Multinational Production, Technology Diffusion, and Economic Growth *

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Abstract

We develop a tractable growth model to study the dynamic macroeconomic effects of multinational production (MP) across countries. In this model, MP is the vehicle of international idea diffusion: when firms produce in a foreign country, they contribute to the local stock of knowledge. We incorporate idea diffusion into a quantitative framework of trade and MP. The model yields tractable expressions for bilateral MP flows, trade flows, and the dynamics of technology that we use in our calibration across a set of 54 economies. Counterfactual analysis reveals that a reduction in MP costs boosts economic growth, especially in developing economies. We also find that reshoring policies have positive short-run effects but negative welfare implications in the long run.

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1 Introduction

Recent decades have witnessed persistent high economic growth and increasing multinational production (MP) occurring simultaneously in countries such as South Korea, China, Vietnam, and Ethiopia. Countries that have been actively facilitating foreign production believe that MP can be a catalyst to economic growth and development, as multinational firms tend to be more productive than domestic firms and could bring new technologies and management skills to local producers (see Keller and Yeaple (2009) for example). While a large literature focuses on identifying technology spillovers (see Harrison and Rodríguez-Clare (2010) for a review), little attention is paid to understanding the growth and welfare effect of these spillovers. This paper studies the global macroeconomic implications of MP.

We develop a tractable multi-country semi-endogenous growth model of trade and MP. The model incorporates frictions of MP, geographic factors, and endogenous evolution of technology. Through the lens of the model, we explore the role of MP as a vehicle of international idea diffusion. We use the model to quantify growth and welfare implications of shocks that affect the global production pattern, including a generalized reduction in MP frictions, an economic sanction on Russia, and the reshoring initiative of the United States. We answer the following questions. How much economic growth can be attributed to MP? What will be the dynamic welfare implications of sanctions on Russia and reshoring policies by the United States?

We consider a world with multiple countries and technology diffusion through multinational production in the host country. We start by describing firm production. As in Ramondo and Rodríguez-Clare (2013), we take a probabilistic approach to model MP in a Ricardian world. There is a continuum of varieties. For each variety, there are many potential firms. Each firm produces one variety, potentially in multiple countries. Hence, a firm is characterized by a vector of productivity representing its production efficiency in different countries. Firms can locate their plants anywhere in the world, choosing where to produce in light of the relative costs of MP, labor, and transportation. We assume perfect competition so only the lowest-cost suppliers actively produce.

The novel and crucial feature of our model is the endogenous evolution of firm productivity driven by innovation and technology diffusion through MP. We model innovation and diffusion as a process happening in the headquarter country. New ideas of production arrive stochastically, and the efficiency of a new idea is a combination of two components: an original component with the potential for production in all countries (a vector) and an insight observed from existing plants (a scalar) within the firm's headquarter country. In particular, the insights can be drawn from an active producer within the country, either a domestically owned plant or a foreign affiliate. As a result, ideas diffuse across borders through MP as foreign affiliates contribute to the local stock of knowledge through their business operations and production. This feature speaks to policy consideration about attracting MP. Our model admits a closed-form law of motion of the knowledge stock as a function of trade and MP shares together with an elasticity that governs the effectiveness of learning.

At any given moment, aggregate production and trade are determined by relative technology and frictions in MP and trade. Over time, the dynamics of technology in turn depend on production. The reason is that technology in a country advances as new ideas of production arrive, and the quality of the new ideas depends on learning from existing producers within the country. In addition, the MP share in each country determines a local firm's relative exposure in the learning process to different technology levels. Building on Buera and Oberfield (2020), we provide conditions under which the technology frontier in a country - a multivariate distribution in the MP setting - follows a multivariate Frechét distribution. Under these conditions, we can describe the evolution of technology by a system of differential equations, where the coefficients are aggregate shares of MP and trade.

We use our model to explore both the static gains and growth implications of openness. Loosely speaking, the static gains of openness are from two sources: higher labor demand and competition from both MP and trade. The former translates into higher wages for the host country of MP, and the later decreases the price level. The static gains are larger than classical gains from openness in the quantitative trade literature when we take MP into consideration. Turning to the dynamic implications, because of idea diffusion, opening to MP boosts the growth rate, especially for countries starting with a lower technology level. We show that even in a semi-endogenous growth model, where the growth rate along the balanced growth paths is exogenous, MP and trade alter the trajectory converging to the balanced growth paths and the average growth rate during the transition. A higher inward MP cost slows down the convergence.

We estimate and calibrate the model using MP, trade, and production data for 54 economies between 2005 and 2016. An important parameter in our model is the learning intensity, which governs the contribution of the active producers to the growth of a firm's productivity. Estimating this parameter is a well-known challenging task (Cai, Caliendo, Parro, and Xiang (2022)), but we manage to make progress. We first back out measures of the knowledge stock across countries over time from our model using trade and MP shares. Next, we use the model implied specification for the law of motion of the knowledge stock to estimate the learning intensity. In particular, we run a non-linear least square regression to obtain the estimate. We proceed with this estimate to conduct quantitative analysis. For sensitivity analysis, we perform counterfactuals using alternative values of the learning intensity. Developing a more sophisticated strategy to identify the learning parameter is an important part of our future research agenda.

Applying dynamic-hat algebra techniques developed in Caliendo, Dvorkin, and Parro (2019), we are able to compute the model without estimating the full set of bilateral trade costs and MP costs. We use the calibrated model to perform several counterfactual exercises to understand the effects of openness on economic growth and welfare across countries. First, we evaluate the role of changes in MP costs, changes in trade costs, and learning in the evolution of TFP between 2005 and 2016. We find that changes in MP costs contribute a sizable portion of TFP growth in developing economies, but less so for developed economies. In contrast, changes in trade costs during the same period have a very small effect on TFP evolution. Second, we calculate the gains from openness. Consistent with the MP literature, we find that the static gains from openness are significant. In addition, compared to autarky, trade and MP also positively affect growth rates of real consumption. Third, we explore the implications of an economic sanction on Russia by forbidding all foreign MP to produce in Russia for 10 years. This sanction decreases welfare in Russia by 7.25% after a decade. Real consumption in Russia immediately drops by 0.63%. The annual growth rate in Russia decreases by 2.16 percentage points during the sanction. The size of the static loss of consumption depends on the level of trade and MP shares; it will be relatively small if the two shares don't change much in response to the shock. However, the magnitude of the change in growth rate is governed not only by the two shares but also the technology level of the country where the active firms are from. A small change in the MP share could translate into a large reduction in growth rate if the source country of MP has a high technology level. Finally, we analyze the implication of a US reshoring policy, considering a permanent twenty-percent increase in outward MP costs from the United States to the rest of the world. With the reshoring policy, the United States remains the global technology leader. While such a policy increases consumption in the US in the short run by 0.14%, it deters global idea diffusion and decreases the annual growth rate in all countries, including the United States. The annual growth rate in the United States decreases by 0.03 percentage points. As a result, overall welfare decreases by 0.1% in the United States.

Our research is related to different strands of research. First, our paper is closely related to recent literature on trade and MP. Ramondo and Rodríguez-Clare (2013), building on Eaton and Kortum (2002), develop a model of trade and MP that allows a country's technology to be used for production abroad. The key difference is that in their static setting, technologies across countries are exogenous. A similar probabilistic structure is used to study MP in Arkolakis, Ramondo, Rodríguez-Clare, and Yeaple (2018), where they allow countries to specialize in innovation or production, and in Tintelnot (2017), which allows for export-platform MP in a general-equilibrium model. Alviarez, Cravino, and Ramondo (2020) presents a development accounting framework leveraging micro-level data on MP to measure firm-embedded productivity across countries. These papers are all with static models, while our dynamic framework allows us to investigate the growth implications of trade and MP in addition to static gains.

The distinctive feature of our dynamic framework is international idea diffusion (see Keller (2021) for a review). The idea that research process has local spillovers dates at least back to Romer (1990) . The process of innovation and diffusion in this paper, where insights and original ideas are combined, builds on Buera and Oberfield (2020). In turn, the Buera and Oberfield model relates to Kortum (1997) where there is no idea diffusion from insights, and to Jones (1995) and Atkeson and Burstein (2019) where intertemporal knowledge spillovers are not modeled explicitly as a function of insights. Van Patten (2021) takes into consideration heterogeneous learning abilities across countries. We focus on one of the channels in Buera and Oberfield (2020), in which insights are drawn from active producers within a country. Our contribution is to extend Buera and Oberfield (2020) to a multivariate setting by incorporating MP. In our setting, producers can be from other countries and they generate international knowledge spillovers. This paper also complements Cai, Caliendo, Parro, and Xiang (2022) who, in a discrete-time setting, study how technology diffuses globally through goods and locally through internal migration.

Previous literature has developed dynamic frameworks with innovation and diffusion. Eaton and Kortum (1999) builds a model where ideas flow between countries, where the diffusion process is exogenous and measured using data on international patenting, productivity, and research. We incorporate trade and MP into this process. Lucas (2009) introduces the feature that knowledge resides in the head of individuals and that intellectual interaction among people stimulates knowledge exchange. We explore MP, a particularly important channel through which ideas flow. Alvarez, Buera, and Lucas (2013) focuses on the pure diffusion of knowledge. More recently, Benhabib, Perla, and Tonetti (2021) and Perla, Tonetti, and Waugh (2021) study the effects of innovation and technology diffusion among producers. They allow firms to make endogenous decisions on innovation or imitation but without international technology diffusion. Cai, Li, and Santacreu (2022) provide a framework for quantifying the cross-country and cross-sector interactions among trade, innovation, and knowledge diffusion. Lind and Ramondo (2022) study global innovation and idea diffusion featuring exogenous innovation and diffusion. In our framework, we emphasize that ideas diffuse across countries through MP, which is endogenously determined by technology instead of being dictated by geographical distance.

Our work relates to the literature that explores the gains from openness. Arkolakis, Costinot, and Rodríguez-Clare (2012) list conditions under which the domestic expenditure share is a sufficient statistic for determining the gains from trade. Ramondo and Rodríguez-Clare (2013) and Arkolakis, Ramondo, Rodríguez-Clare, and Yeaple (2018) explore the gains from openness, taking MP into consideration. The gains from openness in these papers all hold the underlying technology constant. In contrast, Buera and Oberfield (2020) look into the dynamic gains, but their attention is restricted to trade only. Our framework, emphasizing the growth effects of idea diffusions through MP, provides an additional channel on how countries can gain from openness.

The process of idea diffusion from MP in our framework is motivated in part by the well-established strands of literature providing empirical evidence on MP spillovers and knowledge diffusion (e.g., Aitken and Harrison (1999), Javorcik (2004), Keller and Yeaple (2009), Poole (2013), Alfaro (2017), Lu, Tao, and Zhu (2017), and Mercer-Blackman, Xiang, and Khan (2021); see Harrison and Rodríguez-Clare (2010) for a comprehensive review). A recent development in this literature finds positive and sizable spillovers through production linkages (Alfaro-Ureña, Manelici, and Vasquez (2022)), through labor (Setzler and Tintelnot (2021)), and through geographic proximity (Gong (2022)). While most of these papers focus on identifying the effects of MP spillover, we complement them by studying the dynamic effects in a general-equilibrium setting.

The remainder of the paper proceeds as follows. Section 2 builds a model of MP and trade where technology evolution is endogenous, Section 3 calibrates the model to data on bilateral MP and trade flows among 54 economies between 2005 and 2016, and Section 4 conducts counterfactual exercises to highlight the channel of international idea diffusion through MP and its welfare implications. Section 5 concludes.

2 The Model

In this section, we first model the process of technology diffusion and show the endogenous emergence of the technology frontier. Next, we show how the source distribution of new ideas is endogenously determined by the trade and MP pattern. Putting learning and production together, we obtain the law of motion of the technology level. Lastly, we characterize the growth and welfare implications of our model.

Consider a world economy with N countries where labor is the only factor of production. In each country there is a continuum of goods of measure one. The production function for each variety $v \in [0,1]$ has constant returns to scale, i.e., $y(v) = ql(v)$, where $y(v)$ is output, q is productivity, and $l(v)$ is labor input.

There is a large set of potential firms with different productivity to produce each variety. A given firm can set up production plants anywhere in the world with varying productivity levels, which we specify below. Formally, a firm originated in h (the *headquarter* country) is fully described by a vector of productivity $\mathbf{q}_h(v) = (q_{1h}(v), q_{2h}(v), \ldots, q_{Nh}(v))$, where $q_{jh}(v)$ is the productivity of the firm's plant in country j. The firm suffers from an efficiency loss in producing abroad in the form of an iceberg MP cost $\gamma_{jh} \geq 1$, with $\gamma_{jj} = 1$. When the firm produces in j, its productivity is $q_{jh}(v)/\gamma_{jh}$. MP cost γ_{jh} is a reduced-form parameter to model the efficiency friction of foreign subsidiaries of multinational firms.[1] When a firm serves market i with goods produced in j, it incurs an iceberg transportation cost $\tau_{ij} \geq 1$, with $\tau_{ii} = 1$. We assume that trade barriers obey the triangle inequality, i.e., $\tau_{in} \leq \tau_{ij}\tau_{jn}$ for any three countries i, j, n.

2.1 New Ideas

Now we describe the dynamics of new ideas. We build on the Buera and Oberfield (2020) model by introducing multi-dimensional ideas. In each country h, new ideas arrive as a Poisson process. Each idea is about techniques to produce a single variety, drawn randomly from the uniform distribution on $[0,1]$. An idea can be specified by a random vector of efficiencies of production in all countries, $\mathbf{Q} = \mathbf{Z} \cdot Q'^{\rho} = (Z_1 Q'^{\rho}, Z_2 Q'^{\rho}, \ldots, Z_N Q'^{\rho})$. It has two random components. The random vector $\mathbf{Z}$ is the original component, which is drawn from an exogenous distribution. The random scalar Q' is the productivity drawn from the distribution of existing production plants in country h. The parameter $\rho \in [0,1)$ measures the learning intensity or the ability to adapt the observed practice among firms production in h to the firm's own production.

The following assumption is about the original component $\mathbf{Z}$ in the Poisson process.

Assumption 1: *For country h, the arrival rate of ideas with original component $\mathbf{Z}$ better than $\mathbf{z}$ in at least one dimension is*

$$A_{h,t}(\mathbf{z}) = \alpha_{h,t} \left(\sum_{n=1}^{N} z_n^{-\frac{\theta}{1-\eta}} \right)^{1-\eta}$$

[1] For example, one source of such friction is language barriers, as documented in Guillouet, Khandelwal, Macchiavello, and Teachout (2021). We can also think of cultural differences and communication cost, etc.

for any $\mathbf{z} \in \mathbb{R}_+^N$ *and* $\mathbf{z} \neq \mathbf{0}$*, where* $\alpha_{h,t}$ *is an exogenous arrival intensity at time* t*. The parameter* $\theta > 0$ *determines the shape of the right tail. The parameter* $\eta \in [0, 1)$ *measures the correlation among entries of vector* $\mathbf{Z}$*.*

Several factors enter into the arrival rate $A_{h,t}(\mathbf{z})$. The exogenous arrival intensity $\alpha_{h,t}$ captures the innovation ability of a location. A higher $\alpha_{h,t}$ implies a higher arrival rate for any given level of the original component. Ideas with higher efficiencies arrive less frequently, as $\partial A_{h,t}/\partial z_j < 0$ for all j.

In the special case where $\eta = 0$, the only possible arrivals of $\mathbf{z} = (z_1, \ldots, z_N)$ are $z_j > 0$ for some j and $z_i = 0$ for all $i \neq j$. It reduces to the case that an idea can only be applied to one location randomly. In the other special case where $\eta \to 1$, entries of $\mathbf{z}$ are identical to each other. A more detailed discussion is in the appendix.

