and the South, and between trade, innovation and technological transfers, is critical to understanding the Industrial Revolution, the Great Divergence and the subsequent convergence paths of some peripheral economies. Many explanations of divergence rely on institutional differences between various regions of the world (North and Thomas 1973; Acemoglu et al. 2001, 2005). From that perspective economic growth is a matter of establishing the right "rules of the game," and underdevelopment is simply a function of some form of institutional pathology. Our model implicitly assumes that the institutional prerequisites for technological progress are in place, in all times and places. But divergence can still occur, and our model makes the important point that interactions between regions are an independent source of potential divergence and convergence. If so, it may be a mistake to think of differential growth patterns as having been solely generated by institutional differences in economies, which might as well have been operating in isolation from each other.

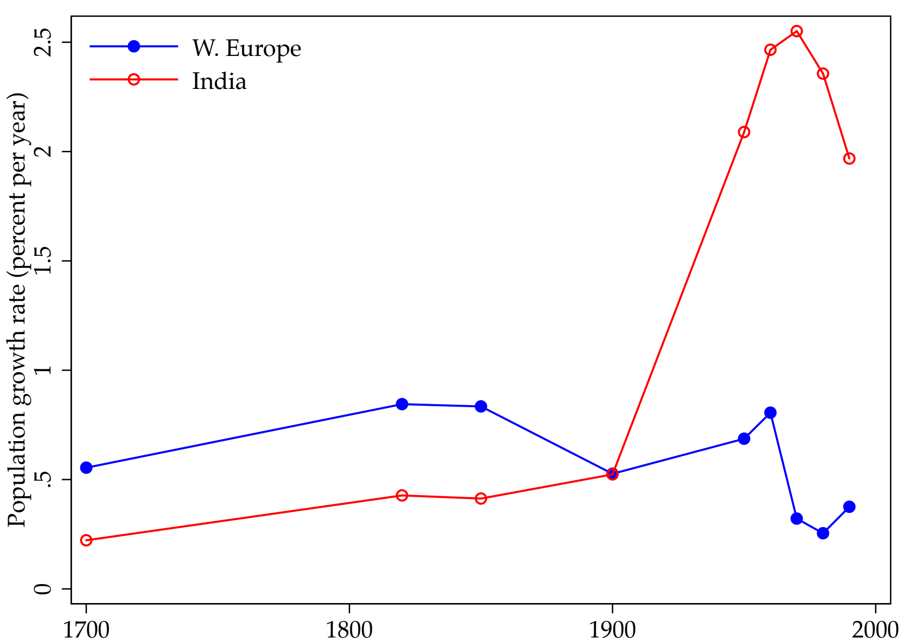
Another potential explanation for the divergence is that peripheral countries were

Figure 2: *Primary school enrollment rates in many economies since 1800*



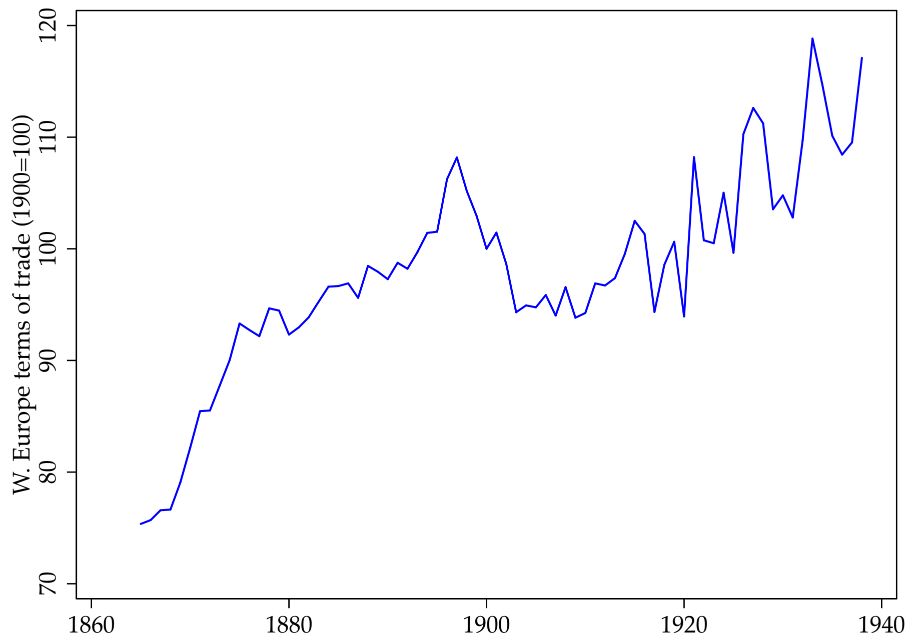
Source: Easterlin (1981).

Figure 3: *Population growth rates in the U.K. and India since 1700*



Source: Maddison (2010).

Figure 4: *Western European terms of trade 1870–1938 (1900 = 100)*



Source: Author's calculations based on Hadass and Williamson (2003).

specializing in *inherently* less-productive industries (Galor and Mountford 2006, 2008). But this is not very convincing — so called low-technology sectors such as agriculture enjoyed large productivity advances during the early stages of the Industrial Revolution (Lipsey and Bekar 1995; Clark 2007). And in the twentieth century, developing countries specialized in textile production which had experienced massive technological improvements more than a century before.

A related puzzle has to do with the size of the developing world. If fully one third of the world had become either Indian or Chinese by the twentieth century (Galor and Mountford 2002), why were Indians and Chinese not wealthier? After all, most semi-endogenous and endogenous growth theories have some form of scale effect, whereby large populations can spur innovation (Acemoglu 2010; Jones 2003).[1] Any divergence story that focuses on the explosive population expansion in peripheral economies faces this awkward implication from the canonical growth literature.

[1]More specifically, in such seminal endogenous growth models as Romer (1986, 1990), Segerstrom, Anant, and Dinopolous (1990), Aghion and Howitt (1992), and Grossman and Helpman (1991), a larger labor force implies faster growth of technology. In "semi-endogenous" growth models such as Jones (1995), Young (1998), and Howitt (1999), a larger labor force implies a higher level of technology.

Relation to Galor and Mountford's "Trade and the Great Divergence" The paper presented here relates most closely and obviously to Oded Galor and Andrew Mountford's theoretical works on the Great Divergence (Galor and Mountford 2006; 2008; henceforward GM). These papers similarly suggest that the South's specialization in unskilled-intensive production stimulated fertility increases which lowered per capita living standards. However, our narrative of the North's launching into modernity and the South's vicious cycle of underdevelopment is distinct in a number of ways.

First, we explicitly model and simulate changes in the terms of trade for each region. In GM the terms of trade are not explicitly discussed, and it remains unclear how they would influence patterns of divergence.[2] Here we demonstrate that demographic divergence will affect the terms of trade by altering the composition of the world economy. This will have important implications for relative incomes.

Second, we endogenize both the scope and the direction of technological progress in both regions. GM make assumptions on the timing and speed of a purely exogenous technological growth process which they claim are "consistent with historical evidence." Specifically, they assume that: (1) modernization either in agriculture or in industry is not initially feasible; (2) modernization occurs first in agriculture; and (3) growth in industrial-sector productivity is faster than growth in agricultural-sector productivity. Compelling as these assumptions may seem, they are not universally shared. Rather than consigning the South to the inherently slower-growing industry, we endogenize the direction and speed of technological development in both regions by introducing a directed technical change mechanism.

Finally, rather than suddenly opening up the North and South from pure autarky to totally free trade, like GM, we allow for *gradual* increases in North-South commerce. The British economy (and other Western economies) presumably did not undergo a discontinuous switch from a closed to an open state, and we thus assume continuously declining transport costs, consistent with well documented evidence from many sources on both directly measured declines in freight rates and shipping costs, and imputed declines in model-based trade costs.[3] This approach also allows us to compare the more realistic scenario of a gradually opening world with more extreme cases of perfectly

[2]Specifically, in GM the opening up of each economy to trade with the other does two basic things ? it speeds up demographic transition in the North relative to the South, and it speeds up technological growth in the North relative to the South. While the former effect can improve the Northern terms of trade (as Southern goods "flood" the relatively smaller North), the latter effect conceivably harms it (as Northern goods "flood" the stagnant and less prosperous South). Which effect might be dominant remains unclear.

[3]For direct freight cost measures see North (1958), Harley (1988), O'Rourke and Williamson (2002), Mohammed and Williamson (2004), and Jacks and Pendakur (2010). For imputed trade costs see Jacks et al. (2010).

closed or open economies, which can serve both as robustness checks and as a guide to the causal role played by declining trade costs.

These key differences allow our model to address two issues on which the GM model is silent. The first relates to the terms of trade between North and South. In our model, the South's specialization in agriculture and low-end manufacturing allowed for plenty of technological advances, but these did not promote Southern per capita growth for two reasons. One is that they fostered fertility increases similar to the process outlined in GM. The other is that the South's terms of trade deteriorated over time. As the South's share of the world population grew, it flooded world markets with its primary products. Northern skill-intensive products became relatively scarcer, and thus fetched higher prices. The South had to provide more and more primary products to buy the same amount of high-end products; through the impact of the terms of trade on factor prices, this served to raise fertility rates even more. This mechanism, not discussed in GM, suggests that productivity growth (and the scale of the Southern economy that generated this growth) could not salvage the South; in fact it contributed to its relative decline.

Also absent from GM is the possibility of technological transfer. This possibility would seem to have been of greater relevance in the 20th and 21st centuries, as peripheral economies have become increasingly capable of adopting ideas from the world technological frontier (as a result of better education, better communications, multinational enterprise, value-chain participation, and so on). We demonstrate that under the assumption of perfect technological diffusion the trade-technology interactions we emphasize can now work in the opposite direction, and actually hasten *convergence* in the long run. Thus we provide the novel insight that the kind of technological diffusion regime in place may play a crucial role in determining whether or not trade generates per capita income divergence.

2. Production with Given Technologies and Factors

We now sketch out a model that we use to describe both a northern and a southern economy (superscripts denoting region are suppressed for the time being).

Total production for a region is given by

$$Y = \left(\frac{\alpha}{2} Q_1^{\frac{\sigma-1}{\sigma}} + (1-\alpha) Q_2^{\frac{\sigma-1}{\sigma}} + \frac{\alpha}{2} Q_3^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}}, \tag{1}$$

where $\alpha \in [0,1]$ and $\sigma \geq 0$ is the elasticity of substitution among the three intermediate

goods Q_1, Q_2, and Q_3. The production of each these goods is given by:

$$\begin{aligned} Q_1 &= A_1 L_1, && (2) \\ Q_2 &= A_2 L_2^{\gamma} H_2^{1-\gamma}, && (3) \\ Q_3 &= A_3 H_3, && (4) \end{aligned}$$

where A_1, A_2 and A_3 are the technological levels of sectors 1, 2, and 3, respectively.[4]

In turn, the technological levels of each sector can be represented by an aggregation of *sector-specific* machines per worker. Specifically,

$$\begin{aligned} A_1 &= \int_0^{N_1} \left(\frac{x_1(j)}{L_1} \right)^{\alpha} dj, && (5) \\ A_2 &= \int_0^{N_2} \left(\frac{x_2(j)}{L_2^{\gamma} H_2^{1-\gamma}} \right)^{\alpha} dj, && (6) \\ A_3 &= \int_0^{N_3} \left(\frac{x_3(j)}{H_3} \right)^{\alpha} dj, && (7) \end{aligned}$$

where $x_i(j)$ is the number of machines of type j that can be employed only in sector i. Intermediate producers choose the amounts of these machines to employ, but the number of *types* of machines in each sector is exogenous to producers. Technological progress in sector i can then be represented by growth in this number of machine-types for the sector, denoted as N_i (which we endogenize later on, by introducing a model of research).

Treating technological coefficients as exogenous for the time being, we can assume that markets for both the final good and intermediate goods are perfectly competitive. Thus, prices are equal to unit costs. Solving the cost minimization problems for producers, and normalizing the price of final output to one, yields the unit cost functions

$$\begin{aligned} 1 &= \left[\left(\frac{\alpha}{2} \right)^{\sigma} (p_1)^{1-\sigma} + (1-\alpha)^{\sigma} (p_2)^{1-\sigma} + \left(\frac{\alpha}{2} \right)^{\sigma} (p_3)^{1-\sigma} \right]^{\frac{1}{1-\sigma}}, && (8) \\ p_1 &= \frac{w_l}{A_1}, && (9) \\ p_2 &= \left(\frac{1}{A_2} \right) w_l^{\gamma} w_h^{1-\gamma} (1-\gamma)^{\gamma-1} \gamma^{-\gamma}, && (10) \\ p_3 &= \frac{w_h}{A_3}, && (11) \end{aligned}$$

[4] Thus sectors vary by *skill*-intensity. While our interest is mainly in the "extreme" sectors (1 and 3), we require an intermediate sector so that production of intermediate goods are determined both by relative prices and endowments, and not pre-determined solely by endowments of L and H. This will be important when we introduce trade to the model.

where p_i denotes the price for intermediate good Q_i, w_l is the wage paid to L and w_h is the wage paid to H.

Full employment of unskilled and skilled labor implies factor-market clearing, with

$$L = \frac{Q_1}{A_1} + \frac{w_l^{\gamma-1} w_h^{1-\gamma} (1-\gamma)^{\gamma-1} \gamma^{1-\gamma} Q_2}{A_2}, \tag{12}$$

$$H = \frac{w_l^{\gamma} w_h^{-\gamma} (1-\gamma)^{\gamma} \gamma^{-\gamma} Q_2}{A_2}. + \frac{Q_3}{A_3} \tag{13}$$

Finally, the demands for intermediate goods from final producers can be derived from a standard CES objective function.[5] Specifically, as shown in the appendix, intermediate goods market clearing requires

$$Q_i = \left(\frac{\xi_i^{\sigma} p_i^{-\sigma}}{\left(\frac{\alpha}{2}\right)^{\sigma} (p_1)^{1-\sigma} + (1-\alpha)^{\sigma} (p_2)^{1-\sigma} + \left(\frac{\alpha}{2}\right)^{\sigma} (p_3)^{1-\sigma}} \right) Y, \tag{14}$$

for $i = 1, 2, 3$, and for convenience we define constants $\xi_1 = \xi_3 = \alpha/2$, and $\xi_2 = 1 - \alpha$.

Provided that we have values for L, H, A_1, A_2 and A_3, along with parameter values, we have thirteen equations [(1)–(4), (8)–(13), and three instances of (14)] with thirteen unknowns [Y, p_1, p_2, p_3, Q_1, Q_2, Q_3, w_l, w_h, L_1, L_2, H_2, H_3]. The solution for all of these variables constitutes the solution for the *static* model in the case of exogenously determined technological and demographic variables.

3. Endogenizing Technologies in Both Regions

In this section we describe how innovators endogenously develop new technologies. In general, modeling purposive research and development effort is challenging when prices and factors change over time. This is because it is typically assumed that the gains from innovation will flow to the innovator over time, and this flow will depend on the price of the product being produced and the factors required for production at each moment in time.[6] If prices and factors are constantly changing (as they will in any economy where trade barriers fall gradually or factors evolve endogenously), a calculation of the true discounted profits from an invention may be impossibly complicated.

[5] Here demands will be negatively related to own price, will be a function of a price index, and will be proportional to total product.

[6] For example, the seminal Romer (1990) model describes the discounted present value of a new invention as a positive function of $L - L_R$, where L is total workforce and L_R is the number of researchers. Calculating this value is fairly straightforward if supplies of production workers and researchers are constant. If they are not, however, calculating the true benefits to the inventor may be difficult.

To avoid such needless complication but still gain from the insights of endogenous growth theory, we assume that the gains from innovation last *one time period only.* More specifically, technological progress is sector-specific, and comes about through increases in the numbers of varieties of machines employed in each sector. New varieties of machines are developed by profit-maximizing inventors, who for one period can *monopolistically* produce and sell the machines to competitive producers of the intermediate goods Q_1, Q_2, or Q_3. However, we assume that the blueprints to these machines become public knowledge the time period after the machine is invented, at which point these machines become old and are *competitively* produced and sold.[7] Thus while we need to distinguish between old and new sector-specific machines, we avoid complicated dynamic programming problems inherent in multiple-period profit streams.[8]

Thus, we can re-define sector-specific technological levels in equations (5)–(7) as a sum over old and new machines at time t (once again suppressing region superscripts):

$$\begin{aligned} A_{1,t} &= \left(\int_0^{N_{1,t-1}} x_{1,old}(j)^\alpha dj + \int_{N_{1,t-1}}^{N_{1,t}} x_{1,new}(j)^\alpha dj\right)\left(\frac{1}{L_1}\right)^\alpha, \\ A_{2,t} &= \left(\int_0^{N_{2,t-1}} x_{2,old}(j)^\alpha dj + \int_{N_{2,t-1}}^{N_{2,t}} x_{2,new}(j)^\alpha dj\right)\left(\frac{1}{L_2^\gamma H_2^{1-\gamma}}\right)^\alpha, \\ A_{3,t} &= \left(\int_0^{N_{3,t-1}} x_{3,old}(j)^\alpha dj + \int_{N_{3,t-1}}^{N_{3,t}} x_{3,new}(j)^\alpha dj\right)\left(\frac{1}{H_3}\right)^\alpha, \end{aligned}$$

where $x_{i,old}$ are machines invented before t, and $x_{i,new}$ are machines invented at t. Thus in each sector i there are $N_{i,t-1}$ varieties of old machines that are competitively produced, and there are $N_{i,t} - N_{i,t-1}$ varieties of new machines that are monopolistically produced (again, suppressing country subscripts).

Next, we must describe producers of intermediate goods in each region. These three different groups of producers each separately solve the following maximization problems:

$$\begin{aligned} &\text{Sector 1 producers:} && \max_{a[L_1, x_1(j)]} \left\{p_1 Q_1 - w_l L_1 - \int_0^{N_1} \chi_1(j) x_1(j) dj\right\}, \\ &\text{Sector 2 producers:} && \max_{[L_2, H_2, x_2(j)]} \left\{p_2 Q_2 - w_l L_2 - w_h H_2 - \int_0^{N_2} \chi_2(j) x_2(j) dj\right\}, \\ &\text{Sector 3 producers:} && \max_{[H_3, x_3(j)]} \left\{p_3 Q_3 - w_h H_3 - \int_0^{N_3} \chi_3(j) x_3(j) dj\right\}, \end{aligned}$$

[7] Here one can assume either that patent protection for intellectual property lasts one time period, or that it takes one time period for potential competitors to reverse-engineer the blueprints for new machines.

