Trapped Factors and China's Impact on Global Growth

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Abstract

In a general equilibrium model of the product-cycle, lower trade barriers increase purchasing power in the South, which lifts the long-run rate of growth by increasing the profit from innovation. In the short run, factors of production must be reallocated inside firms, which temporarily lowers the opportunity cost of innovation (a "trapped factor" effect). Starting from a baseline rate of growth of 2% per year in the OECD, we find that trade integration with low wage countries in the decade around China's accession to the WTO could have increased OECD growth by 0.37% (to 2.37%) per year in the long run. There is an additional short-run effect from trapped factors with growth initially rising by 0.7% per year (to 2.7%). Half of these increases in growth are due to China alone.

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1 Introduction

Ever since Adam Smith published *The Wealth of Nations*, economists have debated the sign and magnitude of the gains from trade. Participants in these debates have long recognized that the static gains could be dwarfed by dynamic effects. Recent evidence from the empirical micro-literature suggests that trade can indeed have a large positive impact on innovation and productivity growth.[1] Likewise some reduced form macro-empirical estimates also suggest that trade can have a large impact on the level of national income or its rate of growth.[2] One puzzle, however, is that in calibrated general equilibrium models the quantitative estimates of the welfare effects of trade still appear so small. A typical calculation suggests that for a nation like the United States, a move from autarky to current levels of trade implies a gain of a few percentage points of GDP.[3]

In this paper, we craft a model to match recent evidence showing that the firms in Europe that faced more direct competition from China's low-wage exports undertook bigger increases in product innovation.[4] To match this response, the model lets firms choose how much to invest in developing new products and processes. In the spirit of models of endogenous growth,[5] the model requires that all increases in productivity come from these firm-level investments in innovation. As a result, it makes it possible to trace the effects that a modest change in trade policy has on firm-level investments in innovation, through to the implied change in the aggregate rate of growth, taking full account of general equilibrium interactions. The model confirms the intuition that the dynamic gains from trade can be large, substantially larger than other comparable exercises suggest.

The challenge in capturing the micro-evidence is to explain why a firm that is more exposed to competition from imports from China has a bigger incentive to develop new goods when imports are liberalized. The model shows that this is precisely what one would expect if factor of production are temporarily "trapped" within firms due to moving costs. If, for example, the skilled engineers at a firm are expensive to train and then lay-off, a negative demand shock to a good they helped produce leaves them in the firm but reduces

[1] See for example Pavnik (2002) on Chile, Bernard, Jensen and Schott (2006) for the US, Amiti and Konings (2006) on Indonesia, Goldberg et al. (2010) looking at imports in India, Lileeva and Trefler (2010) on export induced upgrading in Canada, Aw, Roberts and Xu (2011) on R

[2] See, for example, Frenkel and Romer (1999), or case studies such as Romer (1993) on the effect of an EPZ in Mauritius, Bernhofen, and Brown (2004, 2005) on post-Meiji Japan, Treffler (2004) on CAFTA, Feyrer (2013) on the Suez Canal or Irwin (2005) on the Jefferson embargo.

[3] Costinot and Rodriguez-Clare (2013) simulate that moving from current levels of US to autarky would cause only a small loss of welfare of about 1% (see also Atkeson and Burstein, 2010). Melitz and Redding (2013a) more than double this to 2.5% when they allow for an alternative way to model heterogeneous firms. Eaton and Kortum (2012) argue for larger gains in a Ricardian framework rising from 2% to 3% 20 years ago to 5% today.

[4] Bloom, Draca and Van Reenen (2012).

[5] See for example, Romer (1990), Aghion and Howitt (1992), and Grossman and Helpman (1991).

their opportunity cost. Under this scenario, the firm innovates after the trade shock not just because the value of a newly designed product has gone up but also because the opportunity cost of designing and producing it have gone down. This interpretation is consistent with the evidence that firms shift resources out of activities that compete with imports from low wage countries.[6] The idea is also born out in many case studies of international trade in which firms respond to import competition from a low-wage nation by developing an entirely new type of good that will be less vulnerable to this type of competition.[7]

In addition to this trapped-factor effect of trade on innovation, the model allows for the independent effect that a more integrated world market has on the steady-state growth rate (a "market size" effect). A reduction in trade barriers increases purchasing power in the South, which increases the profit that a Northern firm can earn from sales there. In contrast to the effect of trapped-factors on innovation, which arises only at firms that face direct competition from low-wage imports, this increase in potential profits causes an increase in the rate of innovation at all Northern firms, and is therefore harder to identify from micro-data. It is an incremental version of the scale effect on growth that has been examined in models of trade with endogenous growth by comparing two isolated economies with a single fully integrated economy.[8] This mechanism has not, to our knowledge, been investigated in a model that is rich enough to be used in a calibration. At a minimum, such a model must allow a comparison across equilibria with a continuum of degrees of openness. In a sensitivity analysis, we also verify that over a time horizon of roughly a century, the conclusions from our endogenous growth model are very similar to alternative calibrations based on a model of semi-endogenous growth (like that of Jones, 1995a,b) in which a policy change can have a prolonged effect on the growth rate that eventually converges back to zero.

In our product-cycle model, innovation in the North produces new intermediate inputs that are used by firms in both the North and the South. In a balanced growth equilibrium, trade barriers prevent factor-price equalization, so goods produced in the South have an absolute cost advantage. We calibrate the model to match both the baseline rate of growth and the firm-level decisions about innovation from the micro literature and find that the increased global integration of the OECD with all low-wage countries that took place during

[6] See for example, Bernard, Jensen and Schott (2006).

[7] For example, Freeman and Kleiner (2005) report that when a large American shoe firm was faced with rising imports of cheap shoes from China it abandoned production of mass-market mens' shoes. But, rather than simply close its factory the firm introduced new types of shoes for smaller niche markets, using its newly idle engineers to help develop these and its idle production line to produce these. For example, one new product was a batch of boots with metal hoops in the soles that made it easier for workers to rapidly climb ladders, ordered by a local construction firm. The design for these boots earned a patent. All of this occurred because the abandonment of the production line for mass market shoes in response to Chinese competition, which left its engineers temporarily free to innovate new shoes.

[8] See for example, Grossman and Helpman, (1990) and Romer and Rivera-Batiz (1991).

the decade around China's accession to the WTO increases the long-run rate of growth in the OECD from 2.0% per year to almost 2.37% per year. Of this increase, approximately one half, or 0.2%, can be attributed to China by alone.

Of course, small increases in growth can generate substantial improvements in welfare. This permanent increase in the rate of growth from trade with the South has a welfare effect that in the absence of faster growth, would be equivalent to increasing consumption by 16%. Of this increase in consumption, 14% is from the increased profitability of innovation and 2% is from the trapped-factor effect. But although the trapped-factors mechanism has a smaller long-run welfare effect it is front-loaded, so over the first decade after the trade shock its effect on the rate of growth is similar in magnitude to the market-size effect and might therefore be of comparable interest in policy debates. For trade with all low wage countries, the trapped-factor effect increases the rate of growth by an additional 0.3% per year in the first decade after the liberalization, with about one third being due to China alone.

Our results connect to several other lines of work. To simplify the analysis, the model allows for heterogeneity among firms only in the degree of import competition that they face. One natural extension would allow for other dimensions of heterogeneity (e.g Melitz and Redding, 2013b). We also assume that firms also operate in only one region, so another natural extension would allow for multinational firms that manage R&D and production in both the North and South (see Antras and Yeaple, 2013 for an overview of the evidence and theory work in this area). In a model of growth based on diffusion of heterogeneous stocks of existing knowledge that is complementary to our model based on innovation, Perla, Tonetti, and Waugh (2012) find that trade liberalization can encourage more firms with low productivity to seek out interaction with high productivity firms from whom they can learn. Because the gains from diffusion are never exhausted, faster diffusion in this setting can also, at least in some cases, lead to a permanently faster rate of growth. Recent papers have also considered the interaction between diffusion and heterogeneity.[9] Our estimates are conservative in the sense that all these extensions are likely to generate additional gains from trade.

Our paper connects not just to the general literature cited above on the welfare effects of trade, but also on those papers that look specifically at the impact of trade with China (e.g. Ossa and Hsieh, 2011). Because of concern about increased inequality, an older literature on the distributional effects of trade that arise when labor is industry-specific (e.g. Jones, 1971; Mussa, 1974) is generating renewed interest (Autor, Dorn and Hanson, 2013). In such models, the gains from trade for some groups are offset by welfare losses for others. As we note below, the optimistic conclusions from our analysis of the gains from trade need to be

[9] See for example, Sampson (2012), Bustos (2011) and Constantini and Melitz (2008).

tempered if such effects are large. In contrast to this literature, where specificity has no social benefits, in our second-best model, trapped factors generate additional welfare gains when there are unexpected increases in trade.

The model of innovation spurred by a reduction in the opportunity cost of the inputs used in innovation is reminiscent of the old idea that trade competition can effect X-inefficiency (Leibenstein 1966) without following the type of principal-agent structure[10] that de Loecker and Goldberg (2014) have recently questioned. Finally, our structure, in which firms take advantage of a negative shock by investing in innovation, is similar in spirit to business cycle theories about the "virtues of bad times" described by Aghion and Saint-Paul (1998), who build on Hall (1991).

The road map to the rest of the paper is as follows. In Section 2 we give some basic trade and innovation statistics before starting with the closed economy model in Section 3. Section 4 extends this to the open economy, and Section 5 looks at trade shocks in the open economy in the fully mobile and trapped factor case. Section 6 moves on to the quantitative exercise, and Section 7 offers some extensions and robustness tests. Section 8 concludes. The Appendices contain many technical details of the theoretical proofs (A), calibration (B), solutions (C), an extension to a semi-endogenous growth approach (D), and an extension to an alternative R&D cost function (E).

2 Descriptive statistics on trade and innovation

The type of change in worldwide trade policy that we want to consider is roughly comparable to the trade liberalization experienced over the last couple of decades. Figure 1 plots imports from non-OECD countries into OECD countries between 1997 and 2006, measured as a percentage of total GDP in the OECD. Low-wage import shares almost doubled from 3.9% in 1997 to 7% in 2006. China accounted for about half of this increase. This ten-year period from 1997-2006 is of particular interest because it brackets China's WTO accession in December 2001. The discrete-time model we present has a period length of a decade so we calibrate over the decade 1997-2006.

In our model we want to explain three stylized facts from the impact of Chinese trade on European firms discussed in Bloom, Draca, and Van Reenen (2012):

- Greater Chinese import competition led to increases in innovation - R&D expenditure, patenting, TFP growth and IT investment all went up in the impacted industries.
- The increase in innovation occurred *within* incumbent firms - that is even though the prices and profits of these firms was falling, those that did not exit increased their

[10] See for example Schmidt (1997).

rates of innovation.

- The response to import competition from high-wage countries like Japan in contrast had little impact on innovation.

The case study evidence helps to interpret these three results. As noted above, Freeman and Kleiner (2005) showed that US shoe manufacturers switched from making low-cost mass market shoes to innovative niche products when faced with rising Chinese competition. Likewise, Bartel, Ichniowski and Shaw (2007) document that UK and US valve manufacturers were forced in the face of low-wage import competition to use their resources to produce new, higher-tech valves which could be used more intensely for more specialized purposes. In Italy Bugamelli et al. (2012) show a range of manufacturers from ceramic tiles to women's clothing switched to more innovative high-end products in response to rising low-wage competition. Consequently, these stylized facts from the econometric and anecdotal evidence focus us into modeling competition in existing product lines from lower cost producers in developing countries as the driver of innovation.[11]

Another channel of influence could be from rising innovation in China itself. But this is unlikely to be a major factor. Figure 2 shows that although the proportion of USPTO patents granted (dated by application years 1977-2006) to inventors located in non-OECD countries has risen rapidly the numbers are tiny in magnitude. In particular, Chinese patenting picks up after 1990 but remains extremely low, with an average of 0.02% of all US patents.[12] Such evidence suggests that non-OECD competition operates in a product-cycle context, such as that first documented by Vernon (1966) where low-wage competitors eventually price high-wage countries out of the product markets for preexisting goods.

3 Closed Economy Model

We introduce the basic structure of the model for a closed economy. This lets us describe the technology and highlight the key equation in the model. It characterizes the rate of growth of the variety of inputs, which can also be interpreted as the rate of growth of patents

[11] To fit this evidence, and the evidence from Bernard, Jensen, Schott (2006) that firms shift toward the production of new goods, sometimes even goods in new industries, we develop a model in which innovation leads to new goods (Romer, 1987, 1990) rather than quality improvements (Aghion and Howitt, 1992.) A model of quality improvement based on "escape competition" as in Aghion, et al. (2005) would be more applicable to trade liberalization between countries with similar factor prices than the case we consider of liberalization with a South that has a pure cost advantage in any goods it can export production.

[12] Chinese and non-OECD patenting rates remain extremely low relative to the OECD. Note, however, that Puga and Trefler (2010) raises the possibility that low-wage countries may be increasingly participating in "incremental innovation," or innovation which involves small steps of improvement in processes and production but is not necessarily evident in patenting statistics. We abstract from such incremental innovation in this paper.

or new designs. Note that in this initial closed-economy equilibrium derivation, we omit discussion of the costs that can trap factors in firms. We bring them in after introducing trade.

3.1 Technology

There are two types of inputs in all types of production, human capital and a variety of produced intermediate inputs. At any date, these inputs can be used in three different productive activities: producing final consumption goods, producing new physical units of the intermediate inputs that will be used in production in the next period, and producing new designs or patents. We assume that the two types of inputs are used with the same factor intensities in these three activities, so we can use the simplifying device of speaking of the production first of final output, and then the allocation of final output to the production of consumption goods, intermediate inputs, or new patented designs. We can also speak of final output as the numeraire, with the understanding that it is in fact the bundle of inputs that produces one unit of final output that is actually the numeraire good.

With this convention, we can write final output Y_t in period t, as the following function of human capital H and intermediate goods $x_{jt,}$ where j is drawn from the range of intermediate inputs that have already been invented, $j \in [0, A_t]$:

$$Y_t = H^{\alpha} \int_0^{A_t} x_{jt}^{1-\alpha} dj$$

Using the convention noted above, we can speak of firms in period t devoting a total quantity Z_t of final output to the production of new patented designs that will increase the existing stock of designs A_t to the value that will be available next period, A_{t+1}. If we let C_t denote final consumption goods, final output is divided as follows:

$$\begin{aligned} Y_t &= C_t + K_{t+1} + Z_t \\ &= C_t + \int_0^{A_{t+1}} x_{jt+1} dj + Z_t \end{aligned}$$

The intermediate inputs are like capital that fully depreciates after one period of use, an assumption that is made more palatable by our choice of period that is 10 years long.

The key equation for the dynamics of the model describes the conversion of foregone output or R&D expenditures Z_t into new patents. In period t, each of a larger number N of intermediate goods firm indexed by f can use final goods (or more explicitly, the inputs that could produce final output) to discover new types of intermediate goods that can then be produced for use in $t+1$. Let M_{t+1} denote the aggregate measure of new goods discovered in period t, and let M_{ft+1} be the measure of these new goods produced at firm f. Here, the letter M is a mnemonic for "monopoly" because goods patented in period t will be subject to monopoly pricing in period $t+1$. Because our patents, like our capital, last for only one period, only the new designs produced in period t will be subject to monopoly pricing in period $t+1$. At a formal level, it simplifies the analysis considerably to assume that capital lasts for only one period and that innovators need to look ahead only one period to calculate their monopoly profits. In particular, these assumptions imply that the model converges in very few periods to a new steady state growth rate after any policy change, as we shall see.

To allow for the problem that firms face in coordinating search and innovation in larger teams, we allow for a form of diminishing marginal productivity for the inputs to innovation in any given period. Let Z_{ft} denote the resources devoted to R&D or innovation at firm f at time t. We assume that the output of new designs will also depend on the availability of all the ideas represented by the entire stock of existing innovations, A_t. Hence we can write the number of new designs at firm f as:

$$M_{ft+1} = (Z_{ft})^{\rho} A_t^{1-\rho}, \tag{1}$$

where $0 < \rho < 1$.

The exponent on A_t is crucial to the long-term dynamics of the model. The choice here, $1-\rho$, makes it possible for an economy with a fixed quantity of human capital H to grow at a constant rate that will depend on other parameters in the model. As an alternative, we could follow the suggestion in Jones (1995b) and use a smaller value for this exponent, in which case we could generate a steady state by allowing for growth in the quantity of H. In either approach, the model has to match the baseline rate of growth that prevails prior to the trade shock. For a given value of ρ, they will respond in qualitatively similar ways to a trade shock. As a result, the two types of model offer different very long-run (100+ year) predictions about the effect that the trade shock on growth, but are similar for the first $\approx$ 100 years, which because of discounting is effectively all that matters for our results. We formally detail and calibrate an extension of our model with semi-endogenous growth and show the results are very similar (see Appendix D).

Another way to characterize the production process for new designs is to convert the innovation production function in equation (1) to a cost function that exhibits increasing marginal costs of innovation in period t,

$$Z_{ft} = \nu M_{ft+1}^{\gamma} A_t^{1-\gamma}, \tag{2}$$

where $\gamma = \frac{1}{\rho} > 1$.

Finally, we note that the parameter ν is a constant which we have introduced to the innovation cost function and will adjust so that different choices of the number of intermediate goods firms N and the innovation cost function curvature γ generate the same balanced growth rate. (See Appendix A or Section 3.3 for details.)

Given the innovation cost function for a single intermediate goods firm f, we have that the aggregate R&D expenditure is immediately given by $Z_t = \sum_{f=1}^{N} Z_{ft}$. In most cases, symmetry will allow for substantial simplification of this expression.

3.2 Preferences

A representative household in this economy consumes the final good in the amount C_t each period, inelastically supplies labor input H, and has preferences over consumption streams given by

$$\sum_{t=0}^{\infty} \beta^t \frac{C_t^{1-\sigma}}{1-\sigma}.$$

The representative household receives labor income, owns all the firms, and trades a one-period bond with zero net supply. As usual, if consumption grows at a constant rate $g = \frac{C_{t+1}-C_t}{C_t}$, and if r denotes the one period interest rate on loans of consumption goods, these preferences imply the result

$$1 + r = \frac{1}{\beta}(1+g)^{\sigma}. \tag{3}$$

Because the price of consumption goods is always one unit of the numeraire good, r is also the one period interest rate on loans denominated in the numeraire.

3.3 Equilibrium

To characterize the equilibrium in this closed economy, we can assume that final goods are produced by a single competitive constant returns to scale firm which demands as inputs intermediate goods and human capital. We also assume that the labor market is competitive.

It simplifies the exposition to imagine that the intermediate inputs in production are produced by N firms for some large number N. These firms design new goods and produce the intermediate inputs that the new designs make possible. Newly discovered goods are protected by a one-period monopoly patent. After the patent expires, it is convenient and harmless to assume that the firm f that developed a good will continue to produce it. Hence, at any date t, the range of goods $[0, A_t]$ can be divided up in to N disjoint subsets of goods produced by each firm f. Roughly speaking, we would like to assume that any intermediate good j is equally likely to be assigned to any one of the N firms.[13] Finally, we assume that there is a set of potential entrants, that we refer to as "fast copiers", who act as a competitive fringe and force the firms that produce off-patent goods to price them at marginal cost.[14]

The equilibrium in this model takes a familiar form, with perfect competition in markets other than for the goods that are protected by patents, and by monopolistic competition with a zero marginal profit condition for firms that develop new designs that will be protected by patents. The full definition of the equilibrium for this model is given in Appendix A.

The fundamental equation for the dynamics of the model balances the cost of developing a new patented design against the profit that can be earned from the temporary ex post monopoly that it confers. This profit can be calculated as follows. In period $t+1$, the inverse demand for any input will be the derivative of the aggregate production function, which implies the inverse demand curve

$$p = (1-\alpha)H^{\alpha}x^{-\alpha}.$$

The usual markup rule for a constant elasticity demand curve implies that the monopoly price p_M will be marked up by a factor $1/(1-\alpha)$ above its marginal cost. One unit of output today can be converted into one unit of the intermediate that is available for sale tomorrow, so marginal cost in units of output tomorrow, is $(1+r)$ and the monopoly price tomorrow can be written as

$$p_M = \frac{1+r}{1-\alpha}.$$

Together, these two equations imply monopoly output

$$x_M = H\left(\frac{(1-\alpha)^2}{1+r}\right)^{1/\alpha}. \tag{4}$$

Because profit takes the form

$$\pi = \frac{p_M x_M}{1+r} - x_M = \frac{\alpha}{1-\alpha}x_M,$$

this yields

[13] This concept is difficult to formalize precisely with a continuum of goods but can be made precise with a large but finite set of goods taken together with a limit argument that lets the number of goods go to infinity.

[14] This formalism is not needed for the closed economy, but becomes important when the economy is opened for trade and some goods are protected by trade restrictions.

$$\pi = \Omega \left(1+r\right)^{-\frac{1}{\alpha}} H,$$

where $\Omega = \alpha(1-\alpha)^{\frac{2-\alpha}{\alpha}}$.

One easy way to see why profit increases linearly in H is to note that the price the monopolist sets is a fixed markup over marginal cost. This means that profit increases linearly with the quantity the monopolist sells. As in any constant returns to scale production function, at constant prices, an increase in the use of one input such as H will lead to an increase by the same factor in the quantity demanded of all complementary intermediate inputs x_j.

The zero marginal profit condition at the margin for developing new goods implies that this expression for π must be equal to the marginal cost of producing the last innovation at each firm. To express this cost, it helps to define a "pseudo-growth rate"[15] for an individual firm, $g^f_{t+1} = \frac{M_{ft+1}}{A_t}$. We denote the economy-wide growth rate of varieties as $g_{t+1} = \frac{M_{t+1}}{A_t}$ and note that $g_{t+1} = \sum_{f=1}^{N} g^f_{t+1}$. Differentiation of the cost function for innovation yields

$$\frac{\partial Z_{ft+1}}{\partial M_{ft+1}} = \nu\gamma \left(g^f_{t+1}\right)^{\gamma-1}$$

On a balanced growth path, g_{t+1} will be equal to a constant g, which will also be equal to the rate of growth of output and of consumption. By symmetry among the N firms, we also have that $g^f_{t+1} = \frac{1}{N}g$. As a result, the cost of a new design reduces to

$$\begin{aligned}\frac{\partial Z_{ft+1}}{\partial M_{ft+1}} &= \nu\gamma \left(\frac{1}{N}g\right)^{\eta(\gamma-1)} \\ &= \nu\gamma N^{(1-\gamma)} g^{\gamma-1}\end{aligned}$$

If we define ν so that

$$\nu\gamma N^{(1-\gamma)} = 1$$

the cost of a new patent reduces to $g^{\gamma-1}$. Equating this marginal cost with the marginal benefit (*ex post* profit) yields:

$$g^{\gamma-1} = \Omega \left(1+r\right)^{-\frac{1}{\alpha}} H \tag{5}$$

where $\Omega = \alpha(1-\alpha)^{\frac{2-\alpha}{\alpha}}$ is a constant.

Finally, using the fact that in a balanced growth equilibrium, consumption, patents, and total output will all grow at the same rate g, we can substitute in the expression for the

[15] This is a pseudo-growth rate because we have divided by the economy-wide stock of patents rather than the firm's own stock of patents. All other growth rates are true growth rates.

interest rate equation (3) into equation (5) to generate the basic equation relating g and H:

Proposition 1 *Closed-Economy Balanced Growth Path*

The closed economy has a unique balanced growth path with a common constant growth rate g for varieties, output, and consumption, that satisfies the innovation optimality condition

$$g^{\gamma-1} = \Omega\beta^{\frac{1}{\alpha}}(1+g)^{-\frac{\sigma}{\alpha}}H.$$

Proof in Appendix A.

In the closed economy, this proposition says that the marginal cost of a patent must be equal to the appropriately discounted *ex post* profit that it will generate, and that this profit is proportional to the stock of human capital, H. When we extend this to the open economy setting, the same kind of expression in which g is an increasing function of H will still hold except that H will be replaced by an expression that depends on both H in the North, H^* in the South, and the extent of restrictions that limit trade between the two regions.

4 Open Economy

Suppose next that there are two regions or countries, North and South. We treat North as the home country so variables associated with the South are indicated with an asterisk. There are identical representative households in the North and South. The final goods technologies of the two regions are identical, but only Northern intermediate goods firms have access to the innovation technology that produces new patents or designs. This lack of Southern innovation is a realistic approximation as discussed in Section 2. A firm in the South can produce any intermediate good as soon is it is off patent.

To allow for a continuum of possible levels of trade restriction, we assume that the government in the North imposes a trade restriction which allows only a proportion ϕ of off-patent intermediate goods varieties produced in the South to be imported into the North. If we make the simplifying assumption that the goods with the lowest index values are the ones that are allowed to trade, Figure 3 describes the goods that are used in production in the North and the South. The goods with the lowest index values are called I goods to signal that they are imported into the North. In terms of production in period t, the range of the I goods is from 0 to ϕA_{t-1}. These goods are produced in the South for use in the South and also produced in the South and imported into the North. Next come the R (for restricted) goods. These are produced in the North for use in the North and produced in the South for use in the South. Finally, we have the M (for monopoly) goods, which are produced in the North and used in production in both the North and the South. Hence, M_t represents the new goods developed in period $t-1$ for sale in period t; R_t represents the trade-restricted but off-patent goods available for use in production in period t; I_t represents the off patent goods that can be imported into the North for use in period t. In a small abuse of the notation, we will use the symbols I, R, and M to denote both the set of goods and its measure.

In this two economy model, we can consider a unit of final output (or equivalently the bundle of inputs that produces it) in both the South and the North. We will use output in the North as the numeraire and define the Southern terms of trade q_t as the price in units of final output in the North of one unit of final output produced in the South. We impose trade balance in each period so there is no borrowing between North and South. Along any balanced growth path, the interest rates in the North and South will be the same, but the restriction on borrowing is binding during the short transition to the new balanced growth rate that follows a policy change. The terms of trade q adjust to achieve trade balance in each period, which requires that the value of imports into the North, $q_t p_{It}^* I_t x_I$, is equal to the value of the goods that the North sells to the South, $p_M M_t x_M^*$.

As in the usual product cycle model, we are interested only in the case in which the South has a cost advantage in producing goods that it can export, due to its lower wages. On the balanced growth path, this is equivalent to having $q_t < 1$. In our analysis, we restrict attention to the case of values of the trade policy parameter ϕ that are low enough to ensure that this restriction holds.

It is important for the operation of the model that in this case, trade balance does not lead to factor price equalization. Identical workers in the North and the South earn wages that when converted at the terms of trade q are higher in the North and lower in the South. Restricted intermediate inputs that are produced and used only in the South are less expensive there than the same goods produced and used in the North. However, because consumption goods in the South are also less expensive, the difference in the wages is much smaller after a PPP correction.

Although the formal assumptions imply that all intermediate goods could be tradeable if all trade restrictions were removed, the model can easily accommodate the possibility that a portion of them are intrinsically non-tradeable. All that matters is that the restriction imposed by ϕ is binding in the sense that it artificially forces some goods that could be tradeable to be non-traded.

To describe the equilibrium for the open economy, it helps to define a second (irrelevant) constant $\Psi = (1-\alpha)^{\frac{\alpha-1}{2-\alpha}}$ that is analogous to the constant $\Omega = \alpha(1-\alpha)^{\frac{2-\alpha}{\alpha}}$ for the closed economy. For any given value of the trade parameter ϕ, a straightforward extension of the analysis for the closed economy yields a two equation characterization of the balanced growth rate and the associated terms of trade:

Proposition 2 *Open-Economy Balanced Growth Path*

For low enough values of the trade parameter ϕ, the world economy follows a balanced growth path with a common, constant growth rate of varieties, worldwide output, and consumption in each region. The growth rate $g(\phi)$ and the terms of trade $q(\phi)$ are determined by the zero marginal profit condition for innovation

$$g(\phi)^{\gamma-1} = \Omega\beta^{\frac{1}{\alpha}}(1+g(\phi))^{-\frac{\sigma}{\alpha}}\left(H + q(\phi)^{\frac{1}{\alpha}}H^*\right) \tag{6}$$

and the balanced trade condition

$$q(\phi) = \left(\frac{\phi H}{g(\phi)H^*}\right)^{\frac{\alpha}{2-\alpha}}\Psi \tag{7}$$

and $q(\phi) < 1$.