The insight component, Q', is drawn randomly from the distribution of the efficiency level of all producers in country h regardless of the variety they produce. We denote the distribution of efficiencies of actively producing plants located in country h at time t as $G_{h,t}(q')$.

We turn to the arrival process of new ideas that make a technological advance somewhere. Under Assumption 1 and taking the distribution of Q' as given, the arrival rate of ideas of quality $\mathbf{Q}$ better than $\mathbf{q}$ in at least one dimension is

$$\tilde{A}_{h,t}(\mathbf{q}) = \alpha_{h,t}\Lambda_{h,t}\left(\sum_{n=1}^{N} q_n^{-\frac{\theta}{1-\eta}}\right)^{1-\eta}, \tag{1}$$

where $\Lambda_{h,t} := \int_0^\infty x^{\rho\theta} dG_{h,t}(x)$ is the learning effect. We derive equation (1) in the appendix.

2.2 The Technology Frontier

The state of the art for producing a particular variety v using ideas originated in h is a vector $\mathbf{Q}^{(1)}(v)$, where the n-th entry in the vector is the highest efficiency of production in country n. Because of randomness in the arrival and quality of new ideas in h, the vector is random, with a cumulative distribution function $F_{h,t}$ characterized as a multivariate Fréchet distribution.

Proposition 1: *At time* t*, given the arrival rate characterized by equation* (1)*, the cumulative distribution function* $F_{h,t}$ *of state-of-the-art efficiencies takes the form of a multivariate Fréchet* *distribution,*

$$\Pr[\mathbf{Q}^{(1)}(v) \leq \mathbf{q}] = F_{h,t}(\mathbf{q}) = \exp\left(-\lambda_{h,t}\left(\sum_{n=1}^{N} q_n^{-\frac{\theta}{1-\eta}}\right)^{1-\eta}\right), \tag{2}$$

with support $q_n > 0$ for all n.[2] *The location parameter $\lambda_{h,t} := \int_{-\infty}^{t} \alpha_{h,\tau}\Lambda_{h,\tau}d\tau$ is the cumulated knowledge stock of country h at time t.*

Proof. See the appendix.

For a given variety, state-of-the-art efficiencies do not necessarily come from a single idea. In fact, a single idea may be on the frontier in one location j, or in several, but it would be a rare occurrence for a single idea to be on the frontier for all locations. That property will be determined by η. Intuitively, η captures the correlation among production efficiencies across countries for a given idea. If $\eta = 0$ then a single idea is on the frontier in at most one country,[3] and so there is no MP in a traditional sense (any multinational would have one affiliate, and it would not produce in the home country; if it produced in the home country it would not be a multinational). As η approaches 1 it becomes more likely for multinationals to have affiliates in many countries.

While we derived (2) for a given variety, the technology frontier of country h is also the distribution of state-of-the-art efficiencies across varieties. All varieties are symmetric and have the same probability distribution for the best efficiencies. By the law of large numbers, the proportion of varieties with best efficiencies of production using ideas from country h no greater than $\mathbf{q}$ at time t is also $F_{h,t}(\mathbf{q})$.

2.3 Static MP and Trade

Given the results of the technology frontier, we build the static MP and trade theory based on Ramondo and Rodríguez-Clare (2013).

Consumers all over the world have the same preferences over the continuum of varieties, which are constant elasticity of substitution (CES) with elasticity $\sigma > 1$. Consider consumers in country i. They get utility $u(C_{i,t})$ from the CES aggregate

$$C_{i,t} = \left(\int_0^1 c_{i,t}(v)^{\frac{\sigma-1}{\sigma}} dv\right)^{\frac{\sigma}{\sigma-1}}$$

[2] Here, $\mathbf{Q}^{(1)}(v) \leq \mathbf{q}$ means $Q_n^{(1)}(v) \leq q_n$ for all $n \in \{1, \ldots, N\}$.

[3] When $\eta = 0$, there is at most one non-zero entry in the vector of productivity for any ideas.

where $c_{i,t}(v)$ is the consumption of variety v. The associated price index is

$$P_{i,t} = \left(\int_0^1 p_{i,t}(v)^{1-\sigma} dv \right)^{1/(1-\sigma)},$$

where $p_{i,t}(v)$ is the price of variety v in country i.

We now describe how prices are determined. Consider a firm whose headquarter is in h that produces variety v in country j. The efficiency level, $q_{jh}(v)$, is discounted by the MP cost, γ_{jh}, so the unit cost of production is $w_j \gamma_{jh} / q_{jh}(v)$, where w_j is the wage rate in country j. If the firm ships the good to market i, the unit cost incorporates transportation cost, τ_{ij}, as well. Denoting this augmented cost as

$$\kappa_{ijh,t} = \tau_{ij,t} w_{j,t} \gamma_{jh,t}, \tag{3}$$

the unit cost of serving market i with goods produced in j using ideas from h is

$$p_{ijh,t}(v) = \frac{\kappa_{ijh,t}}{q_{jh}(v)}.$$

Consumers take prices as given. We assume perfect competition so $p_i(v)$ is equal to the lowest cost to serve market i:[4]

$$p_{i,t}(v) = \min\{p_{ijh,t}(v);\ j, h = 1, \ldots, N\}.$$

Given the probabilistic representation of technologies in the previous section, where the technology frontier in each country follows a multivariate extreme value distribution as specified in (2), we can characterize the allocation of expenditures and production with only the knowledge stocks, λ, and the augmented cost bundles, κ. In particular, the share of total expenditure in market i on goods produced using technology from h (the expenditure share) is

$$\pi^E_{ih,t} = \frac{\lambda_{h,t} \left(\sum_{k=1}^N \kappa_{ikh,t}^{-\frac{\theta}{1-\eta}} \right)^{1-\eta}}{\sum_{n=1}^N \lambda_{n,t} \left(\sum_{k=1}^N \kappa_{ikn,t}^{-\frac{\theta}{1-\eta}} \right)^{1-\eta}}. \tag{4}$$

[4] By assuming perfect competition, we implicitly assume that once an idea arrives, it becomes a public good *within* the country where it originates from. Alternatively, we can assume that an idea can be patented and used by only one firm. Firms engage in Bertrand competition, as in Bernard, Eaton, Jensen, and Kortum (2003) and Buera and Oberfield (2020). In either scenario, consumers buy from the lowest-cost supplier, and the aggregated MP and trade shares remain the same, similar to Bernard, Eaton, Jensen, and Kortum (2003). Later we will show that technology evolution only depends on aggregated MP and trade shares.

The goods i buys from h will be produced in the countries where the cost is the lowest. The conditional probability that such a good is produced in j is

$$\psi_{ijh,t} = \frac{\kappa_{ijh,t}^{-\frac{\theta}{1-\eta}}}{\sum_{k=1}^{N} \kappa_{ikh,t}^{-\frac{\theta}{1-\eta}}} \tag{5}$$

It follows that the share of expenditure of i on goods produced in j and originating in h (trilateral share) is

$$\pi_{ijh,t} = \psi_{ijh,t} \cdot \pi_{ih,t}^{E} = \frac{\kappa_{ijh,t}^{-\frac{\theta}{1-\eta}}}{\sum_{k=1}^{N} \kappa_{ikh,t}^{-\frac{\theta}{1-\eta}}} \frac{\lambda_{h,t}\left(\sum_{k=1}^{N} \kappa_{ikh,t}^{-\frac{\theta}{1-\eta}}\right)^{1-\eta}}{\sum_{n=1}^{N} \lambda_{n,t}\left(\sum_{k=1}^{N} \kappa_{ikn,t}^{-\frac{\theta}{1-\eta}}\right)^{1-\eta}}. \tag{6}$$

We can easily construct other aggregate shares of interest from the trilateral shares. For example, the share of total expenditure in market i on goods produced in j (the bilateral trade share) is $\pi_{ij}^{T} = \sum_{h=1}^{N} \pi_{ijh}$. We relegate the derivations to the appendix.

The expenditure share (4) resembles a gravity equation. The knowledge stock λ_h measures the technology level of h. The higher the knowledge stock, the more market i spends on goods produced using ideas from h. The efficiency index $\sum_{k=1}^{N} \kappa_{ikh}^{-\theta/(1-\eta)}$ measures the overall efficiency of serving market i using ideas from h, which takes into consideration the possibility of producing in any country and the geographic barriers in trade and MP. In general, lower augmented costs κ_{ikh} leads to a higher efficiency index for the *market-headquarter (ih)* pair, and i's expenditure share on goods produced using ideas from h is larger. The trade elasticity with respect to κ_{ikh} also depends on η, so that the higher correlation across locations in the idea vector (η close to 1) means a larger elasticity. Related is the conditional production probability (5). For the same *(ih)* pair, when the augmented cost to produce in j (i.e. κ_{ijh}) is smaller, the conditional production probability ψ_{ijh} is larger.

We use the labor market clearing condition to close the model. Let L_i be the measure of labor in country i. Under the assumption of trade balance, the labor market clearing condition is

$$w_{j,t}L_{j,t} = \sum_{i=1}^{N} \pi_{ij,t}^{T} w_{i,t} L_{i,t} = \sum_{i=1}^{N}\sum_{h=1}^{N} \pi_{ijh,t} w_{i,t} L_{i,t}. \tag{7}$$

We define the equilibrium in the static model as follows.[5]

[5]We normalize the wage in the United States to be 1. In the rest of the paper, wages to refer to wages relative to that the United States.

Definition 1: Given $\left(\{\lambda_{i,t}\}_{i=1}^{N}, \{\gamma_{ij,t}, \tau_{ij,t}\}_{i=1,j=1}^{N,N}, \{L_{i,t}\}_{i=1}^{N}\right)$, a *temporary equilibrium* is a vector of wages $\{w_{i,t}\}_{i=1}^{N}$ that satisfies equations (3) to (7).

At each point in time, given the current technology level, trade cost and MP cost, the temporary equilibrium in our model characterizes the relative wage rate in different countries. Once we have the relative wage rate, equation (6) determines the trilateral trade shares $\pi_{ijh,t}$. Consequently, other shares, including the expenditure shares and conditional production shares, are determined as well. As we will see in the next section, these shares are sufficient statistics for solving the dynamics of the knowledge stock.

2.4 Learning

In Sections 2.1 and 2.2, we showed that the arrival of new ideas and the knowledge stock in h depend on the learning effect, $\Lambda_{h,t}$. In this section, we show that the learning effect, $\Lambda_{h,t}$ in equilibrium can be characterized using only the aggregate shares defined in section 2.3 and knowledge stock parameters λ, and therefore so can the law of motion of the knowledge stock itself. We then define a sequential equilibrium that describes the whole path of the world economy.

Recall that the knowledge stock is given by $\lambda_{h,t} = \int_{-\infty}^{t} \alpha_{h,\tau} \Lambda_{h,\tau} d\tau$, hence

$$\dot{\lambda}_{h,t} = \alpha_{h,t} \Lambda_{h,t}.$$

The learning effect is

$$\Lambda_{h,t} = \int_0^\infty x^{\rho\theta} dG_{h,t}(x),$$

where $G_{h,t}(\cdot)$ is the distribution of efficiencies of actively producing plants located in country h at time t. It follows from our assumption that all actively producing plants are equally likely to be sampled when a new idea arrives. In particular, if the plant sampled is from country k, the observed efficiency q' is the actual efficiency in use, $q' = q_{hk}/\gamma_{hk}$.

Proposition 2: *If all actively producing plants in h are equally likely to be sampled when a new idea arrives, the evolution of $\lambda_{h,t}$ can be characterized using only the aggregate shares and knowledge stocks:*

$$\dot{\lambda}_{h,t} = \alpha_{h,t} \Gamma(1-\rho) \sum_{j=1}^{N} \underbrace{\frac{\pi_{hhj,t}}{\sum_{n=1}^{N} \pi_{hhn,t}}}_{\text{technology exposure}} \underbrace{\left(\frac{\lambda_{j,t}}{\pi_{hj,t}^{E} \psi_{hhj,t}^{1-\eta}} \right)^{\rho}}_{\text{adjusted technology level}} \tag{8}$$

for $h = 1, \ldots, N$, where $\Gamma(\cdot)$ is the Gamma function.

Proof. See the appendix.

A sequential equilibrium in our model characterizes the whole path of economic development due to accumulation of the knowledge in each country.

Definition 2: Given initial $\{\lambda_{i,0}\}_{i=1}^N$, and $\left(\{\alpha_{h,t}\}\{\gamma_{ij,t}, \tau_{ij,t}\}_{i=1,j=1}^{N,N}, \{L_{i,t}\}_{i=1}^N\right)_{t\geq 0}$, a *sequential equilibrium* is a path of wage rates and knowledge stocks $\left(\{w_{i,t}\}_{i=1}^N, \{\lambda_{i,t}\}_{i=1}^N\right)_{t\geq 0}$ that solves equations (3) - (8).

Equation (8) shows the law of motion of the knowledge stock. At t, the growth of the knowledge stock in country h has an intuitive specification. First, the learning pool consists of active plants originated from different countries that are producing in h. The learning pool is endogenous because all the shares $\pi_{hhn}, \pi_{hj}^E, \psi_{hhj}$ are equilibrium outcomes in the model. The learning effect can be characterized by a weighted sum over all countries. The weight $\frac{\pi_{hhj,t}}{\sum_{n=1}^N \pi_{hhn,t}}$ measures how much expenditure on locally produced goods in h actually uses ideas from country j.[6] This term is higher if more subsidiaries from j are producing in h, and we denote it as the technology exposure of h to j. The average technology level of j's production plants in h is given by $\frac{\lambda_{j,t}}{\pi_{hj,t}^E \psi_{hhj,t}^{1-\eta}}$, which results from competition among firms. For a given level of $\lambda_{j,t}$, a smaller $\pi_{hj,t}^E$ or $\psi_{hhj,t}$ indicates a higher level of selection for firms from j to produce in h, thus a higher average productivity of j's plants in h. The learning intensity ρ determines how much this adjusted technology level matters.

Second, the growth of the knowledge stock depends on the arrival rate of ideas $\alpha_{h,t}$. The higher is $\alpha_{h,t}$, the more the knowledge stock grows. In this model, because the learning intensity ρ is smaller than one, learning has diminishing returns in the level of knowledge stocks. To sustain a constant growth rate, we need new ideas to arrive faster over time.[7]

Assumption 2: *The arrival rate of ideas has a common constant growth rate: $\dot{\alpha}_{h,t}/\alpha_{h,t} = g_\alpha$.*

If labor, trade cost and MP cost do not change in the long run, and if assumption 2 holds, a balanced growth path exists. Along the balanced growth path all equilibrium variables grow at a constant rate or stay constant. In particular, all equilibrium shares $(\pi_{ijh}, \pi_{ih}^E, \psi_{ijh})$ stay constant, and the growth rate of the knowledge stock is $g_\lambda = \frac{g_\alpha}{1-\rho}$.

[6]The exact format of weights comes from the assumption that all actively producing plants are equally likely to be sampled as q', regardless of the sizes. Readers should note that the weight is related to, but not exactly the same as "foreign production share", $\frac{\sum_i X_i \pi_{ijh}}{\sum_i \sum_h X_i \pi_{ijh}}$, where X_i is the total consumption of country i.

[7]This is a feature shared by many papers with semi-endogenous growth model, for a few example, see Jones (1995), Kortum (1997), Atkeson and Burstein (2019), and Cai, Caliendo, Parro, and Xiang (2022).

