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Trapped Factors and China's Impact on Global Growth

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Abstract

When China's accession to the WTO exposed European firms to import competition, they responded by increasing their investment in innovation. This response was stronger in industries and firms where factors of production were less mobile. Motivated by this evidence, we incorporate "trapped factors" at the micro level into a general equilibrium model of product-cycle trade and growth. In a calibrated version of the model that starts with a baseline growth rate of 2%, trade integration between the OECD and low-wage countries can increase the steady-state growth rate to 2.4% per year. Factors that are trapped at a firm by an unexpected change in trade policy do not change this long-run growth rate, but in the medium run, they could have a noticeable e↵ect on aggregate growth. Simulations of the model show that in the first decade after liberalization, growth jumps to 2.7% per year and that trapped factors account for almost all of the 0.3% = 2.7% − 2.4% increase above the steady state growth rate.

Key words: Innovation, trade, China, endogenous growth
JEL: D92, E22, D8, C23

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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.[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 small. A typical calculation suggests that for a nation like the United States, a move from complete autarky to current levels of trade implies a gain of a few percentage points of GDP.[3]A possible reason for this is that the calibrations are based on static models that do not allow for the dynamic effects of endogenous innovation on growth.

In this context, 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 empirical response, our 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 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-empirical evidence is to explain why a firm that

[1] See for example Pavcnik (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 Taiwan, de Loecker (2011) on Belgium, and Bustos (2011) on Argentina.

[2] See, for example, Frankel and Romer (1999), or case studies such as Romer (1992) on the effect of an Export Processing Zone in Mauritius, Bernhofen, and Brown (2005) on post-Meiji Japan, Trefler (2004) on CAFTA, Feyrer (2013) on the Suez Canal, or Irwin (2005) on the Jefferson embargo.

[3] For example, Costinot and Rodriguez-Clare (2013, Table 1) calculate that moving the US from current levels of trade to autarky would cause only a small loss of welfare of about 2% of GDP. Moving to a multi-sector model increases these to about 4% (Eaton and Kortum, 2012, have an estimate of 5%). The welfare calculations in Costinot and Rodriguez-Clare (2013) are based on the trade elasticity combined with the import share of GDP (see also Arkolakis, Costinot and Rodriguez-Clare, 2012). Melitz and Redding (2015) show that in a heterogeneous firm model, these are not sufficient statistics for calculating welfare gains. They find that reducing trade costs from current US levels, has larger welfare effects in their more structural approach. Note that in each of these cases, larger welfare effects of trade can be generated by allowing for traded intermediates or by focusing on more open economies than the US.

[4] Bloom, Draca and Van Reenen (2015).

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

is more exposed to import competition from China has a bigger incentive to develop new goods. We show within our model that this pattern is precisely what one would expect if factors of production are temporarily "trapped" within firms due to moving costs. If, for example, skilled engineers develop firm-specific or industry-specific knowledge and 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 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 for the market as a whole, but also because the opportunity cost of designing and producing the product have gone down within that firm.

This interpretation of trapped factors is consistent with some existing empirical 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] However, before embedding our notion of trapped factors into the model, we go further to empirically test its plausibility.

We exploit a micro-level database, first constructed in Bloom, Draca, and Van Reenen (2015), on European firms' patenting rates and exposure to Chinese import competition over the period of intense trade liberalization in the late 1990s and early 2000s. To test our model's micro-level mechanism, we construct various proxies for the level of input adjustment costs or trapped factors within firms such as industry-specific wage premia. In the data, patent growth is higher for firms in industries with higher levels of Chinese import growth, but this effect is stronger for firms with higher levels of our proxies for trapped factors. This is the correlation between patenting and trapped factors that the model predicts.

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

[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.

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 based on a binary comparison of two isolated economies versus 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 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 even though the asymptotic change in the growth rate in such models is always 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 steady-state equilibrium, trade barriers prevent factor-price equalization, so goods produced in the South have an absolute cost advantage. We find in a calibrated quantitative experiment that the increased global integration of the OECD with all low-wage countries that took place during 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 2.4% 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 increase in the rate of growth from trade with the South has a welfare effect that 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. Although the trapped-factors mechanism has a smaller long-run welfare effect, it will have extra salience because the effect is front-loaded. Over the first decade after the trade shock, the trapped-factor effect on the rate of growth is similar in magnitude to the market-size effect. For trade with all low-wage countries, the trapped-factor effect increases the rate of growth by an additional 0.3% per year (i.e. the combined effect of the market size and trapped factors effects raises the growth rate from 2.0% to 2.7% per year) in the first decade after the liberalization, with about one-third being due to China alone.

Although these magnitudes may appear large in light of the subsequent slowdown in global and Chinese growth in recent years, it is important to emphasize that we are focusing purely on trade effects rather than business cycle fluctuations or transitional growth in developing economies. We therefore calibrate based on frontier growth data preceding the global crisis of 2008-9, and we leave to future work the possibility that such large cyclical fluctuations may have long-lasting effects on income. Given the potentially large positive

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

effects on innovation we find from integration with emerging economies like China, our findings strike a more positive note on the future of frontier growth than, say, Gordon (2012). However, the main implications of our model hold both in the baseline model with permanent increases in growth from liberalization as well as in a semi-endogenous version of the model with no permanent impact on growth rates.

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, 2013).[9] We also assume that firms 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 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.[10] 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, 2010). Because of concern about increased inequality, an older literature on the distributional effects of trade that arise when labor is industry-specific (e.g. 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 tempered if a trade liberalization increases inequality. Relative to the existing literature, in which specific factors do not imply efficiency gains, in our second-best model, trapped factors can 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 reduces X-inefficiency. We

[9] Atkeson and Burstein (2010) consider a heterogeneous firm trade model with endogenous process innovation. They find that reductions in trade costs lead to no greater increases in welfare in such models compared to homogeneous firm models. Like Atkeson and Burstein (2010) we also find that the steady-state increase in welfare is determined by the insight from the older literature that larger market size increases the returns to product innovation. Unlike them, however, we generate *more* growth in the transition to the new steady state due to our new trapped factor effect.

[10] See for example Sampson (2014) or Costantini and Melitz (2008).

generate such effects without appealing to the type of principal-agent models (e.g. Schmidt, 1997) 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) or Hall (1991).

The road map to the rest of the paper is as follows. We start by introducing empirical evidence in Section 2 which links trade liberalization and innovation to our notion of trapped factors. Section 3 presents our baseline model of trade and long-term growth, laying out our framework for trade shocks in fully mobile and trapped factors cases. Section 4 moves on to the quantitative exercise, and Section 5 offers some extensions and robustness tests. Section 6 concludes. A set of online appendices contain many technical details of the theoretical proofs (A), the data and model calibration (B), the model solution method (C), an extension to a semi-endogenous growth approach (D), an extension to an alternative R&D cost function (E), and an extension to an economy with Southern innovation (F).

2 Trade Shocks, Innovation, and Trapped Factors in the Data

In the last few decades, developed economies have dramatically liberalized trade with developing nations with much lower wages. To illustrate the magnitude of this change, we classify nations into non-OECD and OECD groups. Imports from non-OECD group into the OECD group nearly doubled from 3.9% of OECD GDP in 1997 to around 7.0% in 2006. In Figure 1 the black line with circle markers plots this import-to-GDP ratio for each year in the period. China's individual role, operating through channels such as Chinese WTO accession in 2001, seems particularly important. In the blue line with triangles, Figure 1 displays the ratio of Chinese imports to OECD GDP over the same period. Chinese imports grew from 0.79% to 2.4%, representing over half of the total increase in low-wage imports into the developed world.[11] We conclude that not only was the recent trade liberalization toward low-cost countries large, but also that any analysis of this liberalization must give central importance to understanding the effects of increased trade with China on the world economy.

Within individual firms and industries in rich nations, one might expect that the entry of competitors like China with lower costs and tremendous scale would lead to convulsive effects. Empirically, firms surviving the onslaught of import competition do indeed exhibit substantive changes in their activities. Perhaps surprisingly, however, firms appear to shift towards innovation. In Italy, Bugamelli et al. (2010) show that a range of manufacturers

[11] These ten years from 1997-2006 were chosen to evenly bracket Chinese WTO accession in 2001. The aggregate data in Figure 1 comes from a combination of trade figures from the OECD-STAN database with GDP figures from the Penn World Table. Appendix B contains more information on the data construction.

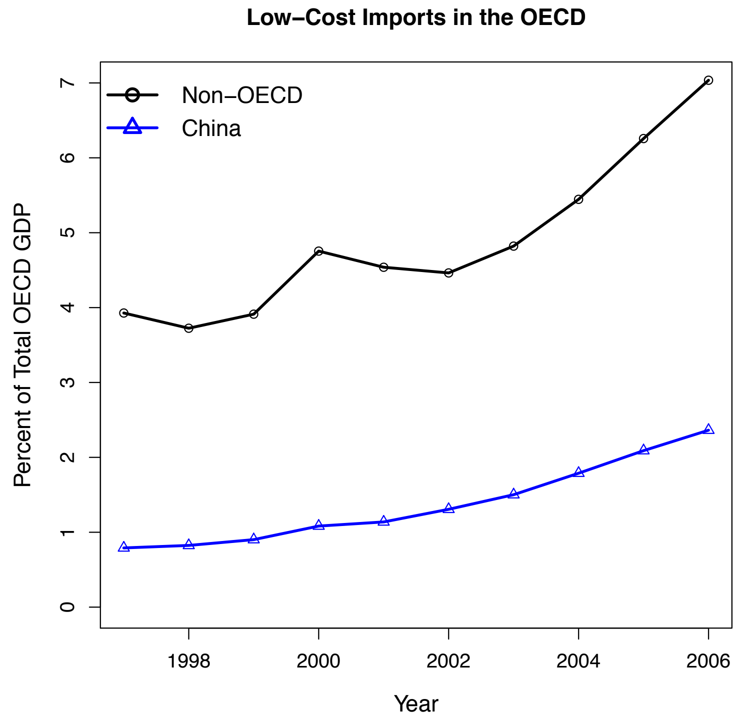

Figure 1: Import Ratios are Increasing

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%.

from ceramic tiles to women's clothing switched to more innovative high-end products in response to rising low-wage competition. Relatedly, Freeman and Kleiner (2005) showed in a case study that US shoe manufacturers switched from making low-cost mass market shoes to innovative products when faced with Chinese competition. This response presents an obvious challenge for economic theory. If it was in the firm's interest to invest in innovation after the shock, why was it not in its interest to do so before the shock?

Bloom, Draca, and Van Reenen (2015) offers systematic evidence of innovation in European firms in the face of Chinese import competition. Those authors construct a database combining three main sources of information on European firms: 1) firm-level accounting statements on employment, sales, wage bills, capital, and materials spanning 12 countries from 1996-2005 and drawn from the Bureau Van Dijk Amadeus database, 2) matched firm-level patent data from the European Patent Office, and 3) disaggregated trade flows at the four-digit industry level from the UN Comtrade database. All together, these data sources lead to a panel including innovation and trade measures for over 8,000 firms spanning around 1,500 country-industry pairs and containing over 30,000 firm-year observations. We make use of the same database. For more details, see Appendix B.

Column 1 of Table 1 replicates findings in the previous paper, presenting an OLS regression of innovation as measured by the five-year change in patenting $\Delta\ \ln(\text{PATENTS})_{ijkt}$ on the corresponding five-year change in Chinese imports $\Delta\ \text{IMP}^{CH}_{jkt}$, measured as the ratio of Chinese imports to total imports in the same industry by country cell. We also control for country-year dummies:[12]

$$\Delta \ln(\text{PATENTS})_{ijkt} = \alpha \Delta \text{IMP}^{CH}_{jkt} + f_{kt} + \nu_{ijkt}$$

The resulting value of $\hat{\alpha}$ is positive and precisely estimated. A 10% increase in Chinese imports within a country-industry pair over is associated with around 3.2% more patenting at the firm level. Instrumenting the change in imports with WTO-related abolition of industry-specific quotas against China leads to qualitatively similar results.

Before we build our trapped factors model, we extend the existing empirical work to investigate this channel. In particular, we build two proxies for the strength of trapped factors: industry-specific wage premia and the level of firm TFP. Intuitively, wage premia may represent the rents from specificity in human capital inputs within industries. Here, industry-specific wage premia are measured as the coefficients on three-digit industry dummies in wage regressions using pooled cross sections of workers in the United Kingdom's Labor Force Survey from 1996 to 2007 (e.g. Krueger and Summers, 1988). We chose the UK because it has the most liberalized labor market in Europe, and we want our trapped factor measure to represent underlying economic forces rather than country-specific institutional features such as union power. Column 2 of Table 1 reports estimates from the specification in Column 1 augmented with the level of our wage premia proxy for trapped factors and its interaction with the change in Chinese imports. Firms in industries with higher wage premia exhibit a significantly stronger positive association between the change in patenting and increased Chinese imports.

Our second measure uses the calculation of measured firm-level TFP that might reflect the accumulated effect of investments in firm-specific inputs that are not easily transferable

[12] As discussed in detail in Bloom, Draca, and Van Reenen (2015), the baseline association between innovation and Chinese import growth is robust to a range of alternative horizons for computing changes, alternative patent-based measures of innovation, and alternative normalizations of Chinese imports on domestic product or apparent consumption.

Table 1: Innovation, Chinese Import Growth, and Trapped Factors

	(1)	(2)	(3)	(4)
Dependent Variable	$\Delta\ln(PATENTS)_{ijkt}$	$\Delta\ln(PATENTS)_{ijkt}$	$\Delta\ln(PATENTS)_{ijkt}$	$\Delta\ln(PATENTS)_{ijkt}$
Estimation Method	OLS	OLS	OLS	OLS
Change in Chinese Imports, ΔIMP^{CH}_{jkt}	0.321***	0.248***	0.287*	-2.479***
	(0.102)	(0.096)	(0.158)	(0.849)
Industry Wage Premium		-0.394***		
		(0.068)		
Change in Chinese Imports		2.808***		
* Industry Wage Premium		(0.959)		
Firm TFP_{it-5}				-0.287***
				(0.051)
Change in Chinese Imports				1.473***
* Firm TFP_{it-5}				(0.463)
Firms	8,480	8,480	5,015	5,015
Years	1996-2005	1996-2005	1995-2005	1995-2005
Industry-Country Clusters	1,578	1,578	1,147	1,147
Firm-Year Observations	30,277	30,277	14,497	14,497
Fixed Effects	Country-Year	Country-Year	Country-Year	Country-Year

Notes: *** denotes 1% significance; ** denotes 5% significance; * denotes 10% significance. Standard errors (in parentheses) are clustered by country and four-digit industry cell. Data on firm-level patenting comes from the European Patent Office linked to the Bureau Van Dijk Amadeus database of firm-level accounting information. Data on Chinese imports by industry-country cell is drawn from the UN Comtrade database, covering 12 nations. The industry wage premia are defined as the coefficients on three-digit industry dummies in a wage regression implemented using United Kingdom Labor Force Survey pooled worker cross-sections from 1996-2008, controlling for a quadratic in experience, schooling, region and gender. Firm level ln(TFP) is calculated using the de Loecker (2011) three-factor production function estimation method using labor, capital, and materials based on a restricted sample requiring each accounting variable, also drawn from the Amadeus database but covering 4 countries.

across firms. Since we measure only observable factor inputs and not the firm specific component, the conventional approach of deducting outputs from weighted inputs will mean that measured TFP is higher for companies with more firm-specific capital (see Appendix B for details).[13] For example, if firm-specific human capital is important and we measure just the number of workers, measured TFP will be much higher in those firms who have more firm-specific human capital.

We use the level of measured firm TFP in period t-5 before the start of the five-year changes in Chinese imports.[14] Measurement of TFP relies upon estimating separate production functions at the two-digit sector level using the de Loecker (2011) method. To do this, we must have data on capital, labor and materials inputs. Since materials inputs are not a mandatory item that needs to be reported in company accounts for all European countries, we focus on the four nations where materials are well reported - France, Italy, Spain and Sweden. Moving to this sub-sample, Column 3 re-estimates the baseline specification linking patenting to Chinese import growth. The link between patenting and Chinese imports is somewhat smaller but robustly positive and precisely estimated. Column 4 reveals that firms with higher levels of TFP exhibit a stronger association between patenting and Chinese import growth, again with a precisely estimated coefficient on the interaction.

Overall, the change in European firm-level patenting during the recent period of increased trade liberalization is consistent with a meaningful role for trapped factors. Not only is patenting higher in industries with more exposure to Chinese import competition, but this relationship appears to be strongest within industries that have more input specificity. This evidence is only suggestive because the measures of trapped factors could potentially reflect other forces than trapped factors. Nevertheless, the empirical findings motivate a deeper investigation of whether a coherent equilibrium model of endogenous growth can be constructed to interpret the patterns in the micro and macro data. We next turn to this task.

3 A Model of Trade and Growth

In this section we first describe the basic structure of the model for a closed economy. This lets us discuss the technology and highlight the key forces in the model. We then introduce product-cycle trade into the model between an innovating Northern economy and a low-cost Southern economy. We develop the open-economy model in two steps. First we compare steady-state growth with different levels of trade between the North and South. Then we

[13] The method of using measured TFP as a proxy for the "wedge" due to adjustment costs, specific capital and other frictions is in the same spirit as Hsieh and Klenow (2009).

[14] The required calculation of TFP before the first period of five-year changes expands the sample window backwards by one year in Table 1 columns 3 and 4.

turn to the transition dynamics between steady-states that arise after an unexpected trade liberalization. We introduce trapped factors in this second stage because they affect the transition dynamics of the model, not the steady state.

3.1 Technology

There are two types of inputs in 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 in a final goods sector, 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, $j \in [0, A_t]$:

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

Using the convention noted above, which broadly follows that in Romer (1987), 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 later calibrated choice of a 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 large number

N of intermediate goods firms indexed by f can use final goods 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 $t+1$. These assumptions imply that our model period of effective monopoly protection, 10 years, is somewhat shorter than the full length of statutory patent protection in the United States, a notion consistent with a range of empirical papers including Budish, Roin, and Williams (2015).

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:

$$M_{ft+1} = (Z_{ft})^{\rho} A_t^{1-\rho}, \tag{2}$$

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 steady-state growth by allowing for growth in the quantity of H. 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 ≈ 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 (2) to a cost function that exhibits increasing marginal costs of innovation in period t,

$$Z_{ft} = \nu M_{ft+1}^{\gamma} A_t^{1-\gamma}, \tag{3}$$

where $\gamma = \frac{1}{\rho} > 1$ and ν is an innocuously introduced scaling parameter.

Given the innovation cost function for a single intermediate goods firm f, the aggregate

R&D expenditure is immediately given by $Z_t = \sum_{f=1}^{N} Z_{ft}$. By symmetry and a choice of units that determines the value of ν, this simplifies to

$$Z_t = \frac{1}{\gamma} M_{t+1}^{\gamma} A_t^{1-\gamma}. \tag{4}$$

It follows from equation (1) that output will be proportional to A_t. Equation (4) then implies that allocating a constant fraction of output to the production of new designs will generate a constant exponential rate of growth of A. When coupled with standard CRRA preferences, standard arguments reviewed in Appendix A show that this economy has an equilibrium that exhibits steady-state growth at a constant exponential rate.

3.2 Open Economy

Next, suppose that there are two integrated economic regions, North and South. We treat the North as the home country and denote Southern variables 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. A firm in the South can subsequently produce any intermediate good as soon is it is off patent.

We show in an extension of the model in Appendix F that allowing for an empirically calibrated level of Southern innovation yields qualitatively similar results. However, no Southern innovation, our baseline assumption, is actually a realistic approximation to the data if we identify the North with OECD nations empirically. As plotted in Appendix Figure B1, patents granted in the US are overwhelmingly from OECD nations. Although non-OECD innovation as measured by patenting is increasing rapidly, the increase is from an extremely low base. For example, China in particular accounts for an average of 0.06% of US patents during 1977-2006.[15]

To allow for a continuum of possible levels of trade liberalization, 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, then Figure 2 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 for import into the North. Next come the R (for restricted) goods. These

[15] Chinese and non-OECD patenting rates remain extremely low relative to the OECD. Note, however, that Puga and Trefler (2010) raise the possibility that low-wage countries may be increasingly participating in "incremental innovation" abstracted from in this paper.

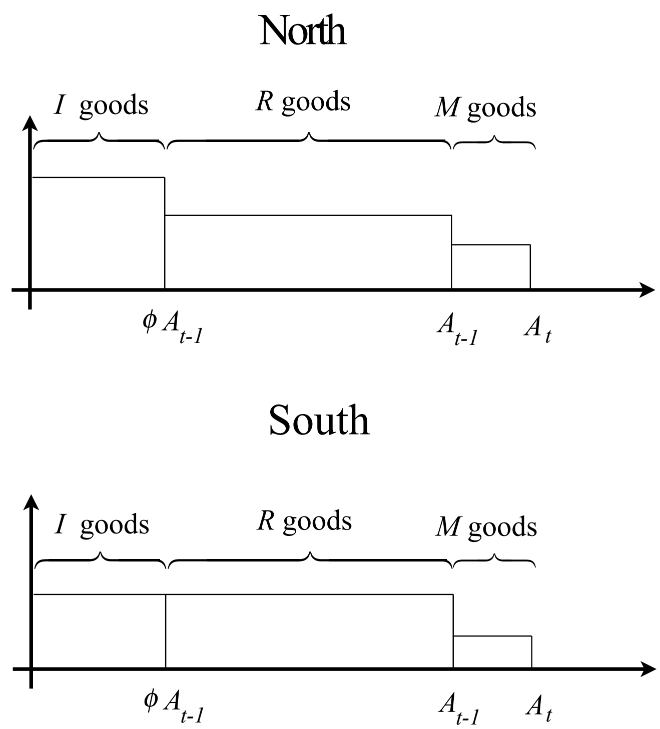

Figure 2: A Product Cycle in the Model

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. The vertical axis plots a stylized version of the equilibrium intensive margin for each class of good.

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 steady-state 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 steady-state growth rate that follows a policy change. The terms of trade q_t adjust to achieve trade balance in each period, which requires that the value of imports into the North, $p_{It}I_t x_{It}$, is equal to the value of the goods that the North sells to the South, $p_{Mt}M_t x^*_{Mt}$.

As in the usual product-cycle model, e.g. Krugman (1979), 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 steady-state 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.

Proposition 1 establishes a two-equation characterization of the steady-state growth rate and the associated terms of trade as functions of the trade parameter ϕ, with further details in Appendix A. Note that we use σ to denote the consumer risk aversion and β to refer to the consumer discount rate. Also, we define $\Omega = \alpha(1-\alpha)^{\frac{2-\alpha}{\alpha}}$ and $\Psi = (1-\alpha)^{\frac{\alpha-1}{2-\alpha}}$.

Proposition 1 *Open-Economy Steady-State Growth Path*

For low enough values of the trade parameter ϕ, the world economy follows a steady-state 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

$$g(\phi)^{\gamma-1} = \Omega\beta^{\frac{1}{\alpha}}(1+g(\phi))^{-\frac{\sigma}{\alpha}}\left(H + q(\phi)^{\frac{1}{\alpha}}H^*\right) \tag{5}$$

and the balanced trade condition

$$q(\phi) = \left(\frac{\phi H}{g(\phi)H^*}\right)^{\frac{\alpha}{2-\alpha}}\Psi \tag{6}$$

with $q(\phi) < 1$. **Proof in Appendix A.**

After substitution of equation (6) into equation (5), the growth rate $g(\phi)$ can be seen to be determined by the intersection of a downward sloping innovation marginal profit curve

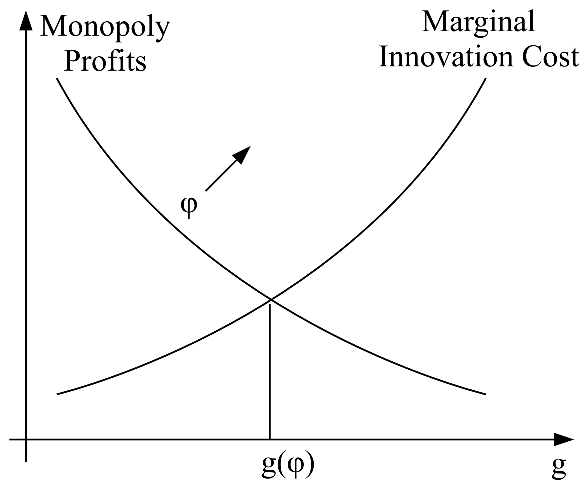

Figure 3: Steady-State Growth Path Equilibrium

Note: The figure plots the equilibrium innovation optimality condition for Northern intermediate goods firms in the steady-state growth path of the open-economy model. The innovation optimality condition pins down steady-state growth path growth rates in this framework, and as implied by Proposition 1 increases in the returns to innovation induced by increases in ϕ lead to strictly higher long-run growth rates.

with an upward sloping innovation marginal cost curve. For clarity, see Figure 3 which plots a stylized version of the equilibrium innovation optimality condition and the result in Proposition 1. The marginal profit of innovation is strictly increasing in the trade openness parameter ϕ, so the the open economy steady-state growth rate is strictly increasing in ϕ. This implies that the terms of trade $q(\phi)$ is also strictly increasing in ϕ.

Proposition 1 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.

In a standard closed economy growth model of this type, an increase in the stock of human capital leads to a higher growth rate. Here the growth rate depends on the term $H + q(\phi)^{\frac{1}{\alpha}} H^*$ which is proportional to the demand for any input and hence the profit that it will generate. 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 includes a downward adjustment induced by the terms of trade.

The long-run mechanics of the model are straightforward. A trade liberalization caused by an increase in ϕ leads to an increased flow of off-patent I goods from South to North. In order to balance trade flows in the face of this shift, the Southern terms of trade q increase. Therefore, Southern I goods become more expensive in the North, while newly innovated Northern M goods become cheaper when purchased in the South. The result is higher sales of M goods in the South, as well as higher overall profits at the margin for new Northern innovations. In response, innovation expenditures and growth rates increase.

3.3 Trade Shocks

The open economy analysis above characterized the constant perfect foresight growth rate associated with a constant value of the parameter ϕ. Next, we start from a steady-state growth path trade with trade policy 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.

First, it helps to think more concretely about the relationship between the trade restriction ϕ and the measure of varieties produced at each intermediate goods firm in the North. 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 exposed to import competition in each period. 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 for 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 which unexpectedly become unprofitable for Northern firms is $A_0(\phi' - \phi)$.

To match the micro data, which indicates that some firms 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 "Shocked" and "No Shock" firms. We assume that all the goods that are unexpectedly exposed to competition from imports are goods that were previously manufactured by the Shocked firms.

With these preliminaries in mind, Figure 4 presents the timeline of events within the period of a trade shock. The trade shock is announced at period 0 and becomes effective in period 1. We present two alternative sets of assumptions. In the first case, the "Fully Mobile" economy, firms can change their input decisions to accommodate the lost R goods production because their input demand choices are made after the new trade policy ϕ' is announced by Northern policymakers. By contrast, in the "Trapped Factors" case, we assume that firms make their input choices before the announcement of the new trade policy. Furthermore, we assume that all inputs, i.e. a bundle of both human capital and intermediates embodied in final output, are trapped within firms in the period of a trade shock. Inputs are trapped because of adjustment costs preventing re-assignment either across firms or into released consumption. The timing of events across the two alternative assumptions is otherwise identical. Furthermore, in all periods before and after the trade shock in period 0, realized policy is identical to anticipated policy and no adjustment frictions bind in either economy.[16]

It is worth pausing here to discuss the plausibility of our Trapped Factors assumption in more detail. In essence, we assume that adjustment costs trapping inputs within firms are entirely prohibitive or infinite in magnitude. While convenient analytically and for exposition, this is *not* required for our quantitative results. As we will highlight in the next section, the shadow value of inputs falls only by around 26% for the most heavily affected Shocked firms in our Trapped Factors economy in the face of a calibrated trade shock. Therefore, alternative finite levels of input specificity or other adjustment costs in a generalized version of the model would need only to be able to prevent adjustment in the face of moderate shifts in the internal value of inputs. Structural studies of input adjustment costs routinely yield empirical estimates much higher than this, e.g. around 35% irreversibility in the case of tangible capital inputs in Bloom (2009), so we find our adjustment cost assumption to be entirely plausible.

In order to calculate the full general equilibrium effects of a trade shock, we must take into account not only 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 trade shock economies can be found in Appendix A.

[16] Note also that in both the Fully Mobile and Trapped Factors economies, a sudden increase in imports from the South requires the immediate takeover of these production lines by Southern intermediate goods firms. We assume that in both cases, Southern intermediate firms anticipate the trade shock to allow for the sudden export jump.

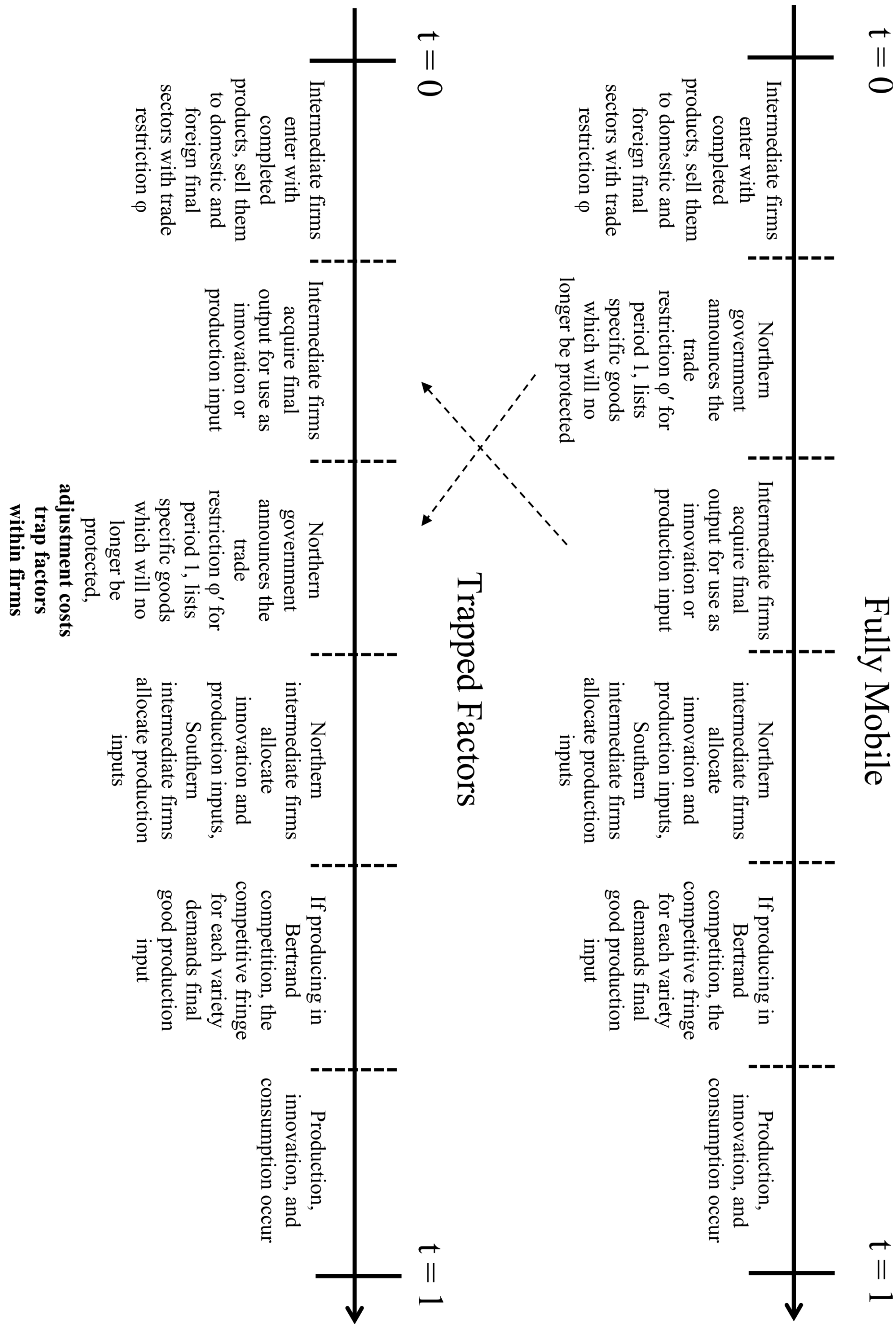

Figure 4: Timing of a Trade Shock

Note: This figure lays out the timing of trade shock announcement in the model. The upper timeline describes the assumptions of the Fully Mobile economy, and the bottom timeline describes the assumptions of the Trapped Factors model.

Before moving to the quantitative analysis, we also note that the description above is based upon an assumption that competition within the market for each off-patent variety takes place between only the intermediate goods firm which innovated that variety and a competitive fringe for that variety. In particular, another innovating firm cannot compete within the off-patent market of another intermediate goods firm, implying that any firms affected by a trade shock need simply to determine their input allocation between innovation of new varieties and production of their own remaining off-patent varieties. Given that our trapped factors timing assumption can be equivalently reframed as an assumption of input specificity, such a partition is natural.[17]

4 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 a trade shock over a full transition path. Appendices B and C give more details on the calibration and solution.

First, as mentioned above, we assume a model period of 10 years. Then, 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. As plotted in Figure 1, imports from non-OECD countries into the OECD almost doubled as a proportion of GDP over this period. China in particular accounts for almost half of the increase in low-wage imports. To match this pattern from the data, the model experiment we consider is an unanticipated, permanent trade shock moving from the steady-state growth path from trade policy ϕ to a new liberalized policy ϕ', as detailed in the theory section above.

4.1 Calibration

We started by specifying the basic parameters about which we have some prior information. 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 $\alpha = \frac{2}{3}$.[18] steady-state growth path real interest

[17] It is easy to analyze what would occur under the alternative assumption that intermediate goods firms could substitute towards production of another intermediate goods firm's off-patent varieties. In this case, Bertrand competition would dictate that the firm with the lower shadow value would take over a market. In equilibrium, the only possible outcome is equalization of shadow values through Shocked firms takeover of varieties previously produced by No Shock firms. Such an assumption would then eliminate heterogeneity in the behavior of Shocked and No Shock firms, directly contradicting our empirical evidence in Section 2 which suggests that innovation systematically varies with low-cost import competition in the cross-section.

[18] In our model the price of M goods is equal to $\frac{1}{1-\alpha} = 3$ times cost given $\alpha = \frac{2}{3}$, so the markup on new varieties is substantial. Importantly, however, the *average* markup in our calibration is much lower, since all

rates of approximately 4% require $\beta = (0.98)^{10}$. 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 on the calculation of H/H^*, and a later section checks robustness to different values of most of the parameters above.

Table 2: 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

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 steady-state 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.

We must also choose the final three parameters H, ϕ, and ϕ' which jointly govern the model's long-run steady-state growth rates and imports to output ratios. 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 steady-state growth paths, respectively. In other words, we require that the model reproduce the endpoints of the non-OECD imports series plotted in Figure 1. 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 frontier per-capita GDP growth. We therefore prefer to calibrate long-run frontier growth to the per-capita GDP growth of the United States rather than the entire OECD. We choose a wide sample window of 1960-2010, yielding a calibration of H to match a pre-shock average annual growth rate of 2.0%.[19]

off-patent varieties of I and R goods are perfectly competitive. In our pre-trade shock baseline steady-state growth path calibration described below, the average markup is approximately 40%.

[19] We take two steps to examine the robustness of our results to this calibration strategy. 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.

4.2 The Long-Term Impact of a Trade Shock

We summarize the long-term impacts of trade liberalization in our model in Table 2. 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, through the effective market size effect discussed in Section 3, a movement in the long-term growth rate from its pre-shock calibrated value of 2.0% to a new value of 2.37%.

4.3 Transition Dynamics in the Fully Mobile Economy

Next we consider the transition dynamics of the fully mobile economy, starting from the steady-state 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.

In Figure 5, we plot the aggregate transition dynamics of the Fully Mobile economy for aggregate variety growth, the terms of trade, and output growth in the North and South. Although it remains unplotted in this figure, consumption growth follows the pattern of output growth almost identically.

The full transition to the new steady-state growth path is complete in approximately 6 periods (60 years). Given the trade liberalization shock, the Southern terms of trade increases rapidly to maintain balanced trade, leading to an associated increase in the returns to innovation and hence the aggregate variety growth rate. Consumption smoothing dictates a slower, smooth transition of output growth rates to their long-run values.[20]

We can also compute the long-run welfare gains from trade in the fully mobile environment, taking the transition path into account, and we report these in Table 3. 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.[21]

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 (2015) and relying primarily upon love of variety gains from liberalization, suggests that welfare gains

[20] 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.

[21] 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.

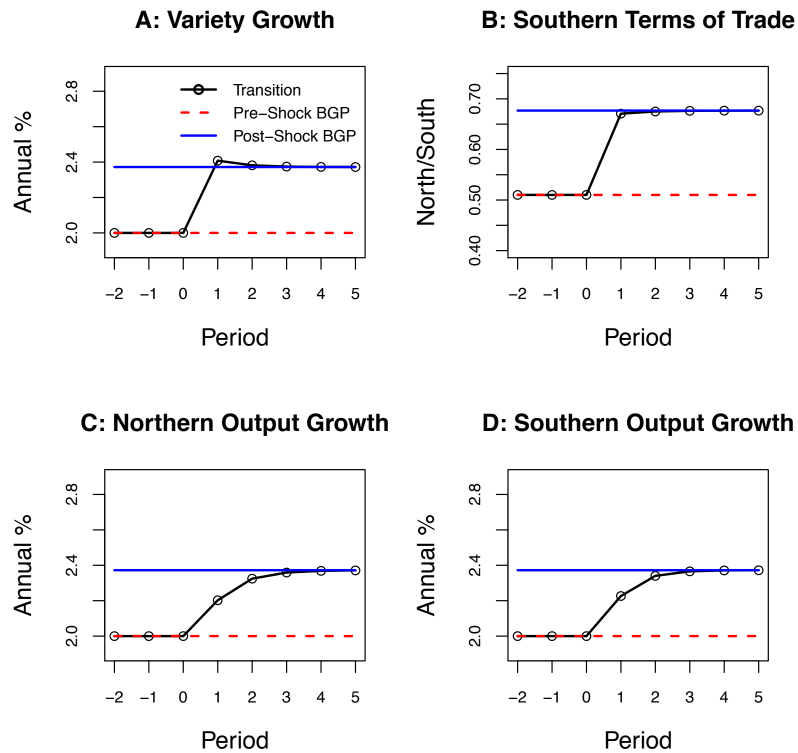

Figure 5: Liberalization Boosts Growth in the Fully Mobile Model

Note: The figure displays the 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 steady-state growth path, and the lower horizontal dashed red line is the pre-shock steady-state growth path.

from *all* trade for the US around the year 2000 are approximately 2.5%. It is clear that the higher rate of growth induced by the liberalization could be a powerful source of welfare improvement from trade.

4.4 Transition Dynamics in the Trapped Factors Economy

In Figure 6 we plot the path of some selected aggregates over a Trapped Factors transition path. Comparing the Trapped Factors transition with the Fully Mobile transition in Figure 5, 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.

Table 3: Trade Shocks, Short-Term Growth, and Welfare Gains

%	Short-Term Growth, $t = 1$	Welfare Gains, Full Transition
Fully Mobile	2.4	14.2
Trapped Factors	2.7	16.3
No China	2.4	7.2

Note: The first column of the table above presents the variety growth rate in the first period of a trade shock, $t = 1$, and the second column presents the consumption-equivalent welfare gain of the Northern consumer from trade liberalization, taking the full transition path into account. Each row represents one of three alternative economies. The first two are the Fully Mobile and Trapped Factors economies, with liberalization experiments and long-run effects of trade shocks identical to those laid out in Table 2. The final economy is a counterfactual No China environment. The No China experiment is described in Section 4.5, representing partial liberalization under the Trapped Factors assumption but omitting the effects of increased Chinese imports into the OECD over the sample period.

Recall that we assume that there are two industries with half of the firms each. One of these industries (Shocked) contains all the shocked firms and bears the brunt of the direct effects of liberalization. The other industry, No Shock, has no liberalized R goods. 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 downward-sloping lines and the red right bar with upward-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 both industries increase patenting during the shock period due to terms of trade movements, the Shocked industry patents approximately 28.8% more in the period after the shock.

The differential impact in Figure 7 of trade shocks on innovation across exposure levels is entirely absent in the Fully Mobile economy. In that environment, by contrast, Shocked and No Shock firms engage in identical levels of patenting in period 1, since fully flexible innovation choices are entirely forward-looking. Our model therefore implies that the presence of trapped factors or input adjustment costs leads to higher sensitivity of patent growth to trade liberalization in the cross-section. This implied link is entirely consistent with our disaggregated empirical results from Table 1 documenting a larger increase in innovation in

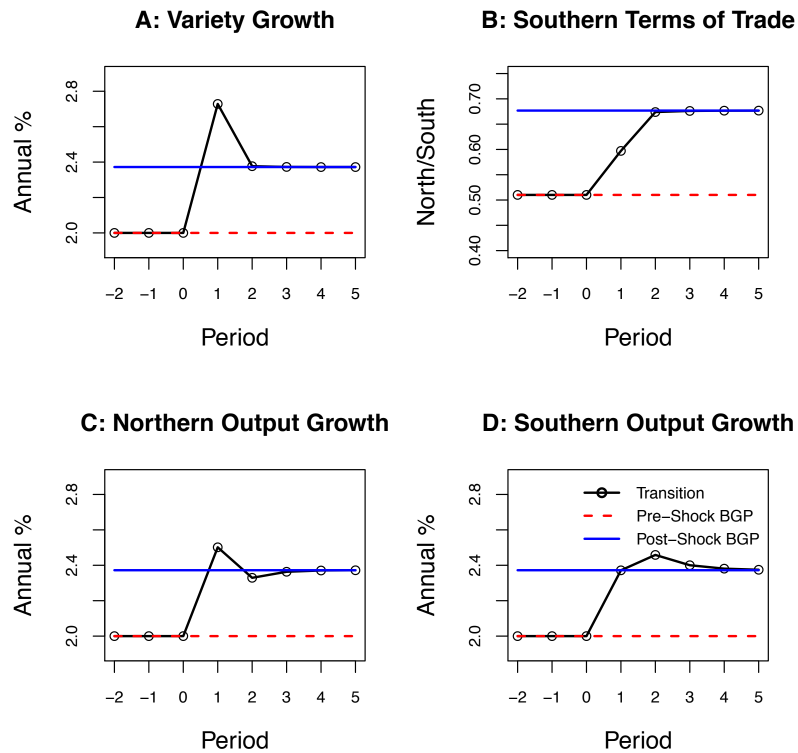

Figure 6: Trapped Factors Increase Short-Run Growth

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 steady-state growth path, and the lower horizontal dashed red line is the pre-shock steady-state growth path.

those industries and firms with higher measured levels of trapped factors.

The stark increase in innovation or patenting at firms in the shocked industry is directly linked to a surplus of resources useful for R&D at those firms, which unexpectedly lose 24% of their R goods varieties to import competition. In Figure 8 we expand the set of variables included in the Trapped Factors transition path. In the top two panels we can see the shadow value of resources in each industry, which in 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 panel we see an opportunity cost or resource shadow value decline of 25.5% in period 1 for firms in the Shocked industry. As noted above, these declines in the shadow value of inputs

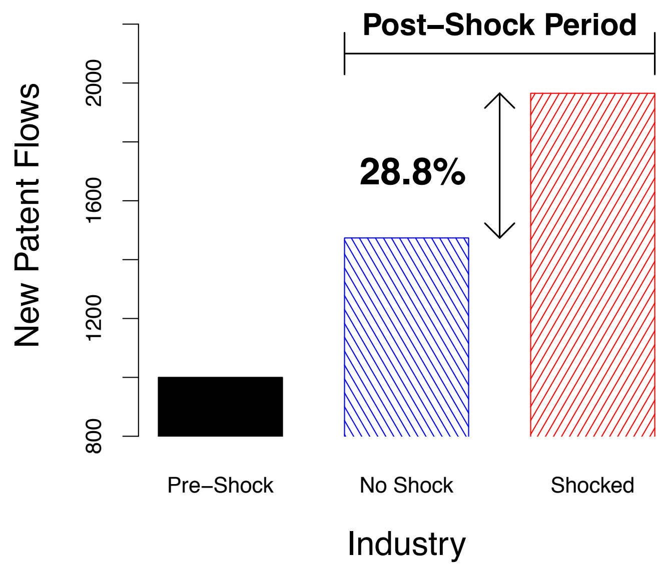

Figure 7: A Shocked Industry Patents More

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 No Shock 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.

are moderate compared to existing empirical estimates of adjustment costs within firms, lending quantitative plausibility to our underlying trapped factors assumption.

In the upper right panel 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. 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'

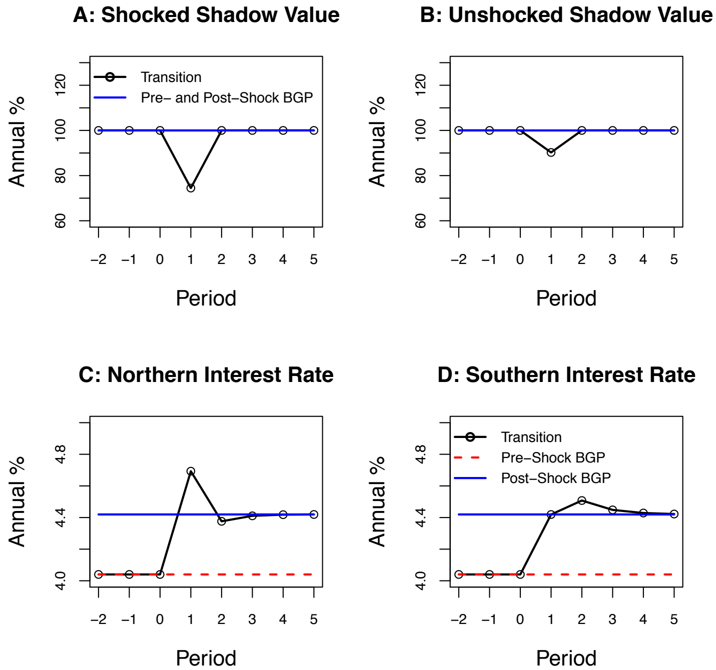

Figure 8: Trapped Factors Interest Rates and Shadow Values

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 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 steady-state growth path, and the lower horizontal dashed red line is the pre-shock steady-state growth path. For the two shadow value figures, shadow values are normalized to equal 100% in non-shock periods.

shadow values to deliver consistency with their value-maximization problem.

Turning again 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. 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 in 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%) in the long-term. However, while this is small overall, in the first period or 10 years of our simulation trapped factors roughly doubles the impact of the trade shock on innovation. So the short-run impact of this mechanism is quite large and may thus be important for policy horizons and empirical analysis.

4.5 What is the Contribution of China to OECD Growth?

Our model suggests that there was a market size effect and a trapped factors effect from the expansion of low-wage country trade from 1997 to 2006. Given the intense policy interest and recent academic literature in the area,[22] we now consider 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 in reality but that exports from China remained constant as a fraction of OECD GDP. With the resulting "No China" counterfactual, maintaining our trapped factors assumption, we can calculate by how much growth and welfare increase in our baseline because of the effect of China alone.

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. Figure 9 plots the Trapped Factors transition path in the baseline and No China cases. The growth and terms of trade effects of liberalization are dampened considerably.

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 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 steady-state 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 crucial when quantifying dynamic gains from liberalization over this period.

A caveat to this strategy is that it assumes a counterfactual world in which policymakers 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-

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

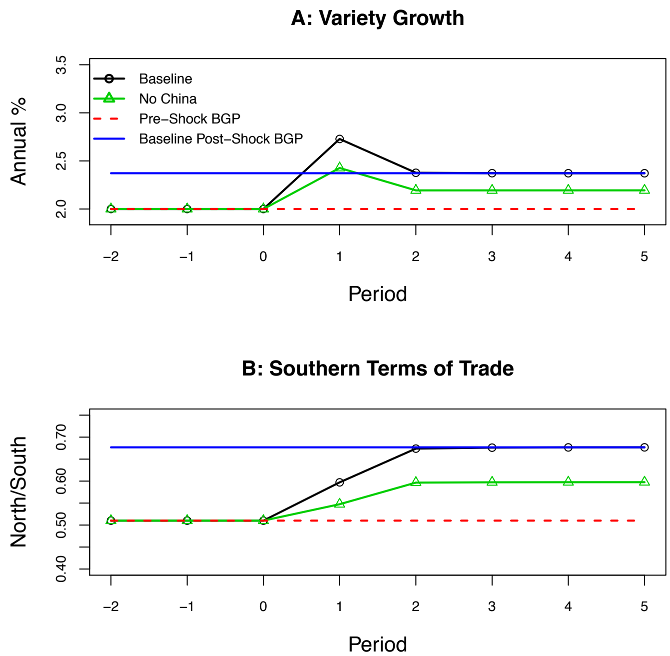

Figure 9: Trade Liberalization without Chinese Import Growth

Note: The figure displays the transition path in response to trade liberalization in two scenarios. The first transition path, in solid black, "Baseline," replicates the Trapped Factors transition path displayed in Figure 6 above. A permanent and unanticipated trade liberalization 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 "Baseline," 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 steady-state growth path, and the lower horizontal dashed red line is the pre-shock steady-state growth path.

Chinese countries. As expected, these results essentially halve the Chinese contribution to innovation and welfare.

5 Extensions and Robustness

In this section we discuss some extensions and the robustness of our results to various alternative assumptions and calibrations.

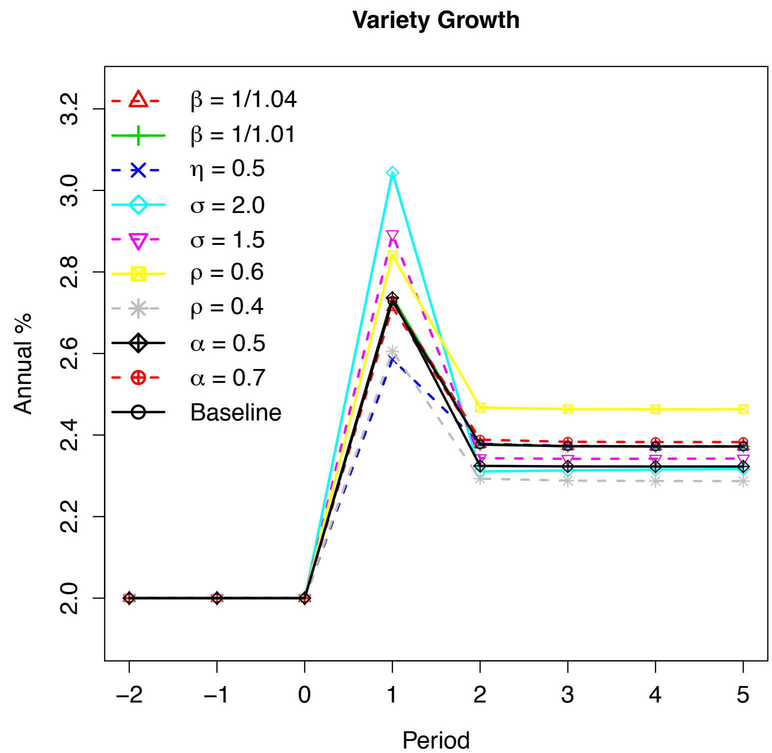

Figure 10: Trapped Factors Transition Dynamics are Robust

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 parameterizations of the model vary only the parameter indicated in the legend, starting from the Trapped Factors calibration described in the text.

5.1 Robustness of Calibration

The qualitative effect of trade liberalization on growth, and the boost of innovation from the trapped factors mechanism, are quite robust to alternative parameterizations. To demonstrate this we vary parameter values and consider the impact upon the variety growth rate in the Trapped Factors transition in Figure 10. In none of these cases is the pattern or magnitude qualitatively changed. Finally, in an unreported robustness check, we used an alternative calibration window of the pre-shock growth rate to the US per capita real GDP growth rate from 1960-2001, with qualitatively similar dynamics starting from a different growth level.

5.2 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 such models, steady-state growth no longer depends on the level of human capital but instead on the growth of human capital. 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, allowing for growth in human capital. Reasonably calibrated transition dynamics are extremely persistent, and long-run differences between our baseline model and the semi-endogenous growth model are heavily discounted into the future. The two model assumptions therefore deliver remarkably similar quantitative welfare results.

5.3 R&D Congestion Effects

Another concern with our baseline model is that R&D could have cross-firm congestion effects from research duplication or patent races. In an extension discussed in detail in Appendix E, we also introduce a model parameter η which allows for R&D congestion externalities. η flexibly nests our baseline case of no congestion externalities, ($\eta = 1$), but also allows for intermediate degrees of congestion all the way to the extreme case of full externalization of R&D costs ($\eta = 0$).

Empirical evidence suggests that these congestion effects are not large in the economy as a whole. Bloom, Schankerman, and Van Reenen (2013) estimate congestion effects from a large sample of US firms and find them to be statistically insignificant (i.e. $\eta = 1$).[23] Consequently, we have chosen to omit R&D cost externalities from the baseline model. For completeness, however, we also consider the intermediate case of $\eta = 0.5$ in Figure 10. In this case, congestion externalities dampen the magnitude of the short-term growth boost from trade. The dampening effect is not quantitatively large, however, and the long-run growth effect remains the same.

5.4 Southern Innovation

Our construction of the baseline model above assumes that no innovation occurs in the Southern economy. In Appendix F we extend the model to incorporate innovation of new varieties by Southern intermediate goods firms. To match low non-OECD patenting rates in the data, we allow for and calibrate lower relative productivity in innovation in the

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

South. As discussed in more detail in Appendix F, the presence of Southern innovation implies that import ratios in the North are less sensitive to trade liberalization, requiring a larger liberalization shock to match the observed increase in low-cost import penetration in the North. Although the dynamic patterns are very similar, the larger required shock with Southern innovation implies that the baseline results above conservatively report the potential long-term dynamic benefits from trade liberalization. In particular, growth rates in the economy with Southern innovation increase from 2.0% to 2.7% in the long-term, which can be compared to the increase from 2.0% to 2.4% observed in the baseline environment without Southern innovation.

5.5 Other Effects of China on Welfare

Trade between OECD countries and low-wage countries like China can have a large number of effects in addition to the ones we consider. We focus on its impact on the incentives for developing new goods because of the sheer potential scale of the dynamic gains from trade.

The most important potential offset to these gains, however, might come from the labor market. Our model, like many others in trade, abstracts away from the unemployment and wage losses that may arise as workers are reallocated. Recent work by Pierce and Schott (2012), Autor and Dorn (2013) and Autor, Dorn, and Hanson (2013) suggests that these dislocation effects can be substantial. There may be long-run effects on inequality through Heckscher-Ohlin factor price equalization effects or imperfect labor markets. 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, with some evidence for the theory in Helpman, Itskhoki, Muendler, and Redding (2012).

When our adjustment costs trap 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, so that in effect our approach is equivalent to making the assumption that there is a perfect insurance market among all residents in the North. 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, it does not immediately follow that adjustment costs necessarily reduce the gains from trade.

5.6 Anticipation Effects

We have modeled the trade shock as being unexpected to firms. Although events such as China's WTO accession were of course partially anticipated, there was some surprise as negotiations were fraught. Moreover, in the entire European Union the liberalizations with China were temporarily reversed due to a political backlash.

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 anticipates the liberalization. Hence, Northern firms will start shifting into innovative activities prior to the liberalization. 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 short-run effect from trade by increasing adjustment costs. Increasing firing costs, for example, will certainly make factors more trapped, but it would itself signal impending liberalization and undue the desired innovative effect.

5.7 Patent Length vs. Adjustment Cost Horizon

Embedded within our analysis is an assumption that the model period, 10 years in our calibration, represents both the monopoly protection period and the period over which factors are trapped. While this is not an unreasonable assumption given large empirical estimates of adjustment costs,[25] it is clearly very stark and worth exploring.

Allowing asset and monopoly lengths to differ would considerably complicate our analysis. However, we can consider the impacts qualitatively by examining the two potential cases arising from delinking the monopoly horizon (T^M) years, from the adjustment cost horizon (T^A). First, if $T^A > T^M$, then adjustment-cost induced periods of immobility are longer than monopoly protection. Trapped inputs would be used for the innovation of multiple cohorts of new varieties, which would likely not change the results qualitatively.

In the alternative case of $T^A < T^M$, pre-innovated cohorts of on-patent varieties may exist within firms at the time of a trade shock. These pre-existing monopoly varieties would offer an alternative substitution possibility into which trapped resources could be directed instead of innovation. 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 markups. Hence, the net impact on welfare is ambiguous.

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

[25] 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. Also, while patent lengths vary between 15 to 20 years, effective patent lengths are typically shorter due to imitation, processing lags, and imperfections in enforcement. As such, a 10 year patent life seems quite reasonable in our theoretical structure.

6 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 input specificity. 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 suggests. Trapped factors in the model can also explain additional cross-sectional patterns which we document, suggesting that the increase in innovation in the face of Chinese competition is stronger for firms with higher levels of input specificity.

The force behind this pattern in our model is a fall in the opportunity cost of R&D caused by a fall in the shadow cost of these trapped factors. The model also contains the more standard theoretical mechanism from the literature on trade and growth, whereby integration increases the profits from innovation.

We calibrate the 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. 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. A moderate fraction of the overall welfare gains from trade in the long-term, 2% out of a total 16%, are due to our trapped factors mechanism. However, the short-term impact of trapped factors is large, contributing an additional 0.3% to growth in the immediate aftermath of liberalization. Such short-term impacts are likely important at a policymaking horizon.

Note that the dynamic gains from trade in terms of growth or welfare depend entirely upon 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. We briefly touch on some additional potential avenues for exploration here. First, we have abstracted from "catch-up" in which growth rates in the South are higher than in North due to imitation or input accumulation. We did this in order to focus on welfare benefits in the North from loosened trade restrictions alone. 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 due to within-OECD liberalization. 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 distributional changes. Workers may suffer wage losses and unemployment if we introduce frictions in the labor market. These do seem to matter empirically, and more work needs to be done in the future to incorporate such effects in quantitative theory models (e.g. Harrison, McLaren, and McMillan 2011; Pessoa 2015).

The main message of our paper is that liberalized trade with the South can have substantial benefits 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 firm can earn from a newly developed good, but also because of a strong contribution from trapped factors in the short run that reduces the opportunity cost of innovation. China alone accounts for almost half of the gains 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 some of the long-term effects we document 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

Appendix A - Theoretical Details and Proofs

In this appendix we give more technical details and proofs of our main results. We begin with a full statement of the equilibrium concept for the closed economy, as well as a characterization of the closed-economy steady-state growth rate referred to in the main text. We then state the open economy equilibrium definition, characterize steady-state open economy growth rates, and define the trapped factors trade shock equilibrium.

Definition 1 *Closed-Economy Equilibrium*

Given initial conditions A_0, x_{j0} , 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

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

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

Final Goods Firm Optimizes: Taking wages w_t and intermediate goods prices p_{jt} 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

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

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_{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

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

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

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

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

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

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:

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

Proposition A1: Closed-Economy Steady-State Growth Path
The closed economy has a unique steady-state growth path with a common constant growth rate g for varieties, output, and consumption, that satisfies the innovation optimality condition

$$g^{\gamma-1}=\Omega\beta^{\frac{1}{\alpha}}(1+g)^{-\frac{\sigma}{\alpha}}H,\quad \Omega=\alpha(1-\alpha)^{\frac{2-\alpha}{\alpha}}.$$

Proof of Proposition A1 To complete the proof of Proposition A1, we need to show that the rates of growth of output, consumption, and varieties are equal on a steady-state growth path. First, note that the first-order conditions of the intermediate goods firm monopoly pricing decision immediately yield

$$p_{Mt+1}=\frac{1+r_{t+1}}{1-\alpha},$$

i.e. they imply that the monopoly price in any future period $t+1$ is a fixed markup over firm marginal cost. Marginal cost is given here by the interest rate r_{t+1} from the current period t into the next period $t+1$. The household Euler equation immediately implies the interest rate $r_{t+1}=\frac{1}{\beta}(\frac{C_{t+1}}{C_t})^{\sigma}$. We then immediately obtain the optimal intermediate goods firm pricing rule $p_{Mt+1}=\frac{1}{\beta}(\frac{C_{t+1}}{C_t})^{\sigma}\frac{1}{1-\alpha}$. For later reference, note that the pricing of off-patent varieties, which we will label R goods, is given by $p_{R+1}=1+r_{t+1}=\frac{1}{\beta}(\frac{C_{t+1}}{C_t})^{\sigma}$ via perfect competition and the household Euler equation.
Now write the final goods market clearing condition

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

where we are using the notation that the measure of off-patent varieties is given by R_t

and equal to $R_t = A_{t-1}$, and the measure of innovated varieties $M_t = gA_{t-1}$. Now, recall the assumption of steady-state 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, i.e. the first-order condition of an intermediate goods firm with respect to R&D expenditures, 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 steady-state 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 steady-state 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 0 when $g = 0$, 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 0 as $g \to \infty$. We conclude that a steady-state growth path equilibrium exists and is uniquely determined by the value of g which satisfies the innovation optimality condition. This completes the proof.

Definition 2 *Open-Economy Equilibrium*

Given any initial conditions A_0, x_{j0}, x_{j0}^* , 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 $s_{ft}, s_{ft}^*, b_{t+1}, b_{t+1}^*, H_t^D, H_t^{*D}, x_{jt}^D, x_{jt}^{*D}$, x_{jt+1}^S, x_{jt+1}^{*S}, 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

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

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

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

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

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

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

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

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

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

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^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

$$\begin{aligned} H^D_t &= H, \ H^{*D}_t = H^*, \\ b_{t+1} &= 0, \ b^*_{t+1} = 0, \\ s_{ft} &= 1, \ s^*_{ft} = 1, \\ x^D_{jt} &= x^S_{jt}, \ x^{*D}_{jt} = x^{*S}_{jt}. \end{aligned}$$

Final Goods Markets Clear

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

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

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 M goods that the firm plans to produce for next period, as well as the number of R goods 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 R goods held by each firm f, as well as the actual allocation of the trade shock liberalization among existing firms' measures of R goods. We now define some additional notation. Let $\widetilde{s}_f$ be the share of off-patent R goods production firm f anticipates doing before the trade shock, where $\sum_{f=1}^{N} \widetilde{s}_f = 1$. Then, let the trade shock allocate destruction of R goods production opportunities across firms so that only the proportion χ_f of R goods varieties can still be produced in each firm. As long as we have the consistency condition

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

an arbitrary choice of χ_f will be consistent with the trade shock $\phi \to \phi'$. We will henceforth make the assumption that $\widetilde{s}_f = \frac{1}{N}$ for all firms, i.e. that pre-shock allocations of R goods 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 the "No Shock" industry, industry 1. The other half of firms in the economy, those in the "Shocked" industry 2, experience a loss of R goods production opportunities during the trade shock with only a fixed proportion χ_2 of R goods 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 1 in our environment. We now define a trapped factors equilibrium formally.

Definition 3 *Trapped Factors Trade Shock Equilibrium*

Given any initial conditions A_0, x_{j0}, x^*_{j0} and a sequence of trade restrictions

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

where the trade shift from ϕ to $\phi' > \phi$ is unanticipated and affects only Shocked industry 2, leaving the proportion χ_2 of R goods in industry 2 restricted, 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 $s_{ft}, s^*_{ft}, b_{t+1}, b^*_{t+1}, H^D_t, H^{*D}_t, x^D_{jt}, x^{*D}_{jt}, x^S_{jt+1}, x^{*S}_{jt+1}$, $M_{ft+1}, A_{ft}, A^*_{ft}, d_{ft}, d^*_{ft}, M_t, I_t, R_t$, and A_t such that the following hold.

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

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

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

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

$$\max_{C^*_t, b^*_{t+1}, s^*_{ft}} \sum_{t=0}^{\infty} \frac{\beta^t \left(C^*_t\right)^{1-\sigma}}{1-\sigma}$$

$$b^*_{t+1} + C^*_t + \sum_{f=1}^{N} q^*_{ft}(s^*_{ft} - s^*_{ft-1}) \leq (1 + r^*_{t+1})b^*_t + w^*_t H^* + \sum_{f=1}^{N} d^*_{ft} s^*_{ft}.$$

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^D_t and intermediate goods input demands x^D_{jt}, 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, 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

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

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

$$\int_{A_{ft+1}} (x_{jt+1} + x_{jt+1}^*) dj + Z_{ft} \geq X_{ft}\left(\phi_{t,t+1}^E\right)$$

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

where we have that

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

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_{jt+1}^S, x_{jt+1}^{*S}, i.e. these quantities solve

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

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

Labor, Bond, Stock, and Intermediate Goods Markets Clear

$$H_t^D = H,\ H_t^{*D} = H^*,$$
$$b_{t+1} = 0,\ b^*_{t+1} = 0,$$
$$s_{ft} = 1,\ s^*_{ft} = 1,$$
$$x^D_{jt} = x^S_{jt},\ x^{*D}_{jt} = x^{*S}_{jt}.$$

Final Goods Markets Clear:

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

$$Y_t^* = (H^*)^\alpha \int\limits_0^{A_t} \left(x^*_{jt}\right)^{1-\alpha} dj = C_t^* + \int_{R_{t+1}} x^*_{jt+1}dj + \int_{I_{t+1}} (x_{jt+1} + x^*_{jt+1})dj$$

No Arbitrage Pricing Condition Holds

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

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.

Proof of Proposition 2: Open Economy Steady-State Growth Path The demand schedules for intermediate goods, based on the Northern and Southern final goods firms' technologies, are given by

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

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

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

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

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

where $\Psi = (1 - \alpha)^{\frac{\alpha-1}{2-\alpha}}$. Applying the assumption of steady-state 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 $A1$, the final goods market clearing conditions for each economy, together with the assumption of steady-state growth, imply that the ratios

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

are constant, so that we conclude that

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

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

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

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 steady-state growth path equilibrium for this economy, and that it is the unique steady-state 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 - Data and Model Robustness Checks

This Appendix first describes the firm-level data sources and variable construction used in for the production of Table 1 in Section 2. Then, we describe the aggregate data sources and construction of the series used to calibrate our model and for various figures throughout the paper. We conclude by listing the results of robustness checks to alternative model calibrations and assumptions for the quantitative trade liberalization exercises in Section 4.

Innovation & Trade Data from Bloom, Draca, and Van Reenen (2015)

This subsection describes the data used in Bloom, Draca, and Van Reenen (2015) as well as in Section 2 of this paper to construct Table 1. First, we broadly describe the data sources involved. Then we discuss the construction of the industry wage premium proxy for trapped factors, as well as the calculation of firm-level TFP. Further details on the sample selection, variable construction, and descriptive statistics can be found in the main text as well as Appendices A and B of Bloom, Draca, and Van Reenen (2015).

The baseline specifications in Table 1 draw upon the firm-level accounting information from both public and private European firms contained in the Bureau Van Dijk Amadeus database. In columns 1 and 2, data comes from twelve European countries Austria, Denmark, Finland, France, Germany, Ireland, Italy, Norway, Spain, Sweden, Switzerland and the United Kingdom. This is broadly the population of firms who we then match to the population of patent applications in the European Patent Office. The measure $\ln(\text{PATENTS})_{ijkt}=\ln(1+\text{PAT}_{ijkt})$, where PAT_{ijkt} is the number of successful patent applications filed by firm i in industry j in country k in year t. Then, four-digit industry codes from the Amadeus database allow for a link to the UN Comtrade database on industry by country imports and exports. Imports from China in industry j in country k in year t are equal to the ratio of Chinese imports in the same industry-country-year cell to total imports in the same industry-country-year cell, i.e. $\text{IMP}^{CH}_{jkt} = \frac{M^{China}_{jkt}}{M^{World}_{jkt}}$. For firms that operate across multiple four digit industries we use a weighted average of Chinese import shares across these different industries. Five year differencing yields $\Delta \ln(\text{PATENTS})_{ijkt} \equiv \ln(\text{PATENTS})_{ijkt} - \ln(\text{PATENTS})_{ijkt-4}$ and $\Delta\text{IMP}^{CH}_{jkt} \equiv \text{IMP}^{CH}_{jkt} - \text{IMP}^{CH}_{jkt-4}$.

In column 2 of Table 1 we augment $\Delta \ln(\text{PATENTS})_{ijkt}$ and $\Delta\text{IMP}^{CH}_{jkt}$ with data on industry wage premia. These are computed from auxiliary worker-level Mincerian wage regressions on data from pooled cross sections in the United Kingdom's Labor Force Survey (LFS). The LFS data provides representative cross-sections of worker-level hourly wages in two quarters, representing the first and last periods of five quarters of data collection for each worker in a given year's sample. Altogether, the sample consists of 107,622 observations drawn from the 1996 to 2007 releases, covering 1996-2008. For three-digit industry j, the industry specific wage premium υ_j is defined as the coefficient on an industry dummy from the OLS regression

$$\ln w_{lt} = \psi' x_{lt} + \sum_j \upsilon_j IND_j + \xi_{lt},$$

where w_{lt} are hourly wages for worker l in quarter t, IND_j is a dummy for each of the three-digit industry codes in the LFS sample, and x_{lt} is a vector of controls including dummies for each of four education levels, a quadratic in age, as well as gender, year, and regional dummies.

In columns 3 and 4 restrict the analysis to France, Italy, Spain, and Sweden, which are the only nations for which accounting regulations insist on detailing materials inputs and hence have wide coverage of this item in BVD Amadeus. We follow the extension of the Olley-Pakes control function method de Loecker (2011). As described in detail in Appendix

B of Bloom, Draca, and Van Reenen (2015) we estimate production functions allowing for imperfect product market competition. These are estimated separately by two digit sector based on a control function approach.

To understand how we can proxy trapped factors using TFP consider the basic production function:

$$\ln Y = A + \sum_f \alpha^f \ln X^f,$$

where Y is output, A is "true" TFP, and X^f is factor input f (L is labor, K is capital, and M is materials in our case) with output elasticities in the vector α. Now allow each factor to be composed of a base input X_B and a firm-specific element, $X_S = \theta^f X_B$, $\theta^f \geqslant 0$. The econometrician observes only the base input X_B. An example would be labor where the econometrician observes the number of workers, and possibly their observable characteristics like schooling and age, but not the fact that some workers have firm-specific human capital due to training, etc. Conventionally measured TFP, $MTFP$ is:

$$\ln MTFP = \ln Y - \sum_f \alpha^f \ln X_B^f = \ln A + \sum_f \alpha^f \ln(1+\theta^f)$$

So measured TFP will be equal to true TFP (A) plus a positive term ($\sum_f \alpha^f \ln(1+\theta^f)$) that is increasing in the importance of trapped factors. If there are no trapped factors $\theta^f = 0$ and measured TFP is equal to true TFP. But for firms who have more trapped factors, measured TFP will be higher. If A is the same for all firms in an industry, then a firm's MTFP relative to the industry average, which is what we use in the empirical work, is the correct measure of the importance of trapped factors for a firm.[26]

A drawback of this method is that we only identify within industry variation in trapped factors. If all firms have exactly the same amount of trapped factors in an industry, because TFP is measured relative to an industry average if will appear as if there are no trapped factors. This is an intrinsic problem when we are not prepared to make TFP comparisons across industries. It is why it is useful to use this method in conjunction with the previous method that focuses on industry-wide wage premia as an alternative measure of trapped factors.

Calculating the ratio of H to H^* for model calibration

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 are 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

[26] Using a Solow residual approach instead of the regression based approach used here for estimating the $\alpha' s$ would also work. Even if one were to use firm-specific shares in costs, factors will not be paid their full marginal product and so their contribution to output will be underestimated. For example, consider firm-specific human capital. The firm generally pay some of the cost of the initial training cost of the worker acquiring firm specific human capital as the worker cannot realize this value if she leaves the firm. In the Becker model the firm pays all of the firm-specific training costs and does not raise the wage at all after training is acquired.

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 for Figure 1

The real per-capita output growth rate is from the US NIPA tables, computed as the average annual real GDP per capita 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 over the years 1997-2006. The period was chosen to incorporate the accession of China to the WTO in 2001, and the 10-year window accords with the model calibration of a period to 10 years. All of the data and simple calculations performed in the calibration procedure are available on Nicholas Bloom's website: `http://www.stanford.edu/nbloom`. Figure 1 plots the non-OECD imports to OECD GDP ratio over this period, together with Chinese imports into the OECD.

Computing Patent Ratios for Figure B1

United States Patent and Trademark Office data on patents granted from 1977-2006, by application year and nationality of assignee, were downloaded from the NBER website for the Patent Data Project in early 2013. This website represents an update of the data which was originally collected and documented in Hall, Jaffe, and 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. Figure B1 plots the proportion of all US patents granted by application year from any foreign nation, from non-OECD countries, and from Chinese assignees, for the years 1977-2006.

Trade Policy Substitution away from China

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 B2 plots the resulting two trapped factors transition paths, analogous

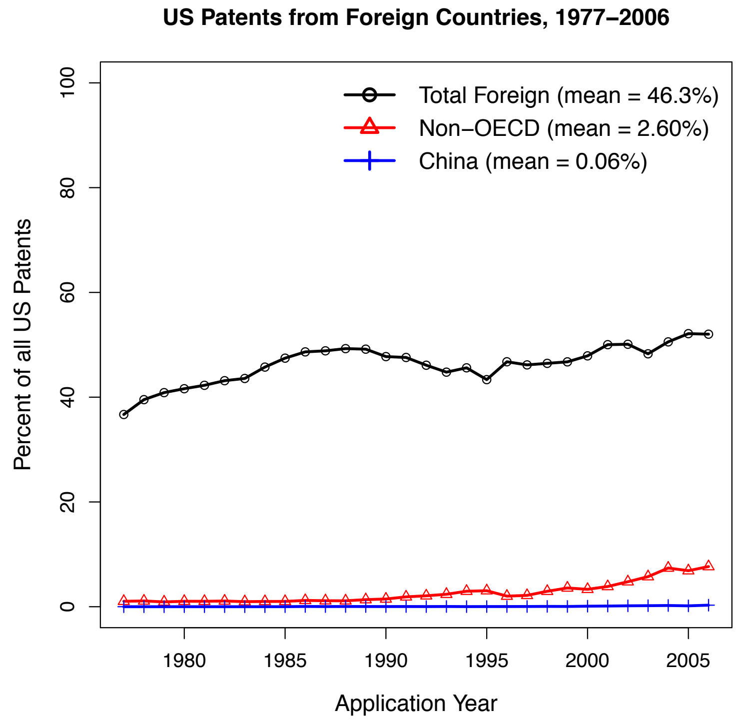

Figure B1: Non-OECD Patent Ratios are Small

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 number of granted US Patent and Trademark Office applications in the same year. The reported means are computed over the full range 1977-2006.

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 steady-state growth path growth rate, as well as the maximum growth rate along the trapped-factors transition path, for a number of alternative parameter choices.

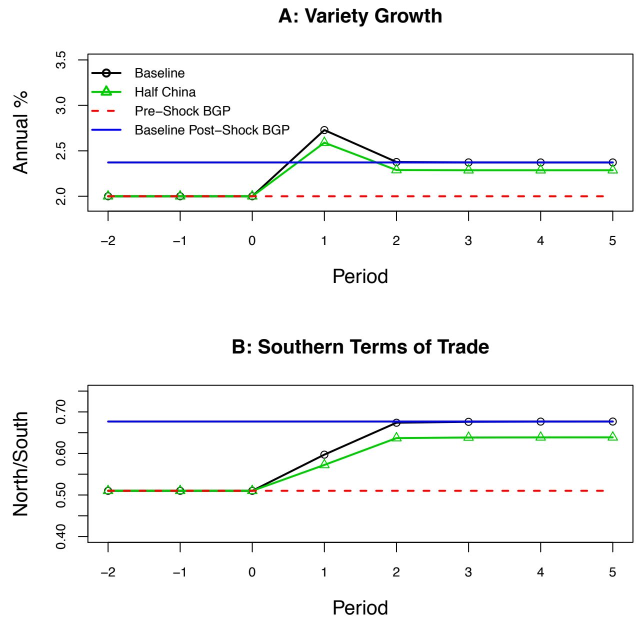

Figure B2: Trade Liberalization with Half of Chinese Import Growth

Note: The figure displays the transition path in response to trade liberalization in two scenarios. The first transition path, in solid black, "Baseline," replicates the Trapped Factors transition path displayed in Figure 6 above. A permanent and unanticipated trade liberalization 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 "Baseline" 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 steady-state growth path, and the lower horizontal dashed red line is the pre-shock steady-state growth path.

Table B1: Growth Rate Robustness Checks

Parameter	Peak Transition Path Growth (%)	Post-Shock steady-state 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 steady-state 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 steady-state 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 steady-state 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 steady-state 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}.

Steady-State growth Path

As documented in the proof of Proposition 2, the steady-state growth path growth rate $g(\phi)$ of the open economy given trade restriction ϕ 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 steady-state 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 steady-state 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 steady-state growth path associated with ϕ' 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 $t = 1, ..., T-1$. 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

$$x_{jt}=(1-\alpha)^{\frac{1}{\alpha}}Hp_{jt}^{-\frac{1}{\alpha}},$$

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

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

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

$$Y_t=H^\alpha\left[M_tx_{Mt}^{1-\alpha}+R_tx_{Rt}^{1-\alpha}+I_tx_{It}^{1-\alpha}\right]$$

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

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

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

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

$$M_{t+1}=g_tA_t$$

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

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

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 I goods production is maintained by the South, justifying our M, R, I goods 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:

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

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

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

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

$$(N g_1^1)^{\gamma-1} = \Omega(1+r_1)^{-\frac{1}{\alpha}} (\mu^1)^{-\frac{1}{\alpha}} (H + q_1^{\frac{1}{\alpha}} H^*)$$

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

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

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

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

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

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

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

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 1 to reflect the fact that flows of M goods from North to South come from both industry 1 and industry 2, with different prices and quantities for each. The final four equations represent the innovation optimality conditions for firms in industry 1 and 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 0 for 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 μ below 1 represents a fall in the shadow value of inputs for an intermediate goods firm. Also, if M_{f1} is the number of new patents innovated by a firm in industry f in period 0 for 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 R goods production and M goods innovation and production expenditure pre-shock (left-hand side) and post-shock (right-hand side). The input constraints differ across industries because the R goods available in the post-shock period in industry 2 for production are reduced by the factor χ_2, where χ_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 0 and 1 which 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 I goods 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 T onwards. The no shock "NS" case is consumption assuming that allocations are those of the pre-shock steady-state 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 $100x^*$.

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 steady-state 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.[27]

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

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

[27] Note that we omit below a term multiplying per capita preferences by the size of the population, which would be proportional to H_t^* given our assumptions. Such an assumption, as will be seen below, results in a level shift in interest rates. However, and importantly, our assumption prevents the mechanical inflation of the welfare gains from trade liberalization (relative to our baseline strong scale effects model with no population growth) simply because liberalization gains occur in the future with a larger population. In unreported results, however, we also solved an alternative model with per-capita preferences weighted by population size. Predictably, this resulted in larger welfare gains from trade liberalization.

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

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 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 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 N Northern intermediate goods firms 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

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

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

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 M goods, trade restriction for an exogenously set proportion $1-\phi_t$ of off-patent goods labeled R goods, and imports from South to North of the exogenously set proportion ϕ_t of off-patent goods labeled I goods.

Equilibrium Summary

- Some sequence of ϕ_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 optimize M goods innovation, M goods monopoly production, and perfectly competitive R goods production decisions
- Southern intermediate goods firms optimize perfectly competitive R and I goods 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 $H^D_t = H_t$, $(H^*)^D_t = H^*_t$
- Final goods market clears/resource constraint is satisfied in the North

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

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

$$Y_t = H^\alpha_t \int_0^{A_t} x^{1-\alpha}_{jt} dj = C^*_t + \int_{A_{t+1}} (x_{jt+1} + x^*_{jt+1}) dj$$

- 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 I goods

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

Equilibrium Conditions for Reference

For later reference in the proof of Proposition $D1$, we now list the equilibrium conditions in this environment. Northern Households' (HH) First Order Conditions (FOC)

$$\beta^t H^{\sigma-1}_t C^{-\sigma}_t = \lambda_t$$

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

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

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

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

Southern Households' FOC's

$$\to (1+r^*_{t+1}) = \frac{1}{\beta}\frac{H^*_{t+1}}{H^*_t}\left(\frac{C^*_{t+1}}{H^*_{t+1}}\frac{H^*_t}{C^*_t}\right)^{\sigma} = \frac{1}{\beta}(1+g_H)\left(\frac{c^*_{t+1}}{c^*_t}\right)^{\sigma}, \quad c^*_t \equiv \frac{C^*_t}{H^*_t}$$

$$\to q^*_{ft} = \sum_{t=0}^{\infty} m^*_t D^*_{ft}, \quad m^*_t \equiv \frac{\lambda^*_t}{\lambda^*_0} = \prod_{\tau=1}^{t} \frac{1}{1+r^*_\tau}$$

Northern Final Goods Firm FOC's

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

$$\alpha H_t^{\alpha-1} x_{jt}^{1-\alpha} - w_t = 0$$

Southern Final Goods Firm FOC's

$$(1-\alpha)(H^*_t)^{\alpha}(x^*_{jt})^{-\alpha} - p^*_{jt} = 0 \to x^*_{jt} = (1-\alpha)^{\frac{1}{\alpha}}(p^*_{jt})^{-\frac{1}{\alpha}} H^*_t$$

$$\alpha(H^*_t)^{\alpha-1}(x^*_{jt})^{1-\alpha} - w^*_t = 0$$

Northern Intermediate Goods Firm FOC's

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Southern Resource Constraint

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

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

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 D1 *A steady-state growth path with constant ϕ exists and is unique. On this steady-state 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 steady-state 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 Proposition D1: Semi-endogenous Steady-state Growth Path 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 $M_t = g_A A_{t-1}, R_t = (1-\phi)A_{t-1}, I_t = \phi A_{t-1}$ 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 I goods. 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 0 as $g_A \to 0$. The decreasing RHS asymptotes to ∞ as $g_A \to 0$ (see the formula for q) and to 0 as $g_A \to \infty$ (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. This completes the 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 ϕ 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 ϕ 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 steady-state 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 , $\frac{\bar{H}^*}{\bar{H}}$, H_{-1} , ϕ , and ϕ' . The values for $\alpha = 2/3, \sigma = 1$, $\beta = 1/1.02$, and $\frac{H_t^*}{H_t} = 2.96$ 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 ϕ steady-state 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 ϕ 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 steady-state growth path values.

Table D1: Semi-endogenous 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 semi-endogenous 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 ϕ to $\phi' > \phi$, where ϕ and ϕ' 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 steady-state 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. ΔW 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.

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 250 years 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 I goods 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 δ implied 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' .

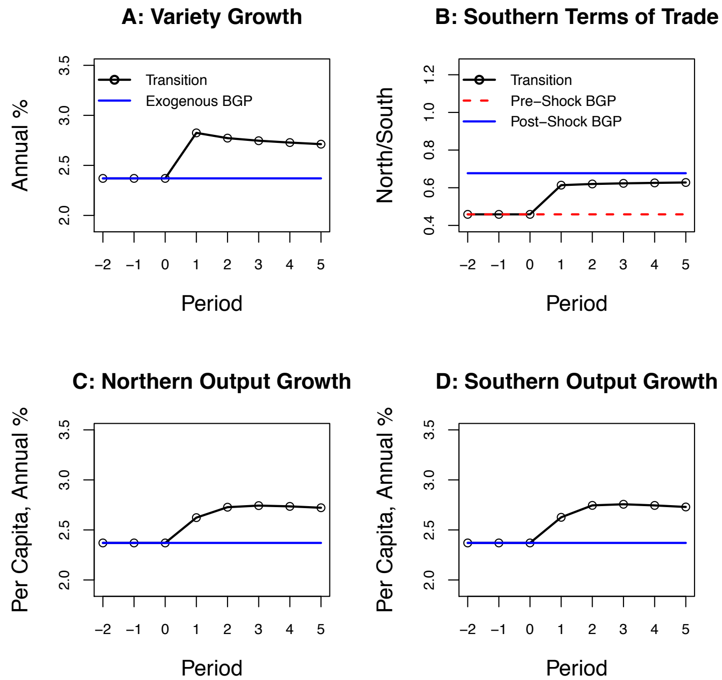

Figure D1: Semi-endogenous Growth Model Trade Liberalization

Note: The figure displays the Fully Mobile transition path in the semi-endogenous 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 steady-state growth path, and the lower horizontal dashed red line is the pre-shock steady-state growth path. Note that since the semi-endogenous growth model's value for variety growth and output growth in the long run does not vary with trade policy, there is only one steady-state growth marker for these series.

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 160 years. 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

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 η increases, 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 η requires a slight change in the scaling constant ν to deliver invariance of steady-state 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 analogues of those in Appendix C above.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$$Y_1 = C_1 + \binom{N}{2} g_2^1 A_1 (x_{M2}^1 + x_{M2}^{*1}) + \binom{N}{2} g_2^2 A_1 (x_{M2}^2 + x_{M2}^{*2}) + \binom{N}{2} \frac{1-\phi}{2} A_1 x_{R2}^1 + \binom{N}{2} \frac{(1-\phi)\chi_2}{2} A_1 x_{R2}^2$$
$$+ Z_2^1 + Z_2^2$$

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

$$Y_2 = H^\alpha \left[\binom{N}{2} g_2^1 A_1 (x_{M2}^1)^{1-\alpha} + \binom{N}{2} g_2^2 A_1 (x_{M2}^2)^{1-\alpha} + \binom{N}{2} \frac{1-\phi}{2} A_1 (x_{R2}^1)^{1-\alpha} \right.$$
$$\left. + \binom{N}{2} \frac{(1-\phi)\chi_2}{2} A_1 (x_{R2}^2)^{1-\alpha} + \phi' A_1 x_{I2}^{1-\alpha} \right]$$

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

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

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

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

Appendix F - Southern Innovation

In the baseline model we assume that the Southern economy cannot innovate. In this appendix we analyze an economy with Southern innovation, allowed under the assumption that Southern firms produce patents or ideas with a different productivity than Northern firms. The remainder of the structure of the economy is identical to the baseline environment. After laying out the optimality conditions characterizing this equilibrium, we first calibrate the relative productivities of Northern and Southern innovation to match observed patent rates. Then, we show that the quantitative impact of a trade liberalization in a global economy with Southern innovation is similar to the baseline case.

Model

First, we'll overview the structure of the economy, outlining each agent and their optimization problem. In particular, the North and South are populated by a set of households which provide labor and make consumption and savings choices. Northern and Southern final good sectors operates a constant returns to scale competitive technology, while intermediate goods firms in both economies innovate new varieties and supply existing intermediate goods varieties to the final goods sectors. Balanced trade in intermediate goods takes place between each economy, subject to various exogenous trade restrictions.

Northern Household

Taking wages w_t, interest rates r_t, intermediate goods firm stock prices q_{ft}, and intermediate goods firm dividends D_{ft} as given, a unit measure of identical Northern households supplies labor with in effective units H inelastically and chooses consumption C_t, portfolio positions S_{ft}, and bond purchases B_{t+1} to maximize their discounted utility as follows:

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

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

Southern Household

Taking wages w_t^*, interest rates r_t^*, intermediate goods firm stock prices q_{ft}^*, and intermediate goods firm dividends D_{ft}^* as given, a unit measure of identical Southern households supplies labor with in effective units H^* inelastically as chooses consumption C_t^*, portfolio positions S_{ft}^*, and bond purchases B_{t+1}^* to maximize their discounted utility as follows:

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

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

Northern Final Goods Sector

The Northern final good serves as a numeraire in this economy. Taking wages w_t and intermediate goods prices in Northern units p_{jt} as given, the Northern final goods sector chooses labor input H_t^D and intermediate goods inputs x_{jt}^D optimally in order to maximize their profits as follows:

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

$$Y_t = H_t^{D\alpha} \int_0^{A_t} x_{jt}^{D\,1-\alpha} dj.$$

Southern Final Goods Sector

Taking wages w_t^* and intermediate goods prices in Southern units p_{jt}^* as given, the Southern final goods sector chooses labor input H_t^{*D} and intermediate goods inputs $x_{jt}^{*\,D}$ optimally in order to maximize their profits as follows:

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

$$Y_t^* = H_t^{*D\alpha} \int_0^{A_t} x_{jt}^{*\,D\,1-\alpha} dj.$$

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 N Northern intermediate goods firms 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

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

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

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

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

Southern 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 N Southern intermediate goods firms f makes monopoly production $x_{M^*jt+1}^*$ and $x_{M^*jt+1}^*$, perfectly competitive production x_{Rjt+1}^*, and innovation decisions M_{ft+1}^* to solve the following problem

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

$$D^*_{ft} + Z^*_{ft} + \int_{A^*_{ft+1}} (x_{jt+1} + x^*_{jt+1}) dj \leq \int_{A_{ft}} p^*_{jt}(x_{jt} + x^*_{jt}) dj,$$

where $\frac{m^*_{t+1}}{m^*_t} = \frac{1}{1+r^*_{t+1}}$ or $m^*_t = \Pi^t_{\tau=1}\frac{1}{1+r^*_\tau}$. 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 first order condition for B^*_{t+1}. At all times, the innovation cost function is given by $Z^*_{ft} = \Delta^{-\gamma}\nu {M^*_{ft+1}}^{\gamma} A^{1-\gamma}_t$, $\gamma = \frac{1}{\rho}$, $\nu = \frac{N^{\gamma-1}}{\gamma}$. Note that $\Delta \in [0,1]$ is a parameter equal to the relative productivity of Southern firms to Northern firms in the innovation of new intermediate varieties.

Trade Restrictions and Market Structure

The total mass of varieties A_t in existence in any period is made up of newly innovated Northern varieties M_t, newly innovated Southern varieties M^*_t, as well as previously innovated varieties. For one period after innovation M and M^* goods are sold under patent or effective monopoly protection. Previously innovated varieties are produced in a competitive environment but split into two groups. A sequence of trade policy is given by fractions $\{\phi_t\}$ of off-patent goods is allowed to flow from South to North in mass I_t, while the remaining fraction $1 - \phi_t$ and mass R_t of off-patent goods is exogenously restricted to not flow from South to North. The masses of varieties satisfy the following equations:

$$A_t = M_t + M^*_t + A_{t-1}, \quad A_{t-1} = R_t + I_t, \quad I_t = \phi_t A_t.$$

Terms of Trade/No Arbitrage Condition

Northern and Southern intermediate goods trade at a relative price or terms of trade q_t in each period which translates pricing of each intermediate goods variety to the units relevant for final goods sector optimization in each economy. This can be expressed as $p_{jt} = q_t p^*_{jt}$.

Equilibrium Conditions

Given some sequence ϕ_t of trade restrictions, we now discuss conditions which characterize the equilibrium of the economy above. First, the demand curve for each intermediate variety is implied by profit maximization in the final goods sector, i.e. in equilibrium

$$x_{jt} = (1-\alpha)^{\frac{1}{\alpha}} H p_{jt}^{-\frac{1}{\alpha}}, \quad x^*_{jt} = (1-\alpha)^{\frac{1}{\alpha}} H^* {p^*_{jt}}^{-\frac{1}{\alpha}}.$$

Competitive pricing of off-patent varieties, monopoly pricing of newly innovated varieties, and the trade structure of the economy imply that prices for each good are given by

$$p_{Mt} = \frac{1+r_t}{1-\alpha}, \quad p^*_{Mt} = \frac{1}{q_t} p_{Mt} \text{ (Northern innovated } M \text{ goods)}$$

$$p_{M^*t} = q_t p^*_{M^*t}, \quad p^*_{M^*t} = \frac{1+r^*_t}{1-\alpha} \text{ (Southern innovated } M^* \text{ goods}$$

$$p_{Rt} = 1 + r_t, \quad p_{R^*t} = 1 + r^*_t \text{ (Off-patent trade-restricted } R \text{ goods)}$$

$$p_{It} = q_t(1+r_t), \quad p_{I^*t} = 1 + r^*_t \text{ (Off-patent non-restricted } I \text{ goods)}$$

Let $\tilde{g}_{t+1} = \frac{M_{t+1}}{A_t}$ and $\tilde{g}^*_{t+1} = \frac{M^*_{t+1}}{A_t}$ be pseudo-growth rates representing the ratio of patents or new varieties created in the Northern and Southern economies in period t for first use in period $t+1$ relative to the total mass of varieties available in period t. It follows that the overall rate of growth of varieties in the global economy is given by $g_{t+1} = \tilde{g}_{t+1} + \tilde{g}^*_{t+1}$. Furthermore, simplified version of the first order conditions for innovation within the Northern and Southern intermediate goods firms can be written

$$\tilde{g}_{t+1}^{\gamma-1} = \Omega(1+r_{t+1})^{-\frac{1}{\alpha}}(H + q_{t+1}^{\frac{1}{\alpha}} H^*)$$

$$\{\tilde{g}^*_{t+1}\}^{\gamma-1}\Delta^{-\gamma} = \Omega(1+r^*_{t+1})^{-\frac{1}{\alpha}}(q_{t+1}^{-\frac{1}{\alpha}} H + H^*)$$

where $\Omega = \alpha(1-\alpha)^{\frac{2-\alpha}{\alpha}}$. Above, the interest rates in the Northern and Southern economies are pinned down by the household first-order conditions with respect to the one-period bond, i.e.

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

$$1 + r^*_{t+1} = \frac{1}{\beta}\left(\frac{C^*_{t+1}}{C^*_t}\right)^{\sigma}$$

The balanced trade condition in the economy can be written and simplified after substitution of intermediate goods demand and pricing as

$$M_t p_{Mt} x^*_{Mt} = I_t p_{It} x_{it} + M^*_t p_{M^*t} x_{M^*t}$$

$$q_t = \left[\frac{H^*}{H}\frac{\tilde{g}_t(1-\alpha)^{\frac{1-\alpha}{\alpha}}(1+r_t)^{\frac{\alpha-1}{\alpha}}}{\phi_t(1+r^*_t)^{\frac{\alpha-1}{\alpha}} + \tilde{g}^*_t(1-\alpha)^{\frac{1-\alpha}{\alpha}}(1+r^*_t)^{\frac{\alpha-1}{\alpha}}}\right]^{\frac{\alpha}{\alpha-2}}.$$

Consumption in each economy must satisfy a resource constraint, and below we list the resource constraint for each economy as well as various simplifications of the output and R&D terms which follow directly from the definitions of each technology.

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

$$Z_t = \frac{1}{\gamma}\tilde{g}^{\gamma}_{t+1}A_t, \quad Y_t = H^{\alpha}\left[M_t x_{Mt}^{1-\alpha} + M^*_t x_{M^*t}^{1-\alpha} + R_t x_{Rt}^{1-\alpha} + I_t x_{It}^{1-\alpha}\right]$$

$$Y^*_t = C^*_t + M^*_{t+1}(x_{M^*t+1} + x^*_{M^*t+1}) + R_{t+1}x^*_{Rt+1} + I_{t+1}(x_{It+1} + x^*_{It+1}) + Z^*_t$$

$$Z^*_t = \frac{\Delta^{-\gamma}}{\gamma}\{\tilde{g}\}^{*\ \gamma}_{t+1}A_t, \quad Y^*_t = H^{*\alpha}\left[M_t {x^*_{Mt}}^{1-\alpha} + M^*_t {x^*_{M^*t}}^{1-\alpha} + R_t {x^*_{Rt}}^{1-\alpha} + I_t {x^*_{It}}^{1-\alpha}\right]$$

These conditions jointly characterize the equilibrium of the economy with Southern innovation, conditional upon the trade decomposition assumed throughout the paper which requires Southern production of imported I varieties. For this to be consistent with cost minimization by the Northern final goods producer, it must be the case that $(1+r^*_t)q_t \leq (1+r_t)$ at all times. Also, note that the assumptions on the timing or mobility of inputs with respect to announcements of trade restrictions here follow the conventions of the Fully Mobile economies discussed in the main text.

Steady-State Growth Path Conditions

By arguments identical to those contained within the proofs of Propositions 1 and 2 in Appendix A above, we can immediately see that in any steady-state growth path associated

Table F1: Quantitative Exercise with Southern Innovation	
Quantity	Value
g_{ϕ}	2.0%
$g_{\phi'}$	2.7%
$\tilde{g}_{\phi}$	1.9%
$\tilde{g}_{\phi'}$	2.65%
$q(\phi)$	0.45
$q(\phi')$	0.80
ΔW	35.6%
ΔW^*	33.4%

Note: The variety growth rates and economy-specific pseudo-growth rates g and $\tilde{g}$ reported above are translated to annual percentage rates. The Southern terms of trade q is expressed in proportions. Quantities with subscript ϕ (ϕ') are calculated from the steady-state growth path associated with trade policy ϕ (ϕ'). The welfare gains from trade liberalization ΔW and ΔW^* reflect the percentage consumption equivalent gains from a trade liberalization $\phi \to \phi'$ relative to remaining on the pre-liberalization steady-state growth path with trade policy ϕ, taking into account the full transition path.

with a constant trade restriction ϕ as well as a stable overall rate of global growth $g = \tilde{g} + \tilde{g}^*$ that each aggregate quantity in the model other than consumption must grow at the rate g. This implies via the resource constraint of each economy that consumption itself grows at rate g. This implies that interest rates along a steady-state growth path must be constant and satisfy

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

At that point, we can write the innovation first-order conditions and balanced trade conditions characterizing a steady-state growth path as

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

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

$$q = \left[\frac{H^*}{H} \frac{\tilde{g}(1-\alpha)^{\frac{1-\alpha}{\alpha}}}{\phi + \tilde{g}^*(1-\alpha)^{\frac{1-\alpha}{\alpha}}} \right]^{\frac{\alpha}{2-\alpha}}.$$

Calibration and Quantitative Results

As in the quantitative analysis in the main text, we now wish to consider the response of this economy to a trade liberalization shock. We follow the conventions of the Fully Mobile case from the main text. We assume that the economy is moving along the steady-state growth path associated with $\phi_s = \phi$ for all $s \leq t$. Then, in period t, we consider an announcement of an unanticipated and permanent change in the trade restriction parameter from ϕ to $\phi_s = \phi'$ for all $s > t$, where $\phi' > \phi$. The objects of interest in this exercise include not only the growth rates and terms of trade in the pre-shock and post-shock steady-state growth paths $(g_{\phi}, \tilde{g}_{\phi}, \tilde{g}^*_{\phi}, q_{\phi})$ and $(g_{\phi'}, \tilde{g}_{\phi'}, \tilde{g}^*_{\phi'}, q_{\phi'})$ but also the transitional dynamics of the economy.

Before analyzing the transitional dynamics of the economy, we must first fix the calibration of the underlying parameters, which include β, σ, α, $\frac{H^*}{H}$, H, ϕ, ϕ', and Δ. Following the logic laid out in the main text, we externally calibrate a ten-year per period economy with the values of $\beta = 0.98^{10}$, $\frac{H^*}{H} = 2.96$, $\alpha = \frac{2}{3}$, and $\sigma = 1$. This approach leaves four parameters left to determine: H, ϕ, ϕ', and Δ. We jointly calibrate the values of each of the four parameters by targeting four moments drawn from OECD trade and production data spanning the years of Chinese WTO accession as well as NBER data on patents filed in the US. The data sources and calculations are described in detail in Appendix B above. Implicit throughout this calibration exercise is a matching of the Northern model economy to the OECD countries.

- The Northern pre-shock imports to GDP ratio in the model along the steady-state growth path with parameter ϕ is equal to the non-OECD imports to OECD GDP ratio in 1997, i.e. $\frac{I}{Y}_{\phi} = 3.9\%$.
- The Northern post-shock imports to GDP ratio in the model along the steady-state growth path with parameter ϕ' is equal to the non-OECD imports to OECD GDP ratio in 2006, i.e. $\frac{I}{Y}_{\phi'} = 7.0\%$.
- The pre-shock global growth rate along the steady-state growth path with parameter ϕ is equal to the rate of growth of real GDP per capita in the US from 1960-2010, i.e. $g_{\phi} = 2.0\%$.
- The pre-shock ratio of Northern to Southern patents along the steady-state growth path with parameter ϕ is equal to the ratio of non-OECD patents filed in the US in 1997 to the total number of patents filed in the US in 1997, i.e. $\frac{M}{M+M^*}_{\phi} = 2.2\%$.

This calibration procedure is joint with no exact one-to-one correspondence between moments and parameters. Intuitively, however, the trade ratios are particularly influential in pinning down the values of ϕ and ϕ', while pre-shock growth rates determine the scale of the global economy as given by H. Finally, the patenting ratios are informative for the relative productivities of Northern and Southern innovation technologies. The calibration procedure results in parameter values of $H \approx 2.80$, $\phi \approx 6\%$, $\phi' \approx 28\%$, and $\Delta \approx 8\%$. Although the human capital level H is in model units difficult to interpret, the other parameters indicate a liberalization from a regime allowing 6% of off-patent goods into Northern markets to a regime allowing 28% of those goods into Northern markets. To match low Southern patenting rates, the productivity of Southern innovation must be only 8% of Northern innovation productivity.

Note that by contrast, calibration of the model without Southern innovation in the main text to match the same import ratios required a much smaller trade shock from $\phi \approx 10\%$ to $\phi' \approx 21\%$. The size of the trade shock is larger with Southern innovation because, as a function of ϕ, the curve of imports to GDP ratios shifts up and flattens. The curve shifts up because of the additional M^* goods flowing from North to South. The curve flattens or responds less to increases in ϕ because the induced Southern terms of trade appreciation results in lower Northern demand for Southern innovated goods, slowing import growth.

Once the calibration is complete, we compute the transition dynamics of the economy following an approach entirely analogous to the one presented in Appendix C for the baseline Fully Mobile economy. The main results of this quantitative exercise are given in Table F1. Qualitatively, the addition of a Southern innovation capacity to the baseline framework with fully mobile inputs changes little. Global growth increases from a pre-shock rate of 2.0% annually to 2.7% with Southern innovation. In the economy without Southern innovation, global growth increased from 2% to 2.37% in the long run. The substantially larger change in growth rates in response to trade liberalization is entirely driven by the larger calibrated trade shock $\phi' - \phi$ required in the economy with Southern innovation.

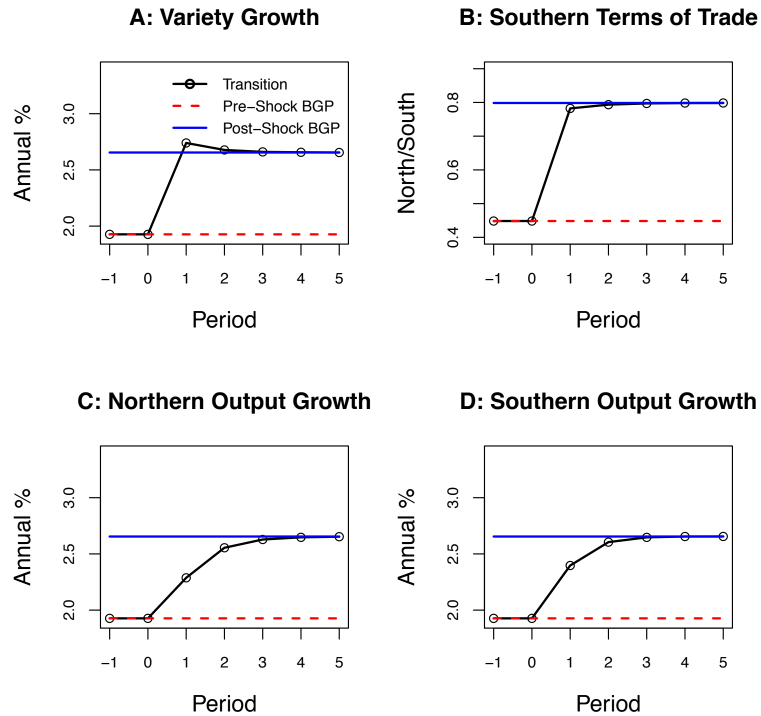

Figure F1: Southern Innovation Model Trade Liberalization

Note: The figure displays the Fully Mobile transition path in the growth model with Southern innovation 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 steady-state growth path, and the lower horizontal dashed red line is the pre-shock steady-state growth path.

Over the full transition path plotted in Figure F1, which normalizes the period of the trade shock to 0, we see similar dynamics as in the baseline Figure 5 without Southern innovation. Trade liberalization leads to a rapid increase in the global variety growth rate and the Southern terms of trade, while output growth rates converge more slowly to their new and higher long-run levels. The gradual behavior of output growth rates relative to variety growth rates is due to underlying and gradual movements in interest rates due to consumption smoothing. Since interest rates determine pricing of intermediate goods, the intensive margins of intermediate goods use and hence overall output growth are slower to respond than the extensive margin or variety growth alone.

As in the baseline case without Southern innovation, the welfare gains from liberalization are large. The consumption equivalent gain from liberalization, computed exactly as laid out in Appendix C and taking into account the full transition path, are 35.6% for the North and 33.4% for the South.

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