Proof in Appendix A.

After substitution of equation (7) into equation (6), the growth rate $g(\phi)$ can be seen to be determined by the intersection of a downward sloping innovation marginal profit curve with an upward sloping innovation marginal cost curve. For clarity, see Figure 4 which plots a stylized version of the equilibrium innovation optimality condition and the result in Proposition 2. The marginal profit of innovation is strictly increasing in the trade openness parameter ϕ, so the the open economy balanced growth rate is strictly increasing in ϕ. This implies that the terms of trade $q(\phi)$ is also strictly increasing in ϕ.

Proposition 2 is an important result as it establishes that trade liberalization will increase growth rates as it increases the incentive to invest in innovation. Essentially this is because the effective size of the market has expanded and this increases the profitability for new goods. R&D investments increase until at the margin ex ante expected profits are again zero, but this will be at a higher growth rate.

Revealingly, the innovation optimality condition (6) is quite similar to the one in the closed-economy version of Proposition 1. Except in place of H, the term $H + q(\phi)^{\frac{1}{\alpha}}H^*$ now determines the extent of the demand for any input and the profit that it will generate. The reason is all innovation takes place in the North. And the worldwide demand for newly invented goods in the North depends on demand in the North, which is proportional to H and on demand from the South, which is proportional to H^* but with a downward adjustment induced by the terms of trade.

A trade liberalization caused by an increase in ϕ leads to an increased flow of imported I goods from North to South. The elasticity of demand for all inputs is $\frac{1}{\alpha} > 1$, so revenue increases when prices fall. This means that in response to the increase in imports into the

North, the prices of the goods that the North imports must go up and the prices that it receives for goods that it sells to the South must go down. Both changes imply an increase in q. Lower prices in the South for the exported monopoly goods increase the returns to innovation. In equilibrium, the rate of innovation, hence the rate of growth must increase, which increases the marginal cost of innovation and re-establishes the zero profit condition at the margin.

5 Trade Shocks

The open economy analysis in the last section calculated the constant perfect foresight growth rate and interest rate associated with a constant value of the parameter ϕ. Next, we start from a balanced growth path trade at an initial level ϕ and consider the effects of an unanticipated and permanent trade shock to a more liberal trade regime with $\phi' > \phi$. To carry this exercise out, we must be more explicit about the timing of decisions relative to the announcement of the change in ϕ.

5.1 Timing with a Trade Shock

To specify the timing, it helps to return to the underlying model with three different productive activities. Recall that there is a group of consumption good producing firms that acquire H and intermediate inputs x_j and use them to produce final consumption goods using the basic production function

$$C_t = H^\alpha \int_0^{A_t} x_{jt}^{1-\alpha} dj.$$

We now want to be more precise about a second group of intermediate input producing firms that demand types of inputs in the same factor proportions and that devote these inputs either to the production of new designs or to the production of physical quantities of its intermediate inputs. For a specific firm f, let inputs with an overbar denote the inputs of a particular intermediate input producing firm f that are allocated to the production of new designs. In this case, the number of new patents that result can be written as

$$\begin{aligned} M_{ft+1} &= (Z_{ft})^\rho A_t^{1-\rho} \\ &= \left(\overline{H}^\alpha \int_0^{A_t} \overline{x}_{jt}^{1-\alpha} dj \right)^\rho A_t^{1-\rho} \end{aligned}$$

In parallel, denote the inputs that firm f devotes to the production of physical units of intermediate inputs with a tilde. Let $\mathbb{A}_f$ denote the set of goods that firm f can produce at time t at a positive profit (if it is still under patent) or at zero profit. Note that there may be some goods that the firm used to produce that are no longer in $\mathbb{A}_f$ because they are now imported from the South and would be unprofitable to produce. Then we can characterize the production of the intermediate goods that this firm will produce in the next period that will be sold in the next period as

$$\int_{\mathbb{A}_f} x_{jt+1} dj = \widetilde{H}^{\alpha} \int_0^{A_t} \widetilde{x}_{jt}^{1-\alpha} dj.$$

The total quantity of an input such as H that is controlled by firm f is the sum of $\overline{H}$, which it devotes to innovation, and $\widetilde{H}$, which it devotes to production of physical units of intermediate goods for sale in the next period. In the same way, the total quantity of any intermediate input that it has available for production can also be split between these same two activities.

This means that we can think of inputs being allocated between the three productive activities in two steps. First, inputs are allocated between the consumption good producing firms and the intermediate input producing firms. Next, the intermediate input producing firms make an internal allocation decision, dividing up their inputs between innovation and the production of physical units of the intermediate inputs that will be for sale in the next period.

When ϕ is constant, a constant fraction of the off-patent goods that each intermediate input firm in the North had previously produced under trade protection are now exposed to import competition. In the aggregate, the total stock of goods that are available as imports in period t is equal to ϕ times the off-patent goods in period t, or ϕA_{t-1}. For simplicity, we assume that this process of exposure is evenly distributed across all intermediate input producing firms. For firm f, this means that if it had a set of goods $\mathbb{A}_f$ that it produced last period with measure $m(\mathbb{A}_f)$,in the current period, it will produce a measure of goods equal to $(1-\phi)m(\mathbb{A}_f) + m(M_f)$ where M_f is the set of new goods that it invents. Firms can take account of the predictable shrinkage in the goods that they can produce when they make their decisions about how much of each type of input to acquire.

In contrast, if a government mandates in period 1 an unanticipated increase in ϕ to ϕ', there will be a jump in the number of goods that are subject to import competition. At the aggregate level, the measure of goods in the goods unexpectedly become unprofitable for Northern firms is $A_0(\phi' - \phi)$.

To match the micro data, which has some firms that are exposed to larger trade shocks than others, we want to allow for the possibility that this range of goods $A_0(\phi' - \phi)$ is not equally distributed among all firms. To do this, we split the set of intermediate input producing firms in the North into two groups of equal size. We refer to these as the Shock ("SK") and No-shock ("NS") firms. We assume that all the goods that are unexpectedly exposed to competition from imports are goods that were previously manufactured by the Shock firms.

5.1.1 Timing with Fully Mobile Inputs

With these definitions in mind, we can describe two different assumptions about the mobility of factors. Consider first the case that we refer to as "Fully Mobile" because all allocation decisions are made after the shock is announced.

1. Intermediate goods firms enter period 0 with completed intermediate goods.

2. The government in the North announces a new lower new level of the trade restriction ϕ' that will be in effect in period 1, together with the specific goods that will no longer be protected, which thereby determines which firms are in the shock group and which are in the no shock group.

3. Workers are hired by firms. Intermediate goods firms sell their goods at the market clearing prices anticipated in period -1 to both domestic and foreign consumption and intermediate input producing firms. Consumption producing firms and intermediate input firms thereby acquire the inputs that they will use to produce.

4. Intermediate goods firms in the North then allocate inputs between innovation and the production of units of intermediate goods that will be available for sale in the next period.

5. The decisions that intermediate input producing firms in both the South and the North make about quantities of inputs of each type to produce are publicly observed. For off-patent goods, the competitive fringe of fast copiers in the North stands ready to enter if these quantities are too low to yield a market price equal to marginal cost for the R goods that will be sold in the North.

In this case, the trade shock of an increase from ϕ to ϕ' will be public information before any inputs are allocated to any firms. In particular, any intermediate input producing firm knows about the trade shock and knows if it is a shock firm or a no-shock firm. If the intermediate input producing firms as a group want to reduce their input demands, inputs can freely move into the production of consumption goods.

5.2 Trapped Factors Case

In the "Trapped Factors" case, we assume that the announcement of the change in ϕ comes after inputs have already been allocated to the intermediate input producing firms. This reverses the timing of steps 2 and 3 above. The new sequence is:

1. Intermediate goods firms enter period 0 with completed intermediate goods.

2′. Workers are hired by firms. Intermediate goods firms sell their goods at the market clearing prices anticipated in period -1 to both domestic and foreign consumption and intermediate input producing firms. Consumption producing firms and intermediate input firms thereby acquire the inputs that they will use to produce.

3′. The new level of the trade restriction ϕ' that will be in effect in period 1 is announced, together with the specific goods that will no longer be protected, which thereby determines which firms are in the shocked group and which are in the no shock group.

4. Intermediate goods firms in the North then allocate inputs between innovation and the production of units of intermediate goods that will be available for sale in the next period.

5. The decisions that intermediate input producing firms in both the South and the North make about quantities of inputs of each type to produce are publicly observed. For off-patent goods, the competitive fringe of fast copiers in the North stands ready to enter if these quantities are too low to yield a market price equal to marginal cost for the R goods that will be sold in the North.

The announcement of the increase in ϕ induces three types of adjustments that can influence the demand that an intermediate input producing firm has for inputs. First, faster growth changes equilibrium interest rates and the desired split between saving and consumption, which has to be mirrored by a split of inputs between firms that produce consumption goods and firms that produce intermediate inputs. Second, an intermediate input producing firm will want to allocate relatively more resources to innovation. Third, an intermediate input producing firm in the Shock group that has lost some of its potential output markets will want to release inputs that can be taken up and used by other firms.

To calculate the full general equilibrium effects of the shock, we must take into account not only these impact effects on input demands but also any induced changes in interest rates and the terms of trade. The full equilibrium definitions for the closed economy, the open economy, and the trapped-factors trade shock economy can be found in Appendix A. Factors will be trapped in a firm in the Shock group if ex post it wishes that had not taken on so many inputs. In this case, the shadow value of its inputs will be lower that it was before the shock hit.

Before moving to the quantitative analysis, we note one final technical detail. For factors of production to be trapped in a firm that has lost lines of production, we have to make an assumption which ensures that it can not simply steal lines of production from other firms. If it could, then there would be no net effect of having trapped factors. Instead of having factors move to the production opportunities, production opportunities can move to the factors. To give the assumption of trapped factors some bite, we make the additional assumption that the cost of producing a unit of any intermediate good is substantially lower for a firm that developed the good and produced it in the past than it would be for an intermediate input producing firm that does not have this kind of experience.

Having made this assumption, we then have to make a further simplifying assumption to ensure that incumbent producers of the protected goods do not have market power. This is where we rely on the existence of a second potential type of intermediate input producing firm, a "fast copier," which has been mentioned before. This means that there are two distinct types of intermediate input producing firms, innovators or fast copiers. Innovators, the type of firm we have been describing so far, can develop new goods but they can't copy the goods developed by other firms. In contrast, fast copiers can produce intermediate inputs developed by other firms at the same cost as the other firm but they are not capable of innovation. We can now be more precise and say that all the intermediate input producing firms in the South are fast copiers. All the intermediate input producing firms that are active in the North are innovators. In equilibrium, fast copiers never produce anything in the North. Nevertheless, their presence limits the pricing decisions of the intermediate input producing firms in the North and forces them to sell off patent goods at marginal cost.

6 Quantitative Analysis: OECD Trade Liberalization with Non-OECD Countries

We can now calibrate and perform a quantitative exercise with the model, considering the impact of trade shocks in the fully mobile and trapped factors cases. Appendices B and C give more details on the calibration and information about how we calculated these equilibria. As noted above we take the model period as 10 years, which then becomes the length of patent protection and the durability of capital.

We calibrate the model economy to match long-run growth rates, and movements in trade flows between the OECD and non-OECD countries from 1997-2006, the ten-year window surrounding Chinese WTO accession in 2001. In particular, the model policy experiment we consider is an unanticipated, permanent trade shock scaled to match data from the OECD's liberalization with the developing world around the time of Chinese WTO accession. After examining the long-term impact of this liberalization in our model, we then compare the fully mobile transition path to this trade shock with the transition path generated by the trapped factors mechanism. In the trapped factors case, we also will compute some cross-sectional measures of the rate of growth of patents, which will differ across firms with the extent of their direct exposure to the liberalization shock.

6.1 Calibration

We started by specifying the basic parameters about which we have some prior information: the human capital share (α), discount rate (β), preference curvature (σ), the quantity of human capital in the North relative to the South ($\frac{H^*}{H}$), the curvature of the innovation cost function (ρ), and the pre-shock trade policy parameter (ϕ). Following Jones (1995a) and King and Rebelo (1999) we consider the case of log utility with $\sigma = 1$ and a labor share in production of $\alpha = \frac{2}{3}$. Balanced growth path real interest rates of approximately 4% requires $\beta = (0.98)^{10}$. We also estimated the ratio $\frac{H^*}{H} \approx 3$ from international schooling data on educational attainment in the OECD and non-OECD countries in the year 2000. Therefore, we identify the OECD nations in our sample with the North and non-OECD nations with the South. We fix the parameter ρ to the baseline value of $\rho = 0.5$ based on Bloom, Schankerman, and Van Reenen (2013). Appendix B contains more information over the calculation of H/H^*, and a later section checks robustness to different values of most of the parameters above.

We must also choose the final three parameters H, ϕ, and ϕ' which jointly govern the model's long-run balanced growth path growth rates and imports to output ratios. First, we focus on ϕ and ϕ'. Given our OECD and non-OECD groupings for North and South, we compute the ratio of non-OECD imports to OECD GDP in 1997 (3.9%) and 2006 (7.0%), requiring that the model reproduce these import ratios in the pre- and post-shock balanced growth paths, respectively. These import ratios are heavily influenced by our choice of ϕ and ϕ', leaving us still to determine the model's scale through the choice of H to match growth rates from the data.

We note that the model's concept of growth is most closely aligned with per capita GDP growth. Given the accession of newly developed and transition economies into the OECD which has occurred in recent decades and the potential for catch-up growth in these economies to affect our measurement of long-term technological progress, we prefer to calibrate long-run frontier growth to the per capita GDP growth of the United States rather than the entire OECD. However, the fact that the model's balanced growth path growth rate depends upon trade policy means that we face a choice about whether to identify the pre-shock or post-shock growth rate with the measured growth rate, as well as the choice of which data window to use. In order to make use of the largest possible sample for our model's long-term concept, we choose a sample window of 1960-2010. To avoid confounding trade or long-term factors with cyclical movements, we require through choice of H that the model's pre-shock rather than post-shock growth rate matches the average annual growth rate of 2.0% seen in the United States data over this period. We take two steps to examine the robustness of our results to this calibration strategy, neither of which qualitatively changes our main conclusions. First, in a robustness check discussed further in a later section we consider an alternative calibration window ending at Chinese WTO accession in 2001 for the pre-shock growth rate, and second we also solve a version of the model with "semi-endogenous growth" and therefore only level rather than growth effects on output from changes in trade policy. Details on the semi-endogenous growth version of the model can be found in Appendix D.

6.2 The Long-Term Impact of a Trade Shock

Now that the baseline calibration of the model is completed, we can consider the long-term impacts of trade policy liberalization from ϕ to ϕ'. Table 1 summarizes the long-term effects of our calibrated trade shock. To reproduce the changes in the OECD imports to GDP ratio observed in the data requires an exogenous increase in trade policy ϕ from 9.7% to 20.7%, and this exogenous change produces a movement in the long-term growth rate from its pre-shock calibrated value of 2.0% to a new value of 2.37%, a movement in the Southern terms of trade q from 0.5 to 0.7, and an increase in long-term real interest rates from 4.0% to 4.4%. As explained in Section 4, in the long run trade liberalization induces appreciation of the Southern terms of trade and hence increases the purchasing power of the South of newly innovated Northern M goods. This scale effect increases the returns to innovation for the Northern intermediate goods firms and hence the long-term growth rate.

Table 1: Long-Run Impact of Liberalization

%	Pre-Shock	Post-Shock
ϕ	9.7	20.7
Imports to GDP	3.9	7.0
Growth Rate	2.00	2.37
Southern Terms of Trade	0.5	0.7
Interest Rate	4.0	4.4

Note: The table above displays pre- and post-shock values of the main quantities within the model. The values reflect the long run or the balanced growth path associated with the indicated value of the trade policy parameter ϕ. All quantities are in annualized percentages except for the Southern terms of trade which is equivalent to the model relative price q.

6.3 Transition Dynamics in the Fully Mobile Economy

Next we consider the transition dynamics of the fully mobile economy, starting from the balanced growth path associated with trade policy ϕ and allowing an unanticipated and permanent trade policy shock $\phi \to \phi'$ that is announced in period 0, to become effective in period 1. We use the same values of ϕ and ϕ' as in the comparison across balanced growth paths described above.

In the fully mobile economy, Northern intermediate goods firms can immediately respond to the announcement of the trade liberalization by adjusting their input demands, along with their production and innovation decisions. In Figure 5, we plot the aggregate transition dynamics of the economy for aggregate variety growth, the terms of trade, and output growth in the North and South. Consumption growth follows the pattern for output growth. Interest rates are implied by the pattern of consumption growth. Hence, we can focus just on growth in the number of patented goods, the terms of trade, and output growth rates in the two countries.

The full transition to the new balanced growth path is complete in approximately 6 periods (60 years). Given the trade liberalization and increased flow of I goods from North to South, the Southern terms of trade increases rapidly to maintain balanced trade, leading to an associated increase in the returns to innovation and hence the amount of innovation as measured by the aggregate variety growth rate.

There is slower adjustment of most other variables. Consumption smoothing dictates a smooth transition of consumption growth rates, output growth rates, and interest rates in both economies to their long-run values. The slight overshooting of variety growth in period 1 is due to the fact that Northern interest rates are initially lower than their new long-run levels, decreasing the marginal cost of innovation and raising the return to innovation for

Northern firms in the short run. Variety growth and the terms of trade are close to their new balanced growth path values extremely quickly, while output growth, consumption growth, and interest rates smoothly adjust to their new balanced growth path values in each economy.

We we can also compute the long-run welfare gains from trade in the fully mobile environment, taking the transition path into account (see Table 2). The North gains by a consumption equivalent of 14.2%, while the South gains by a consumption equivalent of 13.3%. In other words, we would have to increase the consumption of the Northern household *without* trade liberalization by 14.2% in every period to make it as well off is it would be in the equilibrium with the trade liberalization. The details of the welfare calculations are available in Appendix C. Note that although both economies can utilize new goods and therefore benefit from the increase in long-run growth rates, the terms of trade ensure that the North uses these new goods with higher intensity and therefore benefits slightly more from liberalization.

These welfare gains from trade are large compared to current state-of-the-art quantitative analysis of the welfare gains from trade relative to autarky in static trade models. A recent example of this static type of analysis, done in Melitz and Redding (2013) and relying primarily upon love of variety gains from liberalization, suggests that welfare gains from trade for the US around the year 2000 are approximately 2.5%. Although the trade liberalization gains we obtain are not exactly comparable to these numbers because we consider the gains from partial trade liberalization rather than autarky as a benchmark, it is clear that the higher rate of growth induced by the liberalization could be powerful source of welfare improvement from trade.

6.4 Transition Dynamics in the Trapped Factors Economy

In Figure 6 we plot the path of some selected aggregates over the trapped factors transition path in response to our calibrated trade shock. In this environment, and in contrast to the fully mobile transition path considered above, firms exposed to the trade shock may not rid themselves of extra inputs in the face of low-cost import competition.

Comparing the trapped factors transition with the fully mobile transition in Figure 5 above, we immediately note that the variety growth rate is higher upon impact of the trade shock. Instead of a growth rate of about 2.4% in the shock period as seen in the fully mobile transition, the trapped factors variety growth rate on impact is 2.7%. The increased Northern innovation and flow of M goods from North to South in the shock period slows the appreciation in the Southern terms of trade, and output growth in the North and South both overshoot their long-run levels after the trade shock. Although the transition path is again complete in approximately 6 periods (60 years), the path of innovation is clearly significantly higher in the presence of short-run adjustment costs or trapped factors.

To understand the effect of trapped factors in more detail, it is first useful to understand some of the microeconomic or cross-sectional underpinnings of the transition. Motivated by the evidence of cross-sectional heterogeneity in the exposure of Northern firms to trade liberalization shocks documented in Bloom, Draca, and Van Reenen (2012), recall that we assumed that there are two industries, each with half of the firms in the economy. One of these industries (Shocked) contains all the shocked firms and bears the brunt of the direct effects of liberalization in that all of the liberalized R goods varieties which lose protection are in this industry. The other industry (No Shock) has no liberalized R goods.

Based on this industry classification, in Figure 7 we plot three separate patent flows. In the solid black bar on the left labeled "Pre-Shock," we present period 0 or pre-shock patent flows for the "Shocked" and "No-Shock" industries, which are ex-ante identical. These patent flows are arbitrarily normalized to $1,000$ for ease of reference. The blue middle bar with upward-sloping lines and the red right bar with downward sloping lines, by contrast, plot the patent flows for industry "No-Shock" and for industry "Shocked" during period 1, the period in which policy liberalization becomes effective. Although the scale effect associated with liberalization implies an increase in patenting in both industries during the shock period, industry "Shocked" patents approximately 28.8% more in the period after the shock. The cross-sectional link between industry patenting and exposure to low-cost import competition in the model is consistent with the increased innovation documented by Bloom, Draca, and Van Reenen (2012) in European firms exposed to Chinese import competition relative to their unaffected peers.[16]

The stark increase in innovation or patenting at firms in the shocked industry is directly linked to a surplus of resources (trapped factors) after they unexpectedly lose 24% of their R goods production opportunities. Given adjustment costs preventing the movement of resources out of firms and into alternative uses (such as consumption) the human capital and intermediate goods are repurposed to innovation in the period of the trade shock. In Figure 8 we expand the set of variables included in the transition path in the trapped factors models. In the top two panels we can see the shadow value of resources in each industry, which in normal times without trade shocks is normalized to 100%. Since the lost R goods opportunities imply a surplus of inputs which must be allocated to the unanticipated use of innovation, on the top left figure (A) we see an opportunity cost or resource shadow value decline of 25.5% in period 1 for firms in the shocked industry. Note that the quantitative magnitude of the decline in the opportunity costs of inputs at affected firms is informative, since it implies that our results would maintain qualitatively with a looser assumption of

[16] For example, in European textiles and clothing, a 10% increase in the share of imports from China within a particulary industry and country is estimated to lead to an approximately 19% increase in patenting in that industry. See Table II in Panel A and Column 3.

finite adjustment costs, e.g. irreversibilities or specificity in input decisions.

In the upper right panel (B) of Figure 8 we also see a much more moderate decline in opportunity costs by around 9.8% at firms in the no-shock industry. This is less intuitive and operates entirely through general equilibrium channels. To understand this, we must examine the movements in interest rates also recorded in Figure 8. The sudden increase in variety growth in the Northern economy in the shock period induces an increase in consumption growth rates and hence interest rates. This implies that the representative Northern household would like to consume more in the shock period but is prevented from doing so by the short-run trapped factors adjustment costs. Therefore, even though this does not represent an increases in resources within the no-shock firms, the higher interest rates and hence changed marginal valuations of their Northern owners require a fall in these firms' shadow values to deliver consistency with their value-maximization problem. Intuitively, since movement of quantities into consumption is prevented by adjustment costs in the short-run, shadow prices must move to deliver equilibrium.[17]

Turning to welfare measures the total consumption equivalent welfare increases from the trade shock with trapped factors are 16.3% for the North, compared to the 14.2% dynamic gains in the fully mobile case discussed above.[18] To understand this larger welfare gain from trapped factors, note that the externalities in the innovation process through which previous ideas at one firm assist later innovation by all firms are not taken into account in the firm's innovation optimality conditions. Hence, there is "too little" R&D from a social welfare perspective, as is typical in endogenous growth models. The initial increase in variety growth due to the trapped factors mechanism helps to moderate this social inefficiency and leads to a welfare increase from our model. Compared to the aggregate welfare gains of 14.2% from trade liberalization in the fully mobile case, the marginal impact of the trapped factors mechanism is approximately a tenth of the total gains from trade liberalization (2.1%). However, while this is small overall, in the first period (10 years in our simulation) trapped factors roughly doubles the impact of the trade shock on innovation. So the short-run impact of this mechanism is potentially large, and will thus be important for policy (for

[17] GE effects also explain another pattern in the transition in Figures 6 and 8, which is that the increased variety growth upon impact of the shock in period 1 translates immediately into a spike in Northern output growth but Southern output growth reaches a peak with one period delay in period 2. To understand these effects, recall that the increased flow of M goods from North to South in period 1 delays the appreciation of the Southern terms of trade to its new balanced growth path level. With a low value for q in period 1, new M goods varieties are more expensive for the South to use in production than for the North, implying that the North benefits from higher intensive margins of M goods use and hence higher output and consumption growth in period 1 than the South. After the initial impact of the trade shock on variety growth is dissipated in period 2, the Southern terms of trade q rises to its new long-run level. The South then increases the intensive margin of its use of now-less-costly M goods, and the North must curtail its intensive margin use of now-more-costly I goods. The net effect is a drop in Northern output growth in period 2, with a continued increase in output growth for the South.

[18] The Southern trapped factors trade gains are 15.3%, also an increase from the fully mobile case.

which a 10 year time frame is the long-term) and empirical work.

6.5 What is the Contribution of China to OECD Growth?

Our model suggests that there was a large scale effect and smaller trapped factors effect from the expansion of low-wage country trade from 1997 to 2006, driven in large part by China. Given the intense policy interest and recent academic literature in the area[19] we now consider what was the incremental effect of the increased trade with China alone? To do this, we scale back the trade shock by assuming that from 1997 to 2006, exports from other countries grew as they did but that exports from China remained constant as a fraction of OECD GDP. This is obviously an extreme assumption (which we discuss relaxing below) implying that without the expansion of Chinese trade all other trade shares would have remained constant, but is a useful first-cut estimation of the magnitude of China's impact. With this as the baseline, however, we can calculate by how much growth and welfare increase from this new baseline because of the effect of China alone.

Table 2: The Contribution of China to Northern Growth and Welfare

%	Data Import Ratio $\frac{I}{Y}$	Short-Run Growth g	Model Welfare Gain
Pre-Shock	3.9	2.0	–
Fully Mobile	7.0	2.4	14.2
Trapped Factors, Baseline	7.0	2.7	16.3
No China	5.39	2.4	7.2

Note: The first column represents the ratio of non-OECD to OECD imports relative to OECD GDP in the pre-shock period (1997), and the post-shock period (2006). The No China figures represent imports from the non-OECD excluding China, while the Baseline figures represent imports from the entire non-OECD. Imports data comes from the OECD-STAN database, with Chinese data available directly and non-OECD data imputed as the difference between world and OECD imports into OECD member states. The normalizing GDP measure for the OECD is computed using Version 7.1 of the Penn World Tables and equals the sum of GDP for all OECD members in a given year. The second column presents the pre-shock calibrated growth rate as well as trapped factors transition path growth rates in period 1 (the period after a trade shock), when the model's calibrated trade shock matches the movement in import ratios from column (1). The third Welfare Gain column represents, for the Fully Mobile and Trapped Factors, Baseline cases, the consumption equivalent gain from observed levels of trade liberalization relative to a world with no trade shock. For the No China row, the welfare gain is the consumption equivalent gain from the Trapped Factors, Baseline

[19] For example, Autor, Dorn and Hanson (2013), Kalina and Zhang (2012); Khandelwal, et al. (2011); Pierce and Schott, 2012).

case relative to the No China transition path.

Over the period $1997 - 2006$, Chinese exports as a share of OECD GDP increased by 1.6 percentage points from 0.79% to 2.4%. So of the 3.1 percentage point increase in non-OECD import shares, over half was from China. To compute the contribution of China to innovation and welfare within our model based on these numbers, we first calibrate a counterfactual "No China" trade shock in which the import to GDP ratio increases to the value which would have been seen if there was no growth in Chinese imports to the OECD as a proportion of GDP, and we maintain our trapped factors assumption. Table 2 summarizes the results of this counterfactual exercise, as well as the targeted import to GDP ratios used in calibration, and Figure 9 plots the trapped-factors transition path in the baseline and No China cases. Upon impact, the aggregate variety growth rate in the No China case is equal to 2.4% rather than the 2.7% observed in the baseline trapped factors transition. The underlying terms of trade increase in q is approximately halved in the no China case.

In the North, the consumption equivalent welfare gain for the North of the baseline transition path relative to the No China case is approximately 7.2%, and approximately 6.8% in the South. Compared to the baseline gains from trade liberalization in the trapped factors environment considered above of 16.3%, this implies that the Chinese contribution to the gains from liberalization are approximately 44%. The long-run growth effects of China are similarly substantial, with post-liberalization balanced growth rates in the No China case of 2.2% rather than the baseline 2.4%, a contribution of approximately 0.2%. We conclude that understanding the OECD and Chinese policies which contributed to the increased trade with China is a crucial avenue to consider when quantifying dynamic gains from liberalization over this period.

A caveat to this strategy is that it assumes a counterfactual world in which policy-makers do not "make up the gap" by relaxing restrictions on non-Chinese low wage imports. If such a relaxation did take place this would reduce the marginal contribution of China to welfare. In a robustness check in Appendix B, we compute the marginal impact of China with half of all Chinese import growth allowed in as imports from the non-OECD non-Chinese countries. As expected, these results essentially half the Chinese contribution to innovation and welfare.

6.6 Price and Variety Effects

A useful exercise is to decompose the impact of liberalization on output into dynamic variety effects, which require an endogenous growth structure and price effects that are the focus of more traditional quantitative trade models. The relative contributions of price and variety effects differ in the short run (the period of a trade shock) and the long run on the balanced growth path, so we will both. The results are summarized below, with further detail available in the technical Appendix C. We find that price effects are responsible for about one-third of Northern output gains in the period of trade liberalization, but that in a typical period along the model's balanced growth path, variety effects are dominant, accounting for approximately 95% of output gains.

We first answer the following counterfactual question, starting from the baseline trapped factors transition path: what would be Northern output in the shock period if we shut down any unexpected conversion of protected R goods varieties into imported I goods varieties associated with the movement from ϕ to ϕ'?[20] Call this counterfactual output level $Y_1^{noprice}$. Since I goods are cheaper in the North than R goods, the difference in output relative to the baseline level Y_1 can be interpreted as due to a traditional price effect following trade liberalization. We then consider a further question: what would be the value of Northern output if we shut down not just the unexpected price effects of R to I conversion but also held back the measure of additional newly innovated M goods varieties at its pre-shock level? Call this counterfactual output value $Y_1^{novariety}$. The ratio of price to total output gains in the shock period is $\frac{Y_1 - Y_1^{noprice}}{Y_1 - Y_1^{novariety}} = 0.37$, indicating that slightly more than one third of the output gains from liberalization in the shock period arise from the conversion of existing goods from domestically produced to cheaper imports. The remainder of the output effect, approximately two-thirds, is due purely to new innovation.[21]

The price effects are substantial in the shock period when a large number of goods are unexpectedly released from trade restrictions and allowed in as new imports. By contrast, the contribution of price effects decreases to a miniscule level when we consider the long-run balanced growth path with constant trade restrictions instead. In particular, we first compute Northern output along the balanced growth path in an arbitrary period, say Y_{ss}. Then, we compute output if the normal, ongoing conversion of goods from domestic to lower-price imported varieties is shut down for one period, yielding $Y_{ss}^{noprice}$. Finally, we compute output if the newly innovated varieties in that period are further removed from $Y_{ss}^{noprice}$, yielding $Y_{ss}^{novariety}$. The ratio of price to total output gains along the balanced growth path is $\frac{Y_{ss} - Y_{ss}^{noprice}}{Y_{ss} - Y_{ss}^{novariety}} = 0.05$. Therefore in the long run we see that dynamic variety effects, unique to endogenous growth structures such as ours, are the dominant factor in output growth, about 95% of the total Northern output gains.[22]

[20] For comparability, in all counterfactuals in the shock period we hold all relative prices fixed at their period 1 values and compute comparisons only by varying the extensive margin measures of each type of good. Since relative price effects differ across goods, such exercises have both dynamic variety and price consequences.

[21] Note that trade liberalization does not change the price of off-patent goods in the South, so we focus only on Northern output in these calculations. Also, on the fully mobile transition path, a similar calculation yields an output contribution of approximately 45% from price effects and 55% from dynamic effects, with the difference from the trapped factors case due to slightly different terms of trade in the shock period between the two cases.

[22] The steady-state or balanced growth path counterfactuals here are computed for the pre-shock trade restric-

7 Extensions and Robustness

In this section we discuss some extensions and the robustness of our results.

7.1 Robustness of Calibration to Alternative Parameter Values

The qualitative effect of trade liberalization on growth, and the boost of innovation from the trapped factors mechanism, are quite robust to alternative parametrizations. To demonstrate this we vary parameter values and consider the impact upon the variety growth rate in the trapped factors transition. In particular, Figure 10 plot the results of changing the discount rate β, the innovation cost function curvature ρ, the human capital share in production α, and the curvature of household utility σ. Although parameter choices do impact the exact value of the growth effects, in none of these cases is the pattern or magnitude qualitatively changed. Finally, we also ran a robustness check to a calibration of the pre-shock growth rate to the US per capita real GDP growth rate from 1960-2001, a shorter pre-shock window which yields a growth rate target of 2.37%. Although translated upwards, the transition path is otherwise identical to the baseline.

7.2 Semi-endogenous growth

As discussed above, Jones (1995b) argues for an alternative innovation production function. We have been using $M_{ft+1} = (Z_{ft})^{\rho} A_t^{1-\rho}$, but an alternative is to use an exponent less than $1-\rho$ on $A_t^{1-\rho}$ following Jones' "semi-endogenous" approach. In these models steady state growth no longer depends on the level of human capital ("scale effects") but on the growth of human capital. This model is a bit more complicated to analyze, but in Appendix D, we fully re-derive all the implications for long-term growth from such a model and numerically compute transition paths in this case. The model can still generate a positive steady state growth rate by allowing for an offsetting rate of growth for the stock of human capital, H. We find that for exponents on A_t jointly implied by population growth and per-capita GDP growth rates, the transition dynamics of the Jones-style model are extremely persistent. Therefore, meaningful differences between effects of trade liberalization in our baseline model and the semi-endogenous growth model are heavily discounted into the future. Under all realistic policy-relevant timescales the two models deliver remarkably similar quantitative results. We conclude that our model with exponent $1-\rho$ is a reasonable compromise that is quantitatively robust to changes in the key parameters and which is much easier to analyze because we focus on the parameter values that minimize the transition dynamics.

tion value of ϕ.

7.3 R&D congestion effects

Another concern with our baseline model is that R&D could have cross-firm congestion effects - for example from research duplication or patent race type effects. In a theoretical extension discussed in detail in Appendix E, we also introduce a parameter η which allows for within-period R&D congestion externalities. The parameter η flexibly nests our baseline case of no congestion externalities, corresponding to $\eta = 1$, but also allows for a continuum of intermediate degrees of congestion externalities all the way to the case of $\eta = 0$, which reflects full externalization of R&D costs and an extreme degree of congestion. In some respects, the potential for cost externalities resembles the dampening general equilibrium impact of higher R&D wages in the face of trade-induced technology upgrading seen in Perla, Tonetti, and Waugh (2012), although the mechanism differs from the labor market channel considered in that paper.

As noted above, the empirical evidence suggests that these congestion effects are not large in the economy as a whole. Bloom, Schankerman, and Van Reenen (2013) empirically estimate congestion effects on a large sample of US firms and find that congestion effects are statistically insignificant (i.e. they cannot reject $\eta = 1$).[23] Consequently, we have chosen to omit R&D cost externalities from the main discussion of our paper, but for completeness we also consider the intermediate case of $\eta = 0.5$ in Figure 10. As would be expected, with cost externalities, increases in firm innovation caused by trade shocks along the trapped factors transition path leads to a reduction in patenting at firms not exposed to trade and therefore quantitatively dampens the magnitude of the trapped factors boost from trade. The dampening effect is not quantitatively large, however with short-run variety growth falling to 2.6% instead of 2.7% in the baseline, and the long-run growth effect remains the same.

7.4 Other channels through which China influences welfare

Trade between OECD countries and low-wage countries like China can have a large number of effects in addition to the ones considered in this paper. As we note in the introduction, there are many extensions to the model that would add additional channels whereby trade generates welfare gains. We focus on the its impact on the incentives for developing new goods because of the sheer potential scale of the dynamic gains from trade that it offers. Numbers on the order of our baseline 16% welfare gains are considerably larger than state-of-the-art quantitative estimates of the static gains from trade, and therefore analyzing an environment which focuses on innovation is independently interesting.

[23] Table IV of Bloom, Schankerman and Van Reenen (2013) shows how R&D undertaken by firms' product rivals has no negative congestion effects on rates of innovation, and R&D done by firms' rivals technology markets rivals generates the usual large positive knowledge spillovers.

The most important potential offset to these gains comes from the labor market. Our model like almost most other theoretical trade models, abstracts away from the unemployment and wage losses that may arise as workers are reallocated between firms and sectors. Recent work by Pierce and Schott (2012), Autor and Dorn (2013) and Autor, Dorn, and Hanson (2013) suggests that these dislocation effects, which are at the heart of the political economy problems with greater liberalization can be substantial. Even in the absence of frictions, there may be long-run effects on inequality through Heckscher-Ohlin factor price equalization effects or many other mechanisms when labor markets are imperfect. For example, Helpman, Itskhoki and Redding (2010) show how trade may increase steady state unemployment and wage inequality by making the exporting sector more attractive in a search theoretic context (some evidence for the theory is in Helpman, Itskhoki, Muendler, and Redding 2012).

Our model allows for one type of adjustment cost, a cost of moving inputs between firms. When this cost traps factors of production inside a firm, an unexpected increase in low-wage imports will cause losses that must be shared between the workers and the equity holders of an affected firm. We do not model how these losses are shared. In effect, our approach is equivalent to making the unrealistic assumption that there is a perfect insurance market that shares this risk among all residents in the North.

In this admittedly unrealistic full-insurance setting, allowing for a type of adjustment cost leads to welfare gains from trade that are larger not smaller. Because the level of innovation is below the socially optimal level, when there is an unexpected increase in trade, these costs increase welfare because they increase the rate of innovation. To be sure, other types of adjustment costs could reduce welfare by making unemployment worse or exposing people to new uninsured risks. But as our analysis shows, in endogenous models of growth, which typically have equilibria that are Pareto suboptimal because the private incentives that motivate innovation are smaller than the social returns, it does not follow that adding adjustment costs necessarily reduce the gains from trade.

7.5 Anticipation Effects

We have modeled the trade shock as being unexpected the agents. Although events such as China's WTO accession were of course partially anticipated, there was some policy surprise that it actually occurred as negotiations were fraught. Moreover in some trading blocks - like the entire European Union - the liberalizations with China were temporarily reversed due to a political backlash. Southern European producers of apparel and textiles successfully lobbied to have the quotas partially reinstated for three years, highlighting how the success of these types of trade liberalizations are uncertain in advance.

To the extent that a shift from ϕ to ϕ' is announced in anticipated, agents will change their behavior.[24] In particular there will be a disincentive to invest in trapped factors because the firm knows that once the liberalization occurs it will be burdened with too high a level of inputs in producing intermediate goods. Hence, depending on the exact timing and discounting, Northern firms will start shifting into more innovation activities prior to the liberalization and will suffer less from having "too many" trapped factors when the liberalization occurs. The transition dynamics will change even though the long-run post-transition growth rates will remain the same.

These considerations also demonstrate why a policy maker cannot engineer a larger effect from trade by increasing the magnitude of trapped factors. Increasing firing costs, for example, will certainly made factors more trapped, but this will not generally increase the rate of innovation. For anticipated trade shocks, higher adjustment costs will simply cause greater inefficiencies as firms will invest less in the factors which have greater potential to become trapped.

7.6 Patent Length vs. Adjustment Cost Horizon

Currently embedded within our analysis is an assumption that the model period, 10 years in our calibration, represents both the period over which monopoly protection is effective and the period over which factors are trapped in the short run. While this is not an unreasonable assumption - capital and labor adjustment costs are typically estimated at between 10% to 50% of the lifetime cost of the assets (Bloom, 2009) making these long–term investment similar to intellectual property protection[25] - it is clearly very stark and worth exploring.

One challenge to allowing asset and monopoly lengths to differ is this would considerably complicate our analysis through the addition of a number of additional state variables within each firm's problem. However, we can consider the impacts of this qualitatively by examining the two potential cases arising from delinking the monopoly horizon (T^M) years, from the adjustment cost horizon (T^A). There are two cases to differentiate here. First, if $T^A > T^M$, then adjustment-cost induced periods of immobility are longer than monopoly protection and therefore trapped or surplus inputs would be available for the innovation and production of multiple cohorts of new varieties. Such a framework would likely not change the results qualitatively, since it simply would spread the benefits of innovation over multiple periods and cohorts of new varieties.

Importantly, however, if the perhaps more empirically plausible case of $T^A < T^M$ were to be considered, preexisting cohorts of on-patent varieties may exist within firms at the

[24] See Costantini and Melitz (2008) for similar points in the context of technology adoption and trade.

[25] We should note that while patent lengths vary between 15 to 20 years, effective patent lengths are typically shorter due to imitation, lags between application and granting and imperfect patent protection (for example process innovation patents are hard to enforce). As such a 10 year patent life is likely to be more of an upper bound for the average effective length of intellectual property protection.

time of a trade shock. These preexisting monopoly varieties would offer an alternative substitution possibility into which surplus or trapped resources can be directed instead of towards innovation of new varieties. One the one hand this would reduce the innovation boost induced by our trapped factors mechanism, but on the other hand it would also reduce the welfare loss from monopoly mark-ups (the output of the existing monopoly products would rise pushing down the mark-ups). Hence, the net impact on welfare is ambiguous and an area of ongoing research.

8 Conclusion

In this paper we present a new general equilibrium model of trade with endogenous growth that allows factors of production to be temporarily "trapped" in firms due, for example, to specific capital. This trapped factors model allows us to rationalize why in the face of an import shock from a low-wage country like China, incumbent firms in the affected industry may innovate more, as the firm-level micro-data suggest (Bloom, Draca, and Van Reenen 2012; Freeman and Kleiner, 2005). The mechanism behind this effect is a fall in the opportunity cost of R&D caused by a fall in the shadow cost of these trapped factor. The model also contains the more standard theoretical mechanism from the literature on trade and grwoth, whereby integration increases the profits from innovation.

We calibrate a model and quantify the effects of a trade liberalization of the magnitude we observed in the decade around China's accession to the WTO 1997-2006. Empirically, we find a substantial increase in welfare from such trade integration: a consumption equivalent increase of the order of 16% and a permanent increase in growth of around 0.4%. This leads to welfare effects that are much larger than conventional calibrations of static trade models which ignore the dynamic effects of trade on growth because they do not allow for the possibility that more innovation by firms can lead to more productivity growth for the economy as a whole. About a tenth (2% out of a 16% consumption equivalent increase) of the overall welfare gains are due to our trapped factor mechanism, a small but non-trivial proportion. Moreover, these trapped factor gains from growth come in the immediate aftermath of the a trade-liberalization, so will be important to policymakers.

These large dynamic gains from trade depend on increased profits that innovators in the North can earn from sales in the South. In this sense, the model ratifies the increasing attention that trade negotiators are devoting to non-tariff barriers that might limit a foreign firm's ability to earn profits from a newly developed good. We have seen this already in the TRIPS agreement under the WTO and better protection of intellectual property rights is also reported to be a central goal in the US approach to the negotiations leading up to the Trans Pacific Partnership. If this is where the largest welfare gains lie, this is where trade agreements can have their biggest effects.

As noted in the Introduction, there are many ways in which the modeling framework could be extended and made more realistic. First, we have abstracted from “catch-up” in which growth rates in the South are higher than in North due to imitation. We did this in order to focus on welfare benefits in the North from a faster opening up of trade restrictions with the South. Second, we focus on the impact of North-South integration rather than North-North integration. This was motivated by evidence that the pro-innovation effects in the North were far stronger when trade barriers against the South were relaxed compared to richer countries, but an extended framework along say the lines of Aghion et al. (2005) could allow for Schumpeterian and “escape competition” effects. Third, a more careful analysis of the labor market and uninsured risk could offer an important offset to the effects that we identify. Although we have gone beyond steady states to look at transition dynamics we have, as is standard, abstracted away from the distributional changes as workers may suffer wage losses and unemployment when we introduce frictions in the labor market. These do seem to matter empirically so more work needs to be done to also incorporate such effects in quantitative theory models (e.g. Harrison, McLaren, and McMillan, 2011).

The main message of our paper is that liberalized trade with the South can have substantial benefits in for the North and the entire world because it induces more innovation. This increase arises mainly through long-run increases in the profits that a new firm can earn from a newly developed good, but also because of a temporary contribution from trapped factors that reduces the opportunity cost of innovation. China alone accounts for almost half of the increase in welfare we identify.

Because these benefits are less visible than the losses that firms and workers can face from an unexpected increase in trade, and because these effects can take decades to be realized, it is as important as ever for economists to understand why it may be so important to pursue and protect the gains from trade.

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Online Appendices:Not Intended for publication unless requested

9 Appendix A - Theoretical Details and Proofs

In this appendix we give more technical details and proofs of our main model. There are multiple equivalent conventions which can be used in the decentralization of this economy. In the text when describing the intermediate goods firms within the North and South, we found it convenient to treat these firms as each having identical technologies but devoted to the production of consumption goods, innovation of new goods, or production of existing goods. In that structure, although we can for convenience speak of a flow $Y_t$of output, there is no formal "final good" or "final goods firm," and intermediate goods firms directly demand human capital from households and intermediate goods from other firms. However, please note that in the Appendices of the paper we have used an alternative formulation, one which is equivalent in its allocations. In the alternative Appendix formulation which is used in the definitions and proofs below, we speak of a final goods firm operating under perfect competition, which creates a physical flow of final goods output that a single class of intermediate goods firms, which are equity-financed, must direct optimally towards production and innovation in the interest of their owners. Although equivalent in terms of allocations, these formulations do involve different notation.

Definition 1 *Closed-Economy Equilibrium*

Given initial conditions A_0, x_{k0}, an equilibrium is a path of wages, interest rates, stock prices, and intermediate goods prices w_t, r_t, q_{ft}, p_{jt}, together with stock portfolio decisions, debt levels, final goods firm input demands, intermediate goods firms input demands, intermediate goods firm innovation quantities, intermediate goods dividends, aggregate innovation quantities, firm variety portfolios, and aggregate variety quantities s_{ft}, b_t, H_t^D, x_{jt}^D,x_{jt+1}^S, M_{ft+1},d_{ft},A_t, $A_{ft,}M_{t,}$such that

Households Optimize: Taking wages w_t, interest rates r_t, and stock prices q_{ft}as given, the representative household maximizes the present discounted value of its consumption stream by choosing period consumption C_t, debt b_{t+1}, and share purchases s_{ft}, i.e. these decisions solve

$$\max_{C_t,b_{t+1},s_{jt}} \sum_{t=0}^{\infty} \frac{\beta^t C_t^{1-\sigma}}{1-\sigma}$$

$$b_{t+1}+C_t+\sum_{f=1}^{N} q_{ft}(s_{ft}-s_{ft-1}) \leq (1+r_{t+1})b_t+w_tH+\sum_{f=1}^{N} d_{ft}s_{ft}.$$

Final Goods Firm Optimizes: Taking wages $w_t$and intermediate goods prices p_{kt}as given, the competitive representative final goods firm statically optimizes profits by choosing labor demand $H_t^D$and intermediate goods input demands x_{jt}^D,i.e. these decisions solve

$$\max_{H_t,x_{kt}} (H_t)^{\alpha} \int_0^{A_t} (x_{jt})^{1-\alpha}\, dj - w_tH_t - \int_0^{A_t} p_{jt}x_{jt}dj.$$

Intermediate Goods Firms Optimize: Taking marginal utilities m_t, perfectly competitive off-patent intermediate goods prices $p_{jt}, j \leq A_{t-1}$, and aggregate variety and innovation levels A_t, M_{t+1}as given, intermediate goods firms maximize firm value, the discounted stream of dividends, by choosing the measure of newly innovated goods $M_{ft+1}$to add to the existing measure of varieties A_{ft}in their portfolios, the supply of all intermediate goods for use next period x^S_{jt+1},and the price of on-patent intermediate goods $p_{jt}, j \in (A_{t-1}, A_t]$,i.e. these quantities solve

$$\max_{p_{jt}, M_{ft+1}, x_{jt+1}} \sum_{t=0}^{\infty} m_t d_{ft}$$

$$d_{ft} + \int_{A_{ft+1}} x_{jt+1} dj + Z_{ft} \leq \int_{A_{ft}} p_{jt} x_{jt} dj$$

$$Z_{ft} = \nu M^{\gamma}_{ft+1} A^{1-\gamma}_t$$

Labor, Bond, Stock, and Intermediate Goods Markets Clear:

$$H^D_t = H,\ b_{t+1} = 0,\ s_{ft} = 1,\ x^D_{jt+1} = x^S_{jt+1}$$

Final Goods Market Clears:

$$Y_t = C_t + \int_0^{A_{t+1}} x_{jt+1} dj + \sum_{f=1}^{N} Z_{ft}$$

Innovation and Variety Consistency Conditions Hold:

$$A_{t+1} = A_t + M_{t+1},\ A_{ft+1} = A_{ft} + M_{ft+1},\ M_{t+1} = \sum_{f=1}^{N} M_{ft+1},\ A_t = \sum_{f=1}^{N} A_{ft.}$$

Definition 2 *Open-Economy Equilibrium*

Given any initial conditions A_0, x_{k0}, x^*_{k0}, along with a sequence of trade restrictions ϕ_t, an equilibrium in the open economy is a set of terms of trade, interest rates, wages, stock prices, and intermediate goods prices q_t , r_t , $r^*_t, w_t, w^*_t, q_{ft}, q^*_{ft}$,p_{jt}, and p^*_{jt} , along with stock portfolio decisions, debt levels, final goods firm input demands, intermediate goods firms input demands, intermediate goods firm innovation quantities, intermediate goods firm portfolios, intermediate goods dividends, aggregate innovation quantities, imported variety measures, restricted variety measures, and aggregate variety quantities $s_{ft}, s^*_{ft}, b_{t+1}, b^*_{t+1}, H^D_t, H^{*D}_t, x^D_{jt}, x^{*D}_{jt}$, $x^S_{jt+1}, x^{*S}_{jt+1}, M_{ft+1}$, $A_{jt}, A^*_{ft}, d_{ft}, d^*_{ft}, M_t, I_t, R_t$, and A_t such that Northern Household Optimizes: Taking wages w_t , interest rates r_t , and stock prices q_{ft} as given, the representative household in the North maximizes the present discounted value of its consumption stream by choosing period consumption C_t , debt b_{t+1} , and share purchases s_{ft} , i.e. these decisions solve

$$\max_{C_t, b_{t+1}, s_{jt}} \sum_{t=0}^{\infty} \frac{\beta^t C^{1-\sigma}_t}{1-\sigma}$$

$$b_{t+1} + C_t + \sum_{f=1}^{N} q_{ft} \left(s_{ft} - s_{ft-1}\right) \leq (1 + r_{t+1}) b_t + w_t H + \sum_{f=1}^{N} d_{ft} s_{ft} .$$

Southern Household Optimizes: Taking wages w_t^* , interest rates r_t^* , and stock prices q_{ft}^* as given, the representative household in the South maximizes the present discounted value of its consumption stream by choosing period consumption C_t^* , debt b_{t+1}^* , and share purchases s_{ft}^* , i.e. these decisions solve

$$\max_{C_t^*, b_{t+1}^*, s_{ft}^*} \sum_{t=0}^{\infty} \frac{\beta^t \left(C_t^*\right)^{1-\sigma}}{1-\sigma}$$

$$b_{t+1}^* + C_t^* + \sum_{f=1}^{N} q_{ft}^* \left(s_{ft}^* - s_{ft-1}^*\right) \leq (1 + r_{t+1}^*) b_t^* + w_t^* H^* + \sum_{f=1}^{N} d_{ft}^* s_{ft}^* .$$

Northern Final Goods Firm Optimizes: Taking wages w_t and intermediate goods prices p_{jt} as given, the competitive representative final goods firm in the North statically optimizes profits by choosing labor demand H_t^D and intermediate goods input demands x_{jt}^D, i.e. these decisions solve

$$\max_{H_t, x_{jt}} (H_t)^{\alpha} \int_0^{A_t} (x_{jt})^{1-\alpha} \, dj - w_t H_t - \int_0^{A_t} p_{jt} x_{jt} \, dj.$$

Southern Final Goods Firm Optimizes: Taking wages w_t^* and intermediate goods prices p_{jt}^* as given, the competitive representative final goods firm in the South statically optimizes profits by choosing labor demand H_t^{*D} and intermediate goods input demands x_{jt}^{D*}, i.e. these decisions solve

$$\max_{H_t^*, x_{jt}^*} (H_t^*)^{\alpha} \int_0^{A_t} \left(x_{jt}^*\right)^{1-\alpha} \, dj - w_t^* H_t^* - \int_0^{A_t} p_{jt}^* x_{jt}^* dj .$$

Northern Intermediate Goods Firm Optimizes: Taking marginal utilities m_t , perfectly competitive off-patent intermediate goods prices $p_{jt}, j \leq A_{t-1}$, and aggregate variety, trade, and innovation levels A_t, R_t , and M_{t+1} as given, intermediate goods firms f in the North maximize firm value, the discounted stream of dividends, by choosing the measure of newly innovated goods M_{ft+1} to add to the existing measure of varieties A_{ft} in their portfolios, the supply of all intermediate goods in their portfolio for use next period x_{jt+1}^S, x_{jt+1}^{*S}, and the price of on-patent intermediate goods $p_{jt}, j \in (A_{t-1}, A_t]$, i.e. these quantities solve

$$\max_{p_{jt}, M_{ft+1}, x_{jt+1}, x_{jt+1}^*} \sum_{t=0}^{\infty} m_t d_{ft}$$

$$d_{ft} + \int_{A_{ft+1}} \left(x_{jt+1} + x_{jt+1}^*\right) dj + Z_{ft} \leq \int_{A_{ft}} p_{jt} \left(x_{jt} + x_{jt}^*\right) dj$$

$$Z_{ft} = \nu M_{ft+1}^{\gamma} A_t^{1-\gamma}$$

Southern Intermediate Goods Firm Optimizes: Taking marginal utilities m_t^* and perfectly competitive off-patent intermediate goods prices $p_{jt}^*, j \leq A_{t-1}$ as given, intermediate goods firms f in the South maximize firm value, the discounted stream of dividends, by choosing the supply of all intermediate goods in their portfolios A_{ft}^* for use next period $x_{jt+1}^S,\ x_{jt+1}^{*S}$, i.e. these quantities solve

$$\max_{M_{ft+1}, x_{jt+1}, x_{jt+1}^*} \sum_{t=0}^{\infty} m_t^*\ d_{ft}$$

$$d_{ft}^* + \int_{A_{ft+1}^*} (x_{jt+1} + x_{jt+1}^*) dj \leq \int_{A_{ft}^*} p_{jt}^* (x_{jt} + x_{jt}^*) dj.$$

Labor, Bond, Stock, and Intermediate Goods Markets Clear

$$H_t^D = H,\ H_t^{*D} = H^*,$$
$$b_{t+1} = 0,\ b_{t+1}^* = 0,$$
$$s_{ft} = 1,\ s_{ft}^* = 1,$$
$$x_{jt}^D = x_{jt}^S,\ x_{jt}^{*D} = x_{jt}^{*S}.$$

Final Goods Markets Clear

$$Y_t = H^\alpha \int x_{jt}^{1-\alpha} dj = C_t + R_{t+1} x_{Rt+1} + M_{t+1}(x_{Mt+1} + x_{Mt+1}^*) + \sum_{f=1}^{N} Z_{ft}$$

$$Y_t^* = (H^*)^\alpha \int_0^{A_t} \left(x_{jt}^*\right)^{1-\alpha} dj = C_t^* + R_{t+1} x_{Rt+1}^* + I_{t+1}(x_{It+1} + x_{It+1}^*)$$

No Arbitrage Pricing Condition Holds

$$p_{jt} = q_t p_{jt}^*$$

Trade is Balanced

$$I_t p_{It} x_{It} = M_t p_{Mt} x_{Mt}^*$$

Innovation and Variety Consistency Conditions Hold:

$$\phi_t\ (R_t + I_t) = I_t\ , I_t + R_t = A_{t-1}\ , I_t + R_t + M_t = A_t\ ,$$

$$A_{ft+1} = A_{ft} + M_{ft+1},\ M_t = \sum_{f=1}^{N} M_{ft},\ M_t + R_t = \sum_{f=1}^{N} A_{ft},\ I_t + R_t = \sum_{f=1}^{N} A_{ft}^*.$$

Southern Cost Advantage Condition Holds: Off-restriction goods are always produced in the Southern economy only. Although the fully mobile economy with a trade shock has essentially the same equilibrium concept as laid out in the previous section initially discussing the open economy, we must be more explicit about the trapped factors environment. In the trapped factors equilibrium, Northern intermediate goods firms face an additional constraint due to the adjustment costs preventing them from immediately responding in their input usage to the new trade shock. Formally, they must solve the modified problem

$$\max_{p_{ft}, M_{ft+1}, x_{jt+1}, x_{jt+1}^*, X_{ft}} \sum_{t=0}^{\infty} m_t d_{ft}$$

$$d_{ft} + \int\limits_{A_{ft+1}} (x_{jt+1} + x^*_{jt+1})dj + Z_{ft} \leq \int\limits_{A_{ft}} p_{jt}(x_{jt} + x^*_{jt})dj$$
$$\int\limits_{A_{ft+1}} (x_{jt+1} + x^*_{jt+1})dj + Z_{ft} \geq X_{ft}\left(\phi^E_{t,t+1}\right),$$

where $X_{ft}\left(\phi^E_{t,t+1}\right)$is the optimal input demand for period t, given expectations of the trade restriction $\phi^E_{t,t+1}$for the next period. $X_{ft}$is also indexed by $f$and depends both upon the number of Mgoods that the firm plans to produce for next period, as well as the number of Rgoods that the firm has in its portfolio and plans to produce for the next period. Therefore, although these portfolio shares are only allocative in a period in which a trade shock occurs, we must be explicit about the structure we assume for the pre-shock portfolios of Rgoods held by each firm f, as well as the actual allocation of the trade shock liberalization among existing firms' measures of Rgoods. We now define some additional notation. Let $\widetilde{s}_f$be the share of off-patent Rgoods production firm $f$anticipates doing before the trade shock, where $\sum\limits_{f=1}^{N}\widetilde{s}_f = 1$. Then, let the trade shock allocate destruction of Rgoods production opportunities across firms so that only the proportion $\chi_f$of Rgoods varieties can still be produced in each firm. As long as we have the consistency condition

$$\sum_{f=1}^{N}\widetilde{s}_f\chi_f\left(1-\phi\right)A_t = (1-\phi')A_t,$$

an arbitrary choice of $\chi_f$will be consistent with the trade shock $\phi \rightarrow \phi'$. We will henceforth make the assumption that $\widetilde{s}_f = \frac{1}{N}$for all firms, i.e. that pre-shock allocations of Rgoods production is uniform across firms. This assumption grows naturally out of our structure in which we assume that firms continue to be the producers of goods which they invented, even after these goods fall off-patent and become perfectly competitive. We also will now assume that $N$is even, and that half of the firms in the economy are in a no shock industry, industry 1. The other half of firms in the economy, those in industry 2, experience a loss of Rgoods production opportunities during the trade shock with only a fixed proportion $\chi_2$of Rgoods remaining. This framework is a rough approximation of the heterogeneity in the direct effects on firms in developed countries during the trade liberalizations of the early 2000s. Seen in this light, industries such as textiles which experienced a substantial loss of protection against manufacturers in low-wage economies such as China, can be identified with industry 2, while other industries would be represented by firms in group 1in our environment. We now define a trapped factors equilibrium formally.

Definition 3 *Trapped Factors Trade Shock Equilibrium*

Given any initial conditions $A_0, x_{k0}, x^*_{k0}$and a sequence of trade restrictions

$$\phi_s = \begin{cases} \phi, s \leq t, \\ \phi', s > t \end{cases},$$

where the trade shift from $\phi$to $\phi' > \phi$is unanticipated and affects only industry 2, leaving the proportion $\chi_2$of Rgoods in in industry 2restricted, a trapped factors equilibrium in the open economy is a set of terms of trade, interest rates, wages, stock prices, and intermediate goods prices

q_t, r_t, r_t^*, w_t, w_t^*, q_{ft}, q_{ft}^*,p_{jt},and p_{jt}^*, along with stock portfolio decisions, debt levels, final goods firm input demands, intermediate goods firms input demands, intermediate goods firm innovation quantities, intermediate goods firm portfolios, intermediate goods dividends, aggregate innovation quantities, imported variety measures, restricted variety measures, and aggregate variety quantities $s_{ft}, s_{ft}^*, b_{t+1}, b_{t+1}^*, H_t^D, H_t^{*D}, x_{jt}^D, x_{jt}^{*D}$,$x_{jt+1}^S$,$x_{jt+1}^{*S}$, M_{ft+1}, A_{ft},A_{ft}^*,d_{ft}, $d_{ft}^* M_t$,I_t, R_t,and $A_t$such that Northern Household Optimizes: Taking wages w_t, interest rates r_t, and stock prices q_{ft}as given, the representative household in the North maximizes the present discounted value of its consumption stream by choosing period consumption C_t, debt b_{t+1}, and share purchases s_{ft}, i.e. these decisions solve

$$\max_{C_t, b_{t+1}, s_{ft}} \sum_{t=0}^{\infty} \frac{\beta^t C_t^{1-\sigma}}{1-\sigma}$$

$$b_{t+1} + C_t + \sum_{f=1}^{N} q_{ft}(s_{ft} - s_{ft-1}) \le (1 + r_{t+1})b_t + w_t H + \sum_{f=1}^{N} d_{ft} s_{ft}.$$

Southern Household Optimizes: Taking wages w_t^*, interest rates r_t^*, and stock prices q_{ft}^*as given, the representative household in the South maximizes the present discounted value of its consumption stream by choosing period consumption C_t^*, debt b_{t+1}^*, and share purchases s_{ft}^*, i.e. these decisions solve

$$\max_{C_t^*, b_{t+1}^*, s_{ft}^*} \sum_{t=0}^{\infty} \frac{\beta^t \left(C_t^*\right)^{1-\sigma}}{1-\sigma}$$

$$b_{t+1}^* + C_t^* + \sum_{f=1}^{N} q_{ft}^*(s_{ft}^* - s_{ft-1}^*) \le (1 + r_{t+1}^*)b_t^* + w_t^* H^* + \sum_{f=1}^{N} d_{ft}^* s_{ft}^*.$$

Northern Final Goods Firm Optimizes: Taking wages $w_t$and intermediate goods prices p_{jt}as given, the competitive representative final goods firm in the North statically optimizes profits by choosing labor demand $H_t^D$and intermediate goods input demands x_{jt}^D,i.e. these decisions solve

$$\max_{H_t, x_{jt}} (H_t)^{\alpha} \int_0^{A_t} (x_{jt})^{1-\alpha} dj - w_t H_t - \int_0^{A_t} p_{jt} x_{jt} dj.$$

Southern Final Goods Firm Optimizes: Taking wages $w_t^*$and intermediate goods prices p_{jt}^*as given, the competitive representative final goods firm in the South statically optimizes profits by choosing labor demand $H_t^{*D}$and intermediate goods input demands x_{jt}^{D*},i.e. these decisions solve

$$\max_{H_t^*, x_{jt}^*} (H_t^*)^{\alpha} \int_0^{A_t} \left(x_{jt}^*\right)^{1-\alpha} dj - w_t^* H_t^* - \int_0^{A_t} p_{jt}^* x_{jt}^* dj.$$

Northern Intermediate Goods Firm Optimizes: Taking marginal utilities m_t, perfectly competitive off-patent intermediate goods prices $p_{jt}, j \le A_{t-1}$, and aggregate variety, trade, and innovation levels A_t, R_t, M_{t+1}as given intermediate goods firms in the North maximize firm value, the discounted stream of dividends, by first choosing the quantity of inputs $X_{ft}\left(\phi_{t,t+1}^E\right)$given their expectations of trade policy next period, then choosing the measure of newly innovated goods $M_{ft+1}$to add to the existing measure of varieties A_{ft} in their portfolios, the supply of all intermediate goods in their portfolio for use next period x_{jt+1}^S,x_{jt+1}^{*S},and the price of on-patent intermediate goods

$p_{jt}, j \in (A_{t-1}, A_t]$,i.e. these quantities solve

$$\max_{p_{jt}, M_{ft+1}, x_{jt+1}, x^*_{jt+1}, X_{ft}} \sum_{t=0}^{\infty} m_t d_{ft}$$

$$d_{ft} + \int\limits_{A_{ft+1}} (x_{jt+1} + x^*_{jt+1}) dj + Z_{ft} \leq \int\limits_{A_{ft}} p_{jt}(x_{jt} + x^*_{jt}) dj$$

$$\int\limits_{A_{ft+1}} (x_{jt+1} + x^*_{jt+1}) dj + Z_{ft} \geq X_{ft} \left(\phi^E_{t,t+1} \right)$$

$$Z_{ft} = \nu M^{\gamma}_{ft+1} A^{1-\gamma}_t$$

where we have that

$$\phi^E_{s,s+1} = \begin{cases} \phi, & s \leq t \\ \phi', & s > t \end{cases} .$$

Southern Intermediate Goods Firm Optimizes: Taking marginal utilities $m^*_t$and perfectly competitive off-patent intermediate goods prices $p^*_{jt}, j \leq A_{t-1}$as given, intermediate goods firms in the South maximize firm value, the discounted stream of dividends, by choosing the supply of all intermediate goods in their portfolios $A^*_{ft}$for use next period x^S_{jt+1},x^{*S}_{jt+1},i.e. these quantities solve

$$\max_{M_{ft+1}, x_{jt+1}, x^*_{jt+1}} \sum_{t=0}^{\infty} m^*_t d_{ft}$$

$$d^*_{ft} + \int\limits_{A_{ft+1}} (x_{jt+1} + x^*_{jt+1}) dj \leq \int\limits_{A_{ft}} p^*_{jt}(x_{jt} + x^*_{jt}) dj.$$

Labor, Bond, Stock, and Intermediate Goods Markets Clear

$$H^D_t = H, \; H^{*D}_t = H^*,$$

$$b_{t+1} = 0, \; b^*_{t+1} = 0,$$

$$s_{ft} = 1, \; s^*_{ft} = 1,$$

$$x^D_{jt} = x^S_{jt}, \; x^{*D}_{jt} = x^{*S}_{jt}.$$

Final Goods Markets Clear:

$$Y_t = H^{\alpha} \int x^{1-\alpha}_{jt} dj = C_t + \int_{R_{t+1}} x_{jt+1} dj + \int_{M_{t+1}} (x_{jt+1} + x^*_{jt+1}) dj + \sum_{f=1}^{N} Z_{ft}$$

$$Y^*_t = (H^*)^{\alpha} \int_0^{A_t} \left(x^*_{jt} \right)^{1-\alpha} dj = C^*_t + \int_{R_{t+1}} x^*_{jt+1} dj + \int_{I_{t+1}} (x_{jt+1} + x^*_{jt+1}) dj$$

No Arbitrage Pricing Condition Holds

$$p_{kt} = q_t p^*_{kt}$$

Trade is Balanced

$$I_t p_{It} x_{It} = M_t p_{Mt} x^*_{Mt}$$

Innovation and Variety Consistency Conditions Hold:

$$\phi_t(R_t+I_t) = I_t, I_t+R_t= A_{t-1}, I_t+R_t+M_t= A_t,$$

$$A_{ft+1}= A_{ft}+M_{ft+1},\ M_t=\sum_{f=1}^{N} M_{ft},\ M_t+R_t=\sum_{f=1}^{N} A_{ft},\ I_t+R_t=\sum_{f=1}^{N} A^*_{ft}.$$

Southern Cost Advantage Condition Holds: Off-restriction goods are always produced in the Southern economy only. Proof of Proposition 1: Closed Economy Balanced Growth Path To complete

the proof of Proposition 1, we need to show that the rates of growth of output, consumption, and varieties are equal on the balanced growth path. The final goods market clearing condition is

$$C_t = H^{\alpha}\left[M_t x_{Mt}^{1-\alpha} + R_t x_{Rt}^{1-a} + I_t x_{It}^{1-\alpha}\right] - M_{t+1}x_{Mt+1} - R_{t+1}x_{Rt+1} - \sum_{f=1}^{N} Z_{ft},$$

where we note that since it is the measure of off-patent varieties, $R_t = A_{t-1}$,and the measure of innovated varieties $M_t = gA_{t-1}$. Now, recall the assumption of balanced growth. If we define the growth rate of consumption by g_C,and note that the by symmetry the individual firm patenting ratios $g^f = \frac{g}{n}$, we can use the intermediate goods firm pricing rules to rewrite the final goods market clearing condition as

$$\frac{C_t}{A_t} = \frac{1}{1+g}H\left[(1-\alpha)^{\frac{1-\alpha}{\alpha}}\left((1-\alpha)^{\frac{1-\alpha}{\alpha}}+1\right)\beta^{\frac{1-\alpha}{\alpha}}(1+g_C)^{-\frac{\sigma}{\alpha}}\right] - g(1-\alpha)^{\frac{2}{\alpha}}\beta^{\frac{1}{\alpha}}(1+g_C)^{-\frac{\sigma}{\alpha}}H$$
$$-(1-\alpha)^{\frac{1}{\alpha}}\beta^{\frac{1}{\alpha}}(1+g_C)^{-\frac{\sigma}{\alpha}}H - N\nu\left(\frac{g}{N}\right)^{\gamma}.$$

Since $\frac{C_t}{A_t}$is constant, we conclude that $g = g_C$, so that the innovation optimality condition reads

$$\frac{\nu\gamma}{N^{(\gamma-1)}}g^{\gamma-1} = \Omega\beta^{\frac{1}{\alpha}}(1+g)^{-\frac{\sigma}{\alpha}}H.$$

This expression motivates the choice of the scaling constant

$$\nu = \frac{N^{(\gamma-1)}}{\gamma},$$

so that the balanced growth path growth rates are invariant to the number of firms or the degree of cost externalities across firms as well as the number of firms N. We obtain the balanced growth path innovation optimality condition

$$g^{\gamma-1}= \Omega\beta^{\frac{1}{\alpha}}(1+g)^{-\frac{\sigma}{\alpha}}H.$$

The left-hand side, the marginal cost of innovation, is strictly increasing in g, is equal to 0when $g = 0$, and limits to ∞as $g \to \infty$. The right-hand side, the discounted monopoly profits from innovation, is strictly decreasing in g, is equal to $\Omega\beta^{\frac{1}{\alpha}}H > 0$when $g = 0$,and limits to 0as $g \to \infty$. We conclude that a balanced growth path equilibrium exists and is uniquely determined by the value of $g$which satisfies the innovation optimality condition. This completes the proof. Proof of Proposition 2: Open Economy Balance Growth Path The demand schedules for intermediate goods, based on the Northern and Southern final goods firms' technologies, are given by

$$x_{jt} = (1-\alpha)^{\frac{1}{\alpha}}Hp_{jt}^{-\frac{1}{\alpha}}$$
$$x^*_{jt} = (1-\alpha)^{\frac{1}{\alpha}}H^*\left(p^*_{jt}\right)^{-\frac{1}{\alpha}},$$

where $p_{jt}$and $p^*_{jt}$are the prices of intermediate good variety $j$in Northern and Southern output units, respectively, and $p_{jt} = q_t p^*_{jt}$. The optimality conditions for the Northern intermediate goods firm, combined with the Euler equations of the Northern representative household for debt and equity, are given by

$$\begin{aligned} p_{Rt+1} &= 1 + r_{t+1} \\ p_{Mt+1} &= \frac{1 + r_{t+1}}{1 - \alpha} \\ \frac{\partial}{\partial M_{ft+1}} Z_{ft+1} &= \left(\frac{1}{1 + r_{t+1}} p_{Mt+1} - 1 \right) (x_{Mt+1} + x^*_{Mt+1}). \end{aligned}$$

Differentiating the cost function and substituting in the optimal pricing rules we have that the third condition, the innovation optimality condition, is given by

$$\nu\gamma(g^f_{t+1})^{(\gamma-1)} = \Omega\beta^{\frac{1}{a}}(\frac{C_{t+1}}{C_t})^{-\frac{\sigma}{\alpha}}(H + q^{\frac{1}{\alpha}}_{t+1}H^*).$$

Now the balanced trade condition can be written

$$\begin{aligned} M_t p_{Mt} x^*_{Mt} &= I_t p_{It} x_{It} \\ g_t A_{t-1} \frac{(1 + r_t)}{1 - \alpha} (1 - \alpha)^{\frac{1}{\alpha}} H^* \left(\frac{(1 + r_t)}{q_t(1 - \alpha)} \right)^{-\frac{1}{\alpha}} &= \phi A_{t-1} q_t (1 + r^*_t)(1 - \alpha)^{\frac{1}{\alpha}} \left(q_t(1 - \alpha) \right)^{-\frac{1}{\alpha}} H \\ q_t &= \left(\frac{\phi H}{g_t H^*} \right)^{\frac{\alpha}{2-\alpha}} \Psi \left(\frac{1 + r_t}{1 + r^*_t} \right)^{\frac{1-\alpha}{2-\alpha}}, \end{aligned}$$

where $\Psi = (1-\alpha)^{\frac{\alpha-1}{2-\alpha}}$. Now, applying the assumption of balanced growth, we immediately obtain from the Euler equations of both representative households that interest rates in the Northern and Southern economies, as well as the terms of trade, are constant. Also, exactly as in the proof of Proposition 1, the final goods market clearing conditions for each economy, together with the assumption of balanced growth, imply that the ratios

$$\frac{C_t}{A_t}, \frac{C^*_t}{A_t}$$

are constant, so that we conclude that

$$(1 + r) = (1 + r^*) = \beta^{-1}(1 + g)^{\sigma}.$$

Using this, we conclude that

$$q = \left(\frac{\phi H}{g H^*} \right)^{\frac{\alpha}{2-\alpha}} \Psi.$$

Now the innovation optimality condition can be rewritten as

$$g^{\gamma-1} = \Omega\beta^{\frac{1}{a}}(1 + g)^{-\frac{\sigma}{\alpha}}(H + q^{\frac{1}{\alpha}}H^*).$$

Also, substituting the terms of trade formula/balanced trade condition into the innovation optimality condition yields

$$g^{\gamma-1} = \Omega\beta^{\frac{1}{\alpha}}(1+g)^{-\frac{\sigma}{\alpha}}\left(H + \left(\frac{\phi H}{gH^*}\right)^{\frac{1}{2-\alpha}}\Psi^{\frac{1}{\alpha}}H^*\right).$$

As a function of g, the marginal cost of innovation on the left-hand side is strictly increasing in g, starting at 0 and growing exponentially to ∞ as $g \to \infty$. The right-hand side, the discounted monopoly profits from sale of newly patented goods in the North and the South, is strictly decreasing in g, asymptoting to ∞ as $g \to 0$ and to 0 as $g \to \infty$. We conclude both that there exists a balanced growth path equilibrium for this economy, and that it is the unique balanced growth path growth rate. For any given fixed value of ϕ, we denote this growth rate, and the associated terms of trade, by $g(\phi)$ and $q(\phi)$. This completes the proof.

Appendix B - Parameter Values and Robustness Checks

Calculating the ratio of H to H^*

To calculate the ratio of H to H^*, we follow the human capital accounting approach in Hall and Jones (1999) and compute the human capital endowment in country c from the Barro and Lee (2010) data as $H_c = e^{\mu_c S_c} P_c$, where S_c is the average number of years of schooling completed in the adult population above age 25, and P_c is the size of the population of the country c in 2000. We take into account the differences in educational quality and the returns to schooling across countries by using the Mincerian returns to education of immigrants in the United States from country c, μ_c, from Table 4 in Schoellman (2011). If Mincerian returns for a country c is not available in Schoellman (2011), we take $\mu_c = 7\%$ for non-OECD countries and $\mu_c = 9\%$ for OECD countries. These are the averages of returns to schooling for the two categories in Schoellman's sample. We finally define $H_{non-OECD} = 2.1 \sum_{c \notin OECD} H_c$, where the ratio 2.1 corrects for the fact that not all non-OECD countries are represented in the Barro and Lee data. In particular 2.1 is equal to the ratio of the non-OECD to OECD population ratio in 2000 in the Wolfram Alpha database (with full global coverage) to the non-OECD to OECD population ratio in 2000 in the Barro and Lee data. Such a procedure relies on the implicit assumption that the schooling rates and returns to education in countries not represented in the Barro and Lee data are similar to those with data present. From the procedure above we obtain $\frac{H^*}{H} \approx 2.96$, which we round to 3.0 in the text discussion.

Calculating the Trade Shares

The real per capita output growth rate is from the US NIPA tables, computed as the average annual real GDP growth rate from 1960-2010. Trade data was downloaded from the OECD-STAN database, and OECD GDP data comes from the Penn World Tables, Version 7.1. The non-OECD country to OECD imports to OECD output ratios were computed as averages over the years 1997-2001 and 2002-2006. The period was chosen to incorporate the average trade ratios from the period directly preceding the accession of China to the WTO in 2001, with the averaging conducted to smooth the effect on the trade ratio of the 2001 recession in the United States. The full 10-year period accords with the model calibration. All of the data and simple calculations performed in the calibration procedure are available on Nicholas Bloom's website: http://www.stanford.edu/nbloom.

Computing Patent Ratios

United States Patent and Trademark Office data on patents granted from 1977-2006, by application year and nationality of assignee, are downloaded from the NBER website for the Patent Data Project, as of early 2013. This website represents an update of the data which was originally collected and documented in Hall, Jaffe, Trajtenberg (2001). Patents granted to multiple assignees are counted only once, and the nationality of the patent is determined by the first assignee. OECD status is as of application year. Total foreign, non-OECD, and Chinese patent ratios are equal to the number of granted patents with a particular application year, normalized by the total number of granted patents in the same application year. This normalization incorporates the reduction in grant numbers as the application year approaches the end of the sample, the well known application lag/truncation problem with patent data of this form.

Trade policy substitution in the counterfactual away from China towards the rest of the non-OECD

Total observed low-wage import growth into the OECD as a share of GDP from 1997-2006 is equal to 3.1%. Growth in Chinese import shares was equal to 1.61%, implying that non-China/non-OECD countries saw their import shares into the OECD increase by 1.49%. The no China counterfactual in the main text assumed that the growth in Chinese import shares was completely removed from liberalization over this period. If, however, policy-makers partially substituted towards other non-OECD imports in lieu of Chinese imports, we would still see import share growth in the counterfactual. To analyze the quantitative magnitude of this substitution effect, we consider a case where exactly one half of Chinese import growth is realized in the no China counterfactual, via substitution towards other non-OECD countries. Starting with a low-wage import share of 3.9%, this "half substitution" case exhibits import share growth of 0.5*1.61+1.49 = 2.295%, so that the resulting target import to output ratio post-liberalization in the counterfactual is 3.9+2.295 = 6.195%. Figure B1 plots the resulting two trapped factors transition paths, analogous to Figure 9, in the total observed import liberalization and "Half China" cases. As can be seen immediately, the transition paths differ by less than the case in which all Chinese import growth is removed-, which works to reduce the marginal contribution of China to welfare to a total of 3.3% (North) and 3.2% (South). In this alternative counterfactual, the impact of China is equal to 20% (North) and 21% (South) of the overall welfare gains from trade observed in the data.

Other Robustness Checks

In this section we provide the main numbers underlying the robustness checks underlying Figure 10 in the main text. In particular, beginning from our baseline calibration, in Table $B1$we list the post-shock balanced growth path growth rate, as well as the maximum growth rate along the trapped-factors transition path, for a number of alternative parameter choices.

Table B1: Growth Rate Robustness Checks

Parameter	Peak Transition Path Growth (%)	Post-Shock Balanced Growth (%)
$\beta = 1/1.04$	2.71	2.37
$\beta = 1/1.01$	2.74	2.37
$\eta = 0.5$	2.59	2.37
$\sigma = 2.0$	3.04	2.32
$\sigma = 1.5$	2.89	2.34
$\rho = 0.6$	2.84	2.46
$\rho = 0.4$	2.61	2.29
$\alpha = 0.5$	2.74	2.32
$\alpha = 0.7$	2.73	2.38
Baseline	2.73	2.37

Note: The first column records the parameter varied from our baseline calibration. The second column represents the maximum annualized percentage variety growth rate over the trapped factors transition path in the alternative calibrations. The third column represents the post-shock balanced growth path annualized percentage growth rate associated with the alternative calibration. The baseline calibration features parameter choices of $\rho = 0.5$, $\alpha = 0.667$, $\beta = 1/1.02$, $\sigma = 1.0$, and

$\eta = 1.0$.

Also, note that in the text we mention an alternative calibration strategy for the pre-shock balanced growth path growth rate. If we compute the United States per capita real GDP growth rate over the period $1960 - 2001$rather than the baseline calibration window of $1960 - 2010$, we obtain a pre-shock balanced growth rate of 2.3%rather than the baseline 2.0%. However, in this case, the peak transition path growth rate is 3.09%, and the post-shock balanced growth rate is 2.70%. Given the higher initial condition, this is almost a direct translation upwards of the baseline transition path. Given the nonlinearity of the model, such a result is not automatic.

Note that a previous version of our calibration strategy, with results published in "A Trapped Factors Model of Innovation," (*American Economic Review: Papers and Proceedings,* 2013) yielded smaller dynamic impacts of trade liberalization. Our improved calibration strategy here differs from that earlier work in three respects. First, we consider a model period of ten years rather than one year to match a more plausible effective monopoly length. Second, we base the calibration on imports to value added ratios rather than imports to gross output ratios, since data availability for China is better for value added. Third, instead of calibrating the post-liberalization trade openness via a "limiting" highest ϕ' which still maintained product-cycle trade (i.e. $q(\phi') < 1$), the first two calibration changes allow us to now directly match observed pre- and post-liberalization trade ratios in 1997 and 2006, which results in larger growth impacts more aligned with observed trade liberalization.

Appendix C - Solution Technique and Equilibrium Conditions for the Calibration

Please find both replication data files for the calibration exercise, as well as code to duplicate all of the quantitative results in the paper, on Nicholas Bloom's website at http://www.stanford.edu/nbloom/. We solve each of the systems of nonlinear equations laid out below using particle swarm optimization as implemented in R. This is an extremely robust global nonlinear optimization technique, and all solutions are computed with a summed squared percentage error across all equations of less than 10^{-7}.

Balanced Growth Path

As documented in the proof of Proposition 2, the balanced growth path growth rate $g(\phi)$of the open economy given trade restriction $\phi$is fully characterized by the equilibrium innovation optimality condition

$$g(\phi)^{\gamma-1} = \Omega\beta^{\frac{1}{\alpha}}(1+g(\phi))^{-\frac{\sigma}{\alpha}}\left(H + \left(\frac{\phi H}{g(\phi)H^*}\right)^{\frac{1}{2-\alpha}}\Psi^{\frac{1}{\alpha}}H^*\right).$$

All other long-run quantities, in particular the interest rates and exchange rate, are direct functions of this balanced growth path growth rate through the Euler equations and balanced trade condition

$$(1+r(\phi)) = (1+r^*(\phi)) = \beta^{-1}(1+g(\phi))^{\sigma}$$

$$q(\phi) = \left(\frac{\phi H}{g(\phi)H^*}\right)^{\frac{\alpha}{2-\alpha}}\Psi.$$

Fully Mobile Transition Dynamics

To compute the transition dynamics of the fully mobile model in response to a trade shock in period 0, starting from the balanced growth path associated with trade restriction ϕ, we first pick a horizon T. We also normalize $A_0 = 1$. Then, we assume that the model has converged to the balanced growth path associated with $\phi'$by period T. This structure requires that we solve for $3(T-1)$prices, $\{q_t, r_t, r_t^*\}_{t=2}^{T}$. These $3(T-1)$prices are pinned down by $3(T-1)$equations: the balanced trade condition, the Northern Euler equation, and the Southern Euler equation, in periods $1, ..., T-1$. These equations are given by

$$q_t = \left(\frac{\phi H}{g_t H^*}\right)^{\frac{\alpha}{2-\alpha}} \Psi \left(\frac{1+r_t}{1+r_t^*}\right)^{\frac{1-\alpha}{2-\alpha}},$$

$$\left(\frac{C_{t+1}}{C_t}\right)^{\sigma} = \beta(1+r_{t+1}),$$

$$\left(\frac{C_{t+1}^*}{C_t^*}\right)^{\sigma} = \beta(1+r_{t+1}^*).$$

We note that all allocations in the transition path are a function of these three prices. Intermediate goods prices follow the monopoly markup or competitive pricing conditions

$$p_{Mt} = \frac{1+r_t}{1-\alpha}, p_{Rt} = (1+r_t), p_{It} = q_t(1+r_t^*)$$

$$p_{Mt}^* = q_t^{-1}\frac{1+r_t}{1-\alpha}, p_{Rt}^* = (1+r_t^*), p_{It}^* = (1+r_t^*).$$

The final goods firms demand schedules then yield

$$x_{jt} = (1-\alpha)^{\frac{1}{\alpha}} H p_{jt}^{-\frac{1}{\alpha}}$$
$$x_{jt}^* = (1-\alpha)^{\frac{1}{\alpha}} H^* (p_{jt}^*)^{-\frac{1}{\alpha}},$$

The first-order condition for innovation at Northern intermediate goods firms, together with symmetry across firms and the equilibrium price and quantity decisions laid out above, yields the innovation optimality conditions

$$g_{t+1}^{\gamma-1} = \Omega(1+r_{t+1})^{-\frac{1}{\alpha}} \left(H + q_{t+1}^{\frac{1}{\alpha}} H^*\right),$$

which uniquely pin down the variety growth rate g_{t+1}as a function of terms of trade and interest rates. Given our characterization of $g_t$as a function of prices, it only remains to pin down $C_t$and C_t^*as a function of prices. But this is easily accomplished by noting that

$$u_t + M_{t+1}(x_{Mt+1} + x_{Mt+1}^*) + R_{t+1}x_{Rt+1} + Z_t = Y_t$$

$$Y_t = H^{\alpha}\left[M_t x_{Mt}^{1-\alpha} + R_t x_{Rt}^{1-\alpha} + I_t x_{It}^{1-\alpha}\right]$$

$$Z_t = \sum_{f=1}^{N} Z_{ft} = \frac{g_{t+1}^{\gamma}}{\gamma} A_t$$

$$C_t^* + I_{t+1}(x_{It+1} + x_{It+1}^*) + R_{t+1} x_{Rt+1}^* = Y_t^*$$

$$Y_t^* = (H^*)^{\alpha} \left[M_t (x_{Mt}^*)^{1-\alpha} + R_t (x_{Rt}^*)^{1-\alpha} + I_t (x_{It}^*)^{1-\alpha} \right]$$

$$A_{t+1} = (1 + g_{t+1}) A_t$$

$$M_{t+1} = g_t A_t$$

$$R_{t+1} = (1 - \phi_{t+1}) A_t$$

$$I_{t+1} = \phi_{t+1} A_t.$$

Since all allocations in this economy are therefore a function of the $3(T-1)$prices, we can construct the errors in $3(T-1)$equations above given any input sequence of prices. The percentage squared errors of this system of equation are minimized using particle swarm optimization. After solving for the transition path price paths, we check to see if the cost advantage for Igoods production is maintained by the South, justifying our M, R, Igoods partitioning. This is equivalent to checking that, for each period

$$(1 + r_t^*) q_t \leq (1 + r_t).$$

In the baseline results shown in Section 5, we choose $T = 7$.

Trapped Factors Transition Dynamics

The equilibrium conditions which we must solve to compute the transition dynamics for the trapped factors model are identical to those in the fully mobile economy, for period $2, ..., T-1$. There are, however, differences in the equilibrium conditions in the period of the shock. In particular, there is heterogeneity in the response of the affected and unaffected industries to the shock, and instead of solving for simply the $3(T-1)$prices $\{q_t, r_t, r_t^*\}_{t=2}^{T}$as in the fully mobile case, we must solve for these prices and the four additional variables $\{g_2^1, g_2^2, \mu^1, \mu^2\}$. These variables are patenting rates and shadow values of inputs within Northern firms in the unaffected industry (1) and the affected industry (2). Therefore, we must pin down $3(T-1)+4$quantities, which we do with $3(T-1)+4$equations:

$$q_1 = \left[\frac{\phi' H}{H \left[\left(\frac{n}{2}\right) (\mu^1)^{\frac{\alpha-1}{\alpha}} g_1^1 + \left(\frac{n}{2}\right) (\mu^2)^{\frac{\alpha-1}{\alpha}} g_1^2 \right]} \right]^{\frac{\alpha}{2-\alpha}} \Psi \left(\frac{1 + r_1}{1 + r_1^*} \right)^{\frac{1-\alpha}{2-\alpha}}$$

$$q_t = \left(\frac{\phi' H}{g_t H^*}\right)^{\frac{\alpha}{2-\alpha}} \Psi \left(\frac{1+r_t}{1+r_t^*}\right)^{\frac{1-\alpha}{2-\alpha}}, 2, ..., T-1$$

$$\left(\frac{C_{t+1}}{C_t}\right)^{\sigma} = \beta(1+r_{t+1}), t = 1, ..., T-1$$

$$\left(\frac{C_{t+1}^*}{C_t^*}\right)^{\sigma} = \beta(1+r_{t+1}^*), t = 1, ..., T-1$$

$$(Ng_1^1)^{\gamma-1} = \Omega(1+r_1)^{-\frac{1}{\alpha}}(\mu^1)^{-\frac{1}{\alpha}}(H + q_1^{\frac{1}{\alpha}} H^*)$$

$$(Ng_1^2)^{\gamma-1} = \Omega(1+r_1)^{-\frac{1}{\alpha}}(\mu^2)^{-\frac{1}{\alpha}}(H + q_1^{\frac{1}{\alpha}} H^*)$$

$$\frac{1}{N}(1-\phi)(1-\alpha)^{\frac{1}{\alpha}}(1+r(\phi))^{-\frac{1}{\alpha}} H + \frac{1}{N}\frac{g(\phi)^{\gamma}}{\gamma} + \frac{g(\phi)}{N}(1-\alpha)^{\frac{2}{\alpha}}(1+r(\phi))^{-\frac{1}{\alpha}}(H + q(\phi)^{\frac{1}{\alpha}} H^*)$$

$$= \frac{1}{N}(1-\phi)(1-\alpha)^{\frac{1}{\alpha}}(\mu^1)^{-\frac{1}{\alpha}}(1+r_1)^{-\frac{1}{\alpha}} H + \frac{N^{\gamma-1}}{\gamma}\left(g_1^1\right)^{\gamma}$$

$$+ g_1^1(1-\alpha)^{\frac{2}{\alpha}}(1+r_1)^{-\frac{1}{\alpha}}(\mu^1)^{-\frac{1}{\alpha}}(H + q_1^{\frac{1}{\alpha}} H^*)$$

$$\frac{1}{N}(1-\phi)(1-\alpha)^{\frac{1}{\alpha}}(1+r(\phi))^{-\frac{1}{\alpha}} H + \frac{1}{N}\frac{g(\phi)^{\gamma}}{\gamma} + \frac{g(\phi)}{N}(1-\alpha)^{\frac{2}{\alpha}}(1+r(\phi))^{-\frac{1}{\alpha}}(H + q(\phi)^{\frac{1}{\alpha}} H^*)$$

$$= \frac{1}{N}\chi_2(1-\phi)(1-\alpha)^{\frac{1}{\alpha}}(\mu^2)^{-\frac{1}{\alpha}}(1+r_1)^{-\frac{1}{\alpha}} H + \frac{N^{\gamma-1}}{\gamma}\left(g_1^2\right)^{\gamma}$$

$$+ g_1^2(1-\alpha)^{\frac{2}{\alpha}}(1+r_1)^{-\frac{1}{\alpha}}(\mu^2)^{-\frac{1}{\alpha}}(H + q_1^{\frac{1}{\alpha}} H^*).$$

The first $3(T-1)$equations are simply the balanced trade and Euler equations for the Northern and Southern households in periods $1, ..., T-1$. The balanced trade condition must be modified in period 1to reflect the fact that flows of Mgoods from North to South come from both industry 1and industry 2, with different prices and quantities for each. The final four equations represent the innovation optimality conditions for firms in industry 1and industry 2, as well as the trapped factors constraints for firms in each industry. The innovation optimality conditions are simply the first-order conditions of firms with respect to the mass of new varieties to be innovated in period 0for use in period 1. Note that we are defining $\mu^1 = 1-\lambda^1$and $\mu^2 = 1-\lambda^2$, where $m_1\lambda^1$and $m_1\lambda^2$are the multipliers on the trapped factors input constraints in the optimization problem for Northern intermediate goods firms in period 1. A fall in μbelow 1represents a fall in the shadow value of inputs for an intermediate goods firm. Also, if $M_{f2}$is the number of new patents innovated by a firm in industry $f$in period 0for use in period 1, we are following the conventions $g_1^f = \frac{M_{f1}}{A_0}$, and imposing the consistency condition

$$g_1 = \left(\frac{N}{2}\right)(g_1^1 + g_1^2).$$

The trapped factors constraints are simply the input demands for Rgoods production and Mgoods innovation and production expenditure pre-shock (left hand side) and post-shock (right hand side). The input constraints differ across industries because the Rgoods available in the post-shock period in industry 2for production are reduced by the factor χ_2, where $\chi_2$satisfies

$$\frac{1+\chi_2}{2} = \frac{1-\phi'}{1-\phi},$$

which is the consistency condition discussed in the equilibrium definition. Also, the right-hand side on the trapped factors constraints take into account the following optimal pricing rules in the period of the shock:

$$p_{M1}^1 = \mu^1 \frac{1+r_1}{1-\alpha}, p_{R1}^1 = (1+r_1),$$

$$p_{M1}^2 = \mu^2 \frac{1+r_1}{1-\alpha}, p_{R1}^2 = (1+r_1).$$

The demand conditions are identical to those laid out in the fully mobile section. Intermediate goods firm innovation costs on the right hand side of the trapped factors constraint are given by

$$Z_1^1 = \frac{N^{\gamma-1}}{\gamma}\left(g_1^1\right)^{\gamma}$$

$$Z_1^2 = \frac{N^{\gamma-1}}{\gamma}\left(g_1^2\right)^{\gamma},$$

which is a direct application of the definition of the innovation cost function. All of the other quantities needed for construction of the Euler equation errors and balanced trade conditions are identical to those in the fully mobile economy, with the exception of the resource constraints in the North and South in periods 0and 1which must be modified to read

$$Y_0 = C_0 + \left(\frac{N}{2}\right) g_1^1 A_0 (x_{M1}^1 + x_{M1}^{*1}) + \left(\frac{N}{2}\right) g_1^2 A_0 (x_{M1}^2 + x_{M1}^{*2}) + \left(\frac{N}{2}\right) \frac{1-\phi}{2} A_0 x_{R1}^1 + \left(\frac{N}{2}\right) \frac{(1-\phi)\chi_2}{2} A_0 x_{R1}^2 +$$

$$Z_1^1 + Z_1^2$$

$$Y_0^* = C_0^* + (1-\phi') A_0 x_{R1}^* + \phi' A_0 (x_{I1}^* + x_{I1})$$

$$Y_1 = H^{\alpha}\left[\left(\frac{N}{2}\right) g_1^1 A_0 (x_{M1}^1)^{1-\alpha} + \left(\frac{N}{2}\right) g_1^2 A_0 (x_{M1}^2)^{1-\alpha} + \left(\frac{N}{2}\right) \frac{1-\phi}{2} A_0 (x_{R1}^1)^{1-\alpha} + \right.$$

$$\left. \left(\frac{N}{2}\right) \frac{(1-\phi)\chi_2}{2} A_0 (x_{R1}^2)^{1-\alpha} + \phi' A_0 x_{I1}^{1-\alpha}\right]$$

$$Y_1^*= (H^*)^\alpha \left[\left(\frac{N}{2}\right) g_1^1 A_0 (x_{M1}^{*1})^{1-\alpha} + \left(\frac{N}{2}\right) g_1^2 A_0 (x_{M1}^{*2})^{1-\alpha} + (1-\phi')A_0(x_{R1}^*)^{1-\alpha} + \phi' A_0 (x_{I1}^*)^{1-\alpha}\right].$$

After computing the transition path in the above manner, we must verify that $\mu^1, \mu^2 < 1$, justifying our imposition of the trapped factors inequality constraint as an equality constraint. We must also check the Southern cost dominance condition for Igoods in each period, i.e.

$$\min(\mu^1, \mu^2)(1+r_1) \geq q_1(1+r_1^*),$$

$$(1+r_t) \geq q_t(1+r_t^*), t = 2, .., T-1,$$

$$q_0, q_T \leq 1.$$

Welfare Calculations

We illustrate our method of computing the consumption equivalent variation by explicitly laying out the formulas used to compute the welfare gains to trade from the fully mobile trade shock. All other welfare calculations are similar.

$$W^{NS}= \sum_{t=0}^{\infty} \beta^t \frac{\left(C_t^{NS}\right)^{1-\sigma}}{1-\sigma}, W^{*NS}= \sum_{t=0}^{\infty} \beta^t \frac{\left(C_t^{*NS}\right)^{1-\sigma}}{1-\sigma}$$

$$W^{FM}= \sum_{t=0}^{\infty} \beta^t \frac{\left(C_t^{FM}\right)^{1-\sigma}}{1-\sigma}, W^{*FM}= \sum_{t=0}^{\infty} \beta^t \frac{\left(C_t^{*FM}\right)^{1-\sigma}}{1-\sigma},$$

where the consumption allocations on the fully mobile "FM" computed transition path from $0, ..., T-1$are directly computed and consumption is assumed to grow at the rate $g(\phi')$for all economies from period Tonwards. The no shock "NS" case is consumption assuming that allocations are those of the pre-shock balanced growth path with constant growth at rate $g(\phi)$.Then, we solve for $x$and x^*,

$$\sum_{t=0}^{\infty} \beta^t \frac{\left(C_t^{NS}(1+x)\right)^{1-\sigma}}{1-\sigma} = \sum_{t=0}^{\infty} \beta^t \frac{\left(C_t^{FM}\right)^{1-\sigma}}{1-\sigma},$$

$$\sum_{t=0}^{\infty} \beta^t \frac{\left(C_t^{*NS}(1+x^*)\right)^{1-\sigma}}{1-\sigma} = \sum_{t=0}^{\infty} \beta^t \frac{\left(C_t^{*FM}\right)^{1-\sigma}}{1-\sigma}.$$

The welfare numbers reported in the text are $100x$and $100x^*$. Price vs Variety Output Counterfactuals This section provides explicit formulas for the price vs variety decompositions discussed in the main text. Along the fully mobile transition path in shock period 1, we have interest rates and terms of trade which determine prices and therefore intensive margins for each variety of good, say x_{I1}, x_{R1}, x_{M1}. Holding these intensive margins constant, we have that baseline Northern output in shock period 1is given by

$$Y_1 = H^\alpha (M_1 x_{M1}^{1-\alpha} + R_1 x_{R1}^{1-\alpha} + I_1 x_{I1}^{1-\alpha})$$

$$M_1 = A_0 g_1, \; R_1 = A_0(1-\phi'), \; I_1 = \phi' A_0,$$

and in the no price case with $R$to Iconversion shut down we have

$$Y_1^{noprice}= H^{\alpha}(M_1 x_{M1}^{1-\alpha}+A_0(1-\phi)x_{R1}^{1-\alpha}+A_0\phi x_{I1}^{1-\alpha}),$$

with the no variety case given by

$$Y_1^{novariety}= H^{\alpha}(A_0 g_0 x_{M1}^{1-\alpha}+A_0(1-\phi)x_{R1}^{1-\alpha}+A_0\phi x_{I1}^{1-\alpha}).$$

Trapped factors versions reported in the text require generalization to the case of two separate industries' Mgoods varieties but are straightforward versions of the above. Along a balanced growth path with constant trade restriction ϕ, we have that the baseline Northern output level in a given period, with the (arbitrary) level of varieties in that particular period given by $A_{ss}$and considering balanced growth path intensive margins, is equal to

$$Y_{ss} = H^{\alpha}(M_{ss}x_{Mss}^{1-\alpha} + R_{ss}x_{Rss}^{1-\alpha} + I_{ss}x_{Iss}^{1-\alpha})$$

$$M_{ss} = A_{ss}g_{ss},\ R_{ss} = A_{ss}(1-\phi),\ I_1 = \phi A_{ss},$$

and the output level in the no price with no $R$to Iconversion in that period is given by

$$Y_{ss}^{noprice} = H^{\alpha}(M_{ss}x_{Mss}^{1-\alpha} + (A_{ss} - I_{ss-1})x_{Rss}^{1-\alpha} + I_{ss-1}x_{Iss}^{1-\alpha})$$

$$I_{ss-1} = I_{ss}/(1+g_{ss}),$$

with the no variety case given by

$$Y_{ss}^{novariety} = H^{\alpha}((A_{ss} - I_{ss-1})x_{Rss}^{1-\alpha} + I_{ss-1}x_{Iss}^{1-\alpha})$$

$$= Y_{ss}^{noprice} - H^{\alpha}M_{ss}x_{Mss}^{1-\alpha}.$$

Appendix D - Semi-endogenous Growth Model

In this Appendix we consider the semi-endogenous growth model approach to show that it delivers quantitatively similar results to our fully endogenous growth model. As documented in Jones (1995a,b) the implication of a model like that considered in the main text, with "strong scale effects" implying that the long-term growth rate is dependent upon the level of human capital, is rejected by the time series evidence which documents the concurrence of rising populations and researcher numbers with constant growth rates. Jones proposes a small modification to the production function for new varieties, or alternatively, to the cost function for innovation, which implies smaller returns from the existing stock of varieties in the production of new patents. This change to the model converts the structure into a "semi-endogenous" growth model with "weak scale effects," since the long-term growth rate is now proportional to the growth rate of human capital rather than the level of human capital. Analogously, in our context with product-cycle trade, such a modification of the model leads to long-term growth rates proportional to human capital growth rates and, crucially, independent of the trade liberalization policy ϕ. As we will see, however, a reasonable calibration of a semi-endogenous growth model consistent with the data on both per-capita growth rates and population growth displays extremely long transition dynamics and considerable temporary effects on variety growth rates from trade liberalization. Therefore, the temporary growth effects of liberalization (and the permanent level effects), imply similar results for welfare regardless of whether one considers a strong or weak scale effects model. Given that the model with strong scale effects delivers closed-form expressions for the balanced growth path growth rates dependent upon the trade policy parameter ϕ, and given that the transition dynamics for the strong scale effects model are of a more reasonable length, we prefer to work with the strong scale effects model as our baseline version.

Model

We now lay out the model structure and equilibrium concept in the semi-endogenous growth framework, for the fully mobile environment only. Population and Human Capital We assume that in the North and in the South there is a continuum of identical households of measure 1, each with an expanding set of members $[0, L_t]$and $[0, L_t^*]$, respectively. We further assume that there is an constant level of human capital per member of the population, i.e. $H_t = hL_t$and $H_t^* = hL_t^*$, respectively. This assumption implies that preferences of the CRRA form defined over per-capita consumption or over consumption expressed relative to human capital differ only by a constant, and for convenience we express preferences as per unit of human capital. Northern Households Given a sequence of wages w_t, firm stock prices q_{ft}, firm dividends D_{ft}, and interest rates r_t, a Northern household supplies labor inelastically and chooses consumption C_t, portfolio positions S_{ft}, and bond purchases $B_{t+1}$to solve the problem

$$\max_{C_t,B_{t+1},S_{ft}} \sum_{t=0}^{\infty} \beta^t \frac{\left(\frac{C_t}{H_t}\right)^{1-\sigma}}{1-\sigma}$$

$$C_t + B_{t+1} + \sum_{f=1}^{N} q_{ft}(S_{ft} - S_{ft-1}) \leq w_t H_t + (1+r_t)B_t + \sum_{f=1}^{N} S_{ft} D_{ft}$$

Southern Households Given a sequence of wages w_t^*, firm stock prices q_{ft}^*, firm dividends D_{ft}^*, and interest rates r_t^*, a Southern household supplies labor inelastically and chooses consumption C_t^*, portfolio positions S_{ft}^*, and bond purchases $B_{t+1}^*$to solve the problem

$$\max_{C_t^*,B_{t+1}^*,S_{ft}^*} \sum_{t=0}^{\infty} \beta^t \frac{\left(\frac{C_t^*}{H_t^*}\right)^{1-\sigma}}{1-\sigma}$$

$$C_t^* + B_{t+1}^* + \sum_{f=1}^{N} q_{ft}^*(S_{ft}^* - S_{ft-1}^*) \leq w_t^* H_t^* + (1+r_t^*)B_t^* + \sum_{f=1}^{N} S_{ft}^* D_{ft}^*$$

Northern Final Goods Firms Taking as given a sequence of wages $w_t$and intermediate goods prices $p_{jt}$for each variety $j \in [0, A_t]$as given, perfectly competitive Northern final goods firms choose input demands $H_t$and $x_{jt}$to solve the static problem

$$\max_{H_t,x_{jt}} Y_t - \int_0^{A_t} p_{jt} x_{jt} dj - w_t H_t$$

$$\max_{H_t,x_{jt}} H_t^{\alpha} \int_0^{A_t} x_{jt}^{1-\alpha} dj - \int_0^{A_t} p_{jt} x_{jt} dj - w_t H_t$$

Southern Final Goods Firm Taking as given a sequence of wages $w_t^*$and intermediate goods prices $p_{jt}^*$for each variety $j \in [0, A_t]$as given, perfectly competitive Southern final goods firms choose input demands $H_t^*$and $x_{jt}^*$to solve the static problem

$$\max_{H_t^*,x_{jt}^*} Y_t^* - \int_0^{A_t} p_{jt}^* x_{jt}^* dj - w_t^* H_t^*$$

$$\max_{H_t^*,x_{jt}^*} (H_t^*)^{\alpha} \int_0^{A_t} (x_{jt}^*)^{1-\alpha} dj - \int_0^{A_t} p_{jt}^* x_{jt}^* dj - w_t^* H_t^*$$

Northern Intermediate Goods Firms Taking as given a sequence of interest rates r_t, along with aggregate variety stocks A_t, as well as Northern and Southern final goods firms' intermediate demand schedules, each of NNorthern intermediate goods firm $f$makes monopoly production $x_{Mjt+1}$and x_{Mjt+1}^*, perfectly competitive production x_{Rjt+1}, and innovation decisions $M_{ft+1}$to solve the following problem

$$\max_{x_{Rjt+1},x_{Mjt+1},M_{ft+1}} \sum_{t=0}^{\infty} m_t D_{ft},$$

$$D_{ft} + Z_{ft} + \int_{A_{ft+1}} (x_{jt+1} + x_{jt+1}^*) dj \leq \int_{A_{ft}} p_{jt}(x_{jt} + x_{jt}^*) dj,$$

where $\frac{m_{t+1}}{m_t} = \frac{1}{1+r_{t+1}}$or $m_t = \Pi_{\tau=1}^{t} \frac{1}{1+r_\tau}$. This is equivalent to stock price or value maximization as can be seen from iteration on the Northern Household's first order condition for $S_{ft}$and insertion of the Northern household first order condition for B_{t+1}. At all times, the innovation cost function is given by

$$Z_{ft} = \nu M_{ft+1}^{\gamma} A_t^{1-\frac{\delta}{\rho}},$$

where $\gamma = \frac{1}{\rho}$and $\delta \in (0,1)$, and $\nu = \frac{N^{\gamma-1}}{\gamma}$is again a scaling constant discussed in more detail below. This innovation cost function is identical to the strong scale effects innovation cost function, with the exception that $\delta < 1$here and $\delta = 1$in that case. Southern Intermediate Goods Firms Taking as given a sequence of interest rates r_t^*, as well as Northern and Southern final goods firms' intermediate demand schedules, each Southern intermediate goods firm makes perfectly competitive production x_{Ijt}, x_{Ijt}^*, and x_{Rjt}^*decisions to solve the following problem

$$\max_{x_{Ijt}, x_{Ijt}^*, x_{Rjt}^*} \sum_{t=0}^{\infty} m_t^* D_{ft}^*,$$

$$D_{ft}^* + \int_{A_{ft+1}} (x_{jt+1} + x_{jt+1}^*) dj \leq \int_{A_{ft}} p_{jt} (x_{jt} + x_{jt}^*) dj$$

where $\frac{m_{t+1}^*}{m_t^*} = \frac{1}{1+r_{t+1}^*}$or $m_t^* = \Pi_{\tau=1}^{t} \frac{1}{1+r_\tau^*}$. This is equivalent to stock price or value maximization as can be seen from iteration on the Southern Household's first order condition for $S_{ft}$and insertion of the Southern Household's first order condition for B_{t+1}^*. Terms of Trade Notation/No Arbitrage Condition

$$p_{jt} = q_t p_{jt}^*$$

Trade Restrictions and Monopoly Structure There is one-period monopoly protection for any newly innovated Mgoods, trade restriction for an exogenously set proportion $1 - \phi_t$of off-patent goods labeled Rgoods, and imports from South to North of the exogenously set proportion $\phi_t$of off-patent goods labeled Igoods.

Equilibrium Definition

- Some sequence of $\phi_t$is exogenously set by the Northern government
- Northern households optimize consumption, savings, and equity purchase decisions
- Southern households optimize consumption, savings, and equity purchase decisions
- Perfectly competitive Northern final goods sector optimizes human capital and intermediate goods demand
- Perfectly competitive Southern final goods sector optimizes human capital and intermediate goods demand
- Northern intermediate goods firms optimizes Mgoods innovation, Mgoods monopoly production, and fast-copier-constrained de facto perfect competition Rgoods production decisions
- Southern intermediate goods firms or fast copier optimize perfectly competitive $R$and Igoods production decisions
- Trade is balanced: $I_t p_{It} x_{It} = M_t p_{Mt} x_{Mt}^*$
- Bond markets clear: $B_t = B_t^* = 0$
- Equity markets clear: $S_{ft} + S_{ft}^* = 1$
- Human capital market clear $H_t^D = H_t$, $(H^*)_t^D = 0$

- Final goods market clears/resource constraint is satisfied in the North

$$Y_t = H_t^{\alpha} \int_0^{A_t} x_{jt}^{1-\alpha} dj = C_t + \int_{A_{t+1}} (x_{jt+1} + x_{jt+1}^*) dj + \sum_{f=1}^{N} Z_{ft}$$

- Final goods market clears/resource constraint is satisfied in the South

$$Y_t = H_t^{\alpha} \int_0^{A_t} x_{jt}^{1-\alpha} dj = C_t^* + \int_{A_{t+1}} (x_{jt+1} + x_{jt+1}^*) dj$$

- Consistency conditions hold

$$\sum_{f=1}^{N} M_{ft+1} = M_{t+1} = A_{t+1} - A_t$$

$$\phi A_t = I_t, (1-\phi) A_t = R_t$$

$$\frac{H_t^*}{H_t} = \frac{H_0^*}{H_0} = \frac{\bar{H}}{H^*}$$

- Southern cost dominance for Igoods

$$q_t (1 + r_t^*) < (1 + r_t)$$

Equilibrium Conditions for Reference

For later reference in the proof of Proposition 3, we now list the equilibrium conditions in this environment. Northern Households' (HH) First Order Conditions (FOC)

$$\beta^t H_t^{\sigma-1} C_t^{-\sigma} = \lambda_t$$

$$\lambda_t = (1 + r_{t+1}) \lambda_{t+1}$$

$$\lambda_t (D_{ft} - q_{ft}) + \lambda_{t+1} q_{ft+1} = 0$$

$$\rightarrow (1 + r_{t+1}) = \frac{1}{\beta} \frac{H_{t+1}}{H_t} \left(\frac{C_{t+1}}{H_{t+1}} \frac{H_t}{C_t} \right)^{\sigma} = \frac{1}{\beta} (1 + g_H) \left(\frac{c_{t+1}}{c_t} \right)^{\sigma}, \quad c_t \equiv \frac{C_t}{H_t}$$

$$\rightarrow q_{ft} = \sum_{t=0}^{\infty} m_t D_{ft}, \quad m_t \equiv \frac{\lambda_t}{\lambda_0} = \prod_{\tau=1}^{t} \frac{1}{1 + r_\tau}$$

Southern Households' FOC's

$$\rightarrow (1 + r_{t+1}^*) = \frac{1}{\beta} \frac{H_{t+1}^*}{H_t^*} \left(\frac{C_{t+1}^*}{H_{t+1}^*} \frac{H_t^*}{C_t^*} \right)^{\sigma} = \frac{1}{\beta} (1 + g_H) \left(\frac{c_{t+1}^*}{c_t^*} \right)^{\sigma}, \quad c_t^* \equiv \frac{C_t^*}{H_t^*}$$

$$\rightarrow q_{ft}^* = \sum_{t=0}^{\infty} m_t^* D_{ft}^*, \quad m_t^* \equiv \frac{\lambda_t^*}{\lambda_0^*} = \prod_{\tau=1}^{t} \frac{1}{1 + r_\tau^*}$$

Northern Final Goods Firm FOC's

$$(1-\alpha)H_t^\alpha x_{jt}^{-\alpha} - p_{jt} = 0 \rightarrow x_{jt} = (1-\alpha)^{\frac{1}{\alpha}} p_{jt}^{-\frac{1}{\alpha}} H_t$$
$$\alpha H_t^{\alpha-1} x_{jt}^{1-\alpha} - w_t = 0$$

Southern Final Goods Firm FOC's

$$(1-\alpha)(H_t^*)^\alpha (x_{jt}^*)^{-\alpha} - p_{jt}^* = 0 \rightarrow x_{jt}^* = (1-\alpha)^{\frac{1}{\alpha}} (p_{jt}^*)^{-\frac{1}{\alpha}} H_t^*$$
$$\alpha (H_t^*)^{\alpha-1} (x_{jt}^*)^{1-\alpha} - w_t^* = 0$$

Northern Intermediate Goods Firm FOC's

$$\max_{x_{Mt+1}, M_{ft+1}, x_{Rt+1}} \sum_{t=0}^{\infty} m_t D_{ft}$$

$$D_{ft} = \int_{A_{ft}} p_{jt}(x_{jt} + x_{jt}^*)dj - Z_{ft} - \int_{A_{ft+1}} (x_{jt+1} + x_{jt+1}^*)dj$$

$$-m_t \left[\frac{\partial}{\partial M_{ft+1}} Z_{ft} + x_{Mt+1} + x_{Mt+1}^* \right] + m_{t+1} p_{Mt+1}(x_{Mt+1} + x_{Mt+1}^*) = 0$$

$$p_{Mt+1} = \arg\max_p -m_t(1-\alpha)^{\frac{1}{\alpha}} p^{-\frac{1}{\alpha}} (H_{t+1} + q_{t+1}^{\frac{1}{\alpha}} H_{t+1}^*) + m_{t+1}(1-\alpha)^{\frac{1}{\alpha}} p^{1-\frac{1}{\alpha}} (H_{t+1} + q_{t+1}^{\frac{1}{\alpha}} H_{t+1}^*)$$

$$p_{Mt+1} = \frac{m_t}{m_{t+1}} \frac{1}{1-\alpha}$$

$$-m_t + m_{t+1} p_{Rt+1} = 0$$

$$\rightarrow p_{Mt+1} = \frac{1+r_{t+1}}{1-\alpha}, \quad x_{Mt+1} = (1-\alpha)^{\frac{2}{\alpha}} (1+r_{t+1})^{-\frac{1}{\alpha}} H_{t+1}, \quad x_{Mt+1}^* = (1-\alpha)^{\frac{2}{\alpha}} (1+r_{t+1})^{-\frac{1}{\alpha}} q_{t+1}^{\frac{1}{\alpha}} H_{t+1}^*$$

$$\rightarrow p_{Rt+1} = 1 + r_{t+1}, \quad x_{Rt+1} = (1-\alpha)^{\frac{1}{\alpha}} (1+r_{t+1})^{-\frac{1}{\alpha}} H_{t+1}$$

$$\rightarrow \frac{\partial}{\partial M_{ft+1}} Z_{ft+1} = g_{At+1}^{\gamma-1} A_t^{\frac{1-\delta}{\rho}}, \text{ imposes symmetry } g_{Aft+1} = (1/N) g_{At+1}$$

$$\rightarrow Z_t = \sum_{f=1}^{N} Z_{ft} = \frac{g_{At+1}^{\gamma} A_t^{1+\frac{1-\delta}{\rho}}}{\gamma}, \text{ imposes symmetry } g_{Aft+1} = (1/N) g_{At+1}$$

$$\rightarrow g_{At+1}^{\gamma-1} A_t^{\frac{1-\delta}{\rho}} = \Omega (1+r_{t+1})^{-\frac{1}{\alpha}} \left(H_{t+1} + q_{t+1}^{\frac{1}{\alpha}} H_{t+1}^* \right)$$

Southern Intermediate Goods Firm FOC's

$$\max \sum_{t=0}^{\infty} m_t^* D_{ft}^*,$$

$$D_{ft}^* = \int_{A_{ft}} p_{jt}(x_{jt} + x_{jt}^*)dj - \int_{A_{ft+1}} (x_{jt+1} + x_{jt+1}^*)dj$$

$$-m_t^* + m_{t+1}^* p_{Rt+1}^* = 0$$

$$-m_t^* + m_{t+1}^* p_{It+1}^* = 0$$

$$\rightarrow p_{Rt+1}^* = (1 + r_{t+1}^*), \quad x_{Rt+1}^* = (1-\alpha)^{\frac{1}{\alpha}} (1+r_{t+1}^*)^{-\frac{1}{\alpha}} H_{t+1}^*$$

$$\rightarrow p_{It+1}^* = (1 + r_{t+1}^*), p_{It+1} = q_{t+1} p_{It+1}^*, \quad x_{It+1}^* = (1-\alpha)^{\frac{1}{\alpha}} (1+r_{t+1}^*)^{-\frac{1}{\alpha}} H_{t+1}^*,$$

$$x_{It+1} = (1-\alpha)^{\frac{1}{\alpha}}(1+r^*_{t+1})^{-\frac{1}{\alpha}} q_{t+1}^{-\frac{1}{\alpha}} H_{t+1}$$

Balanced Trade Condition

$$I_t p_{It} x_{It} = M_t p_{Mt} x^*_{Mt}$$

$$\phi_t A_{t-1} q_t (1+r^*_t)(1-\alpha)^{\frac{1}{\alpha}}(1+r^*_t)^{-\frac{1}{\alpha}} q_t^{-\frac{1}{\alpha}} H_t = g_{At} A_{t-1} \frac{1+r_t}{1-\alpha}(1-\alpha)^{\frac{2}{\alpha}}(1+r_t)^{-\frac{1}{\alpha}} q_t^{\frac{1}{\alpha}} H^*_t$$

$$q_t = \left(\frac{\phi_t H_t}{g_{At} H^*_t}\right)^{\frac{\alpha}{2-\alpha}} \left(\frac{1+r_t}{1+r^*_t}\right)^{\frac{1-\alpha}{2-\alpha}} \Psi, \quad \Psi = (1-\alpha)^{\frac{\alpha-1}{2-\alpha}}$$

Northern Resource Constraint

$$\begin{aligned} Y_t &= H_t^{\alpha}\left[M_t x_{Mt}^{1-\alpha} + R_t x_{Rt}^{1-\alpha} + I_t x_{It}^{1-\alpha}\right] \\ &= C_t + M_{t+1}\left(x_{Mt+1} + x^*_{Mt+1}\right) + R_{t+1} x_{Rt+1} + Z_t \end{aligned}$$

Southern Resource Constraint

$$\begin{aligned} Y^*_t &= (H^*_t)^{\alpha}\left[M_t (x^*_{Mt})^{1-\alpha} + R_t (x^*_{Rt})^{1-\alpha} + I_t (x^*_{It})^{1-\alpha}\right] \\ &= C^*_t + R_{t+1} x^*_{Rt+1} + I_{t+1}(x_{It+1} + x^*_{It+1}) \end{aligned}$$

Consistency Conditions and Terms of Trade Notation Convention

$$M_{t+1} = A_{t+1} - A_t, \quad R_{t+1} = (1-\phi_{t+1})A_t, \quad I_{t+1} = \phi_{t+1} A_t$$

$$M_{t+1} = \sum_{f=1}^{N} M_{ft+1}, \quad p_{jt} = q_t p^*_{jt}$$

Southern Cost Dominance for I Goods

$$q_t(1+r^*_t) \leq (1+r_t)$$

Proposition 3 *A balanced growth path with constant* ϕ *exists and is unique. On this balanced growth path the growth rate* g_A *of varieties satisfies*

$$(1+g_A)^{\frac{1-\delta}{\rho}} = (1+g_H),$$

interest rates satisfy

$$1+r = 1+r^* = \frac{1}{\beta}(1+g_H)(1+g_A)^{\sigma},$$

and the terms of trade satisfies

$$q = \left(\frac{\phi}{g_A}\frac{\bar{H}}{H^*}\right)^{\frac{\alpha}{2-\alpha}} \Psi, \Psi = (1-\alpha)^{\frac{\alpha-1}{2-\alpha}}.$$

On this unique balanced growth path, output and consumption grow as the factor $(1+g_H)(1+g_A)$ *and per capita consumption has growth rate equal to the number of varieties* g_A*.*

Proof of BGP Formulas Assume constant growth rates of quantities and a constant ϕ. Then the HH Euler equations yield

$$1+r = \frac{1}{\beta}(1+g_H)(1+g_c)^{\sigma}$$

$$1+r^* = \frac{1}{\beta}(1+g_H)(1+g_{c^*})^{\sigma},$$

which implies that interest rates are constant. But the BT condition is then

$$q = \left(\frac{\phi}{g_A}\frac{\bar{H}}{H^*}\right)^{\frac{\alpha}{2-\alpha}} \left(\frac{1+r}{1+r^*}\right)^{\frac{1-\alpha}{2-\alpha}} \Psi,$$

which implies that the terms of trade are constant. But the innovation FOC is

$$g_A^{\gamma-1} A_t^{\frac{1-\delta}{\rho}} = \Omega(1+r)^{-\frac{1}{\alpha}} \left(H_{t+1} + q^{\frac{1}{\alpha}} H_{t+1}^* \right).$$

$$LHS \propto \left((1+g_A)^{\left(\frac{1-\delta}{\rho}\right)} \right)^t, \quad RHS \propto (1+g_H)^t$$

$$\rightarrow (1+g_A)^{\frac{1-\delta}{\rho}} = (1+g_H) \text{ on any BGP}$$

Now note that prices of all goods are constant because they are functions of interest and terms of trade, so the intensive demand margins are also constant multiples of human capital. In particular,

$$x_{Mt} = (1-\alpha)^{\frac{2}{\alpha}}(1+r)^{-\frac{1}{\alpha}} H_t, \quad x_{Mt}^* = (1-\alpha)^{\frac{2}{\alpha}}(1+r)^{-\frac{1}{\alpha}} q^{\frac{1}{\alpha}} H_t^*$$

$$x_{Rt} = (1-\alpha)^{\frac{1}{\alpha}}(1+r)^{-\frac{1}{\alpha}} H_t, \quad x_{Rt}^* = (1-\alpha)^{\frac{1}{\alpha}}(1+r^*)^{-\frac{1}{\alpha}} H_t^*$$

$$x_{It} = (1-\alpha)^{\frac{1}{\alpha}}(1+r^*)^{-\frac{1}{\alpha}} q^{-\frac{1}{\alpha}} H_t$$

$$x_{It}^* = (1-\alpha)^{\frac{1}{\alpha}}(1+r^*)^{-\frac{1}{\alpha}} H_t^*$$

Note also that by the consistency conditions $M_t = g_A A_{t-1}, \quad R_t = (1-\phi)A_{t-1}, \quad I_t = \phi A_{t-1}$are all constant multiples of A_t(given the fact that $A_{t-1} = \frac{1}{1+g_A} A_t$).

$$Y_t = H_t^\alpha \left[M_t x_{Mt}^{1-\alpha} + R_t x_{Rt}^{1-\alpha} + I_t x_{It}^{1-\alpha} \right]$$

$$Y_t \propto H_t A_t \propto ((1+g_H)(1+g_A))^t$$

Now from the uses identity we also have

$$Y_t = C_t + M_{t+1}\left(x_{Mt+1} + x_{Mt+1}^* \right) + R_{t+1} x_{Rt+1} + Z_t$$

But from above

$$M_{t+1}\left(x_{Mt+1} + x_{Mt+1}^* \right) \propto H_t A_t$$

$$R_{t+1} x_{Rt+1} \propto H_t A_t$$

$$Z_t = \frac{g_A^\gamma}{\gamma} A_t^{1+\frac{1-\delta}{\rho}} \propto A_t^{1+\frac{1-\delta}{\rho}} \propto \left((1+g_A)^{1+\frac{1-\delta}{\rho}} \right)^t$$

But since $1 + g_H = (1+g_A)^{\frac{1-\delta}{\rho}}$ on any BGP by the innovation FOC, we have

$$Z_t \propto ((1+g_H)(1+g_A))^t$$

Therefore, we have

$$C_t \propto ((1+g_H)(1+g_A))^t, \quad c_t \propto (1+g_A)^t$$

implying that $g_c = g_A$, so that

$$1 + r = \frac{1}{\beta}(1+g_H)(1+g_A)^\sigma.$$

Now similar reasoning shows that

$$Y_t^* \propto H_t^* A_t, \quad C_t^* \propto H_t^* A_t, \quad c_t^* \propto A_t,$$

so that

$$1 + r^* = 1 + r$$

$$q = \left(\frac{\phi}{g_A} \frac{\bar{H}}{H^*} \right)^{\frac{\alpha}{2-\alpha}} \left(\frac{1+r}{1+r^*} \right)^{\frac{1-\alpha}{2-\alpha}} \Psi = \left(\frac{\phi}{g_A} \frac{\bar{H}}{H^*} \right)^{\frac{\alpha}{2-\alpha}} \Psi.$$

Note that this final expression implies that for sufficiently small ϕ, $q < 1$, which is equivalent along the BGP to Southern cost dominance in Igoods. Finally, uniqueness follows from the innovation FOC

$$g_A^{\gamma-1} A_t^{\frac{1-\delta}{\rho}} = \Omega(1+r)^{-\frac{1}{\alpha}} \left(H_{t+1} + q^{\frac{1}{\alpha}} H_{t+1}^* \right).$$

After dividing both sides by $(1+g_H)^t$, we have that

$$g_A^{\gamma-1} \propto \Omega(1+r)^{-\frac{1}{\alpha}} \left(H_1 + q^{\frac{1}{\alpha}} H_1^* \right).$$

Since $\gamma > 1$, the LHS is increasing in g_A. Since $r$is increasing in $g_A$and $q$is decreasing in g_A, there is at most one solution for g_A. Since all other prices are functions of g_A, they are unique as well. Existence is shown by noting that the increasing LHS asymptotes to ∞as $g_A \to \infty$and to 0as $g_A \to 0$. The decreasing RHS asymptotes to ∞as $g_A \to 0$(see the formula for q) and to 0as $g_A \to \infty$(see the formulas for $r$and q). By the continuity and monotonicity of everything involved, as well as the intermediate value theorem, $g_A$exists uniquely. End of Proof

Calibration Strategy

We would like to consider, as in the fully mobile environment described above, the transition path associated with a shock from the balanced growth path associated with trade policy parameter $\phi$to the balanced growth path associated with trade policy parameter ϕ'. As before, we will consider the impact of a permanent and unanticipated shock moving the policy parameter from $\phi$to ϕ'. The timing conventions are identical to those discussed in the fully mobile trade shock timing section in the main text. According to the OECD National Accounts Main Aggregates dataset and Population dataset, as current in early May 2013, the average total OECD real GDP per-capita growth rate from $1984-2000$is equal to approximately 2.37%per year. The average OECD population growth rates over this same period is approximately equal to 0.78%per year. Now note that the balanced growth path relationship above between $g_H$and $g_A$is a logarithmic equation whose solution yields

$$\delta = 1 - \rho \frac{\log(1+g_H)}{\log(1+g_A)}.$$

Above, note that $g_A$and $g_H$are 10-year versions of the annual growth rates taken from OECD data. Now, with the calibration $\rho = 0.5$from above, we have that $\delta = 0.83$. The remaining parameters to calibrate in the model are β, σ, α, $\frac{\bar{H}^*}{H}$, H_{-1}, ϕ, and ϕ'. The values for $\alpha = 2/3 \sigma = 1$, $\beta = 1/1.02$, and $\frac{H^*}{H} = 2.96$are unchanged from before. The final three parameters which must be calibrated are ϕ, ϕ', and H_1. We jointly pick these three parameters so that the following three conditions hold: $\frac{I}{Y}_{\phi,BGP} = 3.9\%$, $\frac{I}{Y}_{\phi,BGP} = 7.0\%$, and the innovation first order condition for the pre-shock ϕbalanced growth path is satisfied. The first two conditions require that the model match the non-OECD to OECD trade shares which the strong scale effects model is calibrated to match. The final condition requires that the scaling of varieties to human capital at the initial condition of the transition path is consistent with the equilibrium conditions. Given the calibration, the transition path in response to a fully mobile shock moving the economy from $\phi$to ϕ'can be written as a minimization problem in r_t, r_t^*,and q_t, as in the strong scale effects case. The endpoints of each series are known, because they reflect balanced growth path values.

Results

Figure D1 plots the transition path for the semi-endogenous economy in response to the trade liberalization, for variety growth, the Southern terms of trade, and Northern and Southern per-capita output growth. In fact, the transition is not complete 25 periods. Recall that a period in this calibration is one decade, so this represents a transition path which is not complete 250years after the initial shock. However, the broad pattern of the transition path is similar to that observed in the strong scale effects model. In particular, we have that in response to trade liberalization, the appreciation of the Southern terms of trade due to the increased flow of Igoods from South to North causes an increase in the variety growth rate, as well as Northern and Southern output growth rates. Variety growth rates immediately begin to fall, however, as the gains from increased variety levels fade in the semi-endogenous innovation cost function. This process is incredibly persistent, however, because the level of δimplied by OECD evidence on per capita GDP and population growth rates is quite close to 1, yielding something quantitatively similar to the strong scale effects model. Because of consumption smoothing and the implied movements in interest rates, Northern and Southern output growth rates are smoother than variety growth, yet just as persistent. Finally, as the variety growth rate and interest rates begin to return to their normal long-run levels, the Southern terms of trade $q$slowly converges to its new long-run value associated with ϕ'.

Table D1: Semiendogenous Transition Path Summary

Quantity	Value
max g_{At}	2.8%
(max g_{At})$-g_A$	0.45%
Half Life	16 periods
r	5.2%
$q(\phi)$	0.46
$q(\phi')$	0.68
$\frac{I}{Y}_{\phi}$	3.9%
$\frac{I}{Y}_{\phi'}$	7.0%
ΔW	16.5%
ΔW^*	15.4%

Note: The table above displays a summary of the quantitative exercise performed for the semiendogenous model given a calibrated trade liberalization. The long-run annualized value of the interest rate is given as r, and all other quantities are computed from a transition path in response to an unanticipated, permanent movement of trade policy $\phi$to $\phi' > \phi$, where $\phi$and $\phi'$are chosen to match the movement in low-cost imports to OECD GDP observed in the data from 1997-2006 and also displayed in the table. The pre- and post-shock Southern terms of trade $q(\phi)$and $q(\phi')$vary permanently with the trade policy parameter and reflect the balanced growth path for the indicated policy. The maximum level of variety growth $\max g_{At}$and the maximum difference in variety growth from its long-run level over the transition path are displayed in the first two rows, while the half life of the shock to variety growth induced by trade liberalization is indicated in the third row. The model calibration of a period is one decade. $\Delta W$and ΔW^*refer to the permanent consumption equivalent of trade liberalization for a Northern and Southern household, respectively. In particular, this percentage is the permanent fraction by which consumption for a household must increase in each period without the trade shock to make the household indifferent to the allocation with trade liberalization.

More precisely, in Table $D1$we present the detailed statistics associated with trade liberalization in the semi-endogenous model. In particular, note that the half-life of the shock to the variety growth rate is 16 periods, or 160years. Also, note that the welfare gains to the North and to the South from liberalization, $16.5\%$and 15.4%, which are permanent consumption equivalent welfare gains defined analogously to before, are qualitatively similar to those obtained from the strong scale effects model.

Appendix E - R&D Cost Externalities within Strong Scale Effects Model

As noted in the main text, to allow for the problem that firms face in coordinating search and innovation in larger teams, we allow for a form of diminishing marginal productivity for the inputs to innovation in any given period. This diminishing marginal productivity can be internal in the sense that it depends only on the inputs devoted to innovation within the firm, or it could be external in the sense that it depends on total inputs devoted to innovation in the economy. We start first with the fully internal case, which is our benchmark structure considered in the main paper. In this case, the number of new designs at firm $f$is a function of innovation expenditures Z_{ft}within firm f:

$$M_{ft+1} = (Z_{ft})^{\rho} A_t^{1-\rho},$$

where $0 < \rho < 1$.This yields an internal R&D cost function given by

$$Z_{ft} = IC(M_{ft+1}^{\gamma}, A_t) = M_{ft+1}^{\gamma} A_t^{1-\gamma},$$

where $\gamma = \frac{1}{\rho} > 1$and the function name $IC$is a mnemonic for Internal Costs. The other extreme, which is the extension we consider in this section, would be to assume that the costs of innovation for any one firm depend on the total amount of innovation that is taking place in the economy because independent firms could develop redundant designs. In this case, with fully external increasing costs, the aggregate production function for innovation is given by

$$M_{t+1} = (Z_t)^{\rho} A_t^{1-\rho},$$

where $Z_t$is the aggregate quantity of final good devoted to innovation. The corresponding aggregate cost function is

$$Z = M_{t+1}^{\gamma} A_t^{1-\gamma}.$$

In this case, the cost per new patent to an individual firm would be the average economy-wide cost of innovation

$$Z_{ft} = EC(M_{ft+1}, M_{t+1}, A_t) = \frac{M_{ft+1}}{M_{t+1}} M_{t+1}^{\gamma} A_t^{1-\gamma}.$$

where EC is a mnemonic for external costs. To allow for intermediate degrees of internal and external costs of innovation, we nest these two versions in a cost function for firm $f$of the form

$$Z_{ft} = \nu \left(IC(\bullet)\right)^{\eta} \left(EC(\bullet)\right)^{1-\eta},$$

where $0 \leq \eta \leq 1$and the inputs for the functions $IC(\bullet)$and $EC(\bullet)$are as given above. As ηincreases, the cost function exhibits a steeper marginal cost curve within each firm, with less redundancy across firms and hence weaker innovation externalities. The fully internal and fully external innovation cost benchmarks are the cases of $\eta = 1$and $\eta = 0$, respectively. The introduction of ηrequires a slight change in the scaling constant $\nu$to deliver invariance of balanced growth path growth rates to N, η, ρ. However, the equilibrium definition and structure is identical to that considered above, except for the obvious modifications to the innovation first-order conditions and resource constraints. For the fully mobile environment, the symmetry across firms causes invariance of the aggregate allocation to the level of η. Only the trapped factors transition dynamics are modified. For completeness, we reproduce below the modified system of equations solved numerically to compute the transition path in the trapped factors case with an arbitrary level of η. These equations are the direct analogy of those in Appendix Cabove.

$$q_2 = \left[\frac{\phi' H}{H\left[\left(\frac{n}{2}\right)(\mu^1)^{\frac{\alpha-1}{\alpha}} g_2^1 + \left(\frac{n}{2}\right)(\mu^2)^{\frac{\alpha-1}{\alpha}} g_2^2\right]}\right]^{\frac{\alpha}{2-\alpha}} \Psi \left(\frac{1+r_2}{1+r_2^*}\right)^{\frac{1-\alpha}{2-\alpha}}$$

$$q_t = \left(\frac{\phi' H}{g_t H^*}\right)^{\frac{\alpha}{2-\alpha}} \Psi \left(\frac{1+r_t}{1+r_t^*}\right)^{\frac{1-\alpha}{2-\alpha}}, 3, ..., T$$

$$\left(\frac{C_{t+1}}{C_t}\right)^{\sigma} = \beta(1 + r_{t+1}), t = 2, ..., T$$

$$\left(\frac{C_{t+1}^*}{C_t^*}\right)^{\sigma} = \beta(1 + r_{t+1}^*), t = 2, ..., T$$

$$(Ng_2^1)^{\eta(\gamma-1)} (g_2)^{(\gamma-1)(1-\eta)} = \Omega(1 + r_2)^{-\frac{1}{\alpha}} (\mu^1)^{-\frac{1}{\alpha}} (H + q_2^{\frac{1}{\alpha}} H^*)$$

$$(Ng_2^2)^{\eta(\gamma-1)}(g_2)^{(\gamma-1)(1-\eta)}= \Omega(1+r_2)^{-\frac{1}{\alpha}}(\mu^2)^{-\frac{1}{\alpha}}(H+q_2^{\frac{1}{\alpha}}H^*)$$

$$\frac{1}{N}(1-\phi)(1-\alpha)^{\frac{1}{\alpha}}(1+r(\phi))^{-\frac{1}{\alpha}}H+\frac{1}{N}\frac{g(\phi)^\gamma}{\eta(\gamma-1)+1}+\frac{g(\phi)}{N}(1-\alpha)^{\frac{2}{\alpha}}(1+r(\phi))^{-\frac{1}{\alpha}}(H+q(\phi)^{\frac{1}{\alpha}}H^*)$$

$$=\frac{1}{N}(1-\phi)(1-\alpha)^{\frac{1}{\alpha}}(\mu^1)^{-\frac{1}{\alpha}}(1+r_2)^{-\frac{1}{\alpha}}H+\frac{N^{\eta(\gamma-1)}}{\eta(\gamma-1)+1}\left(g_2^1\right)^{\eta(\gamma-1)+1}(g_2)^{(\gamma-1)(1-\eta)}$$

$$+g_2^1(1-\alpha)^{\frac{2}{\alpha}}(1+r_2)^{-\frac{1}{\alpha}}(\mu^1)^{-\frac{1}{\alpha}}(H+q_2^{\frac{1}{\alpha}}H^*)$$

$$\frac{1}{N}(1-\phi)(1-\alpha)^{\frac{1}{\alpha}}(1+r(\phi))^{-\frac{1}{\alpha}}H+\frac{1}{N}\frac{g(\phi)^\gamma}{\eta(\gamma-1)+1}+\frac{g(\phi)}{N}(1-\alpha)^{\frac{2}{\alpha}}(1+r(\phi))^{-\frac{1}{\alpha}}(H+q(\phi)^{\frac{1}{\alpha}}H^*)$$

$$=\frac{1}{N}\chi_2(1-\phi)(1-\alpha)^{\frac{1}{\alpha}}(\mu^2)^{-\frac{1}{\alpha}}(1+r_2)^{-\frac{1}{\alpha}}H+\frac{N^{\eta(\gamma-1)}}{\eta(\gamma-1)+1}\left(g_2^2\right)^{\eta(\gamma-1)+1}(g_2)^{(\gamma-1)(1-\eta)}$$

$$+g_2^2(1-\alpha)^{\frac{2}{\alpha}}(1+r_2)^{-\frac{1}{\alpha}}(\mu^2)^{-\frac{1}{\alpha}}(H+q_2^{\frac{1}{\alpha}}H^*).$$

$$g_2=\left(\frac{N}{2}\right)(g_2^1+g_2^2).$$

$$\frac{1+\chi_2}{2}=\frac{1-\phi'}{1-\phi},$$

$$p_{M2}^1=\mu^1\frac{1+r_2}{1-\alpha},p_{R2}^1=(1+r_2),$$

$$p_{M2}^2=\mu^2\frac{1+r_2}{1-\alpha},p_{R2}^2=(1+r_2).$$

$$Z_2^1=\frac{N^{\eta(\gamma-1)}}{\eta(\gamma-1)+1}\left(g_2^1\right)^{\eta(\gamma-1)+1}(g_2)^{(\gamma-1)(1-\eta)}$$

$$Z_2^2=\frac{N^{\eta(\gamma-1)}}{\eta(\gamma-1)+1}\left(g_2^2\right)^{\eta(\gamma-1)+1}(g_2)^{(\gamma-1)(1-\eta)},$$

$$Y_1= C_1+\left(\frac{N}{2}\right)g_2^1A_1(x_{M2}^1+x_{M2}^{*1})+\left(\frac{N}{2}\right)g_2^2A_1(x_{M2}^2+x_{M2}^{*2})+\left(\frac{N}{2}\right)\frac{1-\phi}{2}A_1x_{R2}^1+\left(\frac{N}{2}\right)\frac{(1-\phi)\chi_2}{2}A_1x_{R2}^2+$$

$$Z_2^1+Z_2^2$$

$$Y_1^*= C_1^*+(1-\phi')A_1x_{R2}^*+\phi'A_1(x_{I2}^*+x_{I2})$$

$$Y_2= H^\alpha\left[\left(\frac{N}{2}\right)g_2^1A_1(x_{M2}^1)^{1-\alpha}+\left(\frac{N}{2}\right)g_2^2A_1(x_{M2}^2)^{1-\alpha}+\left(\frac{N}{2}\right)\frac{1-\phi}{2}A_1(x_{R2}^1)^{1-\alpha}\right.$$

$$\left.+\left(\frac{N}{2}\right)\frac{(1-\phi)\chi_2}{2}A_1(x_{R2}^2)^{1-\alpha}+\phi'A_1x_{I2}^{1-\alpha}\right]$$

$$Y_2^*= (H^*)^\alpha\left[\left(\frac{N}{2}\right)g_2^1A_1(x_{M2}^{*1})^{1-\alpha}+\left(\frac{N}{2}\right)g_2^2A_1(x_{M2}^{*2})^{1-\alpha}+(1-\phi')A_1(x_{R2}^*)^{1-\alpha}+\phi'A_1(x_{I2}^*)^{1-\alpha}\right].$$

$$\min(\mu^1,\mu^2)(1+r_2)\geq q_2(1+r_2^*),$$

$$(1 + r_t) \geq q_t(1 + r_t^*), t = 3, .., T,$$

$$q_1, q_{T+1} \leq 1.$$

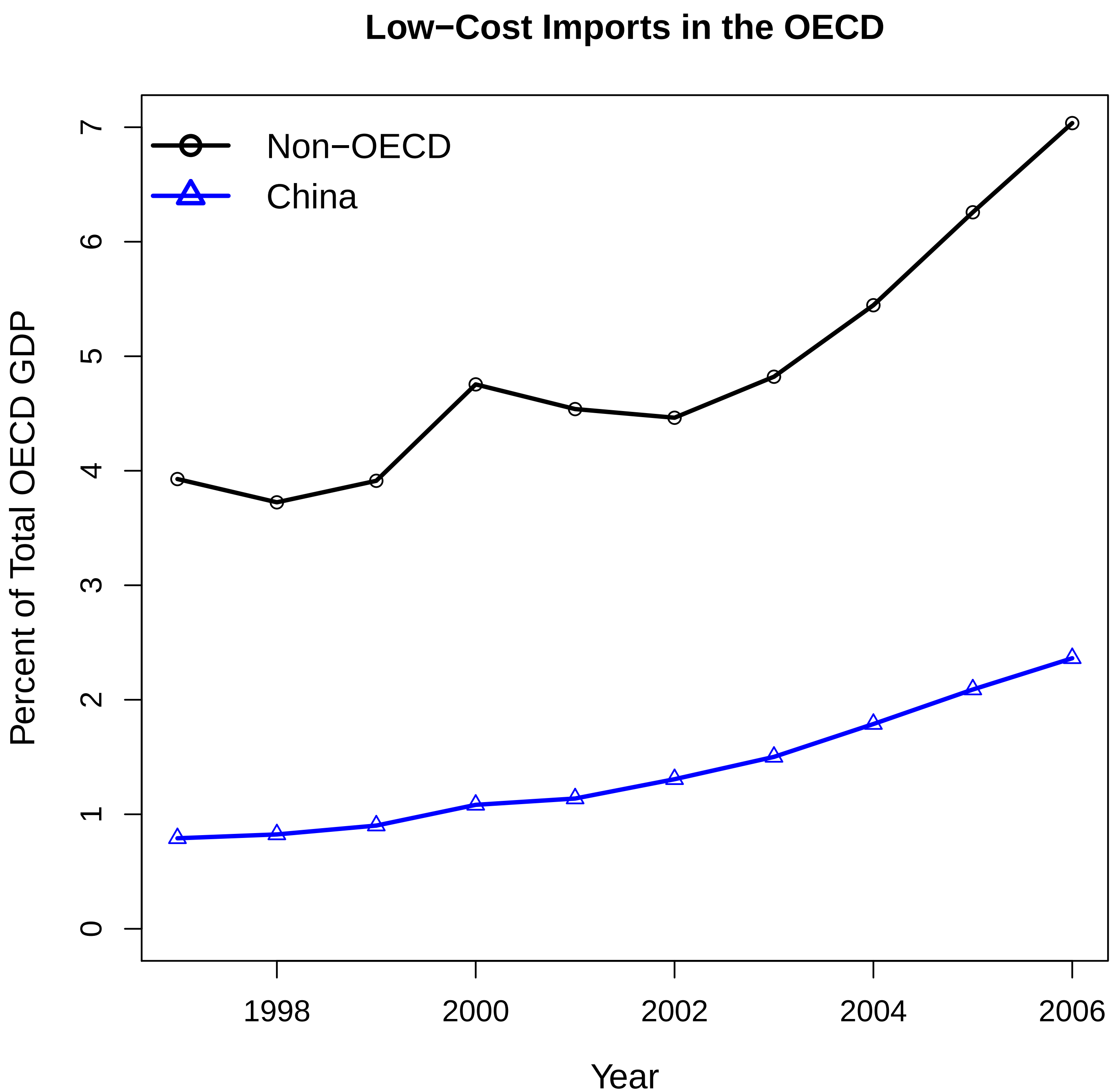

Figure 1: Import Ratios are Increasing

Note: Non-OECD and Chinese imports into OECD countries are from the OECD-STAN database as available in April 2013. Chinese import data is directly available, and non-OECD imports are imputed as the difference between world imports and imports from other OECD members in a given year. The normalizing GDP measure for the OECD is computed from the Penn World Tables version 7.1 and equals the sum of GDP for all OECD members in a given year. The Chinese imports to OECD GDP ratio in 1997 is 0.79% and in 2006 is 2.4%. The total non-OECD imports to OECD GDP ratio in 1997 is 3.9% and in 2006 is 7.0%.

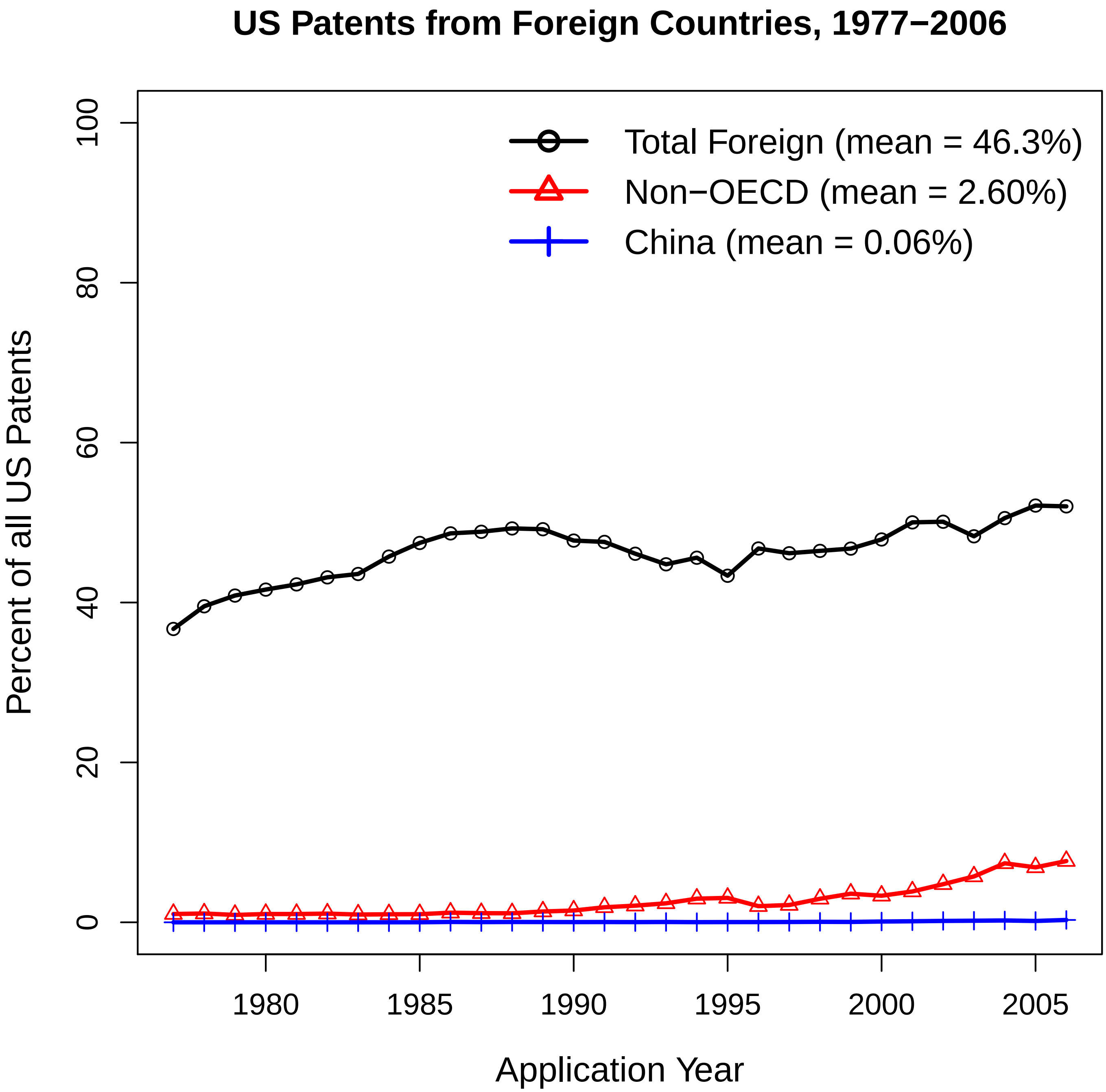

Figure 2: Non-OECD Patent Ratios are Small

Note: Patent fractions are computed from the NBER patent database, accessible via Brownyn Hall's website. Patents granted to multiple assignees are counted only once. The classification of patents by assignee to the required OECD, non-OECD, and Chinese categories is done by the citizenship of the first assignee, and a given country's OECD member status as of the application year. Each series is normalized by the total nubmer of granted US Patent and Trademark Office applications in the same year. The reported means are computed over the full range 1977-2006.

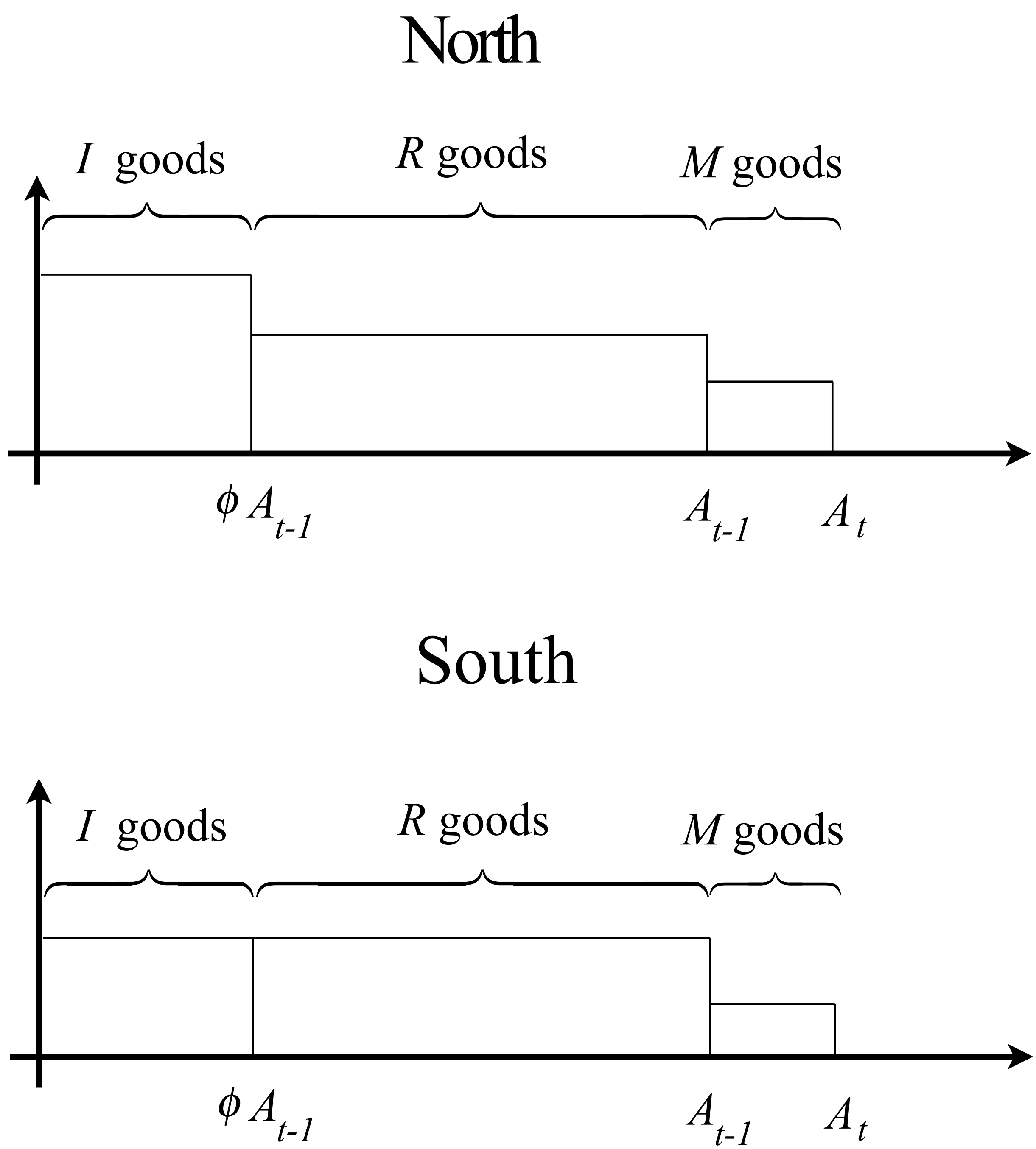

Figure 3: A Product Cycle in the Model

Note: The figure plots the product cycle for intermediate goods in the open-economy model. In the open-economy equilibrium defined and analyzed in the paper, goods in each period will display the above decomposition, into newly innovated M goods produced solely in the North, perfectly competitive but non-traded R goods, produced in the North and the South, and perfectly competitive, traded I goods, produced solely in the South.

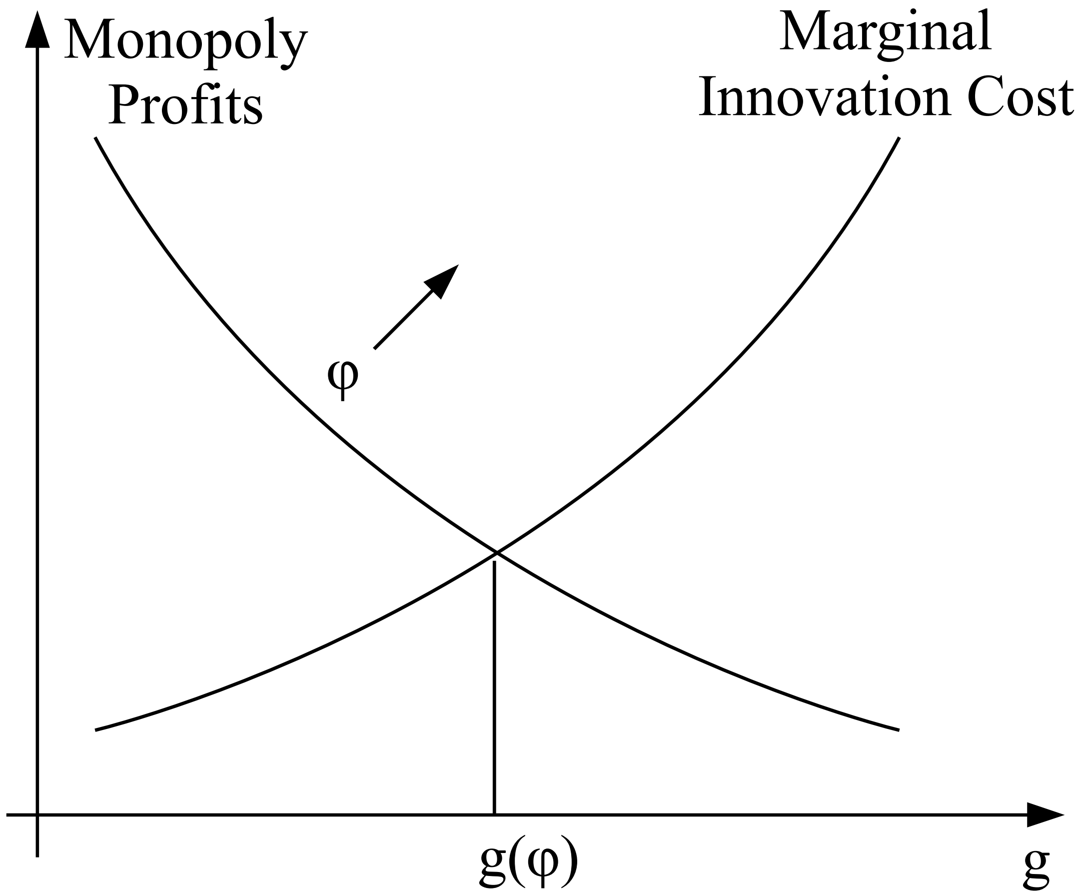

Figure 4: Balanced Growth Path Equilibrium

Note: The figure plots the equilibrium innovation optimality condition for Northern intermediate goods firms in the balanced growth path of the open-economy model. The innovation optimality condition pins down balanced growth path growth rates in this framework, and as proved in Proposition 2, increases in the returns to innovation induced by increases in ϕ lead to strictly higher long-run growth rates.

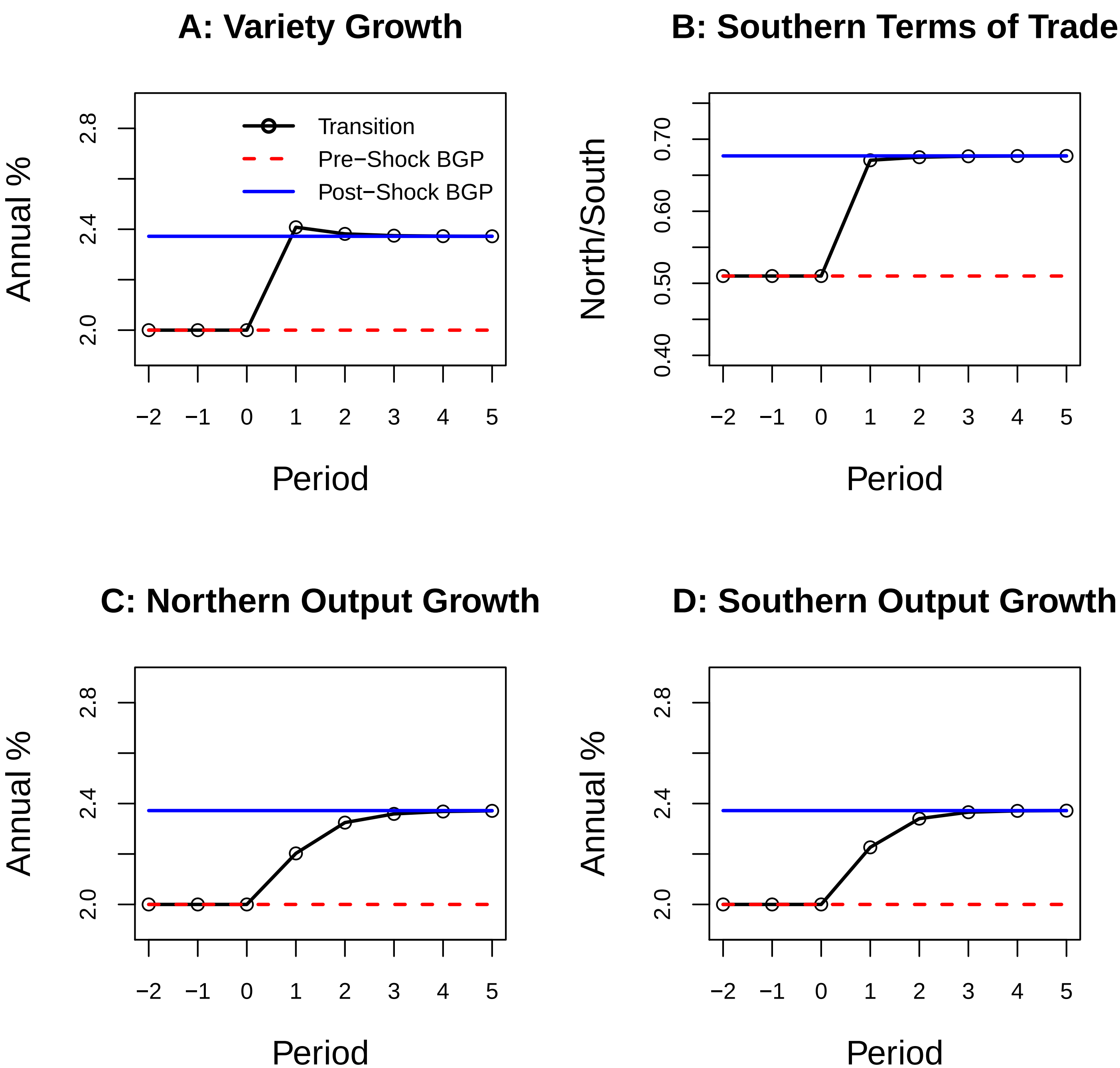

Figure 5: Liberalization Boosts Growth in Fully Mobile Model

Note: The figure displays the benchmark transition path in response to a permanent, unanticipated trade liberalization from policy parameter ϕ to $\phi' > \phi$, which is announced in period 0 to become effective in period 1. The plotted transition is computed in the fully mobile economy, in which intermediate goods firms may respond to the information about trade liberalization without short-term adjustment costs. The solid black line is the transition path, the upper horizontal solid blue line is the post-shock balanced growth path, and the lower horizontal dashed red line is the pre-shock balanced growth path.

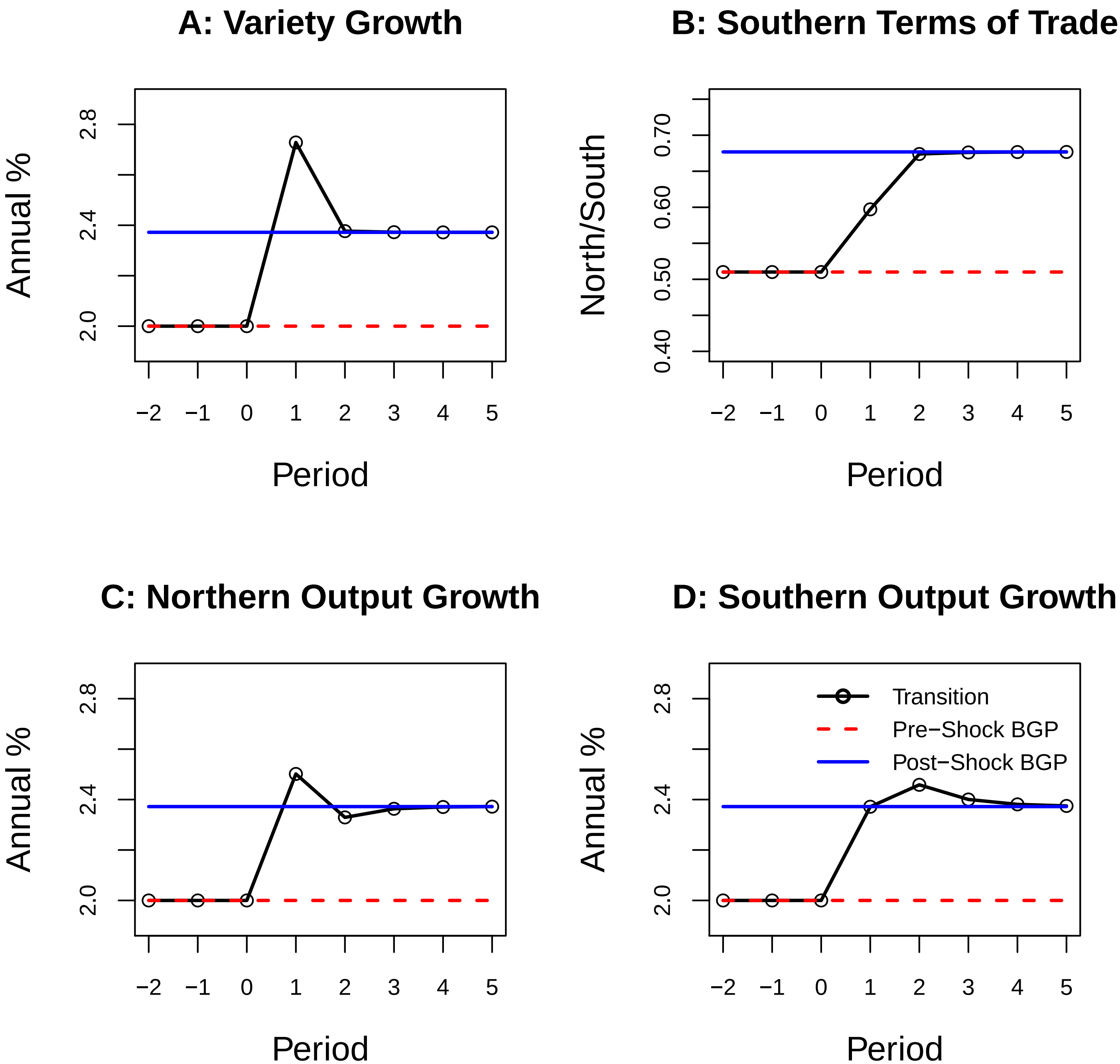

Figure 6: Trapped Factors Increase Short-Run Growth

Note: The figure displays the trapped-factors transition path in response to a permanent, unanticipated trade liberalization from policy parameter ϕ to $\phi' > \phi$, which is announced in period 0 to become effective in period 1. Since the plotted transition is computed in the trapped-factors economy, adjustment costs prevent the movement of resources outside of intermediate goods firms within the period of the shock. The solid black line is the transition path, the upper horizontal solid blue line is the post-shock balanced growth path, and the lower horizontal dashed red line is the pre-shock balanced growth path.

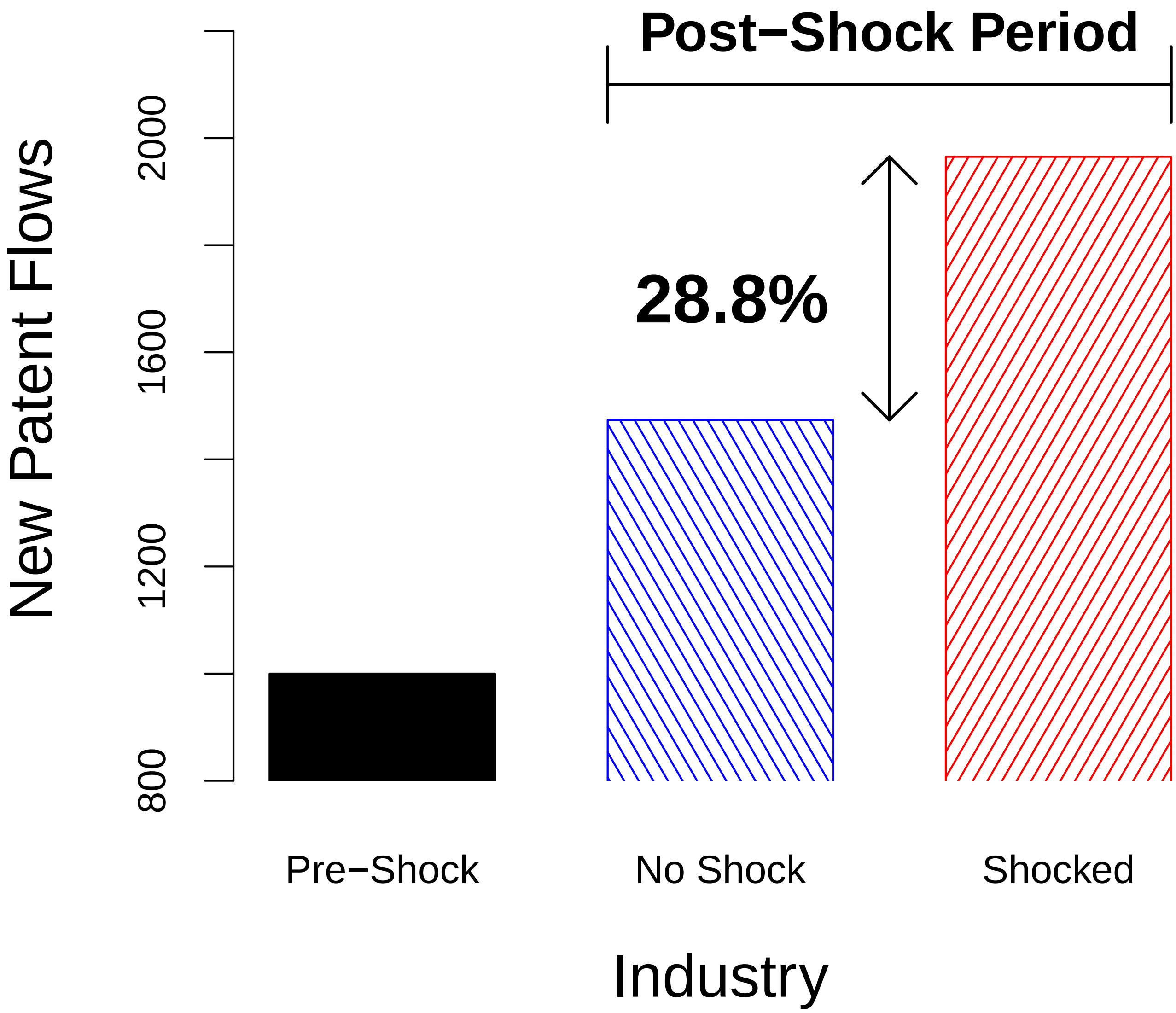

Figure 7: A Shocked Industry Patents More

Note: The solid black bar on the left displays the level of industry patenting in the period before a permanent and unanticipated trade liberalization from policy parameter ϕ to $\phi' > \phi$. Patent flows in the pre-shock period are normalized to equal 1000. The middle blue bar with downward sloping lines and right red bar with upward sloping lines represent the response of the unshocked and shocked industries, respectively, to the trade liberalization in an economy with trapped factors. The shocked industry loses 24.2% of its previously protected R goods production opportunities when these are converted to imported I goods from the South, and the no shock industry does not lose any unanticipated R goods to Southern competition.

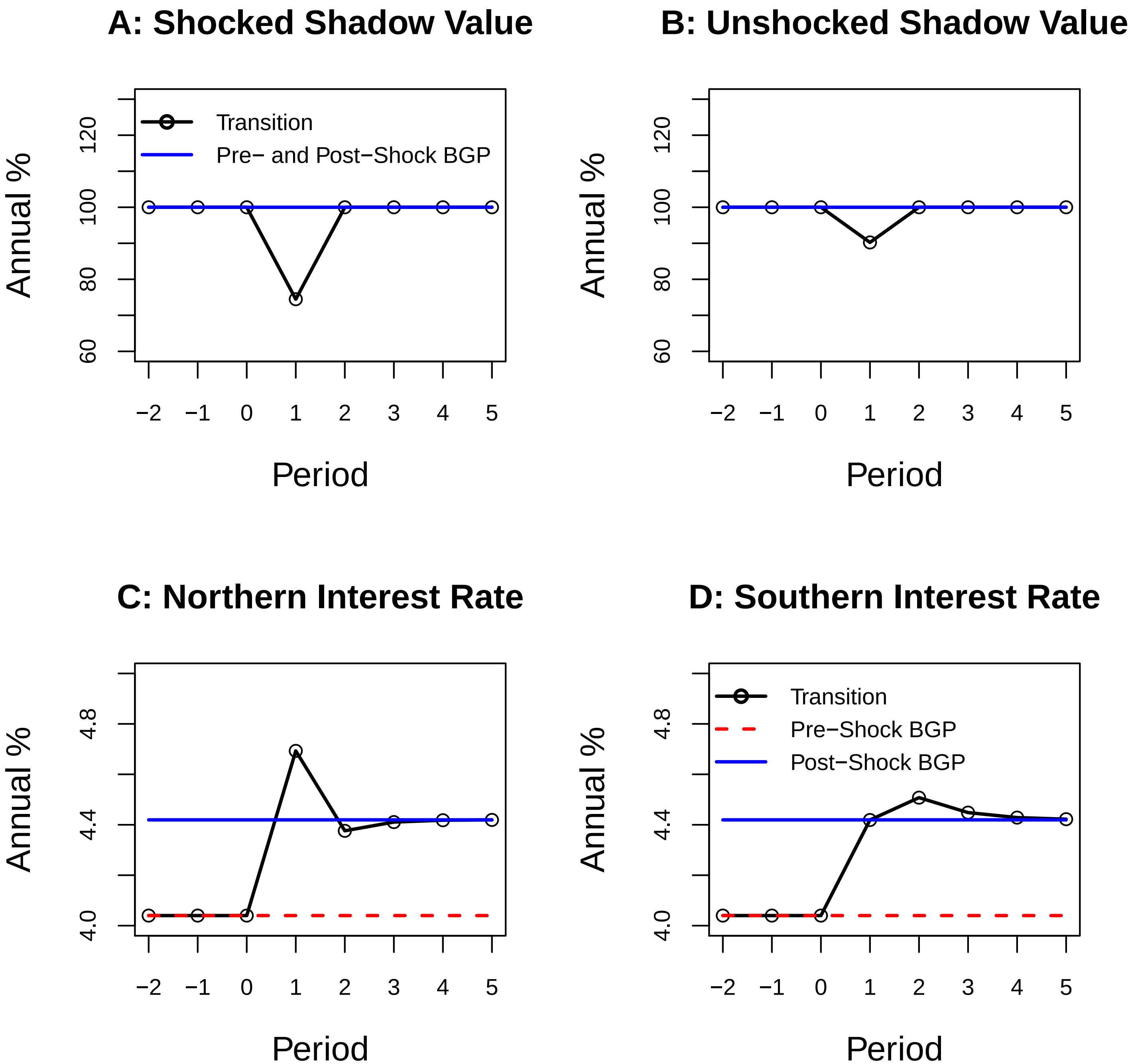

Figure 8: Trapped Factors Interest Rates and Shadow Values

Note: The figure displays the trapped-factors transition path in response to a permanent, unanticipated trade liberalization from policy parameter ϕ to $\phi' > \phi$, which is announced in period 0 to become effective in period 1. Since plotted transition is computed in the trapped-factors economy, adjustment costs prevent the movement of resources outside of intermediate goods firms within the period of the shock. The solid black line is the transition path, the upper horizontal solid blue line is the post-shock balanced growth path, and the lower horizontal dashed red line is the pre-shock balanced growth path. For the two shadow value figures, shadow values are normalized to equal 100% in non-shock periods.

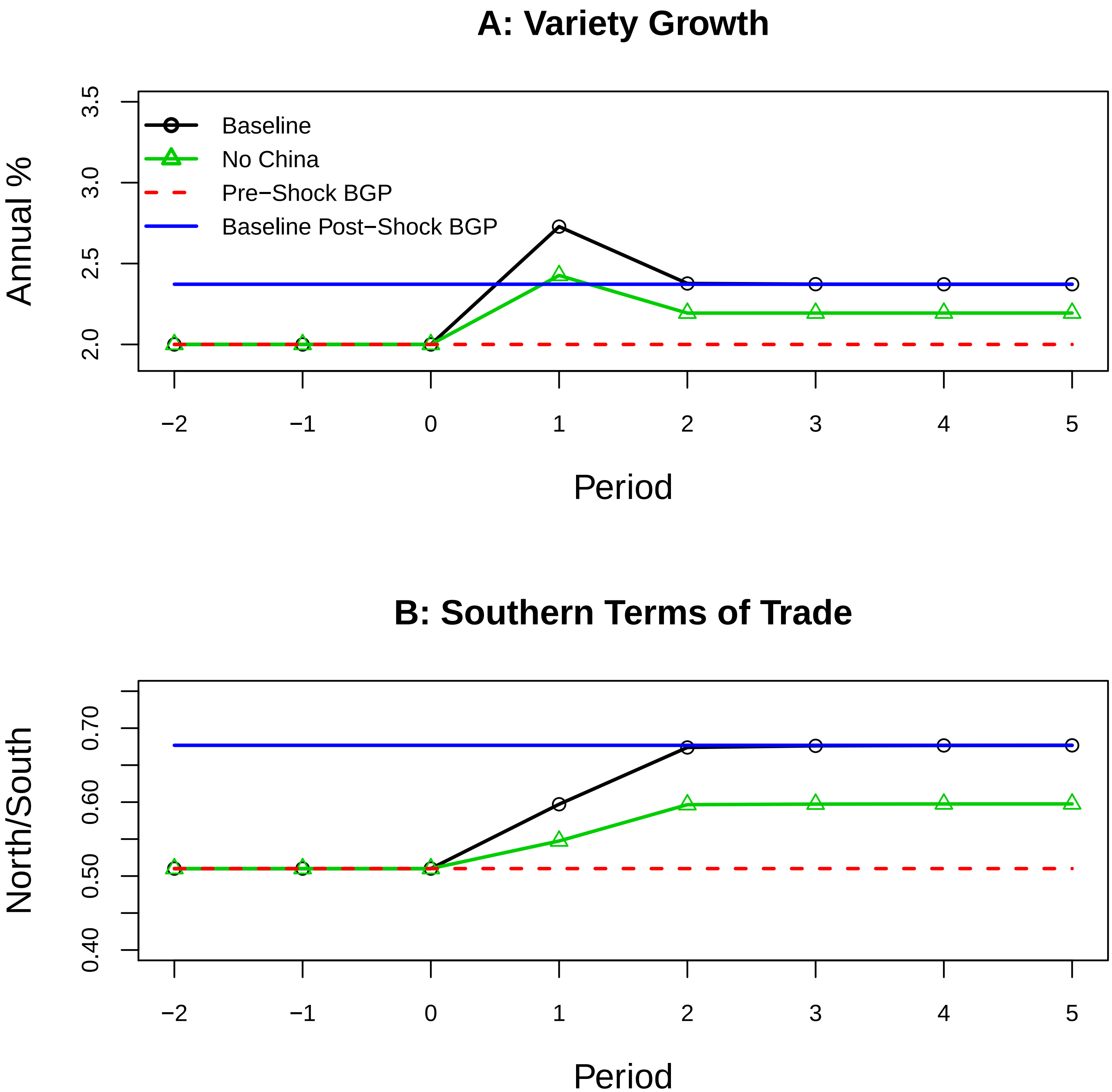

Figure 9: Trade Liberalization without Chinese Import Growth

Note: The figure displays the transition path in response to trade liberalization in two scenarios. The first transition path, in solid black, "Observed," replicates the trapped factors transition path displayed in Figure 6 above. A permanent and unanticipated trade liberalilzation from ϕ to $\phi' > \phi$ is announced in period 0 to become effective in period 1. The second transition path in green with triangle symbols, "No China," plots the trapped factors transition path, starting with the same initial conditions as "Observed," but instead considering a counterfactual increase of ϕ to a level between ϕ and ϕ' which matches post-liberalization imports to GDP ratios assuming no growth in Chinese imports into the OECD. The upper horizontal solid blue line is the post-shock balanced growth path, and the lower horizontal dashed red line is the pre-shock balanced growth path.

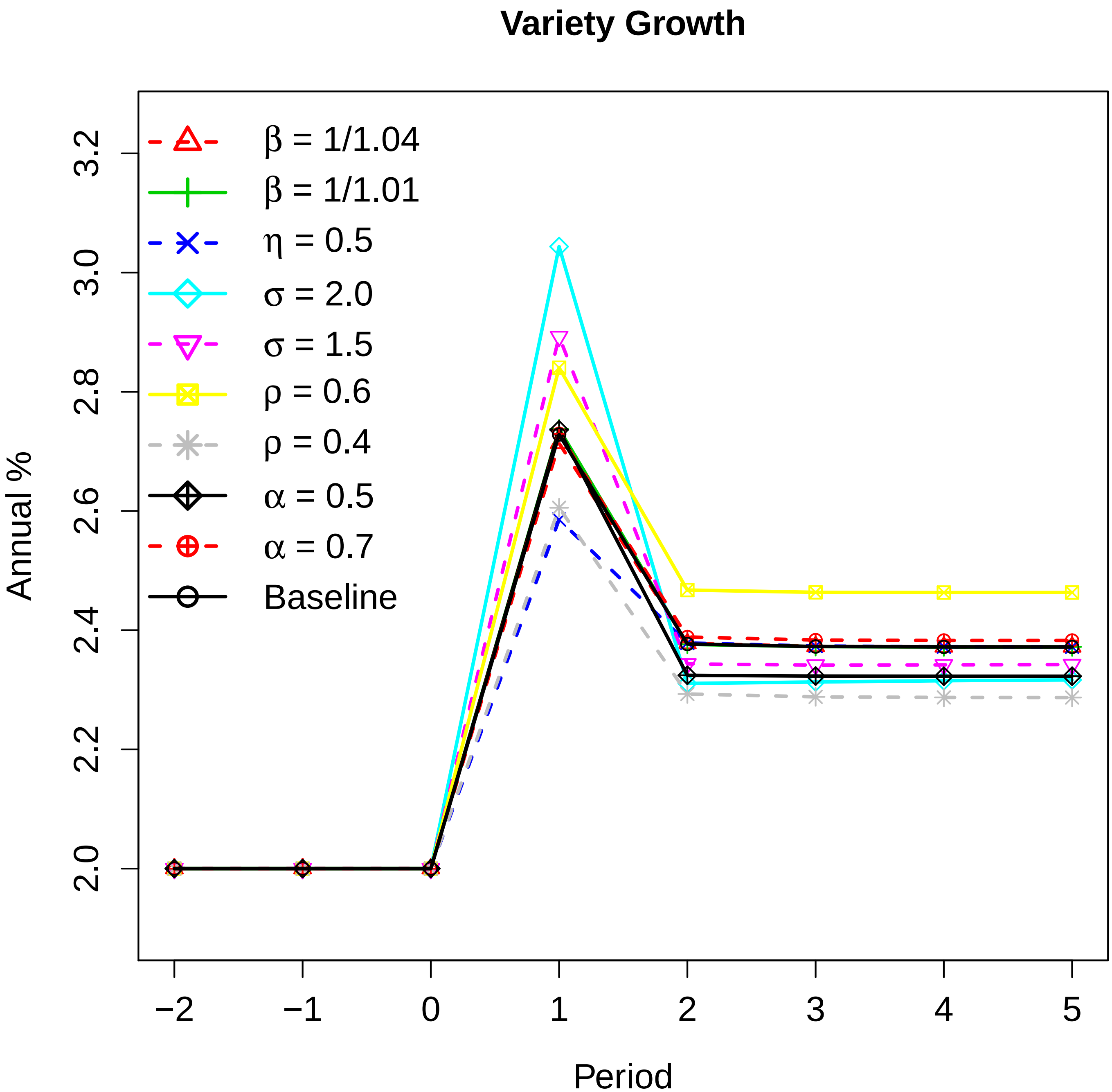

Figure 10: Trapped Factors Transition Dynamics are Robust

Note: The figure displays the trapped-factors transition path in response to a permanent, unanticipated trade liberalization from policy parameter ϕ to $\phi' > \phi$, which is announced in period 0 to become effective in period 1. All plotted parametrizations of the model vary only the parameter indicated in the legend, starting from the baseline trapped factors calibration described in the text.

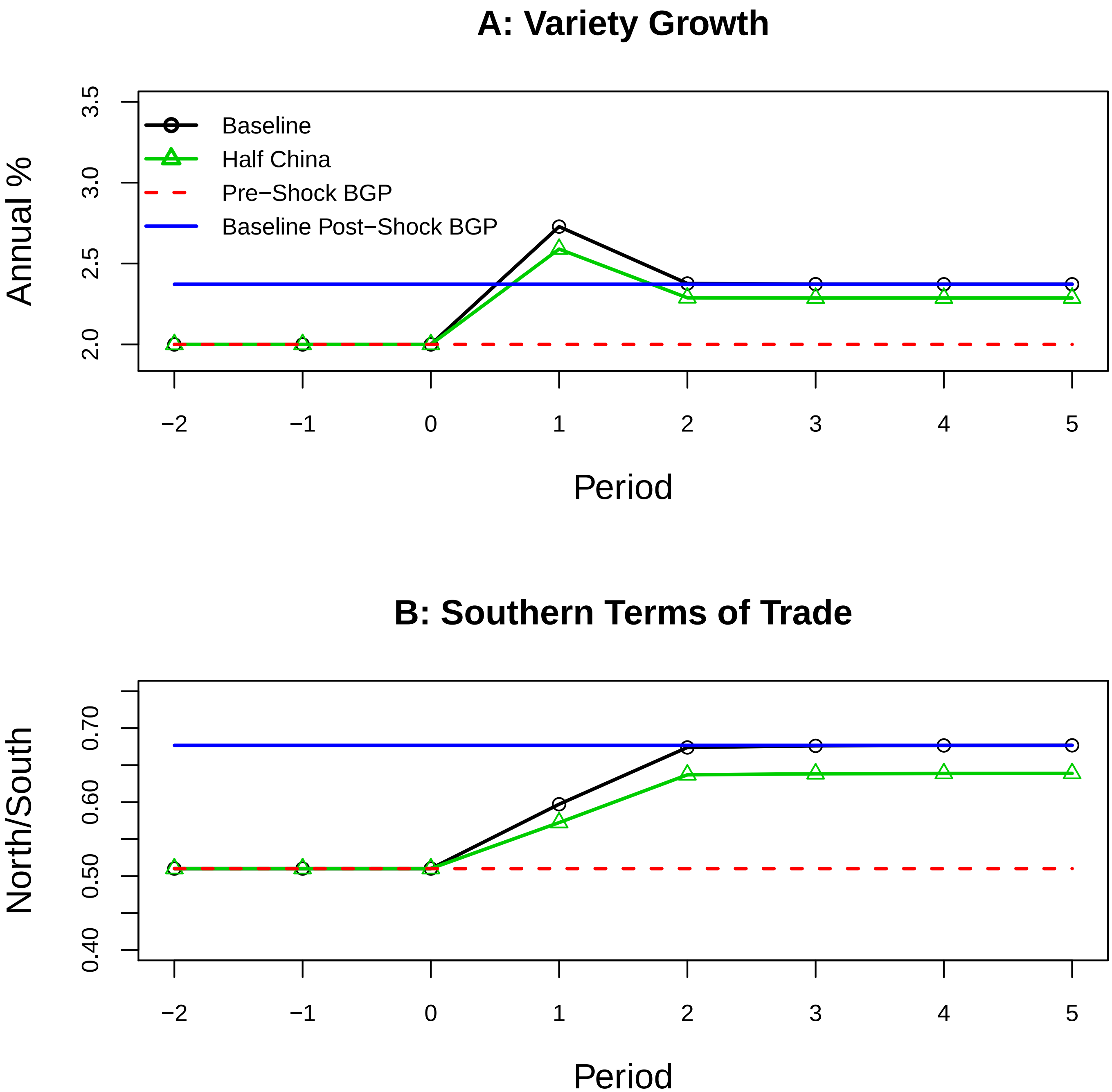

Figure B1: Trade Liberalization with Half of Chinese Import Growth

Note: The figure displays the transition path in response to trade liberalization in two scenarios. The first transition path, in solid black, "Observed," replicates the trapped factors transition path displayed in Figure 6 above. A permanent and unanticipated trade liberalilzation from ϕ to $\phi' > \phi$ is announced in period 0 to become effective in period 1. The second transition path in green with triangle symbols, "Half China," plots the trapped factors transition path, starting with the same initial conditions as "Observed," but instead considering a counterfactual increase of ϕ to a level between ϕ and ϕ' which matches post-liberalization imports to GDP ratios assuming that half the growth in Chinese imports into the OECD occurs through policy substitution to non-China, non-OECD countries. The upper horizontal solid blue line is the post-shock balanced growth path, and the lower horizontal dashed red line is the pre-shock balanced growth path.

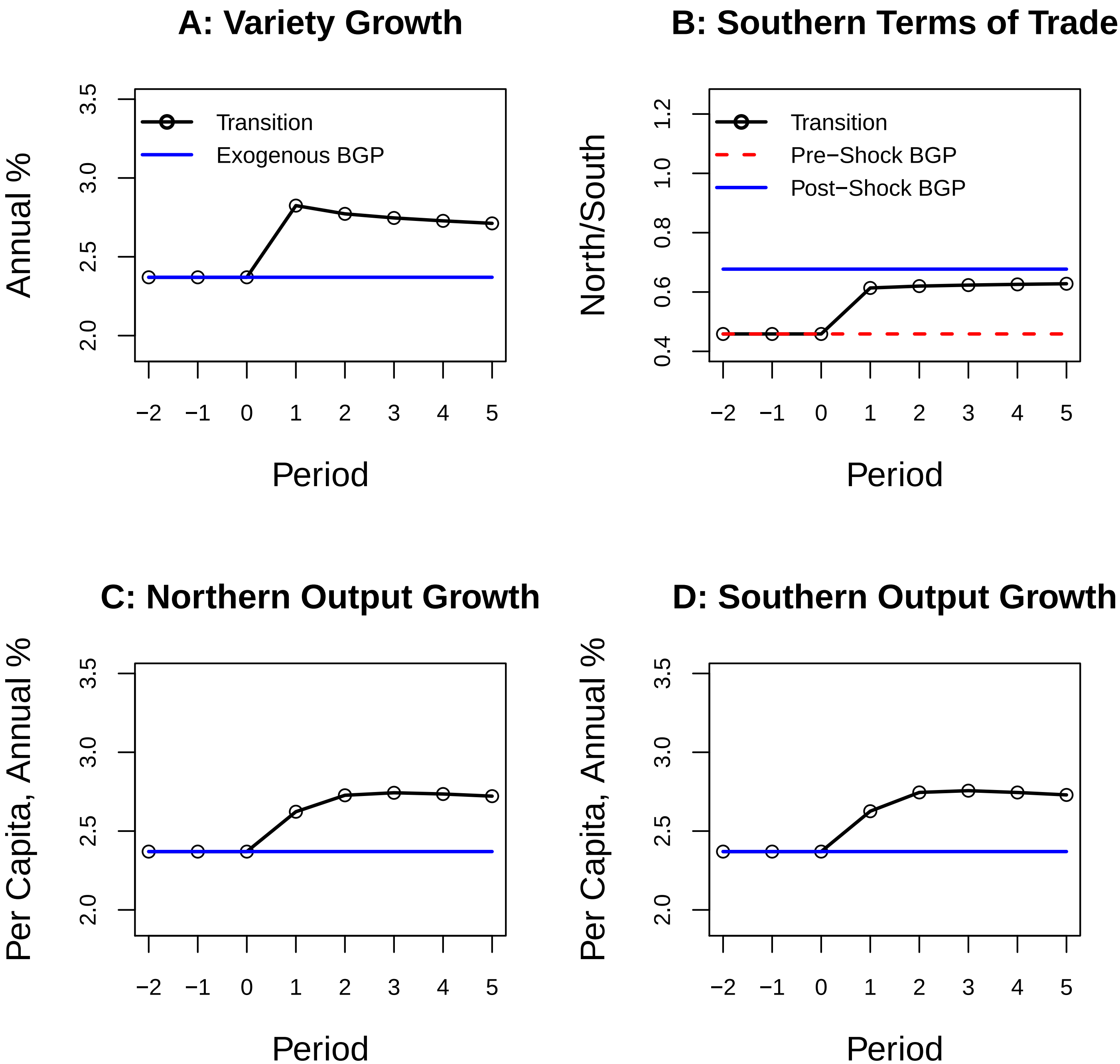

Figure D1: Semi-endogenous Growth Model Trade Liberalization

Note: The figure displays the fully mobile transition path in the semiendogenous growth model in response to a permanent, unanticipated trade liberalization from policy parameter ϕ to $\phi' > \phi$, which is announced in period 0 to become effective in period 1. Intermediate goods firms may respond to the information about trade liberalization without short-term adjustment costs. The solid black line is the transition path, the upper horizontal solid blue line is the post-shock balanced growth path, and the lower horizontal dashed red line is the pre-shock balanced growth path. Note that since the semiendogenous growth model's value for variety growth and output growth in the long run does not vary with trade policy, there is only one balanced growth marker for these series.