[8] See Rahman (2013) for more discussion of this simplifying (but arguably realistic) assumption.

where $\chi_i(j)$ is the price of machine j employed in sector i. For each type of producer, their maximization problem with respect to machine j yields machine demands:

$$x_1(j) = \chi_1(j)^{\frac{1}{\alpha-1}} (\alpha p_1)^{\frac{1}{1-\alpha}} L_1, \tag{15}$$
$$x_2(j) = \chi_2(j)^{\frac{1}{\alpha-1}} (\alpha p_2)^{\frac{1}{1-\alpha}} L_2^{\gamma} H_2^{1-\gamma}, \tag{16}$$
$$x_3(j) = \chi_3(j)^{\frac{1}{\alpha-1}} (\alpha p_3)^{\frac{1}{1-\alpha}} H_3. \tag{17}$$

New machine producers, having the sole right to produce the machine, set the price of their machines to maximize the instantaneous one-period profit. This price will be a constant markup over the marginal cost of producing a machine. Assuming that the cost of making a machine is unitary implies that their prices will be set at $\chi_1(j) = \chi_2(j) = \chi_3(j) = \chi = 1/\alpha$ for new machines. Thus, substituting in this mark-up price, and realizing that instantaneous profits are $(1/\alpha) - 1$ multiplied by the number of new machines sold, instantaneous revenues for new machine producers are given by:

$$r_1 = \left(\frac{1-\alpha}{\alpha}\right) \alpha^{\frac{2}{1-\alpha}} (p_1)^{\frac{1}{1-\alpha}} L_1, \tag{18}$$
$$r_2 = \left(\frac{1-\alpha}{\alpha}\right) \alpha^{\frac{2}{1-\alpha}} (p_2)^{\frac{1}{1-\alpha}} L_2^{\gamma} H_2^{1-\gamma}, \tag{19}$$
$$r_3 = \left(\frac{1-\alpha}{\alpha}\right) \alpha^{\frac{2}{1-\alpha}} (p_3)^{\frac{1}{1-\alpha}} H_3. \tag{20}$$

Old machines, on the other hand, are competitively produced, and this drives the price down to marginal cost, so prices will be set at $\chi_1(j) = \chi_2(j) = \chi_3(j) = \chi = 1$ for all old machines. Sectoral productivities can then be expressed simply as a combination of old and new machines demanded by producers. Plugging in the appropriate machine prices into our machine demand expressions (15)–(17), and plugging these machine demands into our sectoral productivities, we can express these productivities as:

$$A_1 = \left(N_{1,t-1} + \alpha^{\frac{\alpha}{1-\alpha}} (N_{1,t} - N_{1,t-1})\right) (\alpha p_1)^{\frac{\alpha}{1-\alpha}}, \tag{21}$$
$$A_2 = \left(N_{2,t-1} + \alpha^{\frac{\alpha}{1-\alpha}} (N_{2,t} - N_{2,t-1})\right) (\alpha p_2)^{\frac{\alpha}{1-\alpha}}, \tag{22}$$
$$A_3 = \left(N_{3,t-1} + \alpha^{\frac{\alpha}{1-\alpha}} (N_{3,t} - N_{3,t-1})\right) (\alpha p_3)^{\frac{\alpha}{1-\alpha}}. \tag{23}$$

Thus, given the number of types of old and new machines that can be used in each sector (where the evolution of these are described below in section 5.1), we can simultaneously solve equations (8)–(14) and (21)–(23) to solve for prices, wages, intermediate goods and technological levels for a hypothetical economy.

4. Endogenizing Population and Labor-Types in Both Regions

Our next goal is to endogenize the levels of skilled and unskilled labor in this hypothetical economy. We introduce an over-lapping generations framework, where individuals in each region live for two periods.

In the first period, representing youth, individuals work as unskilled workers to earn income for their parents; this income is consumed by their parents. In the second period, representing adulthood, individuals decide whether or not to expend a fixed resource cost to become a skilled worker. Adults also decide how many children to have, and these children earn unskilled income for the adults. Adults, however, forgo some income for child-rearing.

Specifically, an adult i's objective is to maximize current-period income. If an adult chooses to remain an unskilled worker (L), she aims to maximize income I_l with respect to her number of children, so that

$$I_l = w_l + n_l\, w_l - w_l\, \lambda\, (n_l - 1)^{\phi}, \tag{24}$$

where w_l is the unskilled labor wage, n_l is the number of children that the unskilled adult has, and $\lambda > 0$ and $\phi > 1$ are constant parameters that affect the opportunity costs to child-rearing. Note that the costs here include a term in the form $(n_l - 1)$ to ensure that at least replacement fertility is maintained.

If an adult chooses to spend resources to become a skilled worker, she instead maximizes income I_h with respect to her number of children, so that

$$I_h = w_h + n_h\, w_l - w_h\, \lambda\, (n_h - 1)^{\phi} - \tau_i, \tag{25}$$

where w_h is the skilled labor wage, n_h is the number of children that the skilled adult has, and τ_i is the resources she must spend to become skilled.

We solve the first order conditions for each group for optimal fertility. For analytical convenience we solve for fertility in excess of replacement, n_l^* and n_h^*, to obtain

$$n_l^* \equiv n_l - 1 = (\phi\lambda)^{\frac{1}{1-\phi}}, \tag{26}$$

$$n_h^* \equiv n_h - 1 = (\phi\lambda w_h / w_l)^{\frac{1}{1-\phi}}. \tag{27}$$

Note that with $w_h > w_l$, and given $\phi > 1$, optimal fertility for a skilled worker is always smaller than that for an unskilled worker (simply because the opportunity costs of child-rearing are larger for skilled workers). Also note that the fertility for unskilled workers is

constant, while the fertility for skilled workers is decreasing in the skill premium w_h/w_l.

Finally, assume that τ varies across adults. The resource costs necessary to acquire an education can vary across individuals for many reasons, including differing incomes, access to schooling, or innate abilities. For tractability we assume that τ_i is uniformly distributed across $[0, b]$, where $b > 0$. An individual i who draws a particular τ_i will choose to become a skilled worker only if her optimized income as a skilled worker will be larger than her optimized income as an unskilled worker. Let us call τ^* the *threshold* cost to education; this is the education cost where the adult is indifferent between becoming a skilled worker or remaining an unskilled worker. Solving for this, we get

$$\tau^* = w_h + n_h^* \, w_l - w_h \, \lambda \, n_h^{*\phi} - w_l - w_l \, n_l^* + w_l \, \lambda \, n_l^{*\phi}. \tag{28}$$

Only individuals whose τ_i fall below this level will opt to become skilled.

Figure 5 illustrates the optimal fertility rates for two individuals — one with a relatively high τ and one with a relatively low τ. The straight lines illustrate how earnings increase as adults have more children; the slope of these lines is simply the unskilled wage w_l. The earnings line for a skilled worker is shifted up to show that she earns a premium. Cost curves get steeper with more children since $\phi > 1$. For skilled individuals, the cost curve is both higher (to illustrate the resource costs τ necessary to become skilled) and steeper (to illustrate the higher opportunity cost of having children). Notice then that the only difference between the high-τ individual and the low-τ individual is that the latter has a lower cost curve. Given these differences in the fixed costs of education, we can see that the high-τ individual will opt to remain an unskilled worker (and so have a fertility rate of n_l^*), while the low-τ individual will choose to become skilled (and have a fertility rate of n_h^*).

With all the above household machinery in place, we can now describe aggregate supplies of skilled and unskilled labor (the demands for labor are described by full employment conditions (12) and (13)), fertility, and education. Given a total adult population equal to pop, we obtain

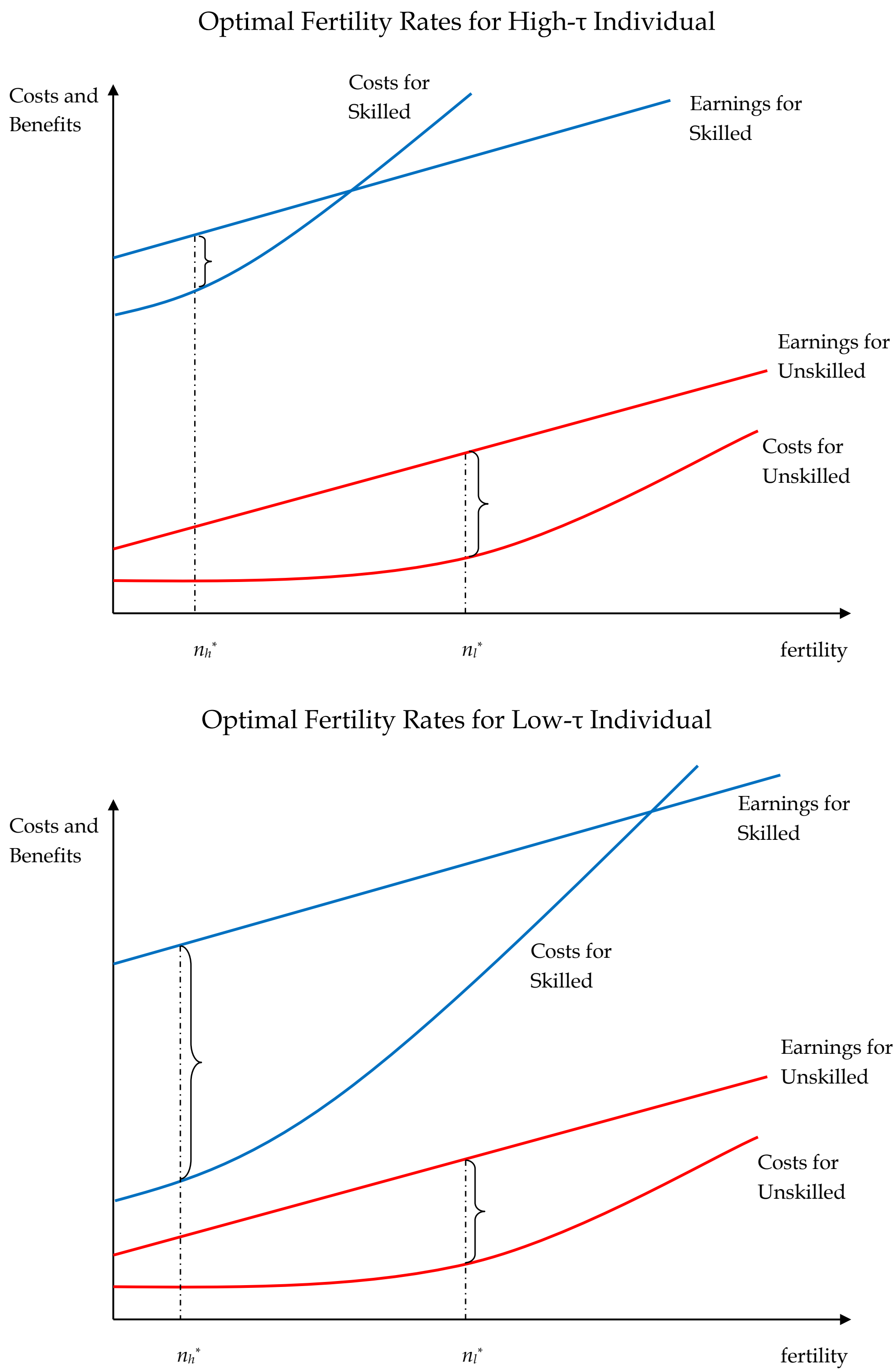
$$H = \left(\frac{\tau^*}{b}\right) pop, \tag{29}$$

$$L = \left(1 - \frac{\tau^*}{b}\right) pop + n \cdot pop, \tag{30}$$

$$n = \left(1 - \frac{\tau^*}{b}\right) n_l^* + \left(\frac{\tau^*}{b}\right) n_h^* + 1, \tag{31}$$

$$e = \frac{\tau^*}{b}, \tag{32}$$

Figure 5: *Optimal Fertility Rates for High and Low τ Individuals (for given w_l and w_h)*



where H is the number of skilled workers (comprised strictly of old workers), L is the number of unskilled workers (comprised of both old and young workers), n is aggregate fertility including replacement (the term 1 is added in), e is the fraction of the workforce that gets an education, and n_l^*, n_h^*, and τ^* are the optimized fertility rates and threshold education cost given respectively by (26), (27), and (28).

This completes the description of the static one-country model. The next section uses this model to describe *two* economies that endogenously develop technologies and trade with each other to motivate a story of world economic history.

5. The Roles Played by the Evolution of Trade and Technologies in Historical Divergence/Convergence

In this section we show how interactions between the growth of trade and evolving factor-biased technologies could have contributed to the Great Divergence of the late 19th and early 20th centuries. We go on to show how such interactions could also have induced per capita income convergence in the later 20th century. Our approach is to simulate two economies, indexed by c for each country or region. The above model describes one hypothetical country — we now use it to describe both a Northern and a Southern economy, where the South is initially relatively more unskilled labor-endowed.

A key issue here is the nature of technological progress and diffusion. We argue that early industrialization was characterized by locally-grown technologies, whereby regions developed their own production processes appropriate for local conditions, and where global technological diffusion was of minimal importance. On the other hand, we later conjecture that 20th century growth saw developing economies move to adopting technologies from the world knowledge frontier (Pack and Westphal 1986; Romer 1992).

These two simulations of our model serve to demonstrate a number of things. Early industrialization in both regions is unskilled labor intensive (O'Rourke, Rahman, and Taylor 2013). Trade between the two regions generates some income convergence early on — specialization induces the North to devote R&D resources to the skill-intensive sector and the South to devote resources to the unskilled-intensive sector. Because the skilled sector is so much smaller than the unskilled sector, the South is able to grow relatively faster at first. But the dynamic effects of these growth paths (notably fertility and education changes) ultimately limit and then sharply reverse income convergence. The mutually reinforcing interactions between technological growth and intercontinental commerce help produce dramatic divergence between the incomes of northern and southern economies.

However, our second set of simulations show that, when industrialization is characterized by diffusion of technologies from the world frontier (generated by the North) to the South, the dynamic of North-South income differentials takes a dramatically different turn. This case still produces some divergence early on, due to the technology-skill mismatch of "inappropriate" imported technologies flowing to the South (Basu and Weil 1998). But the North goes on to develop such highly advanced skill-biased technologies that these are, eventually, implemented by the South regardless. The South is then induced to proceed through its own demographic and education transitions, and starts to catch up on the North.

Our simulations reveal how trade and technological change feed off each other to generate growth paths that broadly mirror historic trends. Distinct from Galor and Mountford (2008), we find that the timing of the opening to trade, and in particular the technological environment, determines the qualitative impact of trade on convergence within the global economy. In order to pin down the impact of trade, for our main cases we show simulations for two trade environments, a case with gradually falling transport costs and an extreme case of no trade.

The remainder of this section presents our central findings, as summarized in the table below:

	Localized Technologies	**Diffusion of Technologies**
Growing Trade	Convergence then Divergence	Divergence then Convergence
No Trade	Stronger Convergence	More Gradual Convergence

5.1. A Dynamic Model — The Evolution of Technology and Trade

How do technologies evolve in each region? We will assume that a region will either develop its own blueprints N, or adopt blueprints from the world frontier. The upcoming discussion relates to the former case. We return to the latter case later on.

Recall that equations (18)–(20) describe one-period revenues r for innovation. There must also be some resource costs $C(.)$ to research, which we now specify. We assume that these costs are rising in N ("applied" knowledge, the already-known blueprints

or machine-types specific to each sector and to each country), and falling in some measure of “general” knowledge, given by B (basic knowledge, common across all sectors and countries). The former means that it gets harder to make innovations when more innovations have already been made, but the latter means that it gets easier the more basic knowledge you have.

Specifically, we assume that the no-arbitrage (free entry) condition for potential researchers in each region can be written

$$r_i^c \leq C(N_i^c, B), \tag{33}$$

for country $c = n, s$ and sector $i = 1, 3$.[9] Specifically, we assume the following functional form for these research costs,

$$C(N_i^c, B) = \left(\frac{N_{i,t+1}^c}{B_t}\right)^{\nu}, \tag{34}$$

for some $\nu > 0$. Given a level of basic knowledge (which we assume grows at an exogenous rate) and the number of existing machines, we can determine the resource costs of research. When basic knowledge is low relative to the number of available machine-types in sector i, the cost of inventing a new machine in sector i is high (see O'Rourke et al. 2013 for a fuller discussion). Thus from (33) and (18)–(20) we see that innovation in sector i becomes more attractive when basic knowledge is large, when the number of machine-types in sector i is low, when the price of good i is high, and when employment in sector i is high.

Note that if $r_i^c > C(N_i^c/B)$ there are profits from research in sector i in region c. However, this will induce local research activity, increasing the number of new machines, and hence the costs of research. In equilibrium, free entry ensures that N_i adjusts upward such that costs of research equal the revenues of new machine production. Thus, increases in global B are matched by increases in local levels of N_i^c such that the no-arbitrage condition holds with equality whenever technological growth in the sector occurs.

Finally, we specify how the mechanics of international trade evolve, which we do by imposing exogenous trends in iceberg costs, which can be calibrated to match historical reality. To do this, we use an amended version of (1), where supply in each region is given by home output minus exports plus foreign output minus exports multiplied by an

[9] For analytical convenience we assume no research occurs in sector 2, so that technological growth is unambiguously factor-biased. Cases where all three sectors grow technologically complicates the model but do not change the evolutions of either economy.

iceberg factor a. In the (relevant) case where North imports good 1, the specification is

$$Y^n = \left(\frac{\alpha}{2}\left(Q_1^n + aZ_1\right)^{\frac{\sigma-1}{\sigma}} + (1-\alpha)\left(Q_2^n\right)^{\frac{\sigma-1}{\sigma}} + \frac{\alpha}{2}\left(Q_3^n - Z_3\right)^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}}, \quad (35)$$

$$Y^s = \left(\frac{\alpha}{2}\left(Q_1^s - Z_1\right)^{\frac{\sigma-1}{\sigma}} + (1-\alpha)\left(Q_2^s\right)^{\frac{\sigma-1}{\sigma}} + \frac{\alpha}{2}\left(Q_3^s + aZ_3\right)^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}}, \quad (36)$$

where time subscripts are suppressed, Z_1 is the amount of good 1 that is exported by the South, Z_3 is the amount of good 3 that is exported by the North, and $0 < a < 1$ is an iceberg factor for traded goods (i.e., the proportion of exports not lost in transit). Thus the North receives only a fraction a of southern exports, and the South receives only a fraction a of northern exports.[10] Intermediate goods production is still described by (2)–(4). To capture improvements in transport technologies over the course of the 18th and 19th centuries, we simply allow a to grow exogenously each time period, such that it reaches the limiting value of 1 by the end of the simulation.

Note that there is a nontraded good: we assume that there is no trade in Q_2 — because this is produced using both L and H, differences in p_2 are very small between the North and the South, and thus the assumption is not very restrictive or important.[11,12]

5.2. Evolution of the World Economy

General equilibrium is a 36-equation system that, given changes in the number of machine blueprints and the iceberg costs, solves for prices, wages, fertility, education, labor-types, intermediate goods, employment, trade, and sectoral productivity levels for both the North and the South. We impose only one parameter difference between the two regions: we assume $b^n < b^s$. This is a way to create an initial asymmetry between the regions to match the stylized facts: it means that there is a bigger range of resource costs for education in the South, and this allows us to match the stylized fact that the South begins with relatively more unskilled labor than skilled labor. All other parameters are *exactly* the same in both regions. Fertility is normalized to one in the beginning for each country, so that population is stable. The equilibrium is described in more detail in the appendix.

[10] In the simulations we present, the (symmetric) case where the North specializes in and exports the *unskilled*-intensive good and the South specializes in and exports the *skilled*-intensive good is ruled out due to the North's relative abundance of skilled labor. The North would have to have very high levels of unskilled-biased technology compared to the South to reverse its comparative advantage in skill-intensive production.

[11] Indeed, trade in all three goods would produce an analytical problem. It is well known among trade economists that when there are more traded goods than factors of production, country-specific production levels, and hence trade volumes, are indeterminate. See Melvin (1968) for a thorough discussion.

[12] One can conceive of Q_2 as the technologically-stagnant and non-tradeable "service" sector. Thus each labor-type can work either in manufacturing or in services.

Due to model complexity, we solve for general equilibrium numerically. Specifically, we assume that both basic technology (B in eq 34) and trade technology (a in eqs 35 and 36) start low enough so that neither technological progress nor trade are possible. Our world is at first in stasis, with no commerce and no growth. We allow however for exogenous growth in basic knowledge and trade technologies, and solve for the endogenous variables each period. Let us first summarize the evolution of these two economies with a few propositions, starting with the nature of early industrialization in the world.

Proposition 1. *If $N_1 = N_3$, $L > H$, and $\sigma > 1$, then initial technological growth will be unskilled-labor biased.*

Remark. From (18)–(20) we can see that revenues from innovation rise both in the price of the intermediate good (the "price effect") and in the scale of sectoral employment (the "market-size effect"). If intermediate goods are grossly substitutable, market-size effects will outweigh price effects (see Acemoglu 2002 for more discussion of this).

Recall that GM had to exogenously order the sequence of modernization events by sector. However, in our model, the sequencing now materializes endogenously due to directed technological change. Here we see that, as basic knowledge exogenously grows, sector 1 will be the first to modernize if unskilled labor is relatively abundant. The logical implication of this is that early industrialization around the world (provided there are intellectual property rights in these countries) will be unskilled-labor-intensive (O'Rourke et al. 2013). □

Proposition 2. *If $\left(\frac{p_3^n}{p_3^s}\right) \cdot \left(\frac{p_1^s}{p_1^n}\right) > a^2$, then $Z_1 = Z_3 = 0$.*

Remark. If transport costs are large (that is, if a is small) relative to cross-country price differences, no trade occurs. As mentioned above, we will assume that early on transport technologies are not advanced enough to permit trade. That is, with a small value of a, each country can produce more under autarky than by trading. Once a reaches a threshold level, trade becomes possible, and further increases in a allow Z_1 and Z_3 to rise as well. □

Proposition 3. *For certain ranges of factors and technologies, the trade equilibrium implies that $Q_3^s = 0$. For other ranges of technologies and factors, the trade equilibrium implies that $Q_1^n = 0$.*

Remark. As trade technologies improve, economies specialize more and more. And divergent technological growth paths can help reinforce this specialization. There is indeed a point where the North no longer needs to produce any Q_1 (they just import it from the South), and the South no longer needs to produce any Q_3 (they just import it from the North). This case we call "specialized trade equilibrium" (described in detail in the appendix). □

Of course, both trade and technological changes affect factor prices. The final proposition states how these in turn affect supplies of the factors of production themselves.

Proposition 4. *If $\phi > 1$, any increase in w_l (keeping w_h constant) will induce a decrease in e and an increase in n; furthermore, so long as ϕ is "big enough," any increase in w_h (keeping w_l constant) will induce an increase in e and a decrease in n.*

Proof. Substituting our expressions for n_l^* and n_h^*, given by (26) and (27), into our expression for τ^*, given by (28), and rearranging terms a bit, we get the following expression:

$$\tau^* = (w_h - w_l) - w_l \lambda^{\frac{1}{1-\phi}} \left(\phi^{\frac{1}{1-\phi}} - \phi^{\frac{\phi}{1-\phi}} \right) + w_l^{\frac{\phi}{\phi-1}} w_h^{\frac{1}{1-\phi}} \lambda^{\frac{1}{1-\phi}} \left(\phi^{\frac{1}{1-\phi}} - \phi^{\frac{\phi}{1-\phi}} \right).$$

First we must have the condition $\partial\tau^*/\partial w_l < 0$ hold. Solving for this and rearranging yields

$$\left(\frac{w_l}{w_h} \right)^{\frac{1}{\phi-1}} < 1 + \frac{1}{\lambda^{\frac{1}{1-\phi}} \left(\phi^{\frac{1}{1-\phi}} - \phi^{\frac{\phi}{1-\phi}} \right)}.$$

Since the inverse of the skill-premium is always less than one, this expression always holds for any $\phi > 1$. Next we show what condition must hold in order to have the expression $\partial\tau^*/\partial w_h > 0$ be true. Solving and rearranging gives us

$$\lambda^{\frac{1}{\phi}} \phi > \frac{w_l}{w_h}.$$

Thus for a given value of λ, ϕ needs to be large enough for this condition to hold. Finally, our expression for total fertility, (31), can be slightly rearranged as

$$n = n_l^* + (n_h^* - n_l^*) \left(\frac{\tau^*}{b} \right) + 1.$$

From (26) and (27) we know that the second term is always negative, and that n_l^* is constant. So any increase in education from wage changes will lower aggregate fertility, and any decrease in education from wage changes will increase aggregate fertility. □

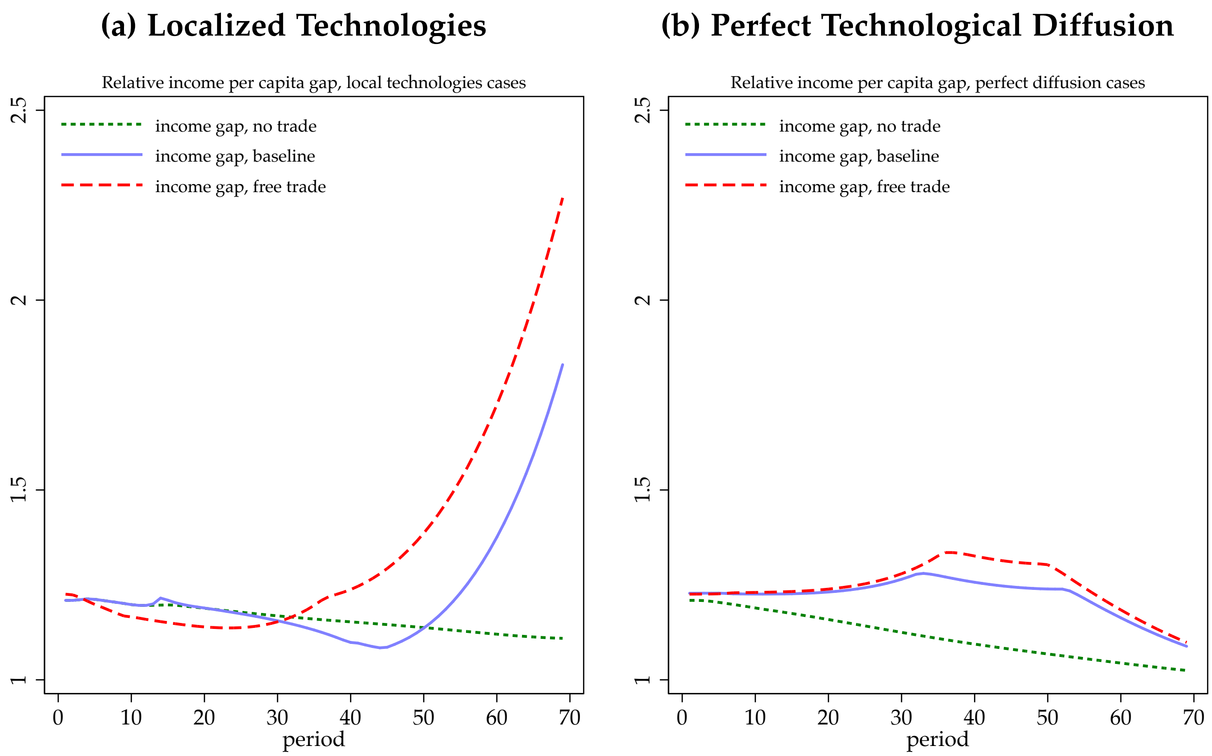
5.3. Simulations

Calibration Overview Here we simulate the model described above to analyze the potential sources of North-South divergence in history. Basic knowledge B and trade costs a are set such that neither technological growth nor trade is possible at first; each, however, exogenously rises over time. We run the simulation for 70 time periods to roughly capture major economic trends during two distinct economic epochs. The parameter values in the simulations are as follows: $\sigma = 3$, $\alpha = 0.5$, $\gamma = 0.5$, $\lambda = 0.5$, $\phi = 10$, $\nu = 2$. These values ensure that Propositions 1 and 4 hold; beyond that, our qualitative findings are not sensitive to specific parameter values. We set $b^n = 2$, $b^s = 6$, and $pop = 2$; this gives us initial factor endowments of $L_n = 3.14$, $L_s = 3.48$, $H_n = 0.86$, $H_s = 0.52$. Initial machine blueprints for both countries are set to be $N_1 = 10$, $N_2 = 15$, $N_3 = 10$. For the case of local technological progress initial trade technology is set to be $a = 0.8$ (here when one-fifth of trade volume is lost in transit, each region is better off in autarky); for the case of perfect technological diffusion, initial $a = 0.9$ (here small volumes of goods are exchanged at first to simulate a 20th century case); in each case a grows linearly such that $a = 1$ after 70 periods. Initial B is set high enough in both scenarios so that growth in at least one sector is possible early in the simulation; B grows 2 percent each time period.

Divergence Implications Preview Before presenting all our results in granular detail we begin by previewing our main findings on long-run divergence, since matching these stylized facts was our core empirical goal in constructing this model. Recall that we solve the model using two sets of assumptions, localized technological development and perfect diffusion of technologies from North to South. Figure 6 shows the predictions of the model for the evolution of the North-South ratio of real income per capita, where the ratio is shown on the vertical axis and 1 means equality of real income per capita. For each of our two assumptions regarding technological progress, three cases are shown. These illustrate the impact of trade on international income gaps, by varying the time path of exogenously imposed international trade frictions.

Localized Technologies In this first configuration the two economies, North and South, are identical in all respects but differ in their initial endowments of skilled and unskilled labor; they then embark on their long-run growth paths with endogenous directed technological change influenced by factor scarcity, leading the North to follow a more skill-intensive path. As shown in panel (a), this configuration has a range of predictions for long-run convergence and divergence.

Figure 6: *Divergence Implications — Localized Technologies versus Perfect Technological Diffusion*



If there is no trade (autarky) at all times, then the result is convergence, as shown by the green dotted line. The intuition is as follows: the South is on a similar path to the North, but effectively is a few periods behind, with a lower level of education, and there is innovation in both sectors in both regions. But eventually, education levels in both North and South asymptotically rise and approach the full education level, and fertility is lowered. As time goes to infinity the two autarkic economies become identical.

If there is free (frictionless) trade at all times, then the result is divergence, as shown by the red dashed line. The intuition is as follows: the North specializes in skilled exports, and South in unskilled exports. For some time specialization is incomplete, and there is innovation in both sectors in both regions. But at some point both regions fully specialize, and innovation becomes specific to the active sector in each country only. North's skill bias gets more extreme, education levels asymptotically rise and approach the full education level, and fertility is lowered. The South's unskilled-labor bias gets more extreme, education levels asymptotically fall, and fertility is raised. As time goes to infinity the two trading economies diverge fundamentally in terms of demography, endowments, economic structures, and income levels.

In our baseline model, we assume that trade is quite costly at the start of the process (mimicking 17th century trade frictions) and become less costly over time (as the 21st century approaches). In this third case the relative income path is, as expected, somewhere between the above cases; it starts like the former, but ends up like the latter.

Perfect Technological Diffusion In this second configuration the two economies, North and South, are fundamentally different. Only the North is capable of the research and development necessary to produce innovations of any kind, in any sector. The South merely inherits the technologies thus generated by a process of perfect technological diffusion. Some might argue that this has in fact been closer to reality than the alternative assumption of localised technological progress over the course of the last 200–300 years, with most frontier innovations occurring in the industrial Northern powerhouses. In this setup, the North still embarks on its long-run growth path with endogenous directed technological change influenced by factor scarcity, but it also sees its innovations spill over to the South instantaneously. The South experiences this as exogenous technological change gained from the North's innovations. The two economies may then trade, and the factor prices generated by either trade or autarky then shape the North's demographic environment and endowments, and hence its innovations, which then spill over into South. As shown in panel (b), this configuration always leads to long-run convergence.

If there is no trade (autarky) at all times, then the result is steady and continuous convergence, as shown by the green dotted line. The rate of convergence here is even faster than in panel (a) for the autarky case. The reason is intuitive. In the case of localized technologies, the South will be influenced by its own factor endowments and will innovate with more of an unskilled bias. But now, with perfect technological diffusion, and inheriting whatever the North innovates, the South is stuck with, as it were, "inappropriate technologies" — but this turns out to be a blessing because it raises the skill premium, triggering a faster response in the South towards higher education and lower fertility, and speeding up the long-run convergence in incomes.

If there is free trade (frictionless) at all times, then the result is divergence at first followed by more rapid convergence, as shown by the red dashed line. The intuition is as follows: the opening up to trade makes the South specialize more in unskilled goods and leads factor prices to diverge between regions, encouraging the South to make low education and high fertility choices at first. This makes Northern technological diffusion even more "inappropriate" for the South. But this phase can only last for a certain amount of time, since it is limited by what the full long-run effects of free trade would be on the South's factor endowment. Even before that point is reached, the dynamic implications

of unlimited technological diffusion start to take over, and drive factor prices toward convergence, no matter how large the initial widening of the gap.

In our baseline model, the relative income path is, as expected, again somewhere between the two cases described above.

The Case of Localized Technological Progress: Detailed Analysis Figures 7–12 summarize the evolution of technologies in both regions. In the left-hand columns we show the baseline case in which trade costs fall linearly. In the right-hand columns we show the case in which trade costs are prohibitively high throughout. For comparative purposes we scale the y axes identically, wherever this is reasonable. We focus our discussion initially on the baseline simulations.

In the beginning, we see that the costs of research are prohibitively high everywhere, so technologies are stagnant. But growth in basic knowledge allows us to see the implications of Proposition 1 — because there is a greater abundance of unskilled labor relative to skilled labor in both the North and the South, the costs of research first dip below revenues in sector 1 in both regions.

This growth in unskilled-labor-intensive technologies increases the relative returns to unskilled labor in both regions, inciting fertility increases and educational decreases, as suggested in Proposition 4. We can see this manifest itself in the North by the increasing revenues generated by innovation — as population rises in the North, the market-size effects caused by fertility increases raise the value of such innovation. Still, because skilled labor remains in relatively scarce supply, the cost of innovation exceeds the benefits in sector 3 at the beginning of the simulation.

However, the North soon starts developing skill-biased technologies as well (at $t = 12$). Notice however that the South never gets to develop skill-biased technologies — looking at the lower panel of Figure 8, something clearly happens to make the value of innovating in the sector fall to zero.

That something is trade, as transport technologies continually improve. Initially, as in proposition 2, a is so low that no trade occurs. We see that around t=15 the South can start exporting the unskilled good and the North can start exporting the skilled good. Producing very little of good 3 even in autarky, the South finds itself importing its entire consumption of the good from the North once the North raises its productivity in the sector, in line with our Proposition 3. Of course, this ultimately means that it will not be able to produce any skill-intensive innovations even with high B values.

Demographic patterns suggest that this case is appropriate for understanding the history of both the Industrial Revolution and the Demographic Transition (see Figures

Figure 7: *Market for Technologies in North — Localized Technologies*

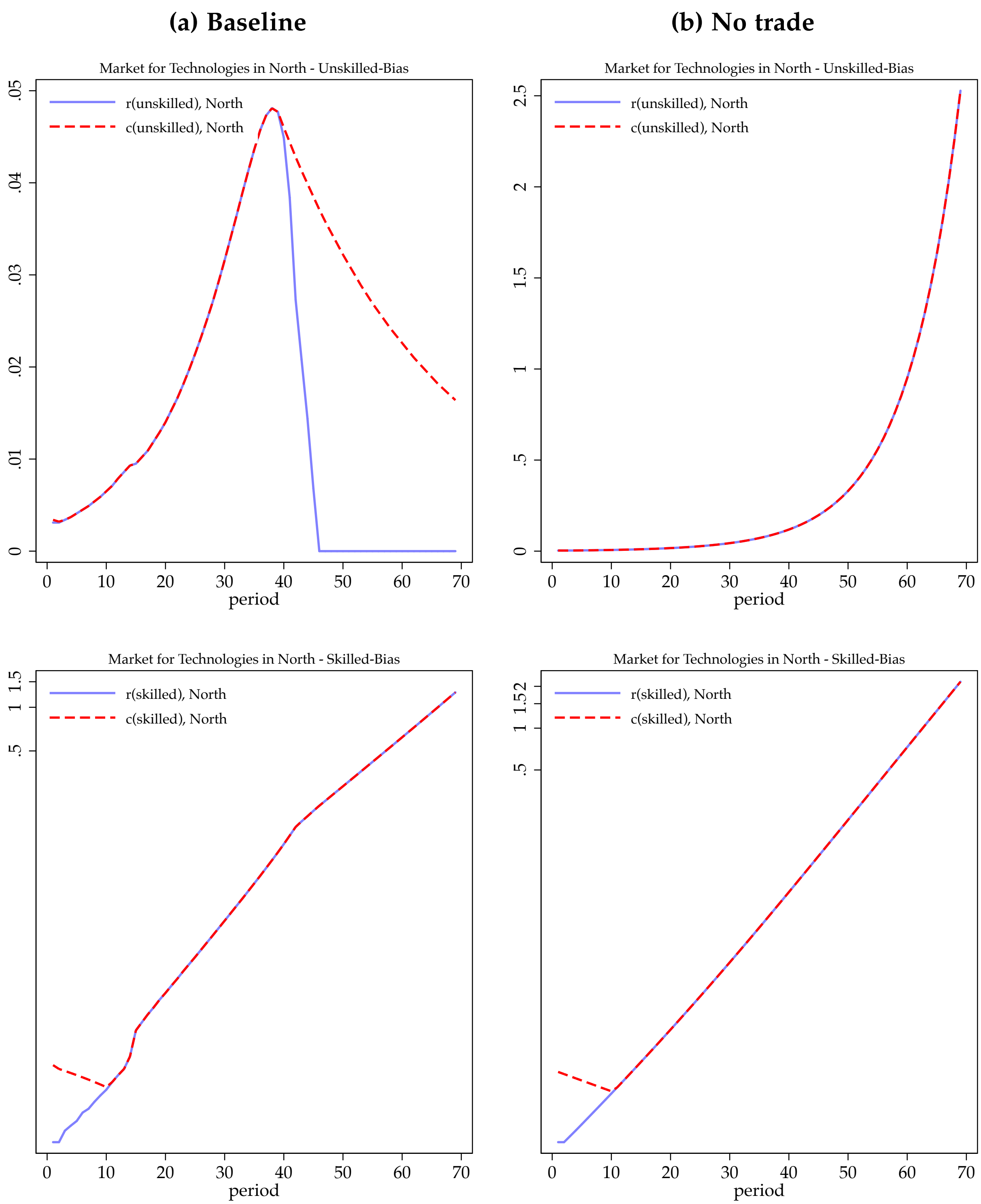


Figure 8: *Market for Technologies in South — Localized Technologies*

(a) Baseline **(b) No trade**

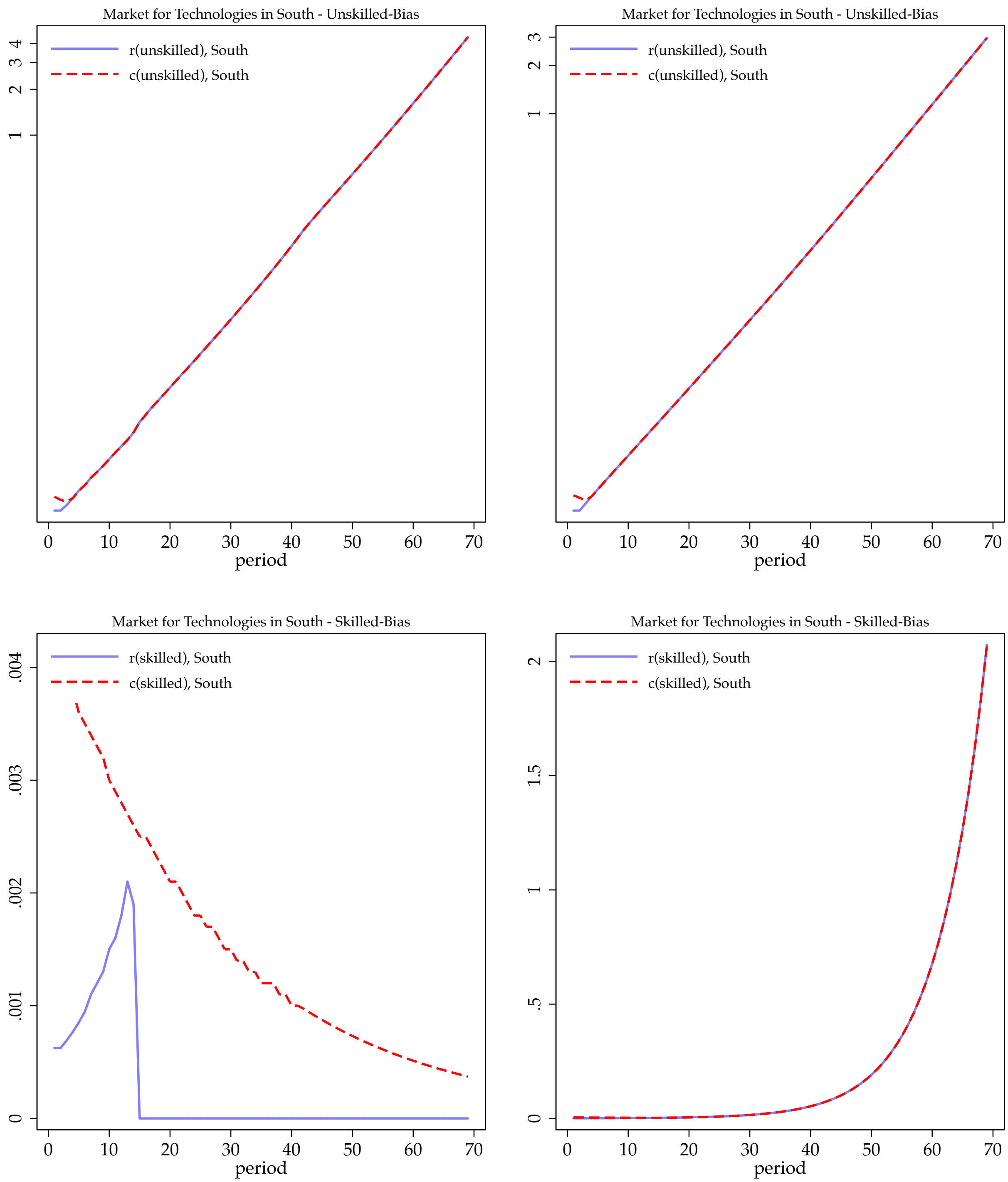


Figure 9: *Factor Productivities — Localized Technologies*

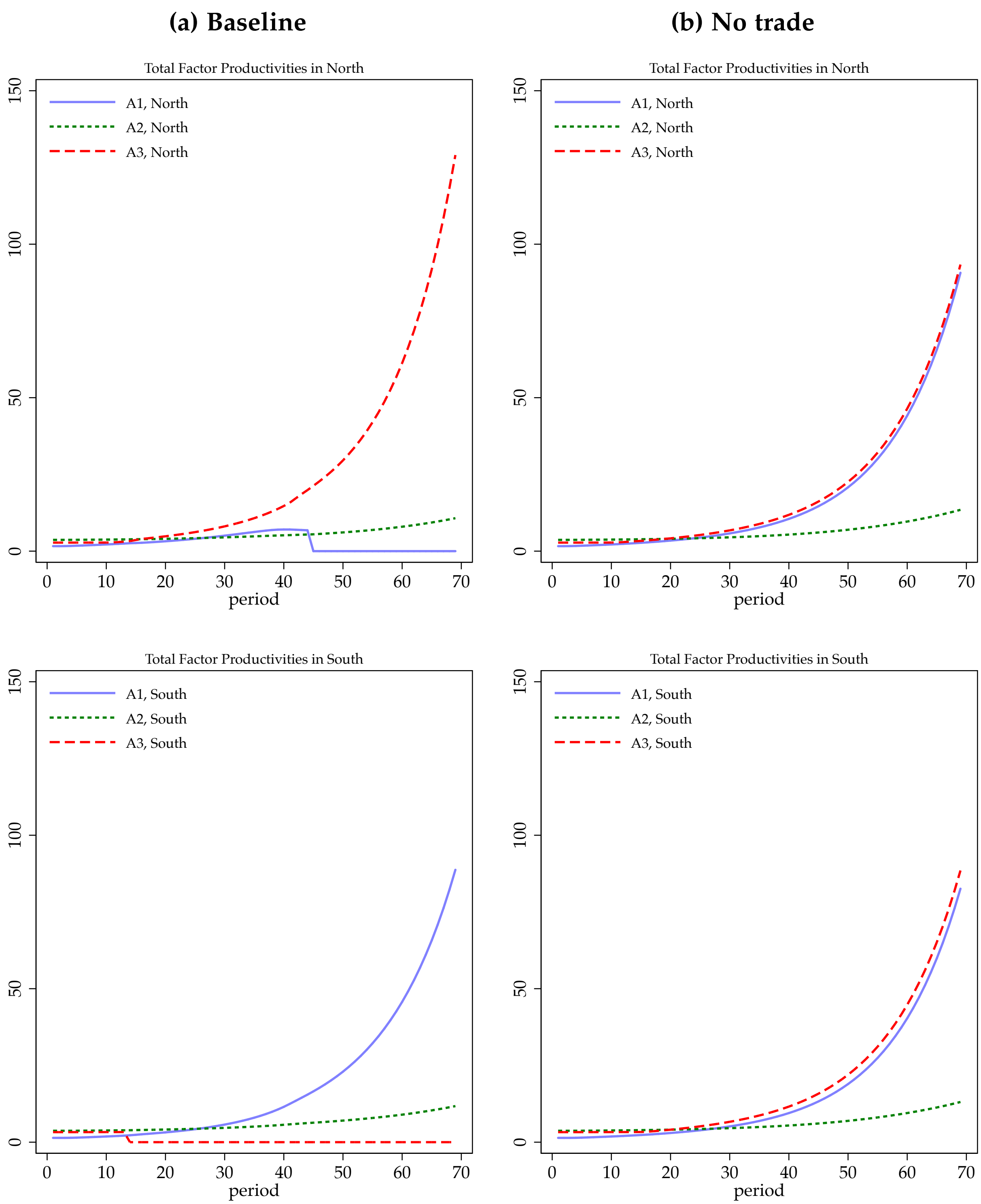
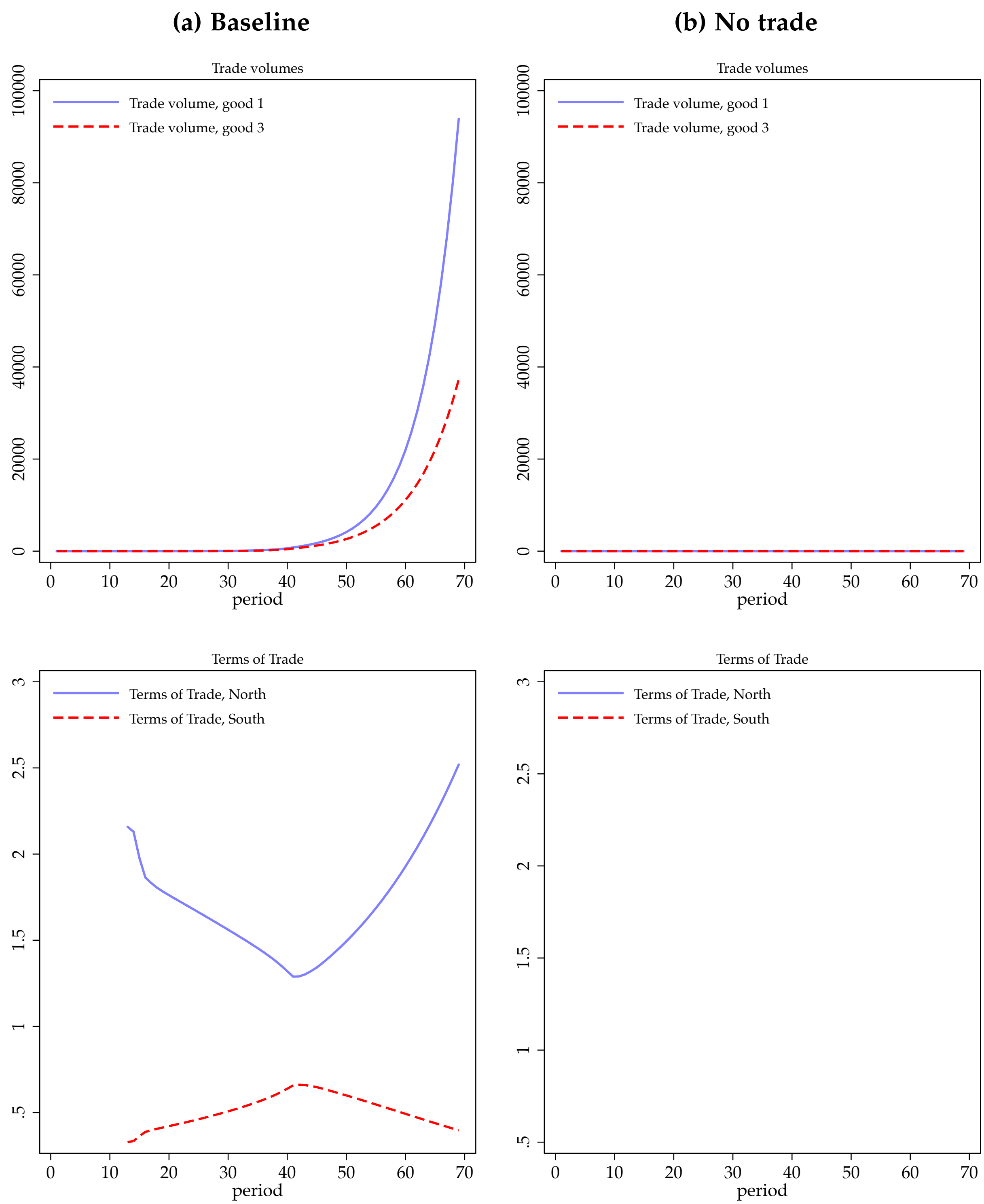


Figure 10: *Trade Volumes and Terms of Trade — Localized Technologies*



2 and 3). The North initially has high fertility and stagnant education. Once it starts developing skill-intensive technologies however, fertility rates begin to drop and education rises. The South on the other hand never goes through a demographic transition.

To help us better understand the forces of convergence or divergence, we can decompose the income per capita gap between the North and South into two components. Define Y^n_{aut} as the GDP for the North in a given year, allowing it to have the technologies from the previous, regular equilibrium, but pretending that the North does not trade with the South. GDP per capita can be decomposed as

$$y^n = \left(\frac{Y^n_{aut}}{pop^n}\right)\left(\frac{Y^n}{Y^n_{aut}}\right). \tag{37}$$

So relative per capita incomes of North versus South can be decomposed into two multiplicative parts,

$$\frac{y^n}{y^s} = \left(\frac{Y^n_{aut}}{pop^n}\Big/\frac{Y^s_{aut}}{pop^s}\right)\left(\frac{Y^n}{Y^n_{aut}}\Big/\frac{Y^s}{Y^s_{aut}}\right). \tag{38}$$

We will call the first term on the right the "autarkic income per capita gap." We will call the second term the "gains from trade gap."

At first, we have convergence. Both countries have lots of unskilled workers and not as many skilled workers, and the South gains in relative terms by developing technologies for this abundant workforce. Indeed, we see the autarky income gap fall throughout. However, as trade continues to grow the South loses in relative terms. Its gains from trade deteriorate because its terms of trade deteriorate — the South must sell more and more of its unskilled good (Q_1) in exchange for its imports of the skilled good (Q_3), as we can see in Figure 10. Symmetrically, the North eventually begins to gain as its terms of trade improve.1

The reason has to do with relative size. The North is small and prosperous; the South is innovative but enormous (its population grows to become ten times that of the North), flooding the world with its output. Divergence here comes about because each region leaves its "cone of diversification." A purely specialized world develops, and the South specializes in a good which generates population growth and deteriorating terms from trade with the North. Technological growth will not save it! Thus we observe economic divergence that arises from an entirely different source than in GM, but that nevertheless has to do with interactions between trade and technological growth.

It is also informative to compare this case with the case of no trade at all (those in the right column, panel (b), in all diagrams). Here, $a = 0$ and constant at all times. First, we see that technological growth is far more balanced in both regions. In Figure 7 we

Figure 11: *Fertility and Education — Localized Technologies*

(a) Baseline **(b) No trade**

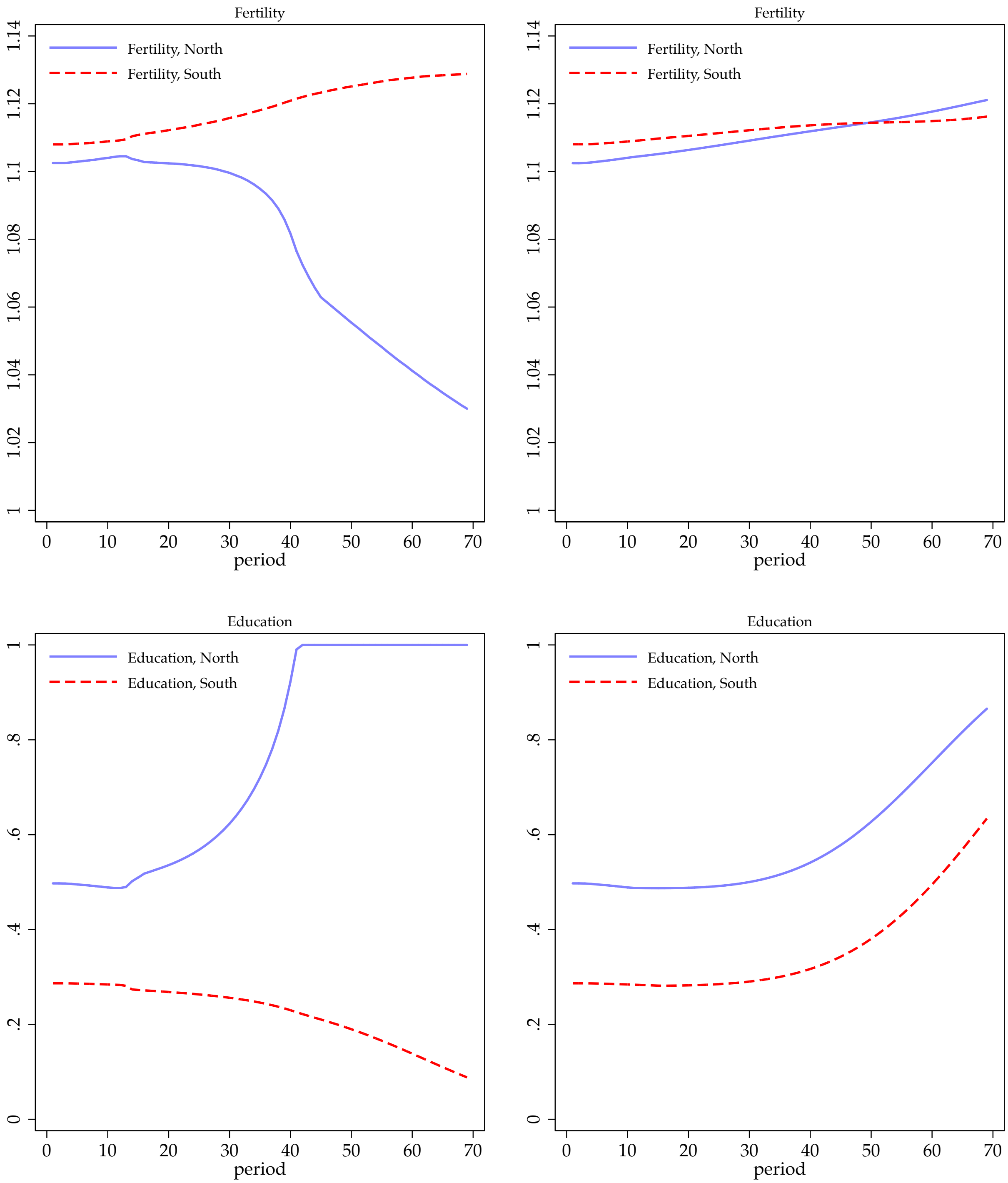
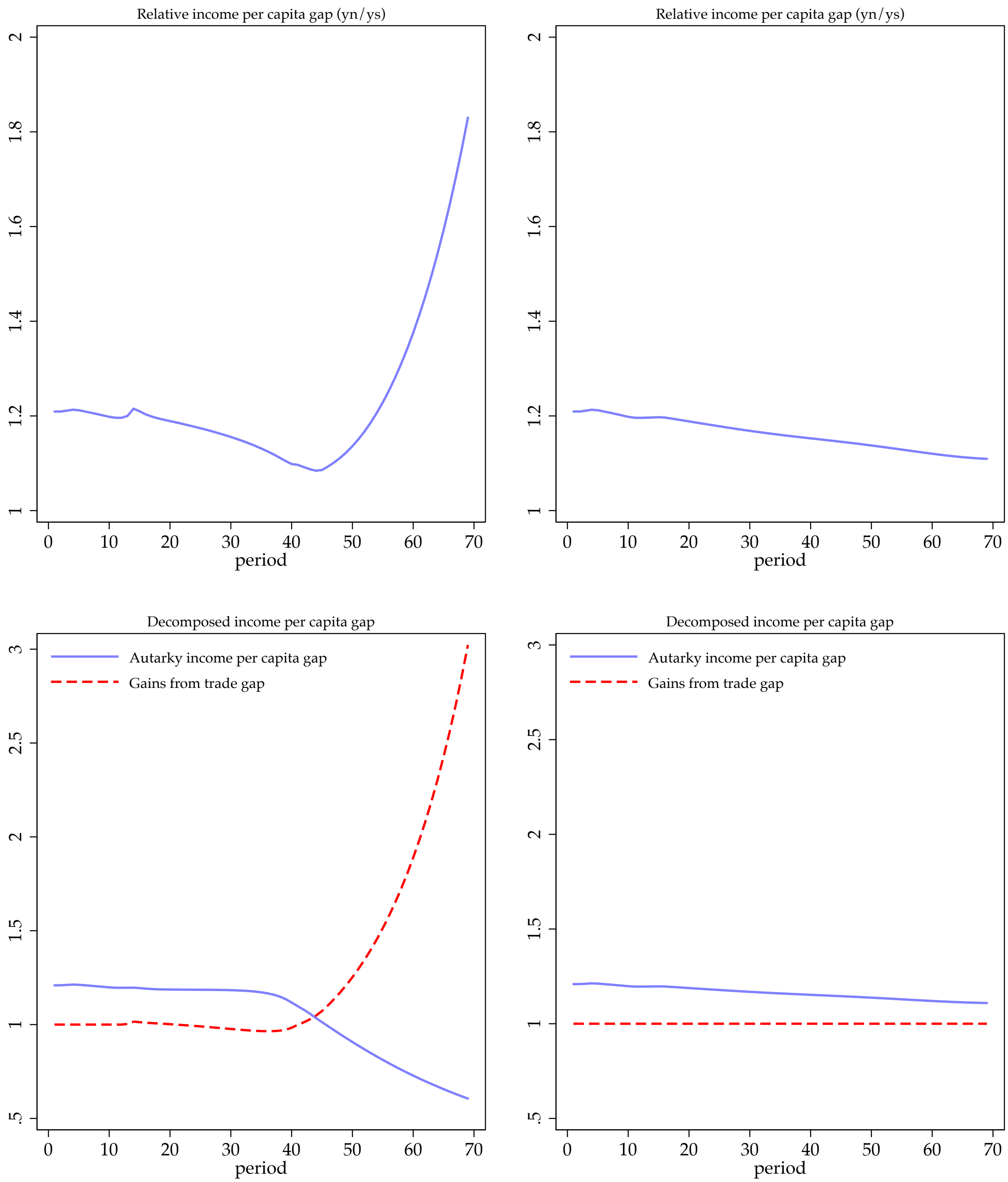


Figure 12: *Relative Income and Divergence — Localized Technologies*

(a) Baseline **(b) No trade**



observe consistent growth in unskilled technologies in the North; in Figure 8 we see growth in skilled technologies in the South. The result is more parallel TFP growth paths for North and South in Figures 9 and thus in per capita terms in Figure 12. Figure 10 shows zero trade flow and, thus, the terms of trade effects shut down. Figure 11 shows how fertility rises for both, and education in both regions stagnates at first and then rises. Note that here we do not observe the quality-quantity tradeoff — more balanced growth in skilled and unskilled wages generates a rise in both fertility and education. We clearly see that goods specialization through trade, interacted with technological specialization, is needed to generate big-time divergence between the North and South.

The Case of Perfect Technological Diffusion: Detailed Analysis This case is shown in Figures 13–17 and shows a marked contrast.

Here we assume that only the North develops technologies (machine blueprints), and that these flow immediately and costlessly to the South for potential use. The South in this case does not bother with research on its own — it "allows" the North to do the research and basically free rides on that. But does free riding pay? This research may be free, but it may not be the most appropriate. Again we first focus on the baseline case of gradually falling transport cost (left column in each figure).

In this case we see the North innovating in both unskilled and skilled technologies early on. However, trade forces the South to abandon skill-intensive production. Therefore, even though technologies diffuse costlessly from the North to the South, comparative advantage means that the South cannot use skilled technologies (see Figure 14). Thus we see per capita income divergence early on (first part of Figure 17) — here the channel is though "inappropriate" technological diffusion from North to South. The South is in effect trading population for productivity (Galor and Mountford 2008), as it devotes more people to the relatively less productive sector. This is not an *inherently* less productive sector (unlike GM), but it is rendered so over time by the North devoting fewer R&D resources to it. Trade is modest but growing (Figure 15), and the terms of trade effect moves sustainably in South's favor as well — in this case, South never grows to a huge population, and the technological lead sticks in the North, so North's lead in tradeable output that is vented onto world markets keeps its export price down relative to South's.

Over time the North's specialization in skilled production makes it devote even more resources towards skill-intensive technologies. Eventually these technologies become so overwhelmingly efficient that the South is finally persuaded to adopt them, despite its smaller skilled workforce. What was once economically inappropriate for the South now becomes increasingly economically appropriate, so large is the technology gap

Figure 13: *Market for Technologies in North — Perfect Technological Diffusion*

(a) Baseline **(b) No trade**

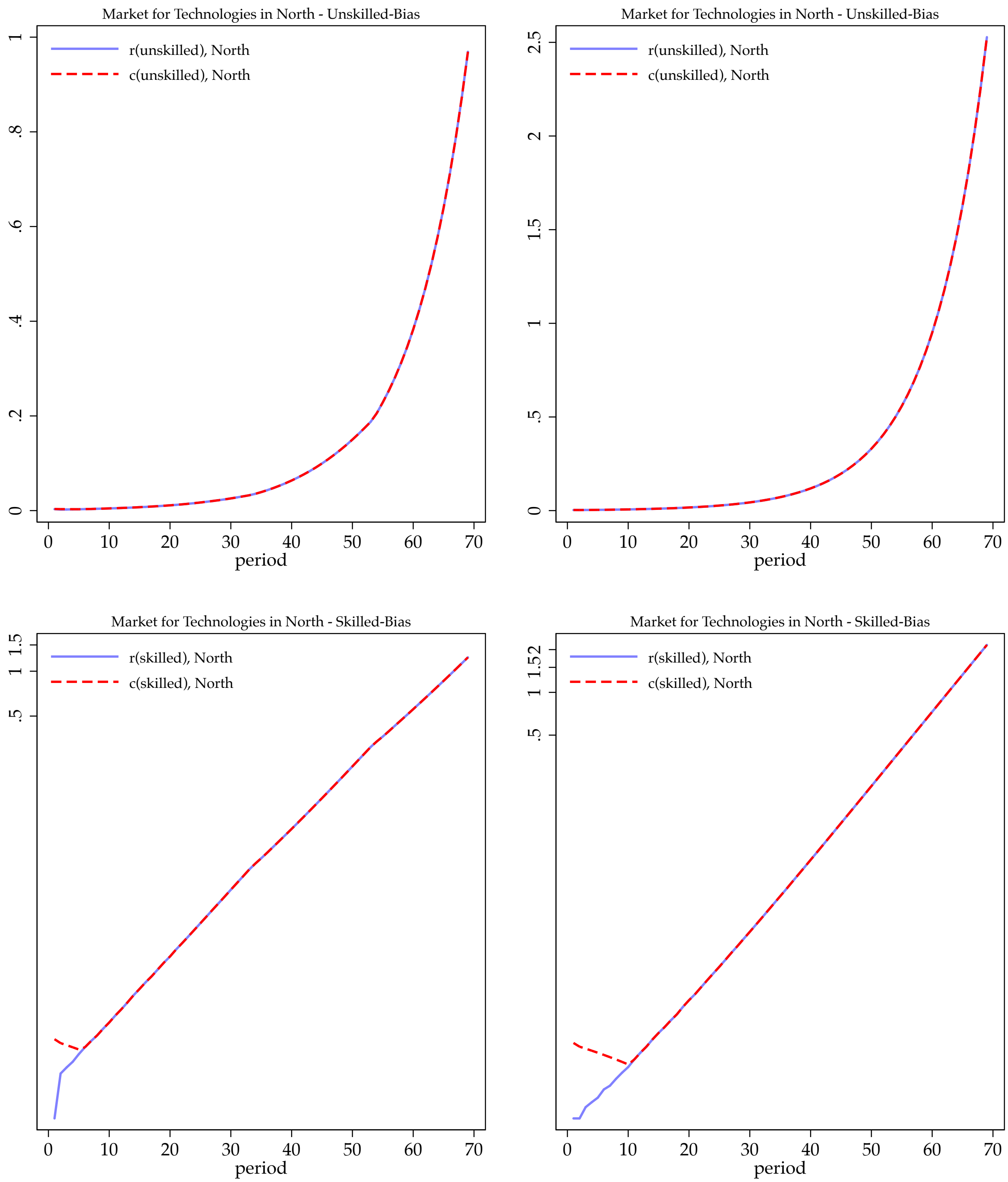
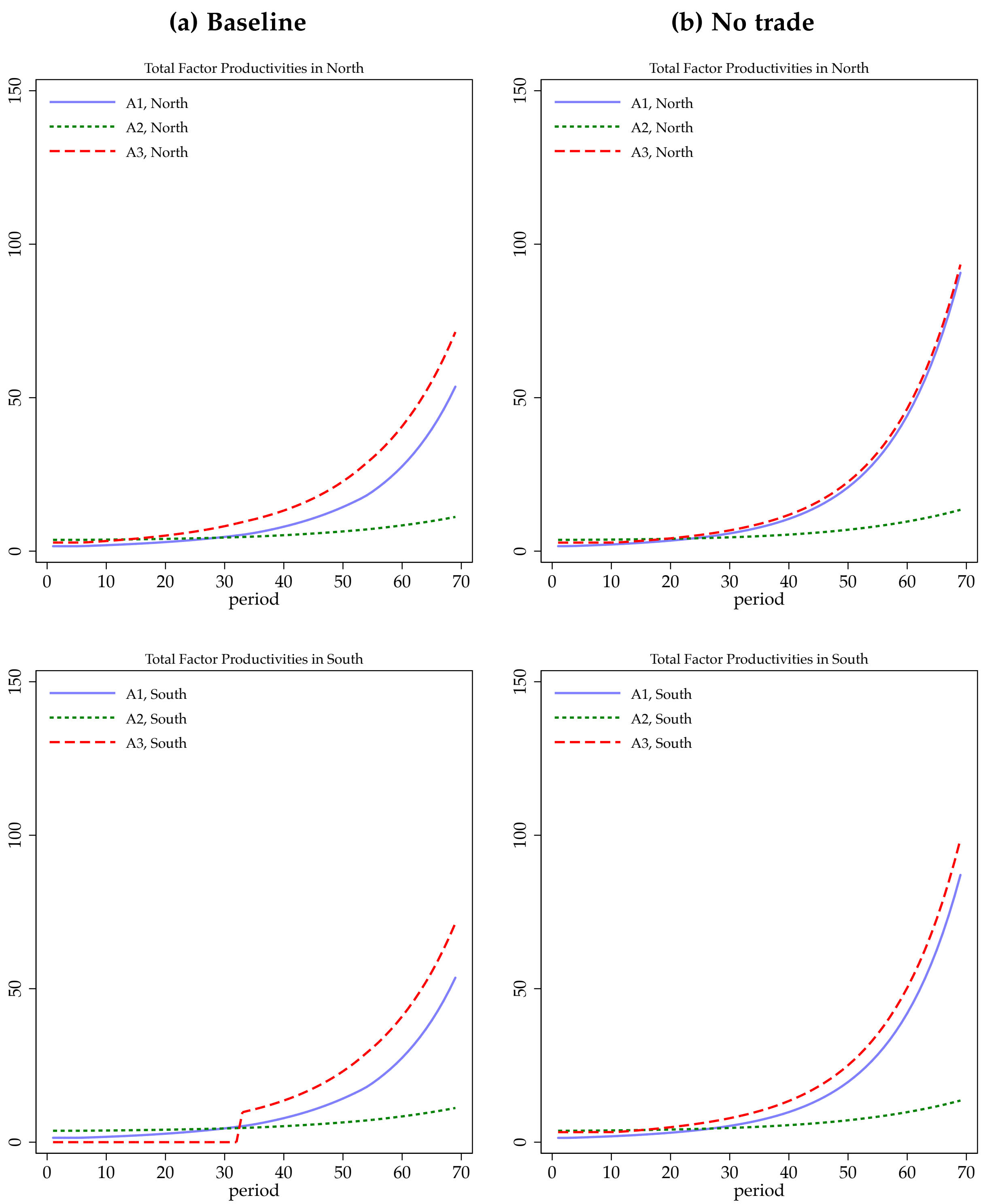


Figure 14: *Factor Productivities — Perfect Technological Diffusion*



between sectors. The fact that the South can eventually reap the gains from Northern skilled innovation means it can finally compete in skilled production globally. The spectacular technological advance imported from the North, coupled with South's low wages, eventually start to turn the tables. When this happens ($t = 33$), each country falls inside its "cone of diversification." The two regions begin to converge. Further, once the North reaches universal education ($t = 52$), convergence happens even faster as South still has some way to go here, and continues to raise education rates. Eventually the South converges to the North in terms of per capita income. The moral of this story is very different to the previous case.

Note that, in this case, the South goes through its own demographic transition, but this is much delayed (see Figure 16). We suggest that this case may better represent certain Southern economies during the 20th century, which were eventually successful in adopting and implementing skill-intensive technologies developed abroad.

Now what if, in this case of perfect diffusion, the possibility of trade were to be delayed or even prevented? We can look at the right-hand columns in Figures 13–17, which display this counterfactual scenario. Technological diffusion keeps the South structurally close to the North, and so the two regions grow in an even more parallel manner than in the no trade case with local technological growth.

So is trade ultimately good for the South in this case? Yes and no. On the one hand trade induces the North to specialize more in skilled technologies. South hitches a ride and eventually adopts these technologies and thereby converges to the North at an even faster rate. On the other hand, the fertility declines that this emerging trade induces in the North create a kind of global technological slowdown, as the scale for innovation in the North becomes limited. The technologies that the South can inherit then are not only "inappropriate," there are fewer of them. One might speculate that in this case, maintaining global innovation at persistently high rates would require the South to also begin innovating. Indeed, as Northern countries today start to worry about the possibility of slowing innovation and secular stagnation, some researchers are beginning to look to the South to maintain global growth rates.

6. Conclusion

We have shown how different dimensions of globalization can have different implications for convergence. We provide two important innovations from the Galor and Mountford framework. One is that we endogenize the terms of trade. This can generate an entirely different source for divergence than in GM. We demonstrate that even when the South

Figure 15: *Trade Volumes and Terms of Trade — Perfect Technological Diffusion*

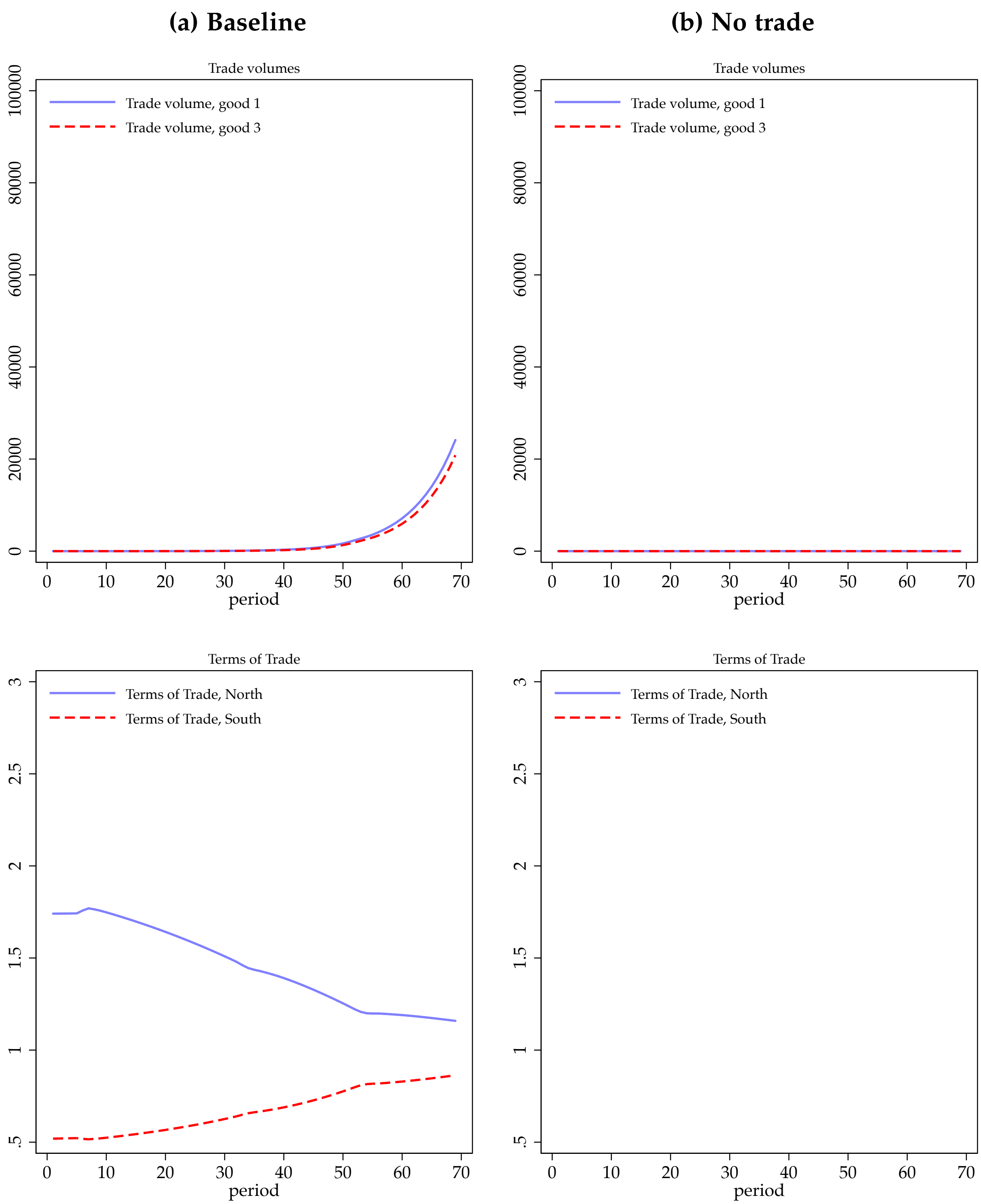


Figure 16: *Fertility and Education — Perfect Technological Diffusion*

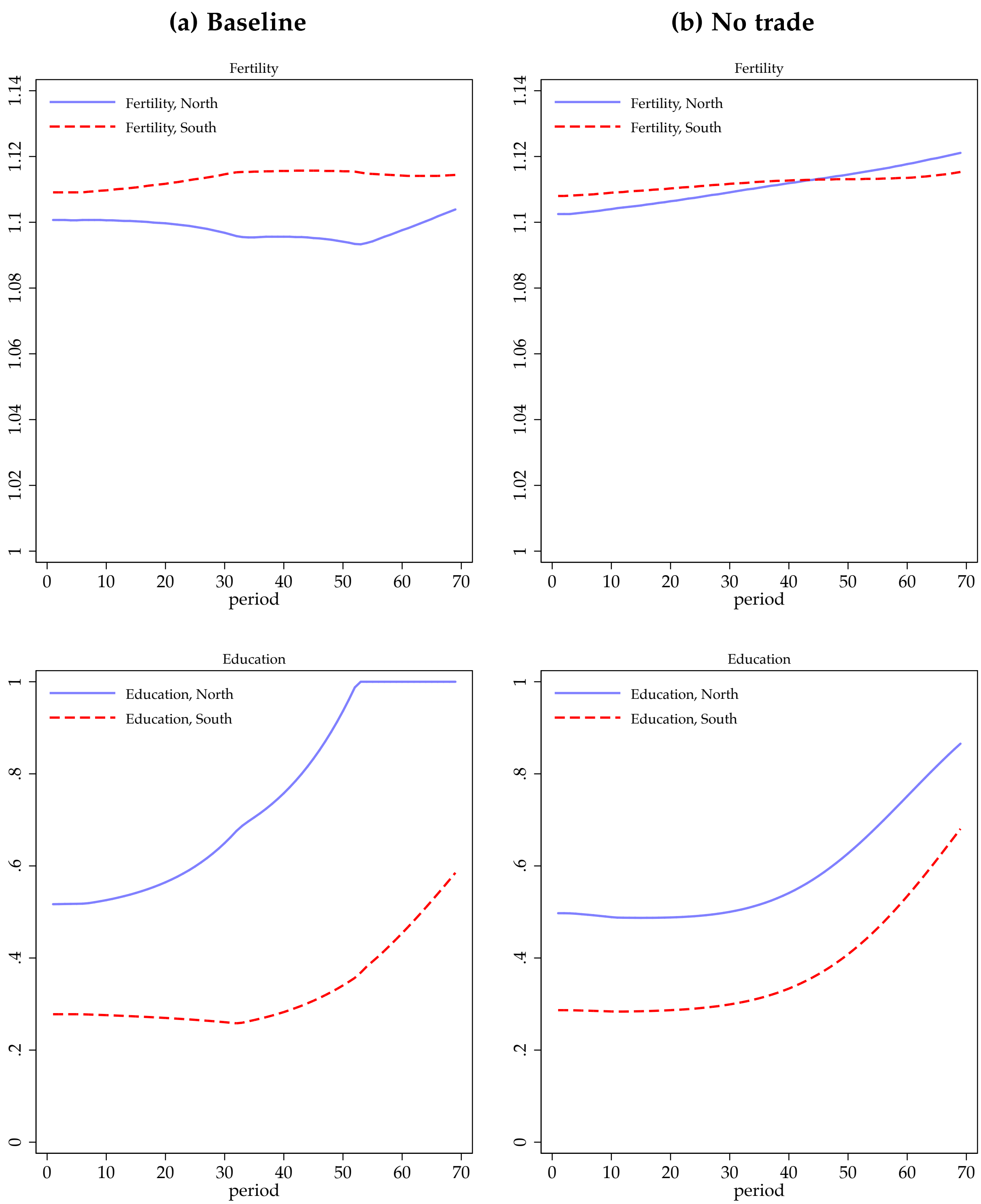
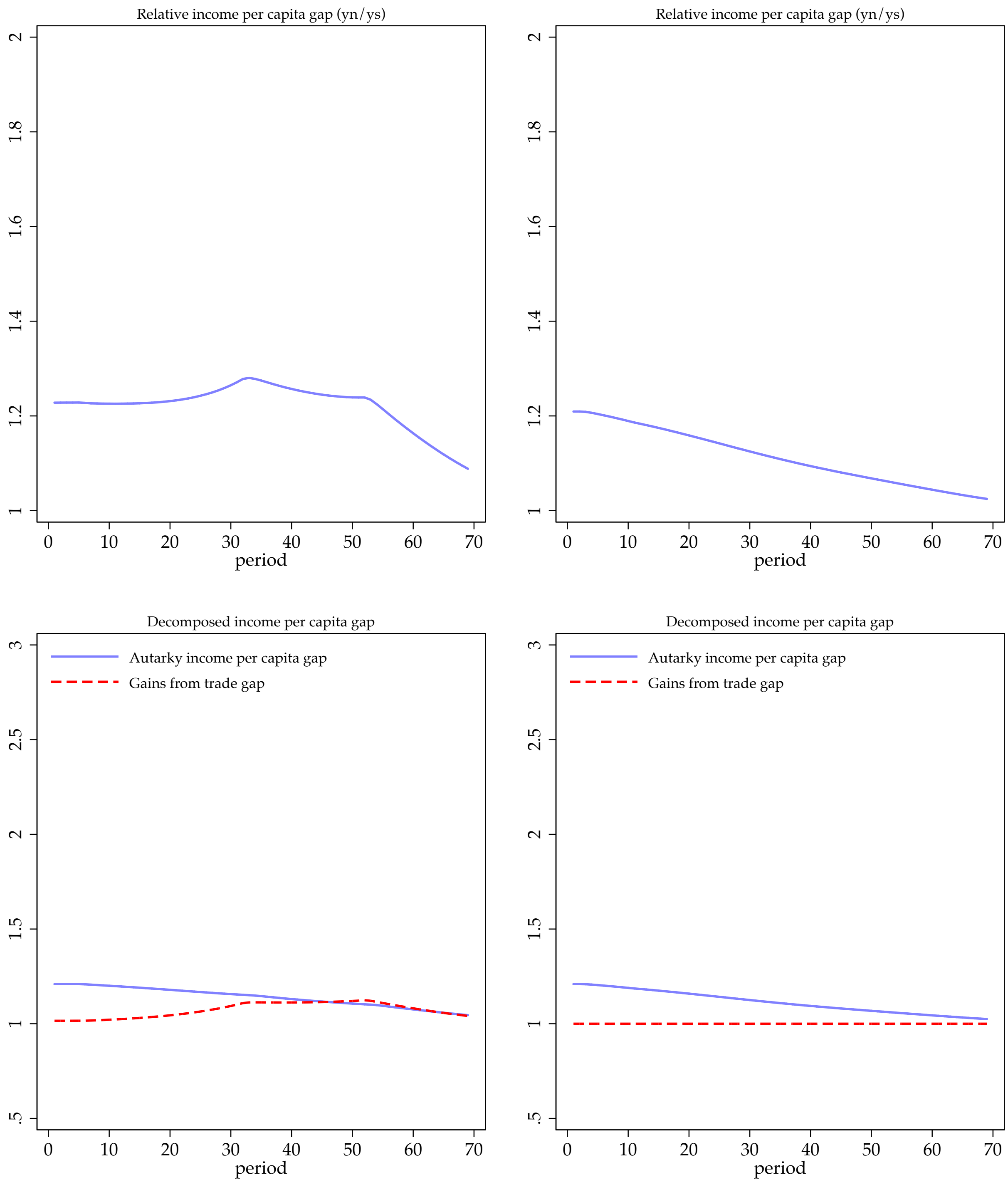


Figure 17: *Relative Income and Divergence — Perfect Technological Diffusion*

(a) Baseline **(b) No trade**



can innovate on its own, specialization patterns can still drive dramatic divergence in incomes. Through this terms of trade effect, we see that larger and in particular growing populations can be economically costly, even in the context where innovation is endogenous.

The other big difference is we analyze the case, arguably more relevant for contemporary economies, of technology transfer. *Ceteris paribus* such transfer should always speed convergence, but we see that trade alters the picture a bit. In this technological regime greater trade fosters more divergence early on but more rapid convergence later on. It is informative that, contrary to GM, globalization will eventually yield income convergence, even as it fosters a more volatile path towards that convergence.

References

Acemoglu, Daron. 2002. Directed Technical Change. *Review of Economic Studies* 69: 781–809.

Acemoglu, Daron. 2010. When Does Labor Scarcity Encourage Innovation? *Journal of Political Economy* 118(6): 1037–78.

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): 546–79.

Aghion, Philippe, and Peter Howitt. 1992. A Model of Growth through Creative Destruction. *Econometrica* 60(2): 323–51.

Basu, Susanto, and David N. Weil. 1998. Appropriate Technology and Growth. *Quarterly Journal of Economics* 113(4): 1025–54.

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

Clark, Gregory, and Robert C. Feenstra. 2001. Technology in the Great Divergence. In *Globalization in Historical Perspective* edited by Michael D. Bordo, Alan M. Taylor, and Jeffrey G. Williamson. Chicago: University of Chicago Press, pp. 277–321.

Cuñat, Alejandro, and Marco Maffezzoli. 2004. Neoclassical Growth and Commodity Trade. *Review of Economic Dynamics* 7(3): 707–36.

de Pleijt, Alexandra M., and Jacob L. Weisdorf. Human Capital Formation from Occupations: The 'Deskilling Hypothesis' Revisited. *Cliometrica*. Forthcoming.

Galor, Oded. 2005. From Stagnation to Growth: Unified Growth Theory. In *Handbook of Economic Growth*, vol. 1, part 1, edited by P. Aghion and S. N. Durlauf. Amsterdam: North Holland, pp. 171–293.

Galor, Oded, and Andrew Mountford. 2002. Why are a Third of People Indian and Chinese? Trade, Industrialization and Demographic Transition. CEPR Discussion Paper 3136.

Galor, Oded, and Andrew Mountford. 2006. Trade and the Great Divergence: The Family Connection. *American Economic Review Papers and Proceedings* 96(2): 299–303.

Galor, Oded, and Andrew Mountford. 2008. Trading Population for Productivity: Theory and Evidence. *Review of Economic Studies* 75(4): 1143–79.

Grossman, Gene M., and Elhanan Helpmann. 1991. *Innovation and Growth in the Global Economy*. Cambridge, Mass.: MIT Press.

Harley, C. Knick. 1988. Ocean Freight Rates and Productivity, 1740–1913: The Primacy of Mechanical Invention Reaffirmed. *Journal of Economic History* 48(4): 851–876.

Howitt, Peter. 1999. Steady Endogenous Growth with Population and R&D Inputs Growing. *Journal of Political Economy* 107(4): 715–30.

Jacks, David S., Christopher M. Meissner, and Dennis Novy. 2010. Trade Costs in the First Wave of Globalization. *Explorations in Economic History* 47(2): 127–141.

Jacks, David S., and Krishna Pendakur. 2010. Global Trade and the Maritime Transport Revolution. *Review of Economics and Statistics* 92(4): 745–755.

Jones, Charles I. 1995. R&D-Based Models of Economic Growth. *Journal of Political Economy*. 103(4): 759–84.

Jones, Charles I. 2003. Population and Ideas: A Theory of Endogenous Growth. In *Knowledge, Information, and Expectations in Modern Macroeconomics: In Honor of Edmund S. Phelps* edited

by P. Aghion, R. Frydman, J. Stiglitz, and M. Woodford. Princeton, N.J.: Princeton University Press, pp. 498–521.

Lipsey, Richard G., and Clifford Bekar. 1995. A Structuralist View of Technical Change and Economic Growth. *Bell Canada Papers on Economic and Public Policy* 3. Proceedings of the Bell Canada Conference at Queen's University. Kingston, Ont.: John Deutsch Institute, pp. 9–75.

Melvin, James R. 1968. Production and Trade with Two Factors and Three Goods. *American Economic Review* 58(5): 1249–68.

Mitchener, Kris J., and Se Yan. 2014. Globalization, Trade, and Wages: What Does History Tell Us About China? *International Economic Review* 55(1): 131–68.

Mohammed, Saif I., and Jeffrey G. Williamson. 2004. Freight Rates And Productivity Gains In British Tramp Shipping 1869–1950. *Explorations in Economic History* 41(2): 172–203.

Mokyr, Joel. 2002. *The Gifts of Athena: Historical Origins of the Knowledge Economy*. Princeton, N.J.: Princeton University Press.

North, Douglass C. 1958. Ocean Freight Rates and Economic Development 1730–1913. *Journal of Economic History* 18(4): 537–555.

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

O'Rourke, Kevin H., Ahmed S. Rahman, and Alan M. Taylor. 2013. Luddites, the Industrial Revolution, and the Demographic Transition. *Journal of Economic Growth* 18(4): 373–409.

O'Rourke, Kevin H., Alan M. Taylor, and Jeffrey G. Williamson. 1996. Factor Price Convergence in the Late Nineteenth Century. *International Economic Review* 37(3): 499–530.

O'Rourke, Kevin H., and Jeffrey G. Williamson. 1994. Late 19th Century Anglo-American Factor Price Convergence: Were Heckscher and Ohlin Right? *Journal of Economic History* 54(4): 892–916.

O'Rourke, Kevin H., and Jeffrey G. Williamson. 1999. *Globalization and History: The Evolution of a. Nineteenth Century Atlantic Economy*. Cambridge, Mass.: MIT Press.

O'Rourke, Kevin H., and Jeffrey G. Williamson. 2002. When Did Globalization Begin? *European Review of Economic History* 6(1): 23–50.

Pack, Howard, and Lawrence Westphal. 1986. Industrial Strategy and Technological Change: Theory versus Reality. *Journal of Development Economics* 22(1): 87–126.

Rahman, Ahmed S. 2013. The Road Not Taken: What Is The "Appropriate" Path to Development When Growth Is Unbalanced? *Macroeconomic Dynamics* 17(4): 747–78.

Romer, Paul M. 1986. Increasing Returns and Long-Run Growth. *Journal of Political Economy* 94: 1002–37.

Romer, Paul M. 1990. Endogenous Technological Change. *Journal of Political Economy* 98(5): S71–S102.

Romer, Paul M. 1992. Two Strategies for Economic Development: Using Ideas and Producing Ideas. *World Bank Economic Review* 6(S1): 63–91.

Segerstrom, Paul S., T. C. A. Anant, and Elias Dinopoulos. 1990. A Schumpeterian Model of the Product Life Cycle. *American Economic Review* 80(5): 1077–91.

Young, Alwyn. 1998. Growth without Scale Effects. *Journal of Political Economy* 106(1): 41–63.

Appendix

A. Diversified Trade Equilibrium

With trade of goods Q_1 and Q_3 between the North and the South, productions in each region are given by (35) and (36).

For each region $c \in n, s$, the following conditions characterize the diversified trade equilibrium:

$$p_1^s = \frac{w_l^s}{A_1^s}, \tag{39}$$

$$p_2^c = \left(\frac{1}{A_2^c}\right) \left(w_l^c\right)^{\gamma} \left(w_h^c\right)^{1-\gamma} (1-\gamma)^{\gamma-1} \gamma^{-\gamma}, \tag{40}$$

$$p_3^n = \frac{w_h^n}{A_3^n}, \tag{41}$$

$$\left(\frac{1}{A_1^c}\right) Q_1^c + \left(\frac{1}{A_2^c}\right) \left(w_l^c\right)^{\gamma-1} \left(w_h^c\right)^{1-\gamma} (1-\gamma)^{\gamma-1} \gamma^{1-\gamma} Q_2^c = L^c, \tag{42}$$

$$\left(\frac{1}{A_2^c}\right) \left(w_l^c\right)^{\gamma} \left(w_h^c\right)^{-\gamma} (1-\gamma)^{\gamma} \gamma^{-\gamma} Q_2^c + \left(\frac{1}{A_3^c}\right) Q_3^c = H^c, \tag{43}$$

$$Q_1^n + a_1 Z_1 = \left(\frac{\left(\frac{\alpha}{2}\right)^{\sigma} \left(p_1^n\right)^{-\sigma}}{\left(\frac{\alpha}{2}\right)^{\sigma} \left(p_1^n\right)^{1-\sigma} + (1-\alpha)^{\sigma} \left(p_2^n\right)^{1-\sigma} + \left(\frac{\alpha}{2}\right)^{\sigma} \left(p_3^n\right)^{1-\sigma}}\right) \cdot Y^n, \tag{44}$$

$$Q_1^s - Z_1 = \left(\frac{\left(\frac{\alpha}{2}\right)^{\sigma} \left(p_1^s\right)^{-\sigma}}{\left(\frac{\alpha}{2}\right)^{\sigma} \left(p_1^s\right)^{1-\sigma} + (1-\alpha)^{\sigma} \left(p_2^s\right)^{1-\sigma} + \left(\frac{\alpha}{2}\right)^{\sigma} \left(p_3^s\right)^{1-\sigma}}\right) \cdot Y^s, \tag{45}$$

$$Q_2^c = \left(\frac{(1-\alpha)^{\sigma} \left(p_2^c\right)^{-\sigma}}{\left(\frac{\alpha}{2}\right)^{\sigma} \left(p_1^c\right)^{1-\sigma} + (1-\alpha)^{\sigma} \left(p_2^c\right)^{1-\sigma} + \left(\frac{\alpha}{2}\right)^{\sigma} \left(p_3^c\right)^{1-\sigma}}\right) \cdot Y^c, \tag{46}$$

$$Q_3^n - Z_3 = \left(\frac{\left(\frac{\alpha}{2}\right)^{\sigma} \left(p_3^n\right)^{-\sigma}}{\left(\frac{\alpha}{2}\right)^{\sigma} \left(p_1^n\right)^{1-\sigma} + (1-\alpha)^{\sigma} \left(p_2^n\right)^{1-\sigma} + \left(\frac{\alpha}{2}\right)^{\sigma} \left(p_3^n\right)^{1-\sigma}}\right) \cdot Y^n, \tag{47}$$

$$Q_3^s + a_3 Z_3 = \left(\frac{\left(\frac{\alpha}{2}\right)^{\sigma} \left(p_3^s\right)^{-\sigma}}{\left(\frac{\alpha}{2}\right)^{\sigma} \left(p_1^s\right)^{1-\sigma} + (1-\alpha)^{\sigma} \left(p_2^s\right)^{1-\sigma} + \left(\frac{\alpha}{2}\right)^{\sigma} \left(p_3^s\right)^{1-\sigma}}\right) \cdot Y^s, \tag{48}$$

$$A_1^n \left(A_1^n L_1^n + a_1 Z_1\right)^{-\frac{1}{\sigma}} = \left(\frac{2(1-\alpha)\gamma}{\alpha}\right) A_2^{n\,\frac{\sigma-1}{\sigma}} \left(L^n - L_1^n\right)^{-\gamma-\sigma+\sigma\gamma} \left(H^n - H_3^n\right)^{\gamma+\sigma-\sigma\gamma-1}, \tag{49}$$

$$A_3^n \left(A_3^n H_3^n - Z_3\right)^{-\frac{1}{\sigma}} = \left(\frac{2(1-\alpha)(1-\gamma)}{\alpha}\right) A_2^{n\,\frac{\sigma-1}{\sigma}} \left(L^n - L_1^n\right)^{-\gamma+\sigma\gamma} \left(H^n - H_3^n\right)^{\gamma-\sigma\gamma-1}, \tag{50}$$

$$A_1^s \left(A_1^s L_1^s - Z_1\right)^{-\frac{1}{\sigma}} = \left(\frac{2(1-\alpha)\gamma}{\alpha}\right) A_2^{s\,\frac{\sigma-1}{\sigma}} \left(L^s - L_1^s\right)^{-\gamma-\sigma+\sigma\gamma} \left(H^s - H_3^s\right)^{\gamma+\sigma-\sigma\gamma-1}, \tag{51}$$

$$A_3^s \left(A_3^s H_3^s + a_3 Z_3\right)^{-\frac{1}{\sigma}} = \left(\frac{2(1-\alpha)(1-\gamma)}{\alpha}\right) A_2^{s\,\frac{\sigma-1}{\sigma}} \left(L^s - L_1^s\right)^{-\gamma+\sigma\gamma} \left(H^s - H_3^s\right)^{\gamma-\sigma\gamma-1}, \tag{52}$$

$$A_1^c = \left(N_{1,t-1}^c + \alpha^{\frac{\alpha}{1-\alpha}} \left(N_{1,t}^c - N_{1,t-1}^c\right)\right) \left(\alpha p_1^c\right)^{\frac{\alpha}{1-\alpha}}, \tag{53}$$

$$A_2^c = \left(N_{2,t-1}^c + \alpha^{\frac{\alpha}{1-\alpha}} \left(N_{2,t}^c - N_{2,t-1}^c\right)\right) \left(\alpha p_2^c\right)^{\frac{\alpha}{1-\alpha}}, \tag{54}$$

$$A_3^c = \left(N_{3,t-1}^c + \alpha^{\frac{\alpha}{1-\alpha}} \left(N_{3,t}^c - N_{3,t-1}^c\right)\right) \left(\alpha p_3^c\right)^{\frac{\alpha}{1-\alpha}}, \tag{55}$$

$$H^c = \left(\frac{\tau^{*^c}}{b^c}\right) pop^c, \tag{56}$$

$$L^c = \left(1 - \frac{\tau^{*^c}}{b^c}\right) pop^c + n^c\, pop^c, \tag{57}$$

$$n^c = \left(1 - \frac{\tau^{*^c}}{b^c}\right) n_l^{*^c} + \left(\frac{\tau^{*^c}}{b^c}\right) n_h^{*^c}, \tag{58}$$

$$e^c = \frac{\tau^{*^c}}{b^c}, \tag{59}$$

$$\frac{p_1^n}{p_3^n} = \frac{Z_3}{aZ_1}, \tag{60}$$

$$\frac{p_1^s}{p_3^s} = \frac{aZ_3}{Z_1}. \tag{61}$$

Equations (39)–(41) are unit cost functions, (42) and (43) are full employment conditions, (44)–(48) denote regional goods clearance conditions, (49)–(52) equate the marginal products of raw factors, (53)–(55) describe sector-specific technologies, , (56)–(65) describe fertility, education and labor-types for each region, and (66) and (67) describe the balance of payments for each region. Solving this system for the unknowns p_1^n, p_1^s, p_2^n, p_2^s, p_3^n, p_3^s, Q_1^n, Q_1^s, Q_2^n, Q_2^s, Q_3^n, Q_3^s, w_l^n, w_l^s, w_h^n, w_h^s, L_1^n, L_1^s, H_3^n, H_3^s, A_1^n, A_2^n, A_3^n, A_1^s, A_2^s, A_3^s, L^n, L^s, H^n, H^s, n^n, n^s, e^n, e^s, Z_1 and Z_3 constitutes the static partial trade equilibrium. Population growth for each region is given simply by $pop_t^c = n_{t-1}^c\, pop_{t-1}^c$. Each region will produce all three goods so long as factors and technologies are "similar enough." If factors of production or technological levels sufficiently differ, the North produces only goods 2 and 3, while the South produces only goods 1 and 2. No other specialization scenario is possible for the following reasons: first, given that both the North and South have positive levels of L and H, full employment of resources implies that they cannot specialize completely in good 1 or good 3. Second, specialization solely in good 2 is not possible either, since a region with a comparative advantage in this good would also have a comparative advantage in either of the other goods. This implies that each country must produce at least two goods. Further, in such a scenario we cannot have one region producing goods 1 and 3: with different factor prices across regions, a region cannot have a comparative advantage in the production of both of these goods, regardless of the technological differences between the two regions. See Cuñat and Maffezzoli (2004) for a fuller discussion.

B. Specialized Trade Equilibrium

The specialized equilibrium is one where the North does not produce any good 1 and the South does not produce any good 3. Productions in each region are then given by

$$Y^n = \left(\frac{\alpha}{2}\left(aZ_1\right)^{\frac{\sigma-1}{\sigma}} + (1-\alpha)\left(Q_2^n\right)^{\frac{\sigma-1}{\sigma}} + \frac{\alpha}{2}\left(Q_3^n - Z_3\right)^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}}, \tag{62}$$

$$Y^s = \left(\frac{\alpha}{2}\left(Q_1^s - Z_1\right)^{\frac{\sigma-1}{\sigma}} + (1-\alpha)\left(Q_2^s\right)^{\frac{\sigma-1}{\sigma}} + \frac{\alpha}{2}\left(aZ_3\right)^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}}, \tag{63}$$

Once again, we do not permit any trade of good 2. For each region $c \in n, s$, the following conditions characterize this equilibrium.

$$p_1^s = \frac{w_l^s}{A_1^s}, \tag{64}$$

$$p_2^c = \left(\frac{1}{A_2^c}\right)\left(w_l^c\right)^{\gamma}\left(w_h^c\right)^{1-\gamma}(1-\gamma)^{\gamma-1}\gamma^{-\gamma}, \tag{65}$$

$$p_3^n = \frac{w_h^n}{A_3^n}, \tag{66}$$

$$\left(\frac{1}{A_2^n}\right)\left(w_l^n\right)^{\gamma-1}\left(w_h^n\right)^{1-\gamma}(1-\gamma)^{\gamma-1}\gamma^{1-\gamma}Q_2^n = L^n, \tag{67}$$

$$\left(\frac{1}{A_2^n}\right)\left(w_l^n\right)^{\gamma}\left(w_h^n\right)^{-\gamma}(1-\gamma)^{\gamma}\gamma^{-\gamma}Q_2^n + \left(\frac{1}{A_3^n}\right)Q_3^n = H^n, \tag{68}$$

$$\left(\frac{1}{A_1^s}\right)Q_1^s + \left(\frac{1}{A_2^s}\right)\left(w_l^s\right)^{\gamma-1}\left(w_h^s\right)^{1-\gamma}(1-\gamma)^{\gamma-1}\gamma^{1-\gamma}Q_2^s = L^s, \tag{69}$$

$$\left(\frac{1}{A_2^s}\right)\left(w_l^s\right)^{\gamma}\left(w_h^s\right)^{-\gamma}(1-\gamma)^{\gamma}\gamma^{-\gamma}Q_2^s = H^s, \tag{70}$$

$$a_1Z_1 = \left(\frac{\left(\frac{\alpha}{2}\right)^{\sigma}\left(p_1^n\right)^{-\sigma}}{\left(\frac{\alpha}{2}\right)^{\sigma}\left(p_1^n\right)^{1-\sigma} + (1-\alpha)^{\sigma}\left(p_2^n\right)^{1-\sigma} + \left(\frac{\alpha}{2}\right)^{\sigma}\left(p_3^n\right)^{1-\sigma}}\right)\cdot Y^n, \tag{71}$$

$$Q_1^s - Z_1 = \left(\frac{\left(\frac{\alpha}{2}\right)^{\sigma}\left(p_1^s\right)^{-\sigma}}{\left(\frac{\alpha}{2}\right)^{\sigma}\left(p_1^s\right)^{1-\sigma} + (1-\alpha)^{\sigma}\left(p_2^s\right)^{1-\sigma} + \left(\frac{\alpha}{2}\right)^{\sigma}\left(p_3^s\right)^{1-\sigma}}\right)\cdot Y^s, \tag{72}$$

$$Q_2^c = \left(\frac{(1-\alpha)^{\sigma}\left(p_2^c\right)^{-\sigma}}{\left(\frac{\alpha}{2}\right)^{\sigma}\left(p_1^c\right)^{1-\sigma} + (1-\alpha)^{\sigma}\left(p_2^c\right)^{1-\sigma} + \left(\frac{\alpha}{2}\right)^{\sigma}\left(p_3^c\right)^{1-\sigma}}\right)\cdot Y^c, \tag{73}$$

$$Q_3^n - Z_3 = \left(\frac{\left(\frac{\alpha}{2}\right)^{\sigma}\left(p_3^n\right)^{-\sigma}}{\left(\frac{\alpha}{2}\right)^{\sigma}\left(p_1^n\right)^{1-\sigma} + (1-\alpha)^{\sigma}\left(p_2^n\right)^{1-\sigma} + \left(\frac{\alpha}{2}\right)^{\sigma}\left(p_3^n\right)^{1-\sigma}}\right)\cdot Y^n, \tag{74}$$

$$a_3Z_3 = \left(\frac{\left(\frac{\alpha}{2}\right)^{\sigma}\left(p_3^s\right)^{-\sigma}}{\left(\frac{\alpha}{2}\right)^{\sigma}\left(p_1^s\right)^{1-\sigma} + (1-\alpha)^{\sigma}\left(p_2^s\right)^{1-\sigma} + \left(\frac{\alpha}{2}\right)^{\sigma}\left(p_3^s\right)^{1-\sigma}}\right)\cdot Y^s, \tag{75}$$

$$A_3^n \left(A_3^n H_3^n - Z_3\right)^{-\frac{1}{\sigma}} = \left(\frac{2(1-\alpha)(1-\gamma)}{\alpha}\right) A_2^{n\frac{\sigma-1}{\sigma}} \left(L^n\right)^{-\gamma+\sigma\gamma} \left(H^n - H_3^n\right)^{\gamma-\sigma\gamma-1}, \tag{76}$$

$$A_1^s \left(A_1^s L_1^s - Z_1\right)^{-\frac{1}{\sigma}} = \left(\frac{2(1-\alpha)\gamma}{\alpha}\right) A_2^{s\frac{\sigma-1}{\sigma}} \left(L^s - L_1^s\right)^{-\gamma-\sigma+\sigma\gamma} \left(H^s\right)^{\gamma+\sigma-\sigma\gamma-1}, \tag{77}$$

$$A_1^s = \left(N_{1,t-1}^s + \alpha^{\frac{\alpha}{1-\alpha}} \left(N_{1,t}^s - N_{1,t-1}^s\right)\right) \left(\alpha p_1^s\right)^{\frac{\alpha}{1-\alpha}}, \tag{78}$$

$$A_2^c = \left(N_{2,t-1}^c + \alpha^{\frac{\alpha}{1-\alpha}} \left(N_{2,t}^c - N_{2,t-1}^c\right)\right) \left(\alpha p_2^c\right)^{\frac{\alpha}{1-\alpha}}, \tag{79}$$

$$A_3^n = \left(N_{3,t-1}^n + \alpha^{\frac{\alpha}{1-\alpha}} \left(N_{3,t}^n - N_{3,t-1}^n\right)\right) \left(\alpha p_n^c\right)^{\frac{\alpha}{1-\alpha}}, \tag{80}$$

$$H^c = \left(\frac{\tau^{*^c}}{b^c}\right) pop^c, \tag{81}$$

$$L^c = \left(1 - \frac{\tau^{*^c}}{b^c}\right) pop^c + n^c\, pop^c, \tag{82}$$

$$n^c = \left(1 - \frac{\tau^{*^c}}{b^c}\right) n_l^{*^c} + \left(\frac{\tau^{*^c}}{b^c}\right) n_h^{*^c}, \tag{83}$$

$$e^c = \frac{\tau^{*^c}}{b^c}, \tag{84}$$

$$\frac{p_1^n}{p_3^n} = \frac{Z_3}{aZ_1}, \tag{85}$$

$$\frac{p_1^s}{p_3^s} = \frac{aZ_3}{Z_1}. \tag{86}$$

C. Alternative Simulations — The Case of Free Trade

As a robustness check, this appendix present the results from an alternative set of "free trade" simulations where trade between North and South is frictionless ($a = 1$) for all periods starting at time 0. The first three figures, show the case of Localized Technologies, exactly as in the main text apart from the free trade assumption. The last three figures, show the case of Perfect Technological Diffusion, exactly as in the main text apart from the free trade assumption. The results show that this case is similar to the Baseline case where trade costs gradually fall, except that the divergence dynamics are more accelerated.

Figure 18: *Case of Free Trade — Localized Technologies*

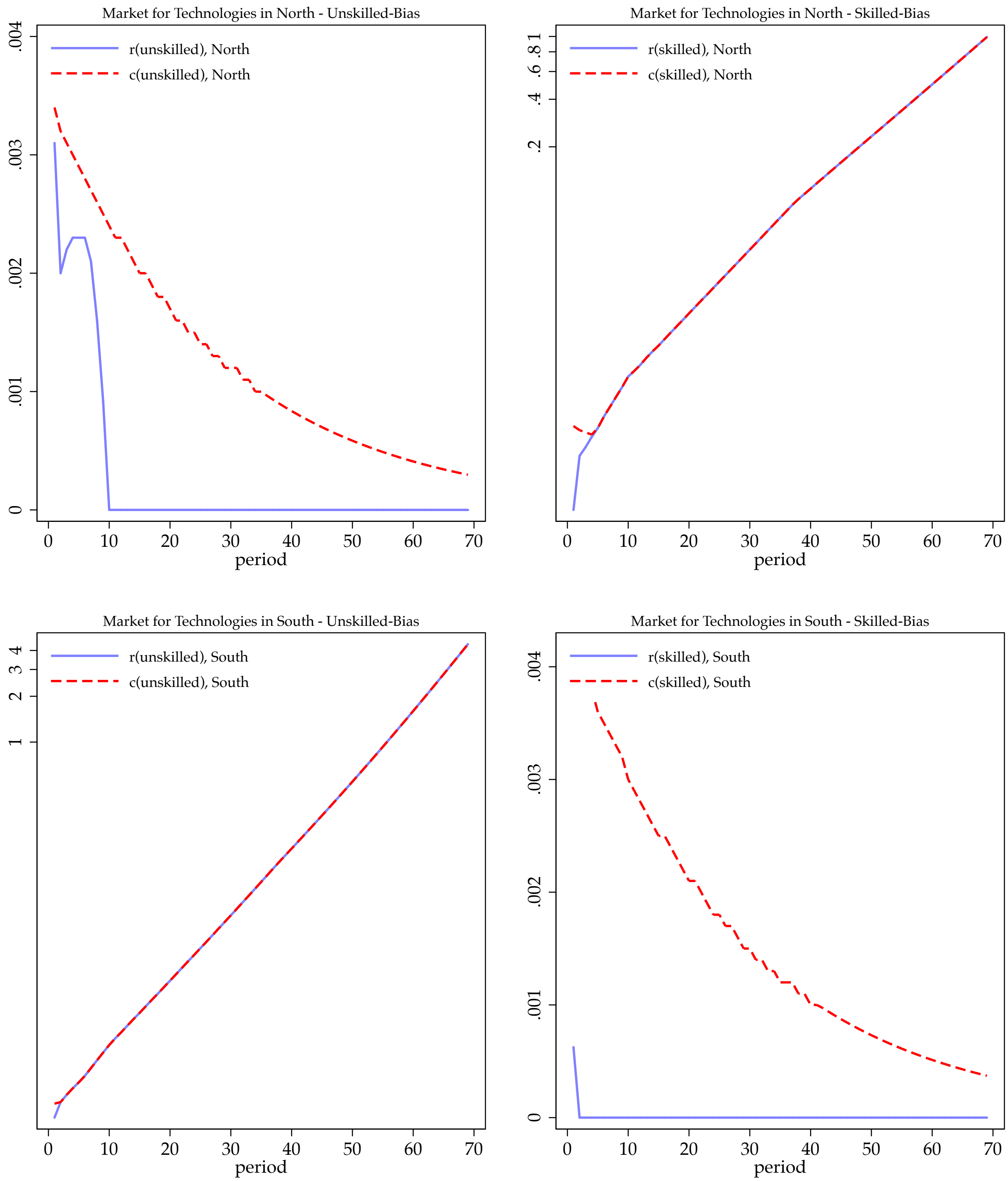


Figure 19: *Case of Free Trade — Localized Technologies*

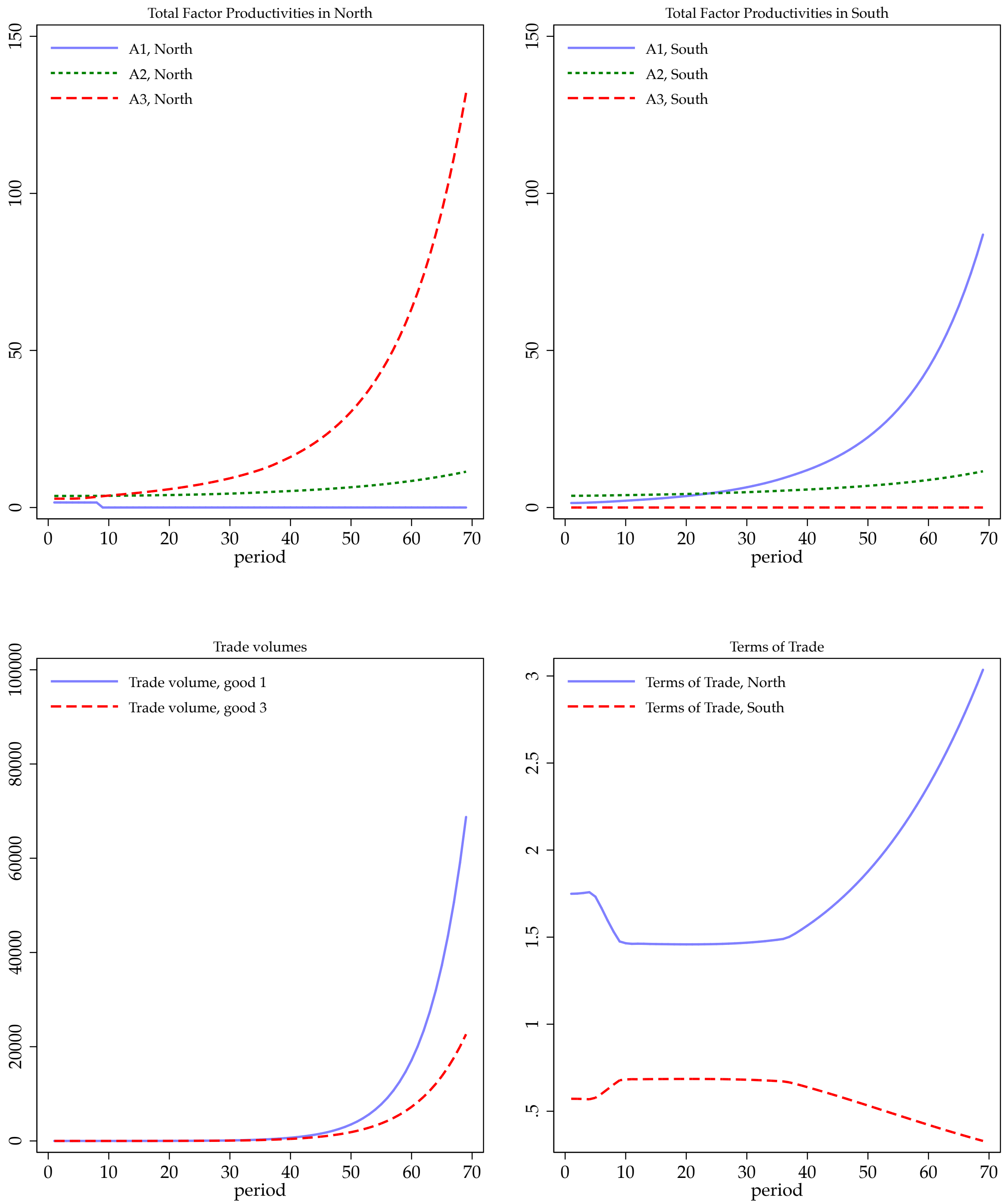


Figure 20: *Case of Free Trade — Localized Technologies*

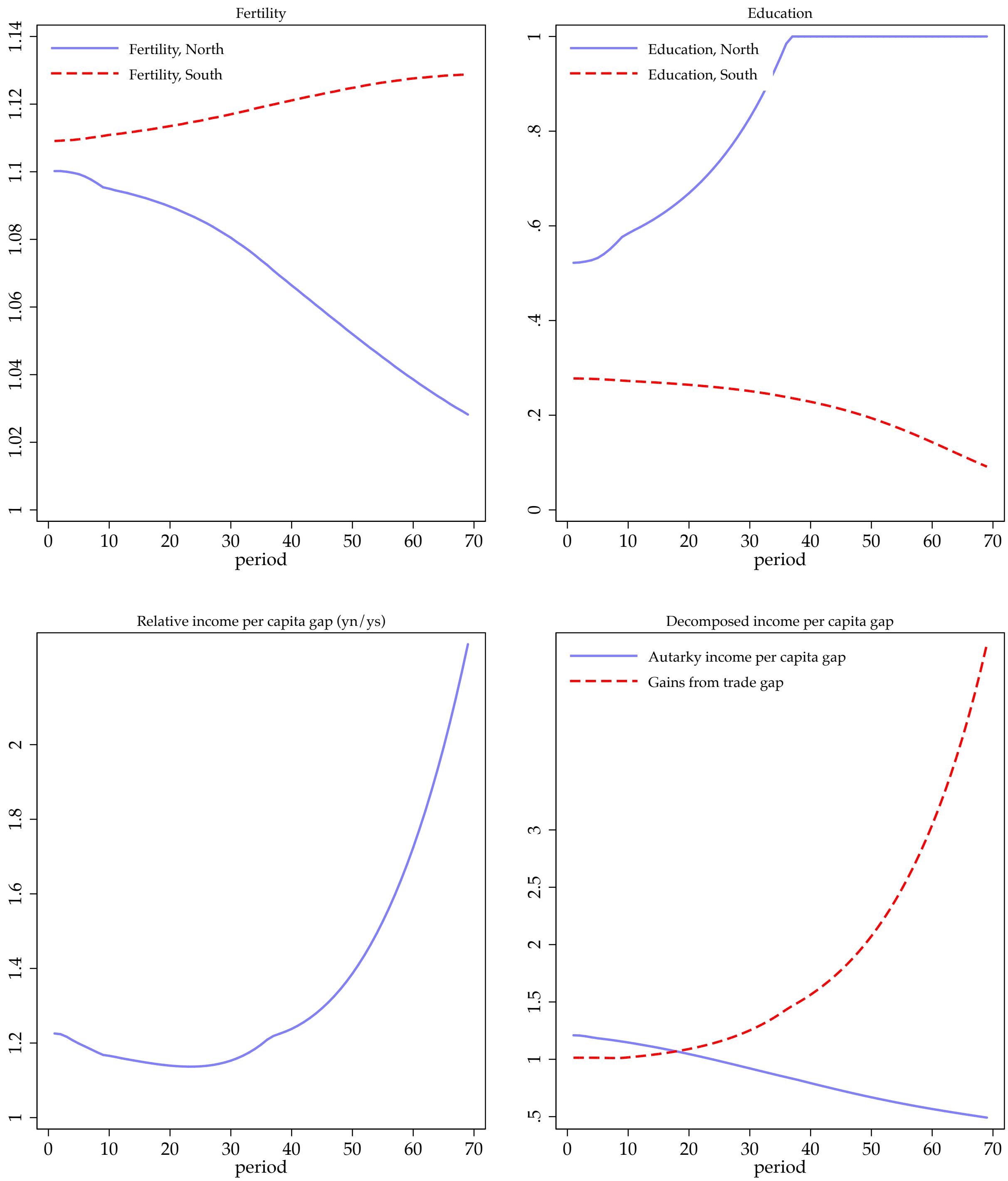


Figure 21: *Case of Free Trade — Perfect Technological Diffusion*

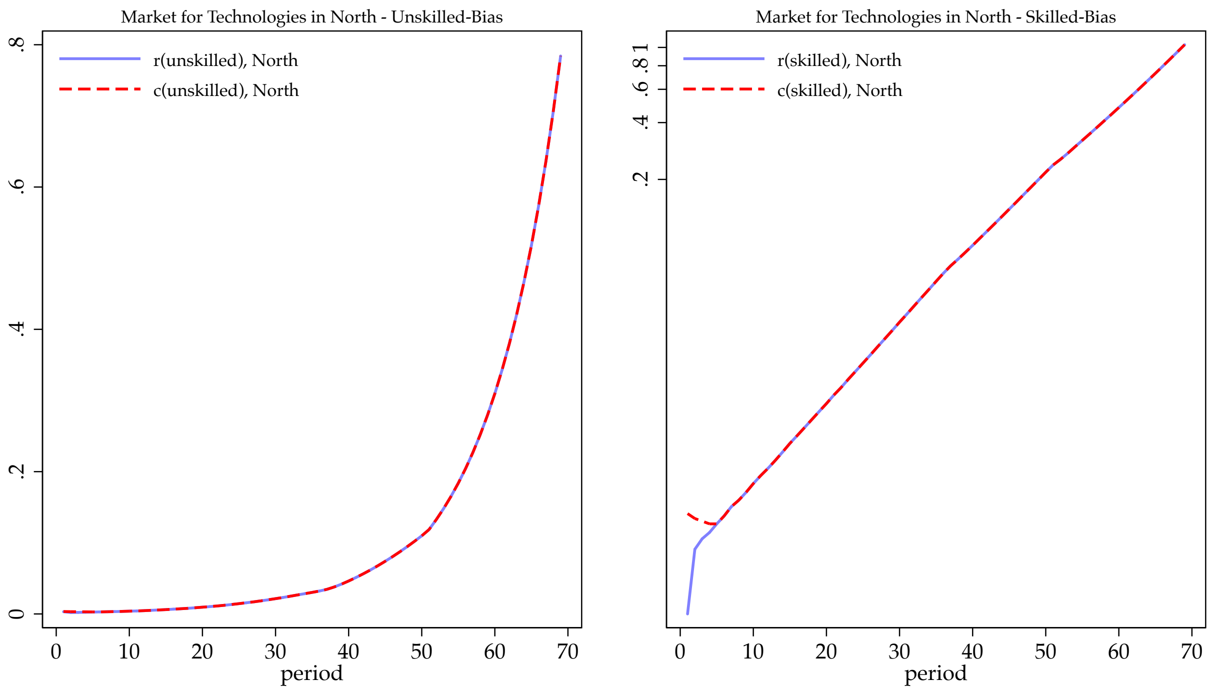


Figure 22: *Case of Free Trade — Perfect Technological Diffusion*

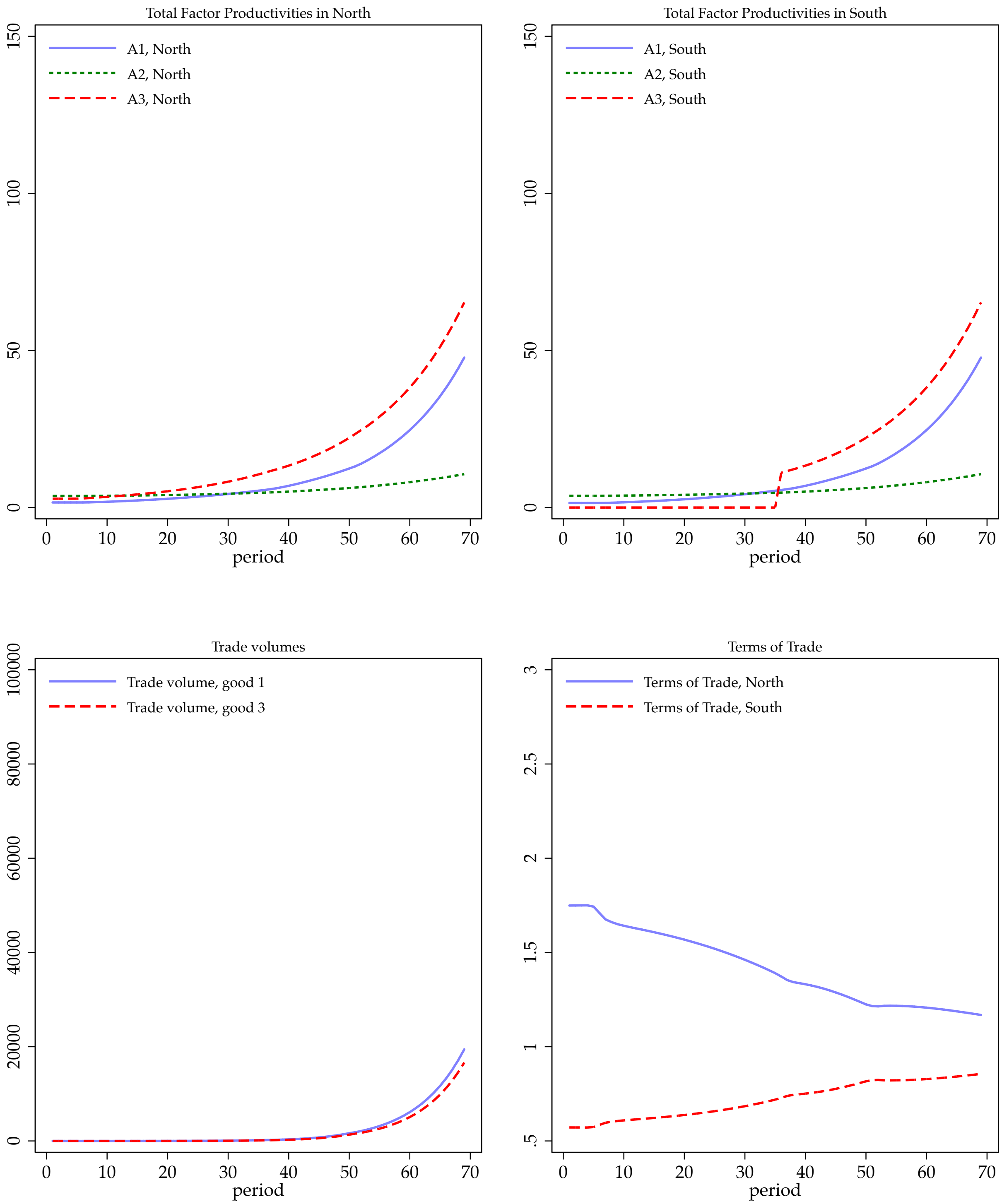


Figure 23: *Case of Free Trade — Perfect Technological Diffusion*