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ABSTRACT

In a general equilibrium product-cycle model, lower trade barriers increase Southern purchasing power, which lifts long-run growth by increasing the profit from innovation. In the short run, factors of production must be reallocated inside firms, which lowers the opportunity cost of innovation, generating an additional trapped factor effect. Starting from a baseline OECD growth rate of 2% we find that trade integration with low-wage countries in the decade around China's WTO accession could have increased long-run growth to 2.4%. There is an additional short-run trapped factors effect, raising growth to 2.7%. China accounts for about half of these growth increases.

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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 so small. A typical calculation suggests that for a nation like the United States, a move from autarky to current levels of trade implies a gain of a few percentage points of GDP.[3]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.[4]

In this paper, we craft a model to match recent evidence showing that the firms in Europe that faced more direct competition from China's low-wage exports undertook bigger increases in product innovation.[5] To match this response, the model lets firms choose how much to invest in developing new products and processes. In the spirit of models of endogenous growth,[6] the model requires that all increases in productivity come from these firm-level investments in innovation. As a result, it

[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, Frenkel and Romer (1999), or case studies such as Romer (1992) on the effect of an EPZ in Mauritius, Bernhofen, and Brown (2004, 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 caclulations 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 (2013a) 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.

[4] Larger welfare effects of trade can be generated by allowing for traded intermediates or by focusing on more open economies than the US.

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

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

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-evidence is to explain why a firm that is more exposed to competition from imports from China has a bigger incentive to develop new goods when imports are liberalized. The model shows that this is precisely what one would expect if factors of production are temporarily "trapped" within firms due to moving costs. If, for example, the skilled engineers at a firm are expensive to train and then lay-off, a negative demand shock to a good they helped produce leaves them in the firm but reduces their opportunity cost. Under this scenario, the firm innovates after the trade shock not just because the value of a newly designed product has gone up, but also because the opportunity cost of designing and producing it have gone down. This interpretation is consistent with the evidence that firms shift resources out of activities that compete with imports from low wage countries.[7] 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.[8]

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

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

[8] 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 potential profits causes an increase in the rate of innovation at all Northern firms, and is therefore harder to identify from micro-data. It is an incremental version of the scale effect on growth that has been examined in models of trade with endogenous growth by comparing two isolated economies with a single fully integrated economy.[9] This mechanism has not, to our knowledge, been investigated in a model that is rich enough to be used in a calibration. At a minimum, such a model must allow a comparison across equilibria with a continuum of degrees of openness. In a sensitivity analysis, we also verify that over a time horizon of roughly a century, the conclusions from our endogenous growth model are very similar to alternative calibrations based on a model of semi-endogenous growth (like that of Jones, 1995a,b) in which a policy change can have a prolonged effect on the growth rate that eventually converges back to zero.

In our product-cycle model, innovation in the North produces new intermediate inputs that are used by firms in both the North and the South. In a balanced growth equilibrium, trade barriers prevent factor-price equalization, so goods produced in the South have an absolute cost advantage. We calibrate the model to match both the baseline rate of growth and the firm-level decisions about innovation from the micro literature. We find 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. But although the trapped-factors mechanism has a smaller long-run welfare effect it is front-loaded, so over the first decade after the trade shock its effect on the rate of growth is similar in magnitude to the market-size effect and might therefore be of comparable interest in policy debates. For trade with all low wage countries, the trapped-factor effect increases the rate of growth by an additional 0.3% per year (i.e. the combined effect of the market size

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

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.

Our results connect to several other lines of work. To simplify the analysis, the model allows for heterogeneity among firms only in the degree of import competition that they face. One natural extension would allow for other dimensions of heterogeneity (e.g. Melitz and Redding, 2013b).[10] 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.[11] 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 such effects are large. In contrast to this literature, where specificity has no social benefits, in our

[10] 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 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.

[11] See for example Sampson (2014) or Constantini and Melitz (2008).

second-best model, trapped factors generate additional welfare gains when there are unexpected increases in trade.

The model of innovation spurred by a reduction in the opportunity cost of the inputs used in innovation is reminiscent of the old idea that trade competition can effect X-inefficiency without following the type of principal-agent structure (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), who build on Hall (1991).

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

2 Closed Economy Model

We introduce the basic structure of the model for a closed economy. This lets us describe the technology and highlight the key equation in the model. It characterizes the rate of growth of the variety of inputs, which can also be interpreted as the rate of growth of patents or new designs. Note that in this initial closed-economy equilibrium derivation, we omit discussion of the costs that can trap factors in firms. We bring them in after introducing trade.

2.1 Technology

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

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

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

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

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

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

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

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

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

where $0 < \rho < 1$.

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

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

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

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

Finally, we note that the parameter ν is a constant which we have introduced to the innovation cost function and will adjust so that different choices of the number of intermediate goods firms N and the innovation cost function curvature γ generate the same balanced growth rate. (See Appendix A or Section 2.3 for details.)

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

2.2 Preferences

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

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

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

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

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

2.3 Equilibrium

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

It simplifies the exposition to imagine that the intermediate inputs in production are produced by N firms for some large number N. These firms design new goods and produce the intermediate inputs that the new designs make possible. Newly discovered goods are protected by a one-period monopoly patent. After the patent expires, it is convenient and harmless to assume that the firm f that developed a good will continue to produce it. Hence, at any date t, the range of goods $[0, A_t]$ can be divided up in to N disjoint subsets of goods produced by each firm f. Roughly speaking, we would like to assume that any intermediate good j is equally likely to be assigned to any one of the N firms.[12] Finally, we assume that there is a set of potential entrants, that we refer to as "fast copiers", who act as a competitive fringe and force the firms that produce off-patent goods to price them at marginal

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

cost.[13]

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

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

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

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

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

Together, these two equations imply monopoly output

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

Because profit takes the form

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

this yields

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

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

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

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

The zero marginal profit condition for developing new goods implies that this expression for π must be equal to the marginal cost of producing the last innovation at each firm. To express this cost, it helps to define a "pseudo-growth rate"[14] for an individual firm, $g^f_{t+1} = \frac{M_{ft+1}}{A_t}$. We denote the economy-wide growth rate of varieties as $g_{t+1} = \frac{M_{t+1}}{A_t}$ and note that $g_{t+1} = \sum_{f=1}^{N} g^f_{t+1}$. Differentiation of the cost function for innovation yields

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

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

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

If we define ν so that

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

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

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

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

Finally, using the fact that in a balanced growth equilibrium, consumption, patents, and total output will all grow at the same rate g, we can substitute in the expression for the interest rate equation (3) into equation (5) to generate the basic equation relating g and H:

Proposition 1 *Closed-Economy Balanced Growth Path*

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

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

Proof in Appendix A.

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

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

3 Open Economy

Suppose next that there are two regions or countries, North and South. We treat North as the home country so variables associated with the South are indicated with an asterisk. There are identical representative households in the North and South. The final goods technologies of the two regions are identical, but only Northern intermediate goods firms have access to the innovation technology that produces new patents or designs. A firm in the South can subsequently produce any intermediate good as soon is it is off patent. A lack of Southern innovation is a realistic approximation to the data, if we identify the North with OECD nations empirically. As shown in Appendix Figure B1, patents granted in the USPTO 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 restriction, we assume that the government in the North imposes a trade restriction which allows only a proportion ϕ of off-patent intermediate goods varieties produced in the South to be imported into the North. If we make the simplifying assumption that the goods with the lowest index values are the ones that are allowed to trade, Figure 1 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

[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.

and also produced in the South and imported into the North. Next come the R (for restricted) goods. These are produced in the North for use in the North and produced in the South for use in the South. Finally, we have the M (for monopoly) goods, which are produced in the North and used in production in both the North and the South. Hence, M_t represents the new goods developed in period $t-1$ for sale in period t; R_t represents the trade-restricted but off-patent goods available for use in production in period t; I_t represents the off patent goods that can be imported into the North for use in period t. In a small abuse of the notation, we will use the symbols I, R, and M to denote both the set of goods and its measure.

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

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

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

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

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

Proposition 2 *Open-Economy Balanced Growth Path*

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

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

and the balanced trade condition

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

and $q(\phi) < 1$.

Proof in Appendix A.

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

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

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

A trade liberalization caused by an increase in ϕ leads to an increased flow of imported I goods from North to South. The elasticity of demand for all inputs is $\frac{1}{\alpha} > 1$, so revenue increases when prices fall. This means that in response to the increase in imports into the North, the prices of the goods that the North imports must go up and the prices that it receives for goods that it sells to the South must go down. Both changes imply an increase in q. Lower prices in the South for the exported monopoly goods increase the returns to innovation. In equilibrium, the rate of innovation, hence the rate of growth must increase, which increases the marginal cost of innovation and re-establishes the zero profit condition at the margin.

4 Trade Shocks

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

4.1 Timing with a Trade Shock

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

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

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

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

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

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

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

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

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

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

To match the micro data, which has some firms that are exposed to larger trade shocks than others, we want to allow for the possibility that this range of goods $A_0(\phi' - \phi)$ is not equally distributed among all firms. To do this, we split the set of intermediate input producing firms in the North into two groups of equal size. We refer to these as the "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.

4.1.1 Timing with Fully Mobile Inputs

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

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

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

3. Workers are hired by firms. Intermediate goods firms sell their goods at

the market clearing prices anticipated in period -1 to both domestic and foreign consumption and intermediate input producing firms. Consumption producing firms and intermediate input firms thereby acquire the inputs that they will use to produce.

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

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

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

4.2 Trapped Factors Case

We also consider a "Trapped Factors" case with less mobility in response to a trade shock. We do so because of evidence on the impact of Chinese trade on European firms from Bloom, Draca, and Van Reenen (2012). They find that exposure to Chinese import competition leads to increases in innovative activity, but much of the increase in innovation occurs *within* incumbent firms. Even though the prices and profits of affected firms were falling, those that did not exit increased their rates of innovation.

Relatedly, Freeman and Kleiner (2005) showed in a case study that US shoe manufacturers switched from making low-cost mass market shoes to innovative niche products when faced with rising Chinese competition. In Italy Bugamelli et al. (2010) show a range of manufacturers from ceramic tiles to women's clothing switched to more innovative high-end products in response to rising low-wage competition. With less mobility across firms, trapped factors within firms may move into innovation after increased import competition.[16] In particular, in the trapped factors case we assume that the announcement of the change in ϕ comes after inputs have already been allocated to the intermediate input producing firms. This reverses the timing of steps 2 and 3 above. The new sequence has new steps $2'$ and $3'$ given by:

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

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

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

To calculate the full general equilibrium effects of the shock, we must take into account not only these impact effects on input demands but also any induced changes in interest rates and the terms of trade. The full equilibrium definitions for the closed economy, the open economy, and the trapped-factors trade shock

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

economy can be found in Appendix A. Factors will be trapped in a firm in the Shock group if ex post it wishes that had not taken on so many inputs. In this case, the shadow value of its inputs will be lower that it was before the shock hit.

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

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

5 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, 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 Appendix Figure B2, 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 balanced growth path from trade policy ϕ to a new liberalized policy ϕ', as detailed in the theory section above.

5.1 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 $\alpha = \frac{2}{3}$.[17] Balanced growth path real interest 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 over the calculation of H/H^*, and a later section checks robustness to different values of most of the parameters above.

We must also choose the final three parameters H, ϕ, and ϕ' which jointly govern the model's long-run balanced growth path growth rates and imports to output ratios. We compute the ratio of non-OECD imports to OECD GDP in 1997 (3.9%) and 2006 (7.0%), requiring that the model reproduce these import ratios in the pre- and post-shock balanced growth paths, respectively. In other words, we require that the model reproduce the endpoints of the non-OECD imports series

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

plotted in Appendix Figure B2. 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%. [18]

5.2 The Long-Term Impact of a Trade Shock

We summarize the long-term impacts of trade liberalization in our model in Table 1. 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%.

Table 1: Long-Run Impact of Liberalization

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

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

[18] 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.

5.3 Transition Dynamics in the Fully Mobile Economy

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

In Figure 3, 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. Consumption growth, and interest rates, follow the pattern for output growth.

The full transition to the new balanced 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 consumption growth rates, output growth rates, and interest rates in both economies to their long-run values.[19]

We can also compute the long-run welfare gains from trade in the fully mobile environment, taking the transition path into account (see Table 2). The North gains by a consumption equivalent of 14.2%, while the South gains by a consumption equivalent of 13.3%. In other words, we would have to increase the consumption of the Northern household *without* trade liberalization by 14.2% in every period to make it as well off is it would be in the equilibrium with the trade liberalization. The details of the welfare calculations are available in Appendix C.[20]

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 (2013a) and relying primarily upon love of variety gains from liberalization, suggests that welfare gains 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

[19] 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.

[20] 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.

liberalization could be powerful source of welfare improvement from trade.

5.4 Transition Dynamics in the Trapped Factors Economy

In Figure 4 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 3 above, we immediately note that the variety growth rate is higher upon impact of the trade shock. Instead of a growth rate of about 2.4% in the shock period as seen in the fully mobile transition, the trapped factors variety growth rate on impact is 2.7%. The increased Northern innovation and flow of M goods from North to South in the shock period slows the appreciation in the Southern terms of trade, and output growth in the North and South both overshoot their long-run levels after the trade shock. Although the transition path is again complete in approximately 6 periods (60 years), the path of innovation is clearly significantly higher in the presence of short-run adjustment costs and trapped factors.

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 in that all of the liberalized R goods varieties which lose protection are in this industry. The other industry (No Shock) has no liberalized R goods. In Figure 5, we plot three separate patent flows. In the solid black bar on the left labeled "Pre-Shock," we present period 0 or pre-shock patent flows for the "Shocked" and "No-Shock" industries, which are ex-ante identical. These patent flows are arbitrarily normalized to $1,000$ for ease of reference. The blue middle bar with upward-sloping lines and the red right bar with downward sloping lines, by contrast, plot the patent flows for industry "No-Shock" and for industry "Shocked" during period 1, the period in which policy liberalization becomes effective. Although both industries increase patenting during the shock period due to terms of trade movements, industry "Shocked" patents approximately 28.8% more in the period after the shock. The cross-sectional link between industry patenting and exposure to low-cost import competition in the model is consistent with the increased innovation documented by Bloom, Draca, and Van Reenen (2012) in European firms exposed to Chinese import competition relative to their unaffected peers.[21]

[21] For example, in European textiles and clothing, a 10% increase in the share of imports from China

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 6 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 normal times without trade shocks is normalized to 100%. Since the lost R goods opportunities imply a surplus of inputs which must be allocated to the unanticipated use of innovation, on the top left panel we see an opportunity cost or resource shadow value decline of 25.5% in period 1 for firms in the shocked industry.

In the upper right panel of Figure 6 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 6. 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' 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 from our model. Compared to the aggregate welfare gains of 14.2% from trade liberalization in the fully mobile case, the marginal impact of the trapped factors mechanism is approximately a tenth of the total gains from trade liberalization (2.1%). However, while this is small overall, in the first period (10

within a particularly industry and country is estimated to lead to an approximately 19% increase in patenting in that industry. See Table II in Panel A and Column 3.

years in our simulation) trapped factors roughly doubles the impact of the trade shock on innovation. So the short-run impact of this mechanism is potentially large, and will thus be important for policy (for which a 10 year time frame is the long-term) and empirical work.

5.5 What is the Contribution of China to OECD Growth?

Our model suggests that there was a large scale effect and smaller trapped factors effect from the expansion of low-wage country trade from 1997 to 2006. Given the intense policy interest and recent academic literature in the area[22] we now consider what was the incremental effect of the increased trade with China alone? To do this, we scale back the trade shock by assuming that from 1997 to 2006, exports from other countries grew as they did but that exports from China remained constant as a fraction of OECD GDP. With the resulting admittedly stark "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.

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

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

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

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

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. Table 2 summarizes the results of this counterfactual exercise, and Figure 7 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 balanced growth rates in the No China case of 2.2% rather than the baseline 2.4%, a contribution of approximately 0.2%. We conclude that understanding the OECD and Chinese policies which contributed to the increased trade with China is a crucial avenue to consider when quantifying dynamic gains from liberalization over this period.

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

5.6 Price and Variety Effects

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

More precisely, we first compute Northern output in the shock period shutting down any unexpected conversion of protected R goods varieties into imported I goods ($Y_1^{noprice}$).[23] Since imported goods are cheaper than domestic goods, the difference in output relative to the baseline level Y_1 can be interpreted as due to a traditional price effect. We then compute the value of Northern output if we shut down not just the unexpected price effects but also hold back the creation of additional newly innovated M goods varieties at its pre-shock level ($Y_1^{novariety}$). The ratio of price to total output gains in the shock period is $\frac{Y_1 - Y_1^{noprice}}{Y_1 - Y_1^{novariety}} = 0.37$, so slightly more than one third of the output gains from liberalization in the shock period arise from the price effect.[24]

The price effects are substantial in the shock period when a large number of cheaper goods are unexpectedly allowed into the North as new imports. By contrast, the contribution of price effects decreases to a miniscule level in the long run. In particular, let Northern output along the pre-shock balanced growth path in an arbitrary period be Y_{ss}. Then, compute output if the ongoing conversion of goods from domestic to lower-price imported varieties is shut down for one period (counterfactual level $Y_{ss}^{noprice}$). Finally, compute output if the newly innovated varieties in that period are further removed, (counterfactual level $Y_{ss}^{novariety}$). The ratio of price to total output gains along the balanced growth path is $\frac{Y_{ss} - Y_{ss}^{noprice}}{Y_{ss} - Y_{ss}^{novariety}} = 0.05$. Therefore in the long run we see that dynamic variety effects, large in endogenous growth structures such as ours, are the dominant factor in output growth, about 95% of the total Northern output gains.

6 Extensions and Robustness

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

6.1 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 parametrizations. To demonstrate this we vary parameter values and consider the impact upon the variety growth rate in the trapped factors transition in Figure 8. In none

[23] Further details on all the counterfactual decompositions in this section are in Appendix C.

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

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.

6.2 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 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.

6.3 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 race type effects. 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. $\eta = 1$).[25] 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 8. In this case, congestion externalities

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

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.

6.4 Other channels through which China influences welfare

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

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 single adjustment cost traps factors of production inside a firm, an unexpected increase in low-wage imports will cause losses that must be shared between the workers and the equity holders of an affected firm. We do not model how these losses are shared, 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 reduces gain from trade.

6.5 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.[26] 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 more innovation 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 made factors more trapped, but it would itself signal impending liberalization and undue the desired innovative effect.

6.6 Patent Length vs. Adjustment Cost Horizon

Embedded within our analysis is an assumption that the model period, 10 years in our calibration, represents both 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[27] - 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 $T^A < T^M$, preexisting cohorts of on-patent varieties may exist within firms at the time of a trade shock. These preexisting 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

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

[27] 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 is quite reasonable in our theoretical structure.

also reduce the welfare loss from monopoly mark-ups. Hence, the net impact on welfare is ambiguous.

7 Conclusion

In this paper we present a new general equilibrium model of trade with endogenous growth that allows factors of production to be temporarily "trapped" in firms due, for example, to specific capital. This trapped factors model allows us to rationalize why in the face of an import shock from a low-wage country like China, incumbent firms in the affected industry may innovate more, as the firm-level micro-data suggest (Bloom, Draca, and Van Reenen 2012; Freeman and Kleiner, 2005). The mechanism behind this effect is a fall in the opportunity cost of R&D caused by a fall in the shadow cost of these trapped 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 a model and quantify the effects of a trade liberalization of the magnitude we observed in the decade around China's accession to the WTO 1997-2006. Empirically, we find a substantial increase in welfare from such trade integration: a consumption equivalent increase of the order of 16% and a permanent increase in growth of around 0.4%. This leads to welfare effects that are much larger than conventional calibrations of static trade models which ignore the dynamic effects of trade on growth because they do not allow for the possibility that more innovation by firms can lead to more productivity growth for the economy as a whole. About a tenth (2% out of a 16% consumption equivalent increase) of the overall welfare gains are due to our trapped factor mechanism, a small but non-trivial proportion. Moreover, these trapped factor gains from growth come in the immediate aftermath of the a trade-liberalization, and so will be important to policymakers.

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

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

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

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

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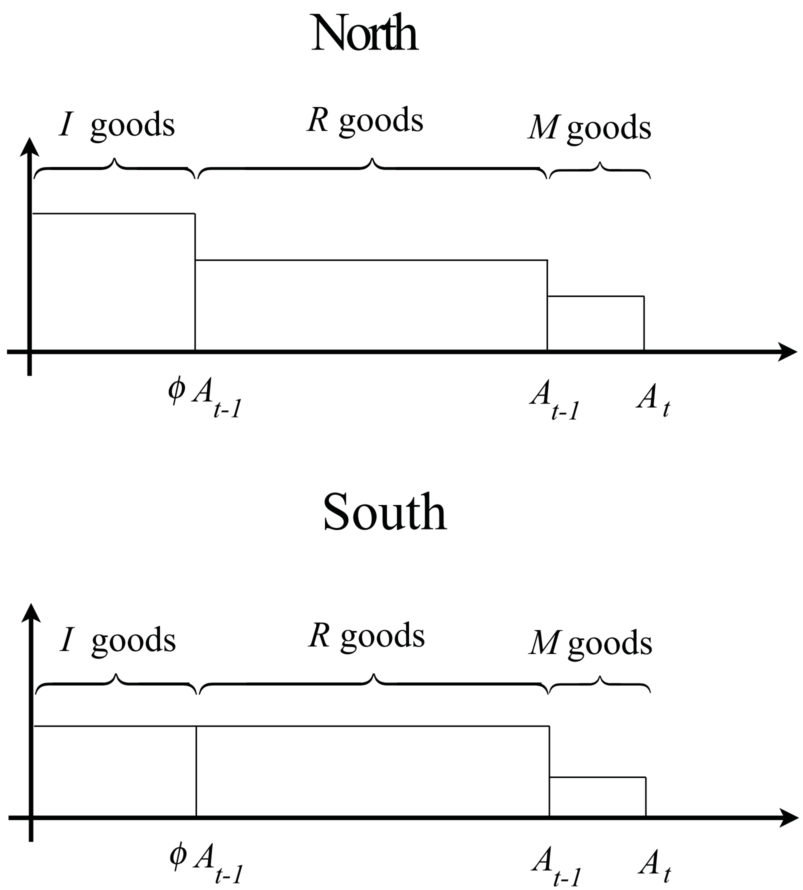

Figure 1: A Product Cycle in the Model

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

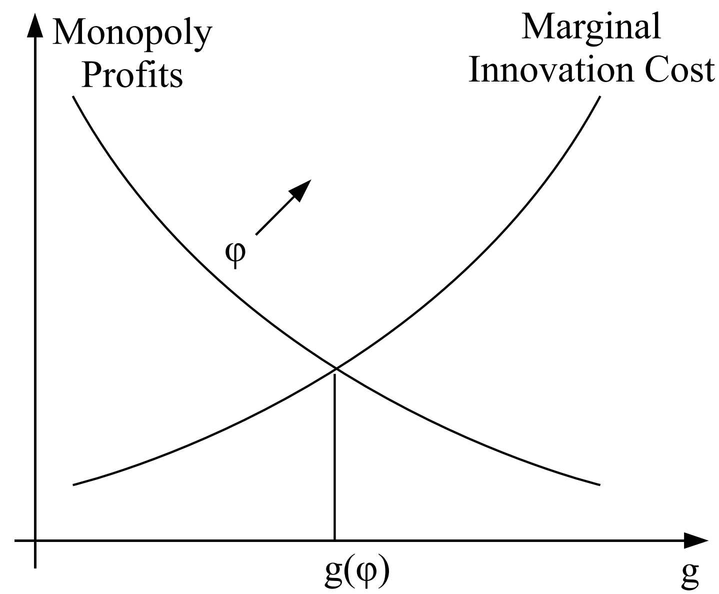

Figure 2: Balanced Growth Path Equilibrium

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

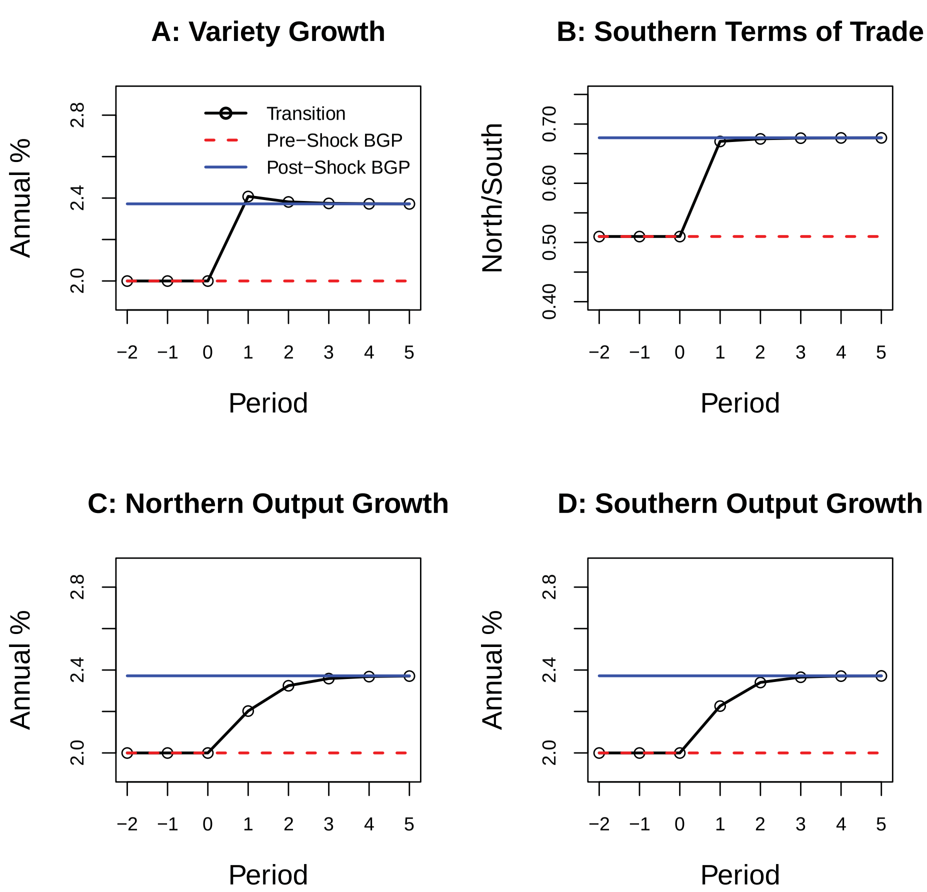

Figure 3: Liberalization Boosts Growth in Fully Mobile Model

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

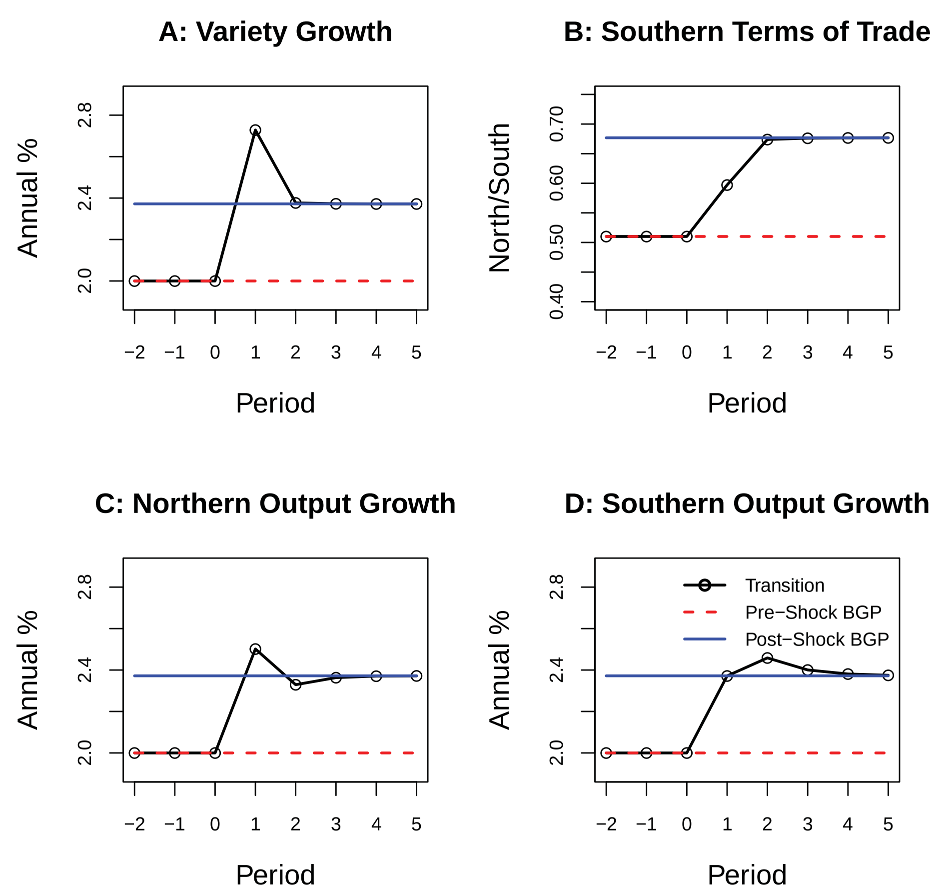

Figure 4: Trapped Factors Increase Short-Run Growth

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

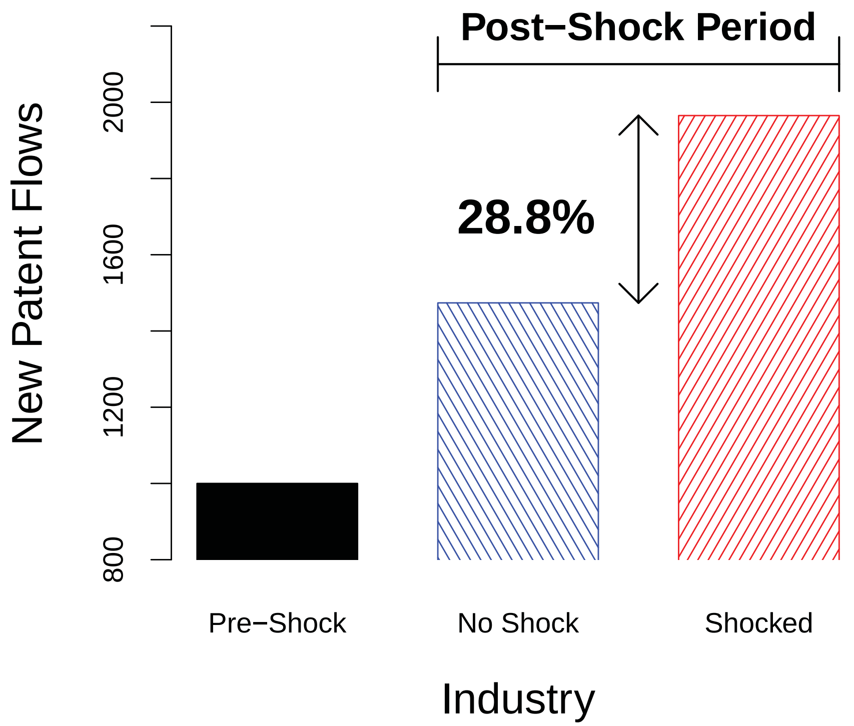

Figure 5: A Shocked Industry Patents More

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

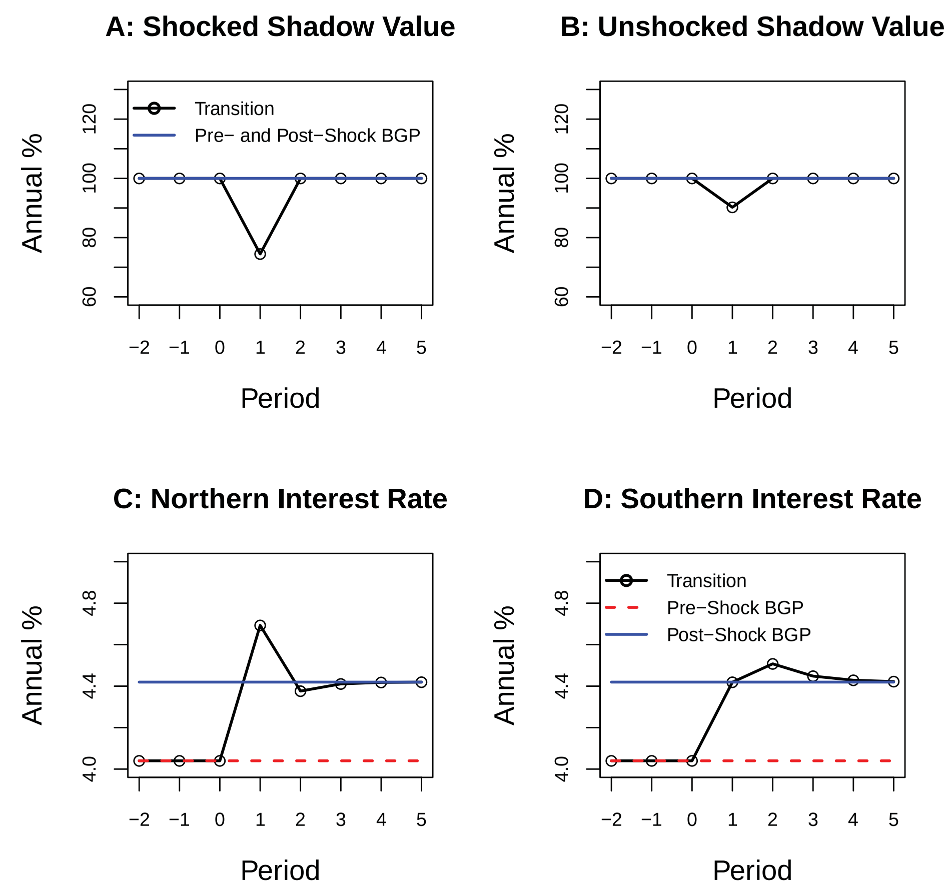

Figure 6: Trapped Factors Interest Rates and Shadow Values

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

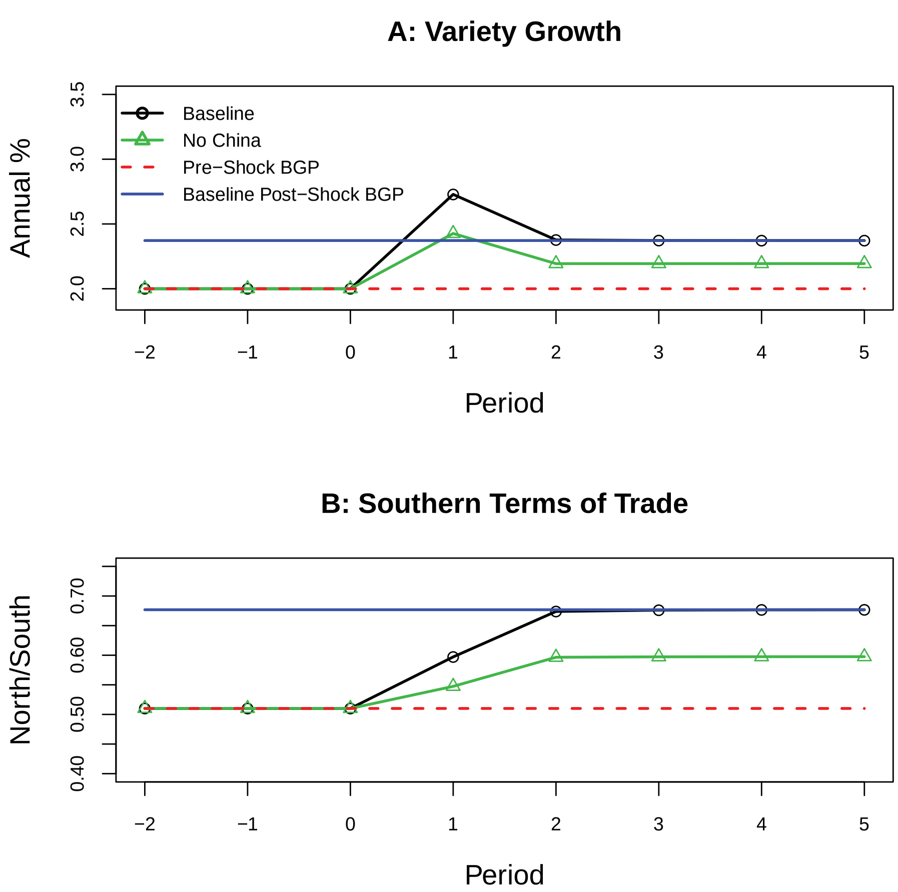

Figure 7: Trade Liberalization without Chinese Import Growth

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 4 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 balanced growth path, and the lower horizontal dashed red line is the pre-shock balanced growth path.

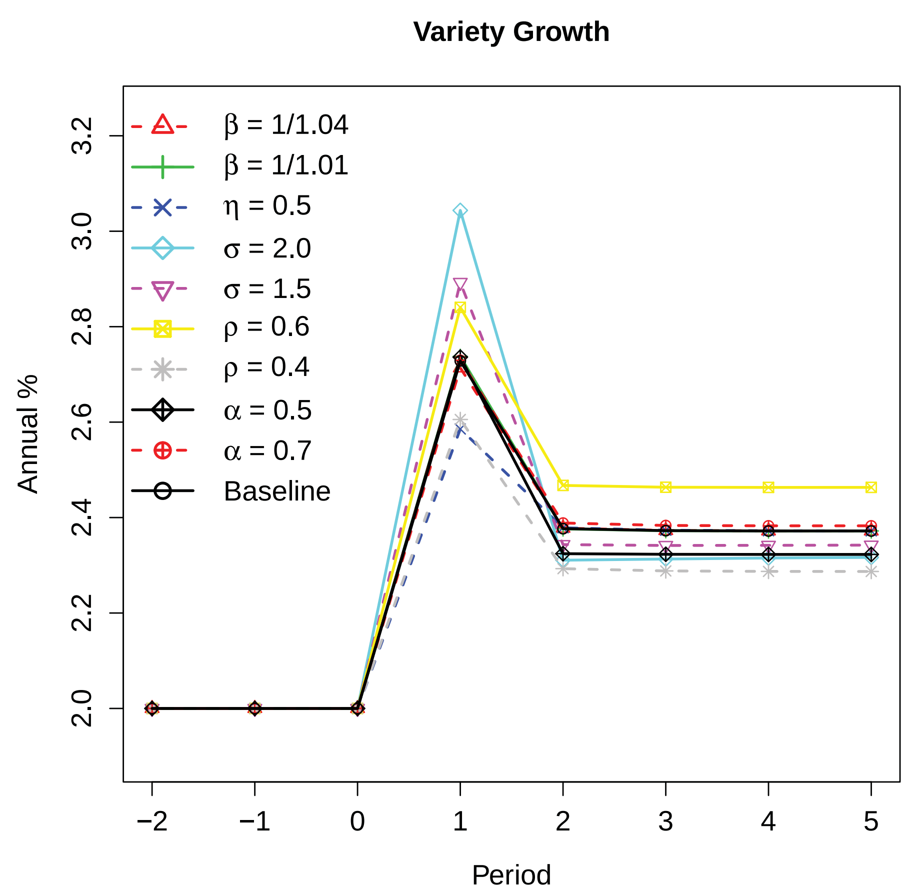

Figure 8: Trapped Factors Transition Dynamics are Robust

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