Finally, we define the detrended steady state. For a generic variable x_t, denote the detrended variable as $\tilde{x}_t := x_t e^{-g_x t}$, where g_x is the growth rate of x along the balanced growth path. When the economy is at a balanced growth path, the detrended economy is at a steady state so that the t subscript can be removed from all variables $\tilde{x}$. Formally, the detrended steady state is defined as follows.

Definition 3: A *detrended steady state* is a vector of relative wage rates[8] $\{w_i\}_{i=1}^N$ and knowledge stocks $\{\tilde{\lambda}_i\}_{i=1}^N$ that satisfies

$$\kappa_{ijh} = \tau_{ij} w_j \gamma_{jh}, \tag{9}$$

$$\pi_{ih}^E = \frac{\tilde{\lambda}_h \left(\sum_{k=1}^N \kappa_{ikh}^{-\frac{\theta}{1-\eta}} \right)^{1-\eta}}{\sum_{n=1}^N \tilde{\lambda}_n \left(\sum_{k=1}^N \kappa_{ikn}^{-\frac{\theta}{1-\eta}} \right)^{1-\eta}}, \tag{10}$$

$$\psi_{ijh} = \frac{\kappa_{ijh}^{-\frac{\theta}{1-\eta}}}{\sum_{k=1}^N \kappa_{ikh}^{-\frac{\theta}{1-\eta}}}, \tag{11}$$

$$\pi_{ijh} = \frac{\kappa_{ijh}^{-\frac{\theta}{1-\eta}}}{\sum_{k=1}^N \kappa_{ikh}^{-\frac{\theta}{1-\eta}}} \frac{\tilde{\lambda}_h \left(\sum_{k=1}^N \kappa_{ikh}^{-\frac{\theta}{1-\eta}} \right)^{1-\eta}}{\sum_{n=1}^N \tilde{\lambda}_n \left(\sum_{k=1}^N \kappa_{ikn}^{-\frac{\theta}{1-\eta}} \right)^{1-\eta}}, \tag{12}$$

$$w_j L_j = \sum_{i=1}^N \sum_{h=1}^N \pi_{ijh} w_i L_i, \tag{13}$$

$$\tilde{\lambda}_i = \frac{1}{g_\lambda} \tilde{\alpha}_i \Gamma(1-\rho) \sum_{h=1}^N \frac{\pi_{iih}}{\sum_{n=1}^N \pi_{iin}} \left(\frac{\tilde{\lambda}_h}{\pi_{ih}^E \psi_{iih}^{1-\eta}} \right)^\rho. \tag{14}$$

2.5 Welfare Implications

We now look into the model's implications of how MP and trade affect welfare in each country. MP and trade affect welfare through two different mechanisms. At any given moment, MP and trade affect the static price level and wage rate, which affect aggregate welfare. In addition, MP and trade also determine the distribution of efficiencies of active plants in each country, which affects the evolution of the knowledge stock. The long-run technology level is thus affected, which will also have an impact on welfare.

In this section, we focus on the welfare implication in the long run by comparing the aggregate real income level along the balanced growth path. We leave the dynamics of

[8] Relative wages where the US wage is normalized to 1.

welfare to Section 4.2. We favor the long-run implications here for its closed-form solution and for an easier comparison to the existing literature.

We start by looking at the ratio between aggregate real income ω at the detrended steady state relative to autarky. In the autarky, there is no trade or MP, but learning from domestic producers is still possible. The detrended knowledge stock in the steady steady state in autarky satisfies

$$\tilde{\lambda}_i^{\text{Aut}} = \frac{1}{g_\lambda}\tilde{\alpha}_i\Gamma(1-\rho)\left(\tilde{\lambda}_i^{\text{Aut}}\right)^{\rho}, \tag{15}$$

which follows from (14) by setting $\pi_{ijh} = 0$ if either $i \neq j$ or $i \neq h$, and $\pi_{iii} = 1$.[9] As we show in the appendix, aggregate real income per worker ω can be summarized by the aggregate shares and the stock of knowledge:

$$\omega_{i,t} = B\left(\frac{\lambda_{i,t}}{\pi_{iii,t}}\left(\psi_{iii,t}\right)^{\eta}\right)^{\frac{1}{\theta}}, \tag{16}$$

where B is a constant. The intuition for equation (24) is as follows. In our model, where labor is the only factor of production, real wage is closely linked with productivity. Consider the special case where the country is in autarky, so $\pi_{ii}^E = \psi_{iii} = 1$. Then, real wage is proportional to the average productivity of all domestic firms on the frontier, which is $\lambda_i^{1/\theta}\Gamma(1-\theta)$.[10] In an open economy, on top of the domestic stock of knowledge, two forces also affect the real income in country i. First, not all firms on the technology frontier can produce. Facing global competition, firms that are the lowest-cost suppliers to the domestic market can remain active. The value of π_{iii} measures the degree of competition. A smaller π_{iii} indicates that a more selected subset of firms from country i remains active in the open economy. Greater selection translates to higher real wage. Second, foreign affiliates can enter and produce in country i. The conditional production share ψ_{iii} measures attractiveness of country i as a location for MP production. A higher ψ_{iii} indicates that country i would attract more MP in the open economy, which also translates to higher wage.

In autarky where there is no trade or MP, $\pi_{iii,t} = \psi_{iii,t} = 1$. So the real wage in autarky is

$$\omega_{i,t}^{\text{Aut}} = B\left(\lambda_{i,t}^{\text{Aut}}\right)^{\frac{1}{\theta}}, \tag{17}$$

Gains from openness as a function of equilibrium shares and the knowledge stock are

[9] In autarky where no trade or MP is possible, the only non-zero term in the summation in (14) is when $h = i$.

[10] This comes from the first moment of Fréchet distribution.

$$GO_i := \frac{\omega_i}{\omega_i^{\text{Aut}}} = \underbrace{\left(\pi_{ii}^E\right)^{-\frac{1}{\theta}} \psi_{iii}^{-\frac{1-\eta}{\theta}}}_{\text{static}} \underbrace{\left(\sum_{h=1}^{N} \frac{\pi_{iih}}{\sum_{n=1}^{N} \pi_{iin}} \left[\frac{\tilde{\lambda}_h}{\tilde{\lambda}_i} \frac{1}{\pi_{ih}^E} \left(\frac{1}{\psi_{iih}}\right)^{1-\eta}\right]^{\rho}\right)^{\frac{1}{1-\rho}\frac{1}{\theta}}}_{\text{dynamic}}, \tag{18}$$

where the dynamic part is the relative level of the knowledge stock, derived from taking ratios between (14) amd (15). This expression nests welfare formulas in the literature. To understand the gains from openness, we consider some special cases.

Model Without Learning

In the first special case, where the learning intensity $\rho = 0$, the diffusion effect disappears, and the gains from openness are reduced to only the static gains,

$$GO_i = (\pi_{ii}^E)^{-1/\theta} \psi_{iii}^{-(1-\eta)/\theta},$$

similar to Ramondo and Rodríguez-Clare (2013) and Arkolakis, Ramondo, Rodríguez-Clare, and Yeaple (2018).[11] The first term $(\pi_{ii}^E)^{-1/\theta}$ captures the benefit of being able to consume goods produced with technologies originating in other countries. If country i spends more on these goods in equilibrium, i.e., the domestic expenditure share π_{ii}^E is smaller, then GO_i is larger. The second term $\psi_{iii}^{-(1-\eta)/\theta}$ captures the benefit of being able to consume goods produced in another country. If country i consumes more goods that are produced by foreign affiliates of i's firms, that is if the conditional local production share ψ_{iii} is lower, then GO_i is larger. All else equal, the second term is decreasing in the correlation coefficient η, as a higher η means the productivity draws in different countries are more similar, which decreases the value of the option to consume goods produced elsewhere.

Model with MP Only

We can consider the extreme case where trade costs approach infinity, $\tau_{ij} \to \infty$ for $i \neq j$, to focus on the effect of MP. In this situation, there is no trade in equilibrium. If country i were to consume some goods from country h, it must be the case that a firm from h has a production plant in i. The trilateral shares collapse into bilateral ones: $\pi_{ijh} = 0$ for all $i \neq j$.

[11] There are some slight differences. Ramondo and Rodríguez-Clare (2013) consider MP for both final goods and intermediate goods, while in our baseline model, we do not consider the intermediate goods. Arkolakis, Ramondo, Rodríguez-Clare, and Yeaple (2018) model monopolistic competition with MP profits, and their indirect effect concerns the net flow of profits. Firms in our model have no profits - the direct effect in their paper corresponds to our static gains.

The expenditure share is such that $\pi^E_{ih} = \pi_{iih}$. The conditional production share ψ_{ijh} is 1 if $i = j$ and 0 otherwise. Then, the gains from openness (18) becomes:

$$GO_i = \underbrace{\left(\pi^E_{ii}\right)^{-\frac{1}{\theta}}}_{\text{static}} \underbrace{\left(\sum_{h=1}^{N} \pi^E_{ih} \left[\frac{\tilde{\lambda}_h}{\tilde{\lambda}_i} \frac{1}{\pi^E_{ih}}\right]^{\rho}\right)^{\frac{1}{1-\rho}\frac{1}{\theta}}}_{\text{dynamic}}. \tag{19}$$

The static component can be measured by the equilibrium home share π^E_{ii}, as in Arkolakis, Costinot, and Rodríguez-Clare (2012). The crucial difference is that π^E_{ii} is not a trade share as we don't have trade in this special case. Rather, it is the expenditure share on goods produced domestically by domestic firms rather than by domestic affiliates of foreign firms.

The dynamic component shows how the knowledge stock increases along the balanced growth path when there is MP. As a country opens up to MP, unproductive domestic firms are replaced by domestic affiliates of foreign firms that are more productive, and the distribution from where the insights are drawn is better. Similar to when we discuss the law of motion of the knowledge stock in (8), the impact of country h on country i depends on the equilibrium expenditure share π^E_{ih}, as well as the relative technology level between the two countries. The share π^E_{ih} appears in two places. On the one hand, it measures the relative importance of country h's firm in country i. A higher π^E_{ih} means that country h has more firms in country i, thus a larger effect on i's knowledge stock level, all else equal. On the other hand, given the knowledge stock levels, a smaller π^E_{ih} means that the set of h's firms in i is more selected, so the average productivity is higher.

In this special case where trade is not possible, the gains from trade in our model are similar to the "learning from sellers" case in Buera and Oberfield (2020). However, the underlying trade equilibrium and learning mechanism is different. In the "learning from sellers" case in Buera and Oberfield (2020), there is trade between countries, and ideas diffuse from sellers to buyers through trade. In contrast, there is no trade in our special case here; ideas diffuse from active producers within a country. Forthermore, in our setting, ideas diffuse across borders through MP. Hence, this special case bears resemblance to Eaton and Kortum (1999), where there is international technology diffusion but no trade. The distinction is that we model learning through MP explicitly, but we do not model endogenous R&D as in Eaton and Kortum (1999).[12]

[12]We can also have endogenous R&D in the model if we model the arrival rate of ideas, $\alpha_{h,t}$ as a function of number of researchers. The two models share a common feature that all countries grow at the same rate along the balanced growth paths.

Model with Trade Only

We turn to look at the effects of trade, considering the extreme case where the MP cost is prohibitive, i.e., $\gamma_{jh} \to \infty$ for all $j \neq h$. In this situation, there is no MP in the equilibrium, and the trilateral shares collapse into bilateral shares: $\pi_{ijh} = 0$ for all $j \neq h$. The expenditure share is the same as the trade share, $\pi^E_{ih} = \pi_{ihh}$. The conditional production share ψ_{ijh} is 1 if $j = h$ and 0 otherwise. Then, the gains from openness (18) becomes:

$$GO_i = \underbrace{\left(\pi^E_{ii}\right)^{-\frac{1}{\theta}}}_{\text{static}} \underbrace{\left(\pi^E_{ii}\right)^{-\frac{\rho}{1-\rho}\frac{1}{\theta}}}_{\text{dynamic}}. \tag{20}$$

The gains from trade consist of two components. The first component is the static gains from trade, which can be measured by the equilibrium home trade share, as in Arkolakis, Costinot, and Rodríguez-Clare (2012). In addition, we still have dynamic gains from trade. Even though foreign firms do not directly produce in country i, as no MP is possible in this special case, opening up through trade still affects the long-run knowledge stocks in country i. Less productive domestic firms exit the market facing competition from foreign products, which improves the distribution of efficiencies of firms that remains. As a result, new ideas draw insights from a more favorable distribution, and the knowledge stock would grow to a higher level in the balanced growth path. Since the dynamic effect comes from selection through trade, a feature of the extreme value distribution is that the size of the dynamic effect is also a function of home trade share in equilibrium. A smaller π_{ii} indicates a more selective sample of domestic firms to draw insights from, so the dynamic effect is larger. All else equal, the dynamic effect is also increasing in the learning intensity ρ.

It's worth pointing out that in this special case where MP is not possible, our model collapses to a model of trade and learning from domestic firms, as in the "learning from producers" case in Buera and Oberfield (2020).

3 Calibration

We now calibrate the model developed in Section 2. We restrict our analysis to 54 economies where we have good data for trade and MP from 2005 to 2016. We begin by externally calibrating several parameters.

We set the shape parameter of the Fréchet distribution θ to 4.5 and the correlation parameter η to 0.55, following Arkolakis, Ramondo, Rodríguez-Clare, and Yeaple (2018).[13] We set the elasticity of substitution σ equal to 3.79, as in Bernard, Eaton, Jensen, and Kortum (2003). The growth rate of α is exogenous in our model. As we show above, it is also closely connected to the growth rate for economies along the balanced growth paths. Following the logic in Jones (1995), we choose the growth rate, g_α, to be 0.7%, which is the annual growth rate of total employment of the 54 economies in the sample period.[14] The discount factor is set to be $\beta = 0.95$, consistent with the average real interest rate 4.7% in 2016, according to the World Bank. We next show how to use our model to back out the trilateral shares π_{ijh} from the data. We then invert the model to characterize the stock of knowledge in each country for each year. We estimate the learning intensity ρ using the recovered aggregate shares and stocks of knowledge.

For trade data, we use the CEPII Gravity database and the multi-region input-output table (MRIO) from the Eora global supply chain database on trade flows as the empirical counterpart of bilateral trade in the model.[15] As a result, for each year between 2005 and 2016, we construct the $N \times N$ matrix of trade shares, $\pi^T_{ij,t}$, and the $N \times 1$ vector of aggregate expenditures $X_{i,t}$. To get the empirical counterpart of bilateral MP data in the model, we use the Analytical AMNE database from OECD.[16] For each year, we construct the $N \times N$ matrix of MP shares, $\pi^M_{jh,t}$.

3.1 Trilateral Flows

It might seem infeasible to back out the N^3 trilateral shares $\pi_{ijh,t}$ from the $N \times N$ matrices of trade shares $\pi^T_{ij,t}$ and MP shares $\pi^M_{jh,t}$. We show that, our model provides enough structure to back out trilateral flows from data on bilateral trade and MP flows.

[13] The shape parameter of the Fréchet distribution, θ, and the correlation parameter, η, relate to trade elasticity. When $\eta = 0$, shape parameter θ is equal to trade elasticity, as in the trade literature. However, when $\eta > 0$, the equality no longer holds. See Arkolakis, Ramondo, Rodríguez-Clare, and Yeaple (2018) for a discussion. Although the model in their work is Melitz style where each firm produces its own variety, the relationship between the parameters and trade elasticity is the same as in our model.

[14] Here we identify the growth rate of arrival of ideas with the average growth rate of employment.

[15] Conte, Cotterlaz, and Mayer (2021) documents the construction of the CEPII Gravity database. For details about the MRIO from Eora, please refer to Lenzen, Kanemoto, Moran, and Geschke (2012) and Lenzen, Moran, Kanemoto, and Geschke (2013). Notably, the Gravity database does not include home sales. We complement the data with Eora to get self-absorption. In particular, we get bilateral trade flows $X^T_{ij,t}$ from the Gravity database, and $\pi^T_{ii,t}$ and from MRIO.

[16] The Analytical AMNE database includes a full matrix of the output of foreign affiliates in 59 countries plus the rest of the world (in the host country, industry, and parent country dimension), as well as matrices for value-added, exports and imports of intermediate inputs (host country and industry) over the period 2005-2016. See Cadestin et al. (2018) for more details.

To see this, define $\xi^M_{jh,t} = \lambda_{h,t}\gamma^{-\theta}_{jh,t}$ and $\xi^T_{ij,t} = (\tau_{ij,t}w_{j,t})^{-\theta}$. We can rewrite (6) as

$$\pi_{ijh,t} = \frac{(\xi^T_{ij,t}\xi^M_{jh,t})^{1/(1-\eta)}}{\sum_{k=1}^N(\xi^T_{ik,t}\xi^M_{kh,t})^{1/(1-\eta)}} \frac{\left(\sum_{k=1}^N(\xi^T_{ik,t}\xi^M_{kh,t})^{1/(1-\eta)}\right)^{1-\eta}}{\sum_{n=1}^N\left(\sum_{k=1}^N(\xi^T_{ik,t}\xi^M_{kn,t})^{1/(1-\eta)}\right)^{1-\eta}}. \tag{21}$$

By definition, the bilateral trade share is $\pi^T_{ij,t} = \sum_h \pi_{ijh,t}$, and the bilateral MP production share is $\pi^M_{jh,t} = \sum_{i,t} X_{i,t}\pi_{ijh,t} / \sum_i \sum_h X_{i,t}\pi_{ijh,t}$. Thus, we can write

$$\pi^T_{ij,t} = \sum_{h=1}^N \frac{(\xi^T_{ij,t}\xi^M_{jh,t})^{1/(1-\eta)}}{\sum_{k=1}^N(\xi^T_{ik,t}\xi^M_{kh,t})^{1/(1-\eta)}} \frac{\left(\sum_{k=1}^N(\xi^T_{ik,t}\xi^M_{kh,t})^{1/(1-\eta)}\right)^{1-\eta}}{\sum_{n=1}^N\left(\sum_{k=1}^N(\xi^T_{ik,t}\xi^M_{kn,t})^{1/(1-\eta)}\right)^{1-\eta}}, \tag{22}$$

$$\pi^M_{jh,t} = \sum_{i=1}^N \frac{X_{i,t}}{Y_{j,t}} \frac{(\xi^T_{ij,t}\xi^M_{jh,t})^{1/(1-\eta)}}{\sum_{k=1}^N(\xi^T_{ik,t}\xi^M_{kh,t})^{1/(1-\eta)}} \frac{\left(\sum_{k=1}^N(\xi^T_{ik,t}\xi^M_{kh,t})^{1/(1-\eta)}\right)^{1-\eta}}{\sum_{n=1}^N\left(\sum_{k=1}^N(\xi^T_{ik,t}\xi^M_{kn,t})^{1/(1-\eta)}\right)^{1-\eta}}, \tag{23}$$

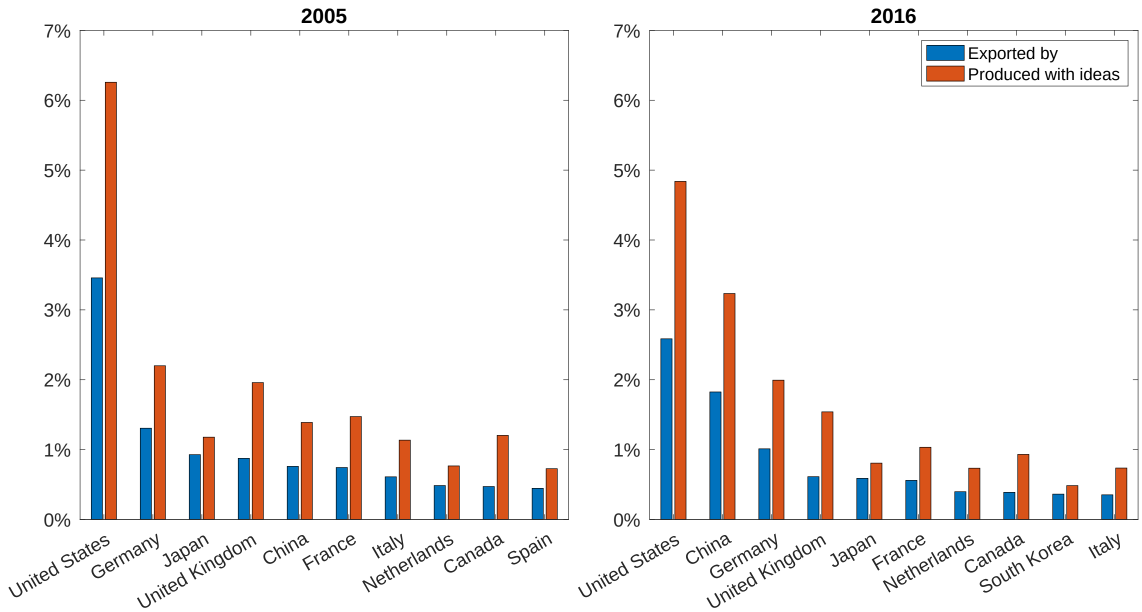
where $X_{i,t}$ is the total expenditure of country i, and $Y_{j,t} = \sum_i \sum_h X_{i,t}\pi_{ijh,t}$ is the total production in country j. Equations (22) and (23) uniquely determine $\xi^M_{jh,t}$ and $\xi^T_{ij,t}$ up to a constant scale. Then, equation (21) determines the trilateral shares that are consistent with the observed data on bilateral trade and MP flows, and are consistent with our model.

From the trilateral shares, we can back out which countries are the top suppliers of the world, measured by either the source of production of exports or by the source of technology used for that production. Figure 1 shows the top exporting countries in the world in 2005 and in 2016, and the shares of foreign consumption accounted for by each country.[17] The blue bar (on the left) shows the percentage of total foreign consumption that is produced by the country. For example, in 2005, US exports accounted for 3.5% of total world consumption (US consumption excluded). The orange bar (on the right) shows the percentage of total foreign consumption that is produced by the country. For example, in 2005, MP from the United States accounted for 6.3% of total world consumption (US consumption excluded).

Two implications of the Figure 1 stand out. First, the distribution of MP ownership by country is more concentrated than the distribution of production by country. In a world with no MP the two bars would be the same for each country as, in that case, all production in a country could only use ideas from the country. The differences between the two bars indicates the prominence of MP in the global economy. Second, from 2005

[17]We show foreign consumption to parse out the home-market-effects in consumption.

Figure 1: Top Exporting Countries



Notes: By authors' calculation. This figure shows the top exporting countries in the world in 2005 and 2016, and the relative shares of foreign consumption accounted for by each country. The blue bar (on the left) shows the percentage of total foreign consumption that is produced by the country. For example, in 2005, US exports accounted for 3.5% of total world consumption (US consumption excluded). The orange bar (on the right) shows the percentage of total foreign consumption that is produced by the country. For example, in 2005, MP from the United States accounted for 6.3% of total world consumption (US consumption excluded).

to 2016, both MP ownership and production are less concentrated. This fact suggests that there is convergence in technology across countries. It is consistent with our model where convergence can occur following a reduction in MP costs as ideas diffuse from more developed countries to less developed ones.

3.2 Knowledge Stocks

To estimate the time series of knowledge stocks across countries, we exploit the close linkage among stocks of knowledge, trade and MP shares, and real income. In particular, recall that real wage in country i is given by

$$\omega_{i,t} = B\left(\frac{\lambda_{i,t}}{\pi_{iii,t}}\left(\psi_{iii,t}\right)^{\eta}\right)^{\frac{1}{\theta}}, \tag{24}$$

where B is a constant.

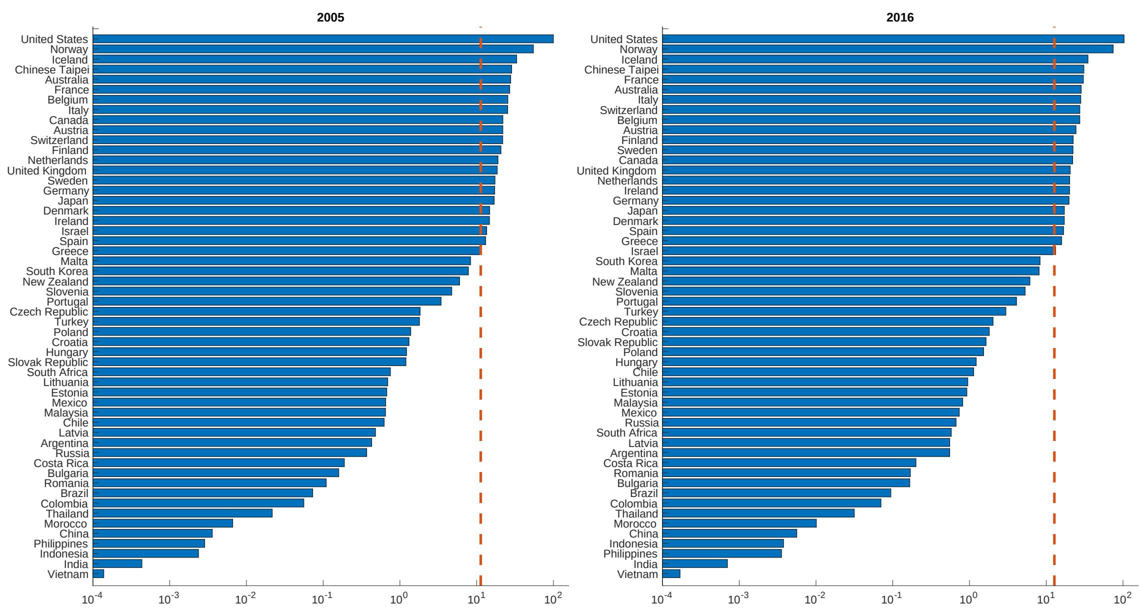
We can solve for the stock of knowledge as

$$\lambda_{i,t} = B^{-1}\omega_{i,t}^{\theta}\pi_{iii,t}\psi_{iii,t}^{-\eta}. \tag{25}$$

The intuition for (25) is as follows. Clearly a high real income (or wage) is indicative of greater knowledge. So is the ability to command a large share of the knowledge used in production for the home market. We need to downweight that by extent to which the high wage is driven by the country's convenience as a production location for MP. We use real output per worker from the Penn World Table 10.0 (Feenstra, Inklaar, and Timmer (2015)) as the empirical counterpart of ω_i.[18] We calculate $\psi_{iii,t}$ using our constructed measure of trilateral shares.

Note that (24) and (25) hold for each country at each time period, regardless of whether the economies are on the balanced growth paths or not. Before estimating the learning intensity ρ, we pause here to discuss the scale normalization of λ's. We can multiply all $\lambda_{i,t}$'s by the a same constant M. The only impact of such normalization is that the calibrated α's will be $M^{1-\rho}$ times larger. To resolve this indeterminacy, we normalize the initial knowledge stock in the United States $\lambda_{USA,2005} = 100$.

Figure 2: Knowledge Stocks



Notes: By authors' calculation. This figure shows the calibrated knowledge stocks in each country on a log scale. The dashed line shows the simple average of knowledge stocks across economies.

Figure 2 shows the heterogeneity in knowledge stocks on a log scale. The left panel presents knowledge stocks in 2005 and the right panel presents those in 2016. The dashed line is the simple average of knowledge stocks across economies. Countries with the highest knowledge stocks are the United States, Norway and Iceland, while countries with the lowest knowledge stocks are Vietnam, India, Indonesia and the Philippines.

[18]In particular, we use the ratio of expenditure-side real GDP at chained PPPs (rgdpe) to the number of persons engaged (emp) as the measure of real output per worker.

3.3 Learning Intensity

We estimate the learning intensity ρ using a nonlinear least square regression. In particular, we run the following regression specification, which is the discrete-time counterpart of the law of motion (8) in Proposition 2:[19]

$$\Delta\lambda_{i,t+1} = \alpha_{i,0}(1+g_\alpha)^t\Gamma(1-\rho)\sum_{h=1}^{N}\frac{\pi_{iih,t}}{\sum_{n=1}^{N}\pi_{iin,t}}\left(\frac{\lambda_{h,t}}{\pi^{E}_{ih,t}\psi^{1-\eta}_{iih,t}}\right)^{\rho} + u_{i,t+1}. \tag{26}$$

The estimation result is as follows. The learning intensity is $\rho = 0.64$ and statistically significant at the 1% level. Because we have relatively short panel data - 11 years in total - we do not have statistically significant estimates of arrival rates $\alpha_{i,0}$'s.

We discuss our estimation of ρ here. Our estimation procedure attributes all the differences in the change of knowledge stock within countries across time to the variation of technology exposure and the adjusted technology level, as guided by the model. An ideal shock that would give us the identification of ρ is an unexpected shock to MP or trade costs that affects the MP shares within a country unexpectedly, but does not affect the growth of a country through another channel. An example of an unexpected shock to MP costs could be the technological advance in communication that makes it easier to manage production abroad.[20] In our model, firms are not forward looking in choosing MP. Firms do not take internalize the growth effect of its own decision on MP. It's because each firm is atomistic (with measure 0) in the continuous distribution, so a single firm's production alone does not affect the growth of host countries. Firms do not need to consider future shocks to the economy because there is no adjustment cost of MP. A potential concern is that factors unaccounted for by the model might be correlated with the trilateral shares or the technology levels. Consider the following example. If foreign firms anticipate a positive shock of the growth in the stock of knowledge of country i at $t+1$, and if they respond by producing more in country i at time t, this would cause a positive correlation between the learning effect and $u_{i,t+1}$. As a result, our estimate of ρ may be biased. When we continue to our quantification result, we would treat 0.64 as the benchmark of the learning parameter and discuss the implication for other values where appropriate.

[19] In the appendix, we show the micro-foundation of the discrete-time version of the model.

[20] Think of Zoom for example.

4 Counterfactual Experiments

In this section, we perform a series of counterfactual experiments to understand the dynamic effects of openness on economic growth and welfare across countries.

In the first counterfactual experiment, we want to evaluate the role of changes in MP costs, changes in trade costs, and learning in the evolution of TFP between 2005 and 2016. We find that both learning and changes in MP costs contributed a sizable portion of TFP growth in developing economies but less so for developed economies. In contrast, changes in trade costs during the period had a very small effect on TFP evolution.

Next, we use 2016, the latest year when we have data for bilateral flows, as our base year. We compute a benchmark economy where trade and MP costs are held constant at their base year levels and contrast it with a situation where the global economy reverts to autarky. Consistent with the MP literature, we find that the static gains from openness are significant. In addition, compared to autarky, trade and MP would also positively affect consumption growth. We calculate static and dynamic gains from trade, MP, and openness. As our paper nests the mechanisms of a set of trade and growth papers, we compare our findings with results in those papers.

Motivated by recent developments in international geopolitics, we consider a counterfactual economic sanction where all foreign MP exits Russia for ten years. The consumption level in Russia would drop by 0.63% immediately, and its subsequent annual growth rate would drop by 3 percentage points during the sanction. Countries that are economically close to Russia, e.g., Latvia and Lithuania, would also experience slower growth.

Finally, we finish by analyzing the implication of a US reshoring policy often put forward as a means to secure supply chains and to retain US technological dominance.[21] We consider a counterfactual where outward MP costs from the United States increase by 20%, permanently. We find that the immediate effect on real consumption is positive for the United States (a 0.14% increase), but negative for many other countries. Because it deters global idea diffusion, such a policy has a negative effect on subsequent growth rates, and even hurts US growth. However, if the policy is designed to maintain US technological advantage relative to other countries, it achieves the objective to some extent.

4.1 The Role of MP, Trade, and Learning

We first use our model to study the role of trade costs, MP costs, and learning in the evolution of TFP over time. We answer the following questions: What is the growth of

[21]See the report by Bloomberg for example (Wu et al. (2022)). The US Congress approved $52 billion funding to aid chip production, but firms getting a US grant may need to curb their production in China.

TFP that can be attributed to measured changes in MP costs? What about changes in MP costs? How much growth would there be if there were no learning?

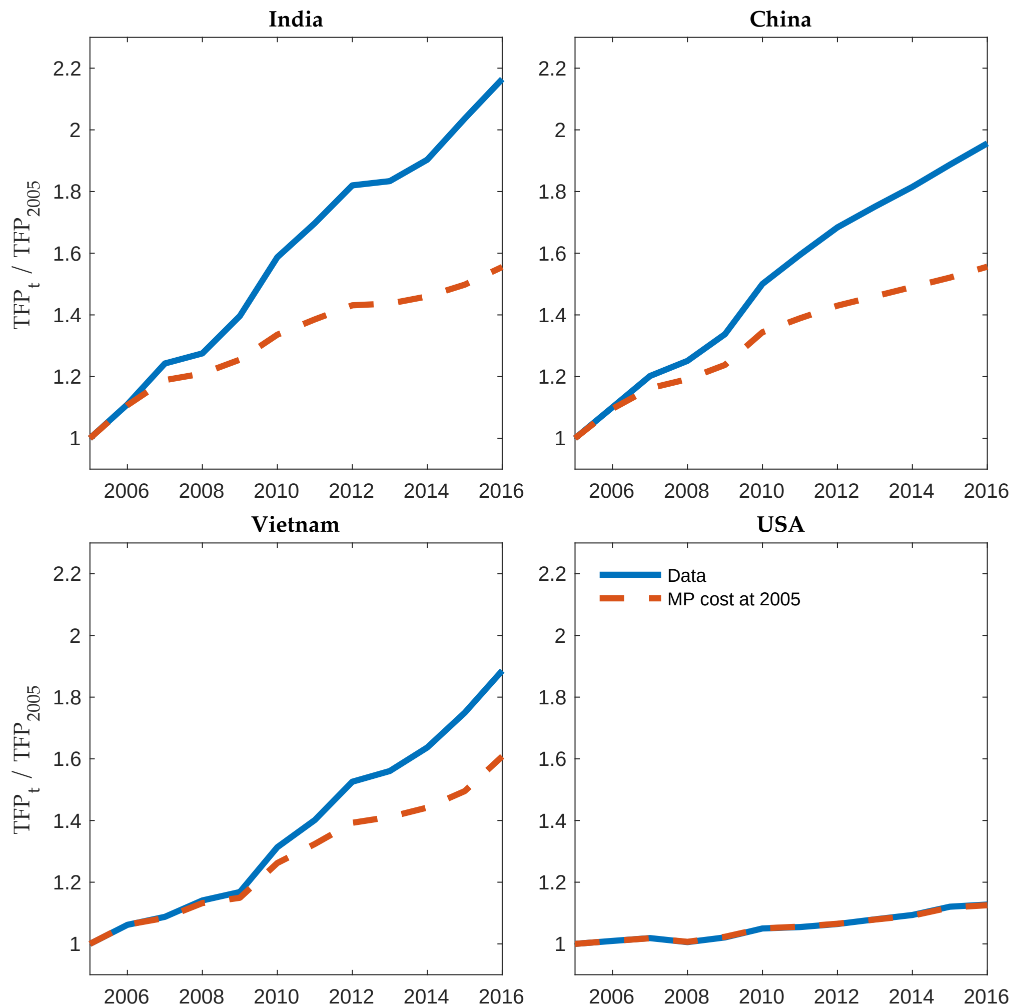
We study the periods between 2005 and 2016 due to data availability. We calibrate the model to the data in the initial year, 2005. Given the estimated learning intensity $\rho = 0.64$, the model can pin down the paths of $\alpha_{i,t}$ for each country that perfectly match the time series of shares and stocks of knowledge from 2005 to 2016.[22] We then compute the economy with the actual path of $\{\alpha_{i,t}, \gamma_{jh,t}, \tau_{ij,t}, L_{i,t}\}$. By design, when $\rho = 0.64$, we perfectly match the time series of the stock of knowledge. We contrast the baseline with a counterfactual where we hold MP costs constant at their 2005 level to understand the effect of changes in MP costs. Similarly, to understand the effect of changes in trade costs, we run a counterfactual holding trade costs constant at their 2005 level. Finally, we simulate the economy with different values of ρ, to show the role of learning in the dynamics of productivity.

MP Costs

We begin by studying what the dynamics of TFP would have been if MP costs were constant at their 2005 level. Figure 3 presents the dynamics of TFP for India, China, Vietnam, and the United States. In each panel, we plot two lines. The solid line is the measured TFP from the data. The dashed line is the measured TFP in the counterfactual exercise where $\{\alpha_{i,t}, \tau_{ij,t}, L_{i,t}\}$ are the same as indicated by the data, but the MP costs γ_{jh} are held fixed at their 2005 level. We interpret the difference between the two lines as the contribution of MP costs changes to the dynamics of TFP for each country. A table with results for all economies is in the appendix.

[22] In this subsection, we relax the assumption that α's grow at a constant rate. We use that assumption to assure the existence of a balanced growth path, but we do not need to impose it in this exercise.

Figure 3: TFP Growth with Constant MP Costs



Notes: The figure presents the changes in measured TFP. In each panel, we plot two lines. The solid line is the measured TFP from the data. The dashed line is what the measured TFP would have been had MP costs been held constant at the starting level in 2005. We plot the results for three developing countries - India, China, Vietnam - and the USA. TFP is calculated as $(\lambda_{i,t}\psi^{\eta}_{iii,t}/(B\pi_{iii,t}))^{1/\theta}$. A table with results for all economies is in the appendix.

An immediate implication is that during the period we are studying (2005-2016), changes in MP costs explain a sizable part of TFP growth in developing economies but not as much in developed economies. India is the economy most affected by the change in MP costs. If MP costs were to remain constant at the initial level over this period, India's TFP in 2016 would be at 72% of the data level. The figures for China and Vietnam are 80% and 85%, respectively. In contrast, the growth of TFP in the United States is barely affected by the change in MP costs.

Trade Costs

We next look at how much changes in trade costs contributed to TFP growth. In the model, a reduction in trade costs has mixed effects on TFP growth for a country. Reducing import costs hurts TFP growth, while reducing export costs is beneficial to TFP growth. To understand why reducing import costs hurts TFP growth, consider a firm that wants to sell to country i. The firm could produce in another country and ship its products to i, or the firm could produce in i to avoid the shipping cost. If the cost to ship to i decreases, the firm is less likely to produce in i and more likely to produce elsewhere. At an aggregate level, a reduction in import costs leads to less MP within the affected country. TFP growth would be negatively affected because of less exposure to foreign technology. On the contrary, if export trade costs in country i decrease, products produced in i would be more competitive for export as well, so i is a more attractive host country for MP. TFP growth would be positively affected as a result of more exposure to foreign technology.

Figure 4 presents the result for the same set of selected countries, and we put a table for all countries in the appendix. Again, the solid line is the measured TFP from the data. The dashed line is the measured TFP in the counterfactual exercise where $\{\alpha_{i,t}, \gamma_{ij,t}, L_{i,t}\}$ are the same as indicated by the data, but the trade costs τ_{ij} are held fixed at the 2005 level.

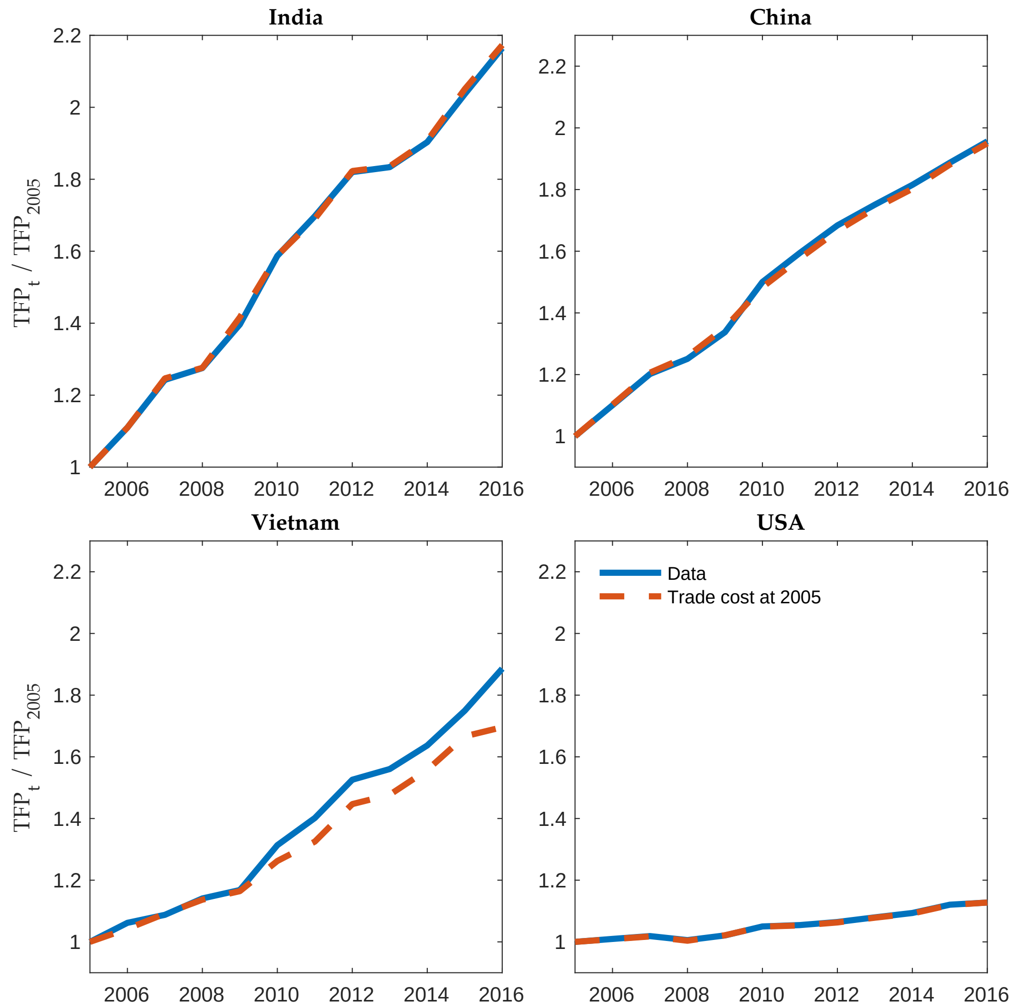
The effect of changes in trade costs is much smaller than the effect of changes in MP costs. Within the same subset of countries, the effect is largest for Vietnam. If trade costs were to remain constant at the initial level over this period, Vietnam's TFP in 2016 would be at 90% of the data level, while the numbers for India, China, and the United States are all very close to 100%. Other countries among the most affected are Malta (97%), Hungary (97%), and Mexico (98%).

Learning

We turn to investigate the role of learning in TFP evolution. To do so, we compute the model assuming different values of ρ, that is, assuming that the learning intensity were different from our benchmark estimation. Figure 5 presents the dynamics of TFP for selected countries. The solid line is the measured TFP from the data, and by design, is also the measured TFP if $\rho = 0.64$, as in our benchmark estimation. The other lines are the measured TFP in a hypothetical path where $\{\alpha_{i,t}, \tau_{ij,t}, \gamma_{jh,t}, L_{i,t}\}$ are the same as indicated by the data, but with different values of the learning intensity ρ. The dashed line is when $\rho = 0.45$. The dotted line is when $\rho = 0$, that is, the only source of TFP growth is from $\alpha_{i,t}$, the arrival of new ideas, the efficiencies of which are drawn from time-invariant exogenous distributions.

Resonating with our finding for changes in MP costs, learning explains a sizable part of TFP growth in developing countries. If $\rho = 0$, i.e., no learning is possible, India's TFP in 2016 would be at 60% of the data level; the statistic is 63% for China and 67% for Vietnam.

Figure 4: TFP Growth with Constant Trade Costs

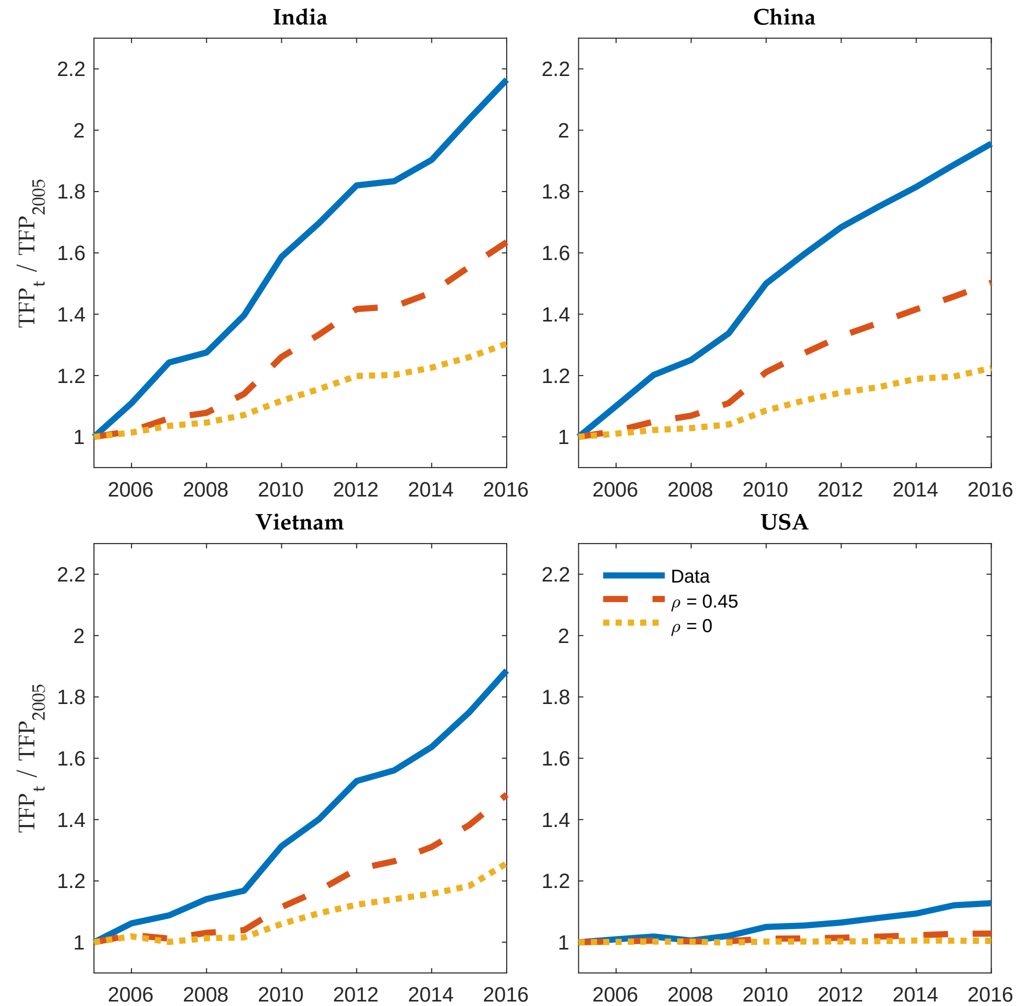


Notes: The figure presents the changes in measured TFP. In each panel, we plot two lines. The solid line is the measured TFP from the data. The dashed line is what the measured TFP would have been had trade costs been held constant at the starting level in 2005. We plot the results for three developing countries - India, China, Vietnam - and the USA. TFP is calculated as $(\lambda_{i,t}\psi^{\eta}_{iii,t}/(B\pi_{iii,t}))^{1/\theta}$. A table with results for all economies is in the appendix.

Even for the United States, the role of learning is not negligible - the US TFP in 2016 would be at 89% of the data level if $\rho = 0$.

It is also worth noting that the effect of learning parameter ρ is not linear. Take India for an example. If $\rho = 0$, i.e., no learning is possible, India's TFP in 2016 would be at 60% of the data level; if $\rho = 0.45$, it would be at 76% of the data level.

Figure 5: TFP Growth with Different Learning Intensity



Notes: The figure presents the changes in measured TFP. In each panel, we plot two lines. The solid line is the measured TFP from the data. The dashed line is when $\rho = 0.45$. The dotted line is when $\rho = 0$. We plot the results for three developing countries - India, China, Vietnam - and the USA. TFP is calculated as $(\lambda_{i,t}\psi^{\eta}_{iii,t}/(B\pi_{iii,t}))^{1/\theta}$. A table with results for all economies is in the appendix.

4.2 Gains from Openness

In Section 4.1, we focus on the evolution of TFP. In this part, we turn to visit the question frequently asked in the quantitative trade literature: What are the gains from openness?

To answer that question, we start from the year 2016 and run the benchmark economy where trade and MP costs are held constant at the level in the base year and contrast it with the other case where the global economy reverts to the autarky state from 2016 onwards. We calculate the gains from openness by comparing the two simulated economies. Furthermore, to explore the role of MP as the vehicle of international idea diffusion, we compute the gains from MP by contrasting the benchmark economy to the economy where countries revert into "MP autarky", i.e., an economy where MP costs approach infinity, $\gamma_{jh} \to \infty$ for all $j \neq h$.

In each scenario, we present the overall welfare effect, measured in terms of annual consumption equivalent variation,

$$(1-\beta)\sum_{t=1}^{\infty}\beta^{t-1}\log\left(\frac{C'_{it}}{C_{it}}\right), \tag{27}$$

where $\beta = 0.95$ is the discount factor, C_{it} is the aggregate consumption per worker in country i at time t in the benchmark economy, and C'_{it} is the counterfactual aggregate consumption per worker. Basically, we are asking this question: What percentage of consumption do we need to take away from in the benchmark economy *annually*, to adjust the discounted value of utility to the level that would occur in the counterfactual? Further, we present both the static and dynamic effects from openness. We define static gains as the change in the current real consumption level immediately after the shock in trade and/or MP costs. We present the dynamic effect as the change in the average growth rate of real consumption. Doing so, we complement our analytics on long-run welfare in Section 2.5.

Before presenting our results, we should acknowledge that our model abstracts from capital accumulation, intermediate goods, and non-tradable goods. As a result, the overall magnitude of our quantitative results on welfare is likely to be biased. As shown in Cai, Caliendo, Parro, and Xiang (2022), including capital accumulation tends to complement the process of TFP growth, hence amplifies the welfare effects. In static models, including intermediate goods in the model would increase the size of welfare gains, but including non-tradable goods would decrease the size. We conjecture that our results are not affected too much with regards of the dynamic pattern across time and the distribution of gains across countries.

Gains from Openness

We start from the overall gains from openness. Taking 2016 as our base year, we run the economy forward, holding all parameters at the 2016 level, and allow the knowledge stock to evolve endogenously. This is our benchmark economy. We then run the counterfactual, asking what would the world look like if there were no trade or MP starting from 2016. We denote the difference between the two economies as the gains from openness.

Table 1 presents the results for selected countries. Column (1) is the welfare gains in terms on annual consumption equivalent variation, as defined in (27). Note that here the economy is going to the new balanced growth paths in autarky. Compared to the autarky state, the gains from openness are equivalent to an annual increase of 11.7% in

Table 1: Gains from Openness: Selected Countries

	Welfare (1)	Static Gain (2)	Δ Growth Rate (Percentage Points) (3)
Australia	20.02%	5.89%	0.71
Brazil	33.81%	4.95%	1.32
Canada	25.90%	10.86%	0.84
China	28.18%	4.17%	1.21
France	20.54%	6.61%	0.72
United Kingdom	27.04%	10.53%	0.87
Hungary	57.95%	36.48%	1.15
India	29.53%	4.22%	1.26
Ireland	43.16%	29.22%	0.70
Mexico	34.75%	13.18%	1.12
United States	11.74%	3.09%	0.47
Vietnam	57.93%	33.72%	1.25

Notes: Column (1) presents overall welfare gains in terms of annual consumption equivalent variation, as defined in (27). Column (2) shows the static gains from openness, i.e., changes in real consumption level between autarky and the benchmark economy in 2016. Column (3) shows the dynamic effect of openness on the average growth rate of real consumption in the following 50 years.

consumption for the United States, and the number is as high as 57.9% for Hungary and Vietnam. The numbers may seem large at first. They are a combination of the immediate effect and the long-lasting effect on growth rates. Column (2) is the static gains from openness, defined as the immediate gap in real consumption levels between autarky and the benchmark economy. Static gains from openness are sizable, and they vary across countries. The static gains ranges from 3% in the United States to 36% in Hungary. Small and open countries like Hungary, Ireland, and Vietnam sees the largest static gains from openness. Column (3) presents the dynamic effect of openness on the average annual growth rate of real consumption levels in the next 50 years. Compared to the state of autarky, the average annual growth rate is larger for all countries, ranging from 0.47 percentage points for the United States to 1.32 percentage points for Brazil.

Gains from MP

To separate the role of MP in the overall gains from openness, we run the counterfactual where the MP costs approach infinity starting from 2016, leaving trade costs and other parameters unchanged. We denote the difference between this economy in the state of "MP autarky" and the benchmark as the gains from MP.

In this exercise, with an increase in MP costs but no changes in trade costs, trade flows

Table 2: Gains from MP: Selected Countries

	Welfare (1)	Static Gain (2)	Δ Growth Rate (Percentage Points) (3)
Australia	16.29%	2.72%	0.68
Brazil	29.69%	1.05%	1.30
Canada	18.01%	3.73%	0.79
China	24.21%	0.34%	1.19
France	14.29%	1.30%	0.67
United Kingdom	20.01%	4.31%	0.82
Hungary	31.92%	11.35%	1.07
India	25.05%	-0.16%	1.25
Ireland	14.70%	6.10%	0.41
Mexico	22.54%	1.66%	1.07
United States	9.40%	1.15%	0.45
Vietnam	23.78%	-0.19%	1.20

Notes: Column (1) presents overall welfare gains in terms of annual consumption equivalent variation, as defined in (27). Column (2) shows the static gains from openness, i.e., changes in real consumption level between autarky and the benchmark economy in 2016. Column (3) shows the dynamic effect of openness on the average growth rate of real consumption in the following 50 years.

would increase. For a firm to sell to a market, trade and MP are substitutes.[23] When MP costs increase, trade becomes relatively more cost-efficient, and aggregate trade flows would increase. The reduction of MP flows is partially offset by the increase in trade flows, mitigating the immediate impact on the real consumption. However, the reduction of MP flows would lead to less international learning, and hence growth. This dynamic effect is still significant despite the increase in trade flows.

Table 2 presents the results for selected countries. Column (1) reports the welfare gains from MP in terms on annual consumption equivalent variation. As one may expect, the gains from MP is smaller than the static gains from openness. Column (2) reports the static gains from MP, defined as the immediate gap in real consumption levels between MP autarky and the benchmark economy. For countries like China, India and Vietnam, the immediate effect of a reduction in MP on consumption levels is entirely offset by the increase in trade. It may be surprising at first sight that the static gains is negative for India and Vietnam. To understand the reason we must think about the general equilibrium effect on relative wages. Countries that host more foreign MP in the base year would

[23] When we think about "bridge MP", i.e., a firm produces in a foreign country and export to a third country, trade and MP are complements. Bridge MP flows account for a small portion of MP, so we focus the substitution between MP and trade to highlight the intuition.

Table 3: Gains from Openness

	TFP evolution	Static Gains Trade	Static Gains MP	Static Gains Openness	Dynamic Gains Trade	Dynamic Gains MP	Dynamic Gains Openness
Idea flows							
Eaton and Kortum (1999)	✓						
Lucas (2009)	✓						
Alvarez, Buera, and Lucas (2013)	✓						
Trade and MP							
Eaton and Kortum (2002)		1.04		1.04			
Ramondo and Rodríguez-Clare (2013)		1.074	1.116	1.221			
Tintelnot (2017)		1.158	1.023	1.217			
Arkolakis et al. (2018)		1.036	1.07	1.246			
Idea flows in open economy							
Buera and Oberfield (2020)	✓	✓		✓	✓		✓
Cai, Li, and Santacreu (2022)	✓	1.109		1.109	1.226		1.226
This Paper	✓	1.090	1.079	1.117	1.094	1.286	1.308

Notes: Numbers for Eaton and Kortum (2002) is the average of welfare change with immobile labor in their Table IX. Numbers for Tintelnot (2017) is average of Column 1 of Table VII (gains from trade), Column 4 of Table A.7 (gains from MP), and Column 1 of Table A.8 (gains from openness) from his paper. Numbers for Ramondo and Rodríguez-Clare (2013) are from Table 5 in their paper. Numbers for Arkolakis et al. (2018) are from Table 5 in their paper. Numbers for Cai, Li, and Santacreu (2022) are from Table 3 in their paper. In this paper, gains from trade are calculated as the consumption ratio between a trade only economy and autarky, and gains from MP are calculated as the consumption ratio between a MP only economy and autarky.

experience a decrease in relative wages in MP autarky, because of the reduction in labor demand from foreign MP. The size of MP in India and Vietnam is relatively small, so they are relatively less affected by the reduction in labor demand. Consequently, the relative real wages increase in these two countries compared to other countries. As a result, the immediate consumption is higher in MP autarky for these two countries because imported goods are cheaper.

Turning to the dynamic effects, reported in Column (6) as the change in the growth rate, we find that the dynamic effect of openness is mostly explained by the dynamic effect of MP. Even when a country has very small static gains from MP, the long-run effects are sizable. For example, compared to MP autarky, the annual growth rate of real consumption increases by 1.2 percentage points in India and 1.2 percentages in Vietnam. A table containing gains from MP for all countries is in the appendix.

Discussion on Quantitative Results

Our paper calculates static and dynamic gains from trade, MP, and openness. As our paper nests the mechanisms of a set of trade and growth paper, it is useful to compare our results with theirs. In Table 3, we summarize gains from trade, MP, and openness in these models. Our paper embeds TFP evolution driven by idea diffusion thus nests Eaton and Kortum (1999), Lucas (2009) and Alvarez, Buera, and Lucas (2013) in the "Idea flows" panel in Table 3. In contrast to those papers, we provide quantitative results about how this mechanism contributes to gains from openness. Before turning to the dynamic gains from openness resulting from the TFP evolution induced by trade and MP, we compare static gains from openness in our model with those predicted by static trade and MP models. In Table 3, we summarize gains from trade, MP, and openness computed by these static models in panel "Trade and MP". Tintelnot (2017) defines the gains from MP as the change in real income when the MP cost goes to infinity in the model with his calibrated parameters. We take the simple average of column 1 of Table VII in his paper. For gains from trade, we take the simple average of column 4 of Table A.7 in Tintelnot (2017). We choose the gains from trade in a pure trade model to make numbers comparable as some papers like Eaton and Kortum (2002) do not incorporate MP. For gains from openness, we take the simple average of column 1 of Table A.8 in Tintelnot (2017). The gains from trade range from 1.04 (Eaton and Kortum (2002) and Arkolakis, Ramondo, Rodríguez-Clare, and Yeaple (2018)) to 1.16 (Tintelnot (2017)), while the gains from MP range from 1.02 (Tintelnot (2017)) to 1.11 (Ramondo and Rodríguez-Clare (2013)). The gains from trade (1.09) and MP (1.08) in our model are similar to those in the existing literature. Interestingly, the gains from openness in Tintelnot (2017), 1.217, are close to what have been estimated by Arkolakis, Ramondo, Rodríguez-Clare, and Yeaple (2018), 1.246, and Ramondo and Rodríguez-Clare (2013), 1.221. The static gains from openness estimated in our paper are slightly lower but still comparable. What distinguishes our paper from the previous literature is the dynamic gains from openness induced by idea flows through MP. The closest papers to ours are Buera and Oberfield (2020) and Cai, Li, and Santacreu (2022). Our paper without MP collapses to the case of "learning from sellers" in Buera and Oberfield (2020). Buera and Oberfield (2020) do not provide numbers for gains from openness. Cai, Li, and Santacreu (2022) incorporate idea flows through trade into a general equilibrium trade model. The dynamic gains from openness in Cai, Li, and Santacreu (2022) are 1.226, while our model, by separating domestic sellers from foreign sellers, obtains a larger value for the dynamic gains, 1.308. To sum up, our model has similar static implications of opening to trade with MP previous literature, while we highlight an additional significant source of gains from openness. The dynamic gains from openness through learning from MP are sizable.

4.3 Economic Sanctions on Russia

Motivated by the recent events of the Russia-Ukraine war, we use Russia as an example to study the impact of economic sanctions on a country. We analyze how they may affect welfare across countries.

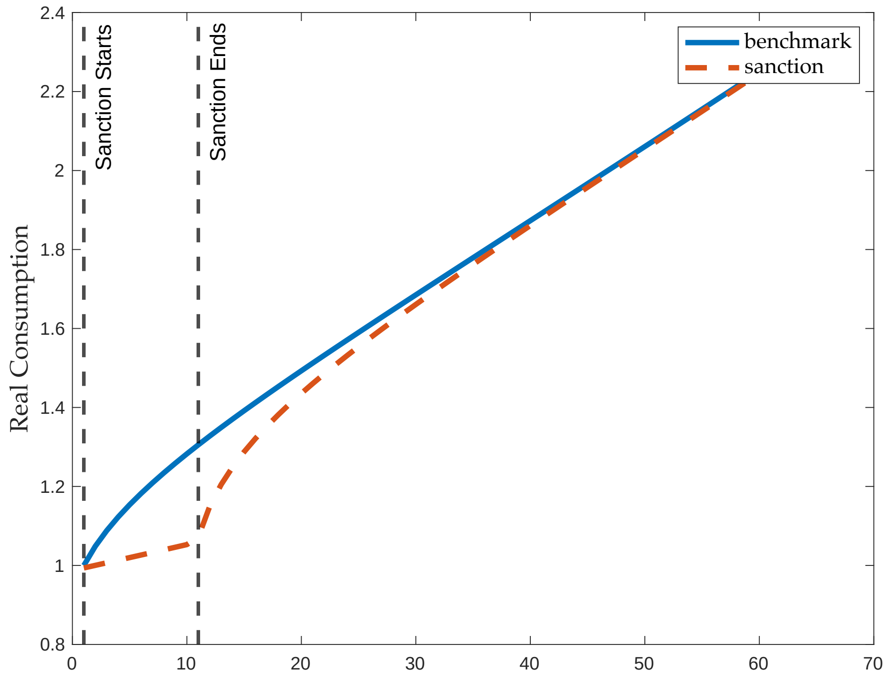
We consider the following counterfactual exercise where the MP frictions from the rest of the world to Russia increases to infinity (i.e., $\gamma_{RUS,h} = \infty$ for all $h \neq RUS$) for ten years. Table 4 shows the results for the most affected countries. Column (1) presents the annual welfare loss for each country. Column (2) presents the immediate impact on real consumption in each country, and column (3) presents the differences between the annual growth rates during the sanction versus the benchmark case.

As one may conjecture, the welfare loss is significant in Russia, and the major reason is the slowed growth as a result of being cutoff from global production. The *ten-year* MP sanction on Russia causes an welfare effect equivalent to a 7.25% annual reduction in real consumption *perpetually*. Real consumption decreases by 0.63% in Russia immediately, and during the period of economic sanction the annual growth rate of real consumption is lower by 2.16 percentage points compared to autarky. Figure 6 shows the evolution of real consumption in Russia. During the sanction, real consumption grows slower than the benchmark case. When the sanction ends, MP costs return to the original level, but it takes time for real consumption to converge back to the benchmark level. Real consumption in Russia is lower than the benchmark case for an extended period of time.

At the same time, countries that have a close economic tie with Russia are also affected. While the sanctions are not targeted at them, and the immediate impact on consumption is negligible, the growth rates in these countries are affected. This might sound counterintuitive at first: if these countries compete with Russia for inward MP, we would expect that economic sanctions on Russia lead to more MP in these countries, which should have a positive impact on their growth rates. The negative effect shows up because of trade and MP relationships with Russia: since the technology level in Russia is lower, countries that import from Russia face an increase in import prices, and countries that host Russian MP would have a lower learning effect. In the appendix we report the results for all countries. We also report the results for another counterfactual where both inward MP and trade costs increase to infinity for Russia, which produces results similar to what we see in this section.

We report what the welfare loss in Russia would be for different lengths of MP sanctions in Figure 7. If the duration of the MP sanction increases from 5 years to 15 years, the welfare loss in Russia increase from 4% to 10%. We also consider another counterfactual where China does not join the MP sanction against Russia. The welfare effect for Russia

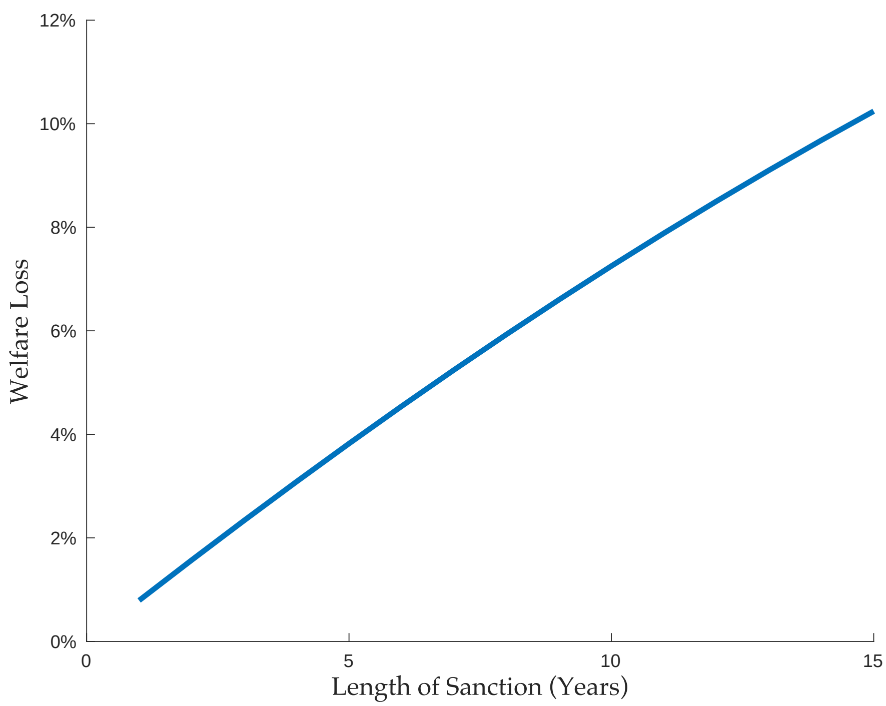
Figure 6: Real Consumption in Russia



Notes: This figure shows the paths of real consumption in Russia with and without MP Sanction (base year is normalized to 1 in the benchmark).

does not change much, becoming slightly less negative, from -7.25% to -7.15%.

Figure 7: Welfare Loss in Russia



Notes: Welfare loss in Russia resulted from an MP sanction with various duration.

Table 4: Economic Sanction on Russia: Selected Countries

	Welfare (1)	Static Gain (2)	Δ Growth Rate (Percentage Points) (3)
Bulgaria	-0.06%	0.02%	-0.01
Lithuania	-0.16%	0.01%	-0.04
Latvia	-0.25%	0.07%	-0.07
Romania	-0.06%	0.00%	-0.01
Russia	-7.25%	-0.63%	-2.16

Notes: Result of an counterfactual exercise where the MP frictions from the rest of the world to Russia increase to infinity for 10 years. Countries mostly affected are show above. The second column presents the immediate impact on real consumption in each country. The last column shows the differences between the annual growth rates during the sanction versus the benchmark case.

4.4 US Reshoring Initiative

Reshoring production back to the United States has drawn much attention, especially in light of the trend of declining manufacturing employment and the supply chain issues brought on by the pandemic and geopolitical risks. We use our model to quantify the effects of a permanent 20% rise in outward MP costs from the United States (i.e., $\gamma'_{j,USA}/\gamma_{j,USA} = 1.2$ for all $j \neq USA$). We contrast the short-run effects to the long-run effects in the United States, and we present the effects of such a policy on selected countries. A table of results for all countries appears in the appendix.

Bringing production back may affect the immediate real consumption level in the United States both positively and negatively. When more production is relocated to the United States, labor demand is higher, which increases the US wage level and positively affects US real consumption. However, the downside is that higher production costs of US firms lead to higher prices of US products, which negatively affects US real consumption. From the results in Table 5, the positive effects dominate, and US real consumption level goes up by 0.14% immediately. Countries that used to host US MP would also see an immediate dent in their real consumption level, mostly because of the decline in labor demand and the decrease in wages as a result. The surprising immediate winner is Vietnam, with a 0.34% increase in its real consumption level. The reason is that in the base year, US MP only accounted for 0.25% of total production in Vietnam, so the reshoring doesn't affect Vietnam through the labor market. When wages in other countries decrease, import prices decrease, and consumption increases for Vietnam.

While the policy has a positive effect on US consumption in the short run, its dynamic implication tells another story. The last column of Table 5 shows the change in the average

Table 5: US Reshoring Initiative

	Welfare	Static Gain	Δ Growth Rate (Percentage Points)
	(1)	(2)	(3)
Canada	-0.88%	-1.58%	-0.04
China	-1.15%	-0.03%	-0.06
United Kingdom	-0.66%	-1.12%	-0.03
Ireland	-0.91%	-3.11%	-0.00
Mexico	-0.93%	-0.83%	-0.04
United States	-0.10%	0.14%	-0.03
Vietnam	-1.31%	0.34%	-0.05

Notes: Result of an counterfactual exercise where the MP frictions from the US to the rest of the world increase by 20% permanently. Countries most affected are show above. The second column presents the immediate impact on the real consumption level in each country. The last column shows the differences between the annual growth rates for the next 50 years versus the benchmark case.

Table 6: US Technological Dominance

	Benchmark	Reshoring	Base Year
	(1)	(2)	(3)
USA / Median	1.56	1.58	1.75
USA / Median of High Income	1.29	1.31	1.37
USA / Median of Low & Middle Income	2.88	2.92	3.11
USA / China	4.83	4.91	5.34

Notes: This table reports the TFP gap between the United States and other economies. Columns (1) and (2) report the TFP ratio 50 years after the shock. Column (3) reports the TFP ratio in the base year as a reference. Overall median is between Greece and Turkey. Malta's TFP is the median among high-income economies. South Africa's TFP is the median among low-and-middle-income economies. We divide the 54 economies in our sample into high-income economies and low-and-middle-income economies according to the World Bank definition for calendar year 2016.

annual growth rate in the next 50 years. The US growth rate decreases by 0.03 percentage points, and it decreases everywhere in the world as well. When production relocates back to the United States, the rest of the world learns less from US ideas, and technology advances slower everywhere. The effect also spills over to the United States, as foreign firms producing there bring fewer insights as they would have.

Some may argue that US reshoring policies aim to maintain US technological dominance. Table 6 compares the TFP ratio between the United States and other countries. Column (1) reports the TFP ratio in 50 years without reshoring, and Column (2) reports that with reshoring. Reshoring policies achieve the goal of maintaining US technological dominance to some extent, as we can see that the TFP ratio is higher in with reshoring.

5 Conclusion

In this paper, we provide a tractable growth model to study the dynamic macroeconomic effects of multinational production (MP) across countries. In our model, aggregate production and trade are determined by technology, together with frictions in MP and trade. Technology in a country advances over time because of the arrival of new ideas for production, and the quality of new ideas depends on learning from existing producers within the country. Hence, the dynamics of technology in turn depends on the production pattern. The model yields tractable expressions for bilateral MP flows, trade flows, and the dynamics of technology that we use in our calibration across a set of 54 economies. Our model also encapsulates much existing work into a single unifying quantitative framework involving only a few parameters once calibrated.

We use the calibrated model to explore the role of MP in international knowledge diffusion by looking at the ability of MP costs to account for changes in measured TFP between 2005 and 2016. We find that changes in MP costs accounted for a sizable proportion of TFP evolution in the sample period, and it varies across countries. Then we perform a series of counterfactual exercises designed to study the welfare and growth implications of shocks to MP and trade costs, a proxy for MP and trade policies. We find that increasing MP cost has an immediate effect on real consumption, and a significant effect on economic growth rates. As a result, economic sanctions where multinational firms exit may have a large and long-lasting welfare effect on the host country. We also find that reshoring policies can have positive short-run effects on wages and consumption, but come with negative long-run welfare implications, highlighting the importance of taking dynamic effects into consideration.

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A Notation Appendix

v	Variety.
y	Output.
$\mathbf{Q}, \mathbf{q}$	Random vector of productivity, and its realization.
q	Productivity, one element of $\mathbf{q}$.
$\mathbf{Z}, \mathbf{z}$	Random vector of original component in new ideas, and its realization.
z	One element of $\mathbf{z}$.
ρ	Learning intensity.
Q', q'	Random variable of observed efficiency, and its realization.
τ_{ij}	Iceberg trade cost of shipping goods from j to i.
γ_{jh}	Iceberg MP cost for a firm from h to produce in j.
$A(\mathbf{z})$	Arrival rate of ideas with original component Z better than $\mathbf{z}$ in at least one dimension.
$\tilde{A}(\mathbf{q})$	Arrival rate of (augmented) ideas Q better than $\mathbf{q}$ in at least one dimension.
$G(q')$	Distribution of efficiency of actively producing plants.
$F(\mathbf{q})$	Technology frontier.
α	Exogenous arrival rate.
θ	Shape parameter of multivariate Pareto Frechét.
η	Correlation of multivariate Pareto and Frechét.
h, i, j, k, n	Locations.
Λ	Learning effect: $\int_0^\infty x^{\rho\theta} dG(x)$.
λ	Knowledge stock, also the location parameter of the Frechét distribution.
σ	Elasticity of substitution.
$c(v)$	Consumption of variety v.
C	Consumption aggregate.
u	Utility.
κ_{ijh}	Cost kernel.
$\pi_{ijh}, \pi^T_{ij}, \pi^E_{ih}$	Trilateral share, trade share and expenditure share.
π^{MP}_{jh}	Bilateral MP *production* share. Directly observable from data.
π^M_{jh}	Bilateral MP *consumption* share, also the technology exposure term.
ψ_{ijh}	Conditional production share.
L	Labor forces.
w	Wage rate.
ω	Real wage.
g_α	Growth rate of the arrival rate.
ξ^M, ξ^T	Used in calibration, MP technology kernel and production efficiency kernel.
β	Discount factor.

B Theory Appendix

This appendix contains derivations and proofs omitted in the main text.

B.1 Derivation of Augmented Arrival Rate

Here we derive equation (1). Under Assumption 1 and taking the distribution of Q' as given, the arrival rate of ideas of quality $\mathbf{Q}$ better than $\mathbf{q}$ in at least one dimension is

$$\begin{aligned}
\tilde{A}_{h,t}(\mathbf{q}) &= \int_0^\infty A_{h,t}\left(\frac{\mathbf{q}}{x^\rho}\right) dG_{h,t}(x) \\
&= \int_0^\infty \alpha_{h,t}\left(\sum_{n=1}^{N}\left(\frac{q_n}{x^\rho}\right)^{-\frac{\theta}{1-\eta}}\right)^{1-\eta} dG_{h,t}(x) \\
&= \alpha_{h,t}\left(\sum_{n=1}^{N} q_n^{-\frac{\theta}{1-\eta}}\right)^{1-\eta} \int_0^\infty x^{\rho\theta} dG_{h,t}(x).
\end{aligned}$$

When we define the learning effect, equation (1) follows immediately.

B.2 Special Cases

Here we discuss Assumption 1 under the special cases where $\eta = 0$ and $\eta \to 1$. When $\eta = 0$, the arrival rate of ideas with original component $\mathbf{Z}$ better than $\mathbf{z}$ in at least one dimension is

$$A_{h,t}(\mathbf{z}) = \alpha_{h,t}\left(\sum_{n=1}^{N} z_n^{-\theta}\right).$$

In the special case, the only possible arrivals of $\mathbf{z} = (z_1, \ldots, z_N)$ are $z_j > 0$ for some j and $z_i = 0$ for all $i \neq j$. It reduces to the case that an idea can only be applied to one location randomly.

To see why this is the case, consider a simpler case where $N = 2$. We claim that for all $x_2 > x_1 > 0, y_2 > y_1 > 0$, the arrival rate of ideas with component $\mathbf{Z}$ such that $Z_1 \in (x_1, x_2], Z_2 \in (y_1, y_2]$ is

$$A_{h,t}\left(\begin{bmatrix} x_1 \\ y_1 \end{bmatrix}\right) - A_{h,t}\left(\begin{bmatrix} x_1 \\ y_2 \end{bmatrix}\right) - A_{h,t}\left(\begin{bmatrix} x_2 \\ y_1 \end{bmatrix}\right) + A_{h,t}\left(\begin{bmatrix} x_2 \\ y_2 \end{bmatrix}\right) = 0.$$

That is to say, when $\eta = 0$, there will be no ideas whose original component is positive in both dimension. In other words, the only possible arrivals of $\mathbf{z} = (z_1, z_2)$ are $z_1 > 0,\ z_2 = 0$

or $z_1 = 0,\ z_2 > 0$. We use the $N = 2$ case only to save on notations. The same argument can be made when $N > 2$.

The other special case where $\eta \to 1$ is relatively straightforward.

B.3 Proof of Proposition 1

Proposition 1 says that the distribution of the frontier at any time t is a multivariate Frechét.

Proposition 1: *At time t, given the arrival rate characterized by equation (1), the cumulative distribution function $F_{h,t}$ of state-of-the-art efficiencies takes the form of a multivariate Fréchet distribution,*

$$\Pr[\mathbf{Q}_{h,t}^{(1)}(v) \leq \mathbf{q}] = F_{h,t}(\mathbf{q}) = \exp\left(-\lambda_{h,t}\left(\sum_{n=1}^{N} q_n^{-\frac{\theta}{1-\eta}}\right)^{1-\eta}\right),$$

with support $q_n > 0$ for all n. The location parameter $\lambda_{h,t} := \int_{-\infty}^{t} \alpha_{h,\tau}\Lambda_{h,\tau}d\tau$ is the cumulated knowledge stock of country h at time t.

Proof. At time t, the arrival rate of ideas of quality $\mathbf{Q}$ better than $\mathbf{q}$ in at least one dimension is

$$\tilde{A}_{h,t}(\mathbf{q}) = \alpha_{h,t}\Lambda_{h,t}\left(\sum_{n=1}^{N} q_n^{-\frac{\theta}{1-\eta}}\right)^{1-\eta},$$

where $\Lambda_{h,t} := \int_0^\infty x^{\rho\theta}dG_{h,t}(x)$ is the learning effect.

Denote the number of ideas with $\mathbf{Q}$ better than $\mathbf{q}$ for producing good v in at least one dimension as $M_{h,t}$. This number $M_{h,t}$ is a random variable and follows a Poisson distribution with parameter

$$\int_{-\infty}^{t} \tilde{A}_{h,\tau}(\mathbf{q})d\tau.$$

Observe that the event "state-of-the-art efficiencies to produce good v, $\mathbf{Q}_{h,t}^{(1)}(v) \leq \mathbf{q}$" is equivalent to the event " number of ideas better than $\mathbf{q}$ in at least one dimension $M_{h,t} = 0$". Hence,

$$\Pr[\mathbf{Q}_{h,t}^{(1)}(v) \leq \mathbf{q}] = \Pr[M_{h,t} = 0] = \exp\left(-\int_{-\infty}^{t} \tilde{A}_{h,\tau}(\mathbf{q})d\tau\right).$$

It follows immediately that

$$\Pr[\mathbf{Q}_{h,t}^{(1)}(v) \leq \mathbf{q}] = \exp\left(-\int_{-\infty}^{t} \tilde{A}_{h,\tau}(\mathbf{q})d\tau\right)$$

$$= \exp\left(-\int_{-\infty}^{t} \alpha_{h,\tau}\Lambda_{h,\tau}\left(\sum_{n=1}^{N} q_n^{-\frac{\theta}{1-\eta}}\right)^{1-\eta} d\tau\right)$$

$$= \exp\left(-\int_{-\infty}^{t} \alpha_{h,\tau}\Lambda_{h,\tau} d\tau \left(\sum_{n=1}^{N} q_n^{-\frac{\theta}{1-\eta}}\right)^{1-\eta}\right)$$

$$= \exp\left(-\int_{-\infty}^{t} \alpha_{h,\tau}\Lambda_{h,\tau} d\tau \left(\sum_{n=1}^{N} q_n^{-\frac{\theta}{1-\eta}}\right)^{1-\eta}\right)$$

$$= \exp\left(-\lambda_{h,t}\left(\sum_{n=1}^{N} q_n^{-\frac{\theta}{1-\eta}}\right)^{1-\eta}\right)$$

where the last equality follows from the definition $\lambda_{h,t} := \int_{-\infty}^{t} \alpha_{h,\tau}\Lambda_{h,\tau} d\tau$. □

B.4 Proof of Proposition 2

Proposition 2 says how knowledge stocks $\lambda_{h,t}$ evolves over time.

Proposition 2: *If all actively producing plants in h are equally likely to be sampled when a new idea arrives, the evolution of $\lambda_{h,t}$ can be characterized using only the aggregate shares and knowledge stocks:*

$$\dot{\lambda}_{h,t} = \alpha_{h,t}\Gamma(1-\rho)\sum_{j=1}^{N} \underbrace{\frac{\pi_{hhj,t}}{\sum_{n=1}^{N}\pi_{hhn,t}}}_{\text{technology exposure}} \underbrace{\left(\frac{\lambda_{j,t}}{\pi^{E}_{hj,t}\psi^{1-\eta}_{hhj,t}}\right)^{\rho}}_{\text{adjusted technology level}}$$

for $h = 1, \ldots, N$, where $\Gamma(\cdot)$ is the Gamma function.

Proof. We first derive the distribution of efficiencies of actively producing plants located in country h at time t, $G_{h,t}(\cdot)$, then we show that the evolution is $\lambda_{h,t}$ is according to (8). In this proof, we will omit time subscript t when there is no confusion.

Let $H_{ijh}(q)$ be the fraction of goods for which the lowest cost provider to i is a plant in j whose headquarter is in h, and the productivity of this plant is weakly less than q, then

$$G_h(q) = \frac{\sum_{n=1}^{N} H_{jjn}(q)}{\sum_{n=1}^{N} H_{jjn}(\infty)}.$$

By definition,

$$H_{ijh}(q) = \Pr\left(q_{jh} \leq q \;\&\; q_{kn} \leq \frac{\kappa_{ikn}}{\kappa_{ijh}} q_{jh} \;\forall k, n\right)$$
$$= \int_0^q \frac{\partial F_h(\frac{\kappa_{i1h}}{\kappa_{ijh}}x, ..., \frac{\kappa_{iNh}}{\kappa_{ijh}}x)}{\partial q_{jh}} \left(\prod_{n\neq h} F_n(\frac{\kappa_{i1n}}{\kappa_{ijh}}x, ..., \frac{\kappa_{iNn}}{\kappa_{ijh}}x)\right) dx.$$

where $\kappa_{ijh} = \gamma_{jh} w_j \tau_{ij}$.

From Proposition 1, we know that $(q_{1h}, ..., q_{Nh})$ follows a multivariate Frechét distribution with location parameter λ_h, $F_h(\cdot)$, so

$$F_n(\frac{\kappa_{i1n}}{\kappa_{ijh}}x, ..., \frac{\kappa_{iNn}}{\kappa_{ijh}}x) = \exp\left(-\lambda_n \left(\sum_{k=1}^N \left(\frac{\kappa_{ikn}}{\kappa_{ijh}}x\right)^{-\frac{\theta}{1-\eta}}\right)^{1-\eta}\right)$$
$$= \exp\left(-\lambda_n \left(\sum_{k=1}^N \left(\frac{\kappa_{ikn}}{\kappa_{ijh}}\right)^{-\frac{\theta}{1-\eta}}\right)^{1-\eta} x^{-\theta}\right).$$

And

$$\frac{\partial F_h(\mathbf{q})}{\partial q_{jh}} = \exp\left(-\lambda_h \left(\sum_{k=1}^N q_{kh}^{-\frac{\theta}{1-\eta}}\right)^{1-\eta}\right) \theta\lambda_h \left(\sum_{k=1}^N q_{kh}^{-\frac{\theta}{1-\eta}}\right)^{-\eta} q_{jh}^{-\frac{\theta}{1-\eta}-1},$$

So

$$H_{ijh}(q) = \int_0^q \theta\lambda_h \left(\sum_{k=1}^N (\frac{\kappa_{ikh}}{\kappa_{ijh}}x)^{-\frac{\theta}{1-\eta}}\right)^{-\eta} x^{-\frac{\theta}{1-\eta}-1} \prod_{n=1}^N \exp\left(-\lambda_n \left(\sum_{k=1}^N \left(\frac{\kappa_{ikn}}{\kappa_{ijh}}\right)^{-\frac{\theta}{1-\eta}}\right)^{1-\eta} x^{-\theta}\right) dx$$
$$= \int_0^q \theta\lambda_h \left(\sum_{k=1}^N (\frac{\kappa_{ikh}}{\kappa_{ijh}})^{-\frac{\theta}{1-\eta}}\right)^{-\eta} \prod_{n=1}^N \exp\left(-\lambda_n \left(\sum_{k=1}^N \left(\frac{\kappa_{ikn}}{\kappa_{ijh}}\right)^{-\frac{\theta}{1-\eta}}\right)^{1-\eta} x^{-\theta}\right) x^{-\theta-1} dx$$
$$= \int_0^q (-\lambda_h) \left(\sum_k (\frac{\kappa_{ikh}}{\kappa_{ijh}})^{-\frac{\theta}{1-\eta}}\right)^{-\eta} \exp\left(\sum_{n=1}^N -\lambda_n \left(\sum_{k=1}^N \left(\frac{\kappa_{ikn}}{\kappa_{ijh}}\right)^{-\frac{\theta}{1-\eta}}\right)^{1-\eta} x^{-\theta}\right) dx^{-\theta}$$
$$= \frac{\lambda_h \left(\sum_k (\frac{\kappa_{ikh}}{\kappa_{ijh}})^{-\frac{\theta}{1-\eta}}\right)^{-\eta}}{\sum_{n=1}^N \lambda_n \left(\sum_{k=1}^N \left(\frac{\kappa_{ikn}}{\kappa_{ijh}}\right)^{-\frac{\theta}{1-\eta}}\right)^{1-\eta}} \exp\left(\sum_{n=1}^N -\lambda_n \left(\sum_{k=1}^N \left(\frac{\kappa_{ikn}}{\kappa_{ijh}}\right)^{-\frac{\theta}{1-\eta}}\right)^{1-\eta} q^{-\theta}\right)$$

$$
\begin{aligned}
&= \frac{\lambda_h \left(\sum_k \left(\frac{\kappa_{ikh}}{\kappa_{ijh}}\right)^{-\frac{\theta}{1-\eta}}\right)^{-\eta}}{\sum_{n=1}^N \lambda_n \left(\sum_{k=1}^N \left(\frac{\kappa_{ikn}}{\kappa_{ijh}}\right)^{-\frac{\theta}{1-\eta}}\right)^{1-\eta}} \exp\left(\sum_{n=1}^N -\lambda_n \left(\sum_{k=1}^N \left(\frac{\kappa_{ikn}}{\kappa_{ijh}}\right)^{-\frac{\theta}{1-\eta}}\right)^{1-\eta} q^{-\theta}\right) \\
&= \kappa_{ijh}^{-\frac{\theta}{1-\eta}} \frac{\lambda_h \left(\sum_k (\kappa_{ikh})^{-\frac{\theta}{1-\eta}}\right)^{-\eta}}{\sum_{n=1}^N \lambda_n \left(\sum_{k=1}^N (\kappa_{ikn})^{-\frac{\theta}{1-\eta}}\right)^{1-\eta}} \exp\left(\sum_{n=1}^N -\lambda_n \left(\sum_{k=1}^N \left(\frac{\kappa_{ikn}}{\kappa_{ijh}}\right)^{-\frac{\theta}{1-\eta}}\right)^{1-\eta} q^{-\theta}\right) \\
&= \pi_{ijh} \exp\left(\sum_{n=1}^N -\lambda_n \left(\sum_{k=1}^N \left(\frac{\kappa_{ikn}}{\kappa_{ijh}}\right)^{-\frac{\theta}{1-\eta}}\right)^{1-\eta} q^{-\theta}\right).
\end{aligned}
$$

Note that

$$
\begin{aligned}
\sum_{n=1}^N -\lambda_n \left(\sum_{k=1}^N \left(\frac{\kappa_{ikn}}{\kappa_{ijh}}\right)^{-\frac{\theta}{1-\eta}}\right)^{1-\eta} q^{-\theta} &= \sum_{n=1}^N \lambda_n \left(\sum_{k=1}^N (\kappa_{ikn})^{-\frac{\theta}{1-\rho}}\right)^{1-\rho} \kappa_{ijh}{}^{\theta} \\
&= \frac{\lambda_h}{\pi_{ijh}\psi_{ijh}^{-\rho}} \\
&= \frac{\lambda_h}{\pi_{ih}^E \psi_{ijh}^{1-\rho}}.
\end{aligned}
$$

So we have

$$
H_{ijh}(q) = \pi_{ijh} \exp\left(-\frac{\lambda_h}{\pi_{ih}^E \psi_{ijh}^{1-\rho}} q^{-\theta}\right),
$$

and

$$
G_h(q) = \frac{\sum_{n=1}^N H_{hhn}(q)}{\sum_{n=1}^N H_{hhn}(\infty)} = \sum_{n=1}^N \frac{\pi_{hhn}}{\sum_{n=1}^N \pi_{hhn}} \exp\left(-\frac{\lambda_n}{\pi_{hn}^E \psi_{hhn}^{1-\rho}} q^{-\theta}\right).
$$

Finally, substituting $G_h(q)$ back to

$$
\Lambda_{h,t} = \int_0^\infty x^{\rho\theta} dG_{h,t}(x),
$$

and recall that

$$
\dot{\lambda}_{h,t} = \alpha_{h,t}\Lambda_{h,t},
$$

we get (8). □

B.5 Discrete-Time Model

In Section 2 we developed a model in continuous. Here, we show a discrete time version of the model to take to data. The key difference is how we model the dynamics of new ideas, and the rest follows naturally.

First, we write the discrete-time counterpart of Assumption 1.

Assumption B.1: *For country h, at between time t and $t+1$, the number of ideas with original component $\mathbf{Z}$ better than $\mathbf{z}$ in at least one dimension follows a Poisson distribution with mean*

$$A_{h,t}(\mathbf{z}) = \alpha_{h,t}\left(\sum_{n=1}^{N} z_n^{-\frac{\theta}{1-\eta}}\right)^{1-\eta}$$

for any $\mathbf{z} \in \mathbb{R}_+^N$ and $\mathbf{z} \neq \mathbf{0}$, where $\alpha_{h,t}$ is an exogenous arrival intensity. The parameter $\theta > 0$ determines the shape of the right tail. The parameter $\eta \in [0,1)$ measures the correlation among entries of vector $\mathbf{Z}$.

Under Assumption B.1, and taking the distribution of Q' as given, between t and $t+1$, the number of new ideas of quality $\mathbf{Q}$ better than $\mathbf{q}$ in at least one dimension follows a Poisson distribution with mean

$$\tilde{A}_{h,t}(\mathbf{q}) = \alpha_{h,t}\Lambda_{h,t}\left(\sum_{n=1}^{N} q_n^{-\frac{\theta}{1-\eta}}\right)^{1-\eta},$$

where $\Lambda_{h,t} = \int_0^\infty x^{\rho\theta} dG_{h,t}(x)$ is the learning effect. Then, we write the discrete-time version of Proposition 1.

Proposition B.1: *Under Assumption B.1, at time t, the cumulative distribution function $F_{h,t}$ of state-of-the-art efficiencies takes the form of a multivariate Fréchet distribution,*

$$\Pr[\mathbf{Q}_{h,t}^{(1)}(v) \leq \mathbf{q}] = F_{h,t}(\mathbf{q}) = \exp\left(-\lambda_{h,t}\left(\sum_{n=1}^{N} q_n^{-\frac{\theta}{1-\eta}}\right)^{1-\eta}\right),$$

with support $q_n > 0$ for all n. The location parameter $\lambda_{h,t} := \sum_{\tau=-\infty}^{t} \alpha_{h,\tau}\Lambda_{h,\tau}$ is the cumulated knowledge stock of country h at time t.

While the static part of the model remains the same, Proposition 2 is adjusted as follows.

Proposition B.2: *If all actively producing plants in h are equally likely to be sampled when a new idea arrives, the evolution of $\lambda_{h,t}$ can be characterized using only the aggregate shares and* *knowledge stocks:*

$$\Delta\lambda_{h,t+1} = \lambda_{h,t+1} - \lambda_{h,t} = \alpha_{h,t}\Gamma(1-\rho)\sum_{j=1}^{N}\frac{\pi_{hhj,t}}{\sum_{n=1}^{N}\pi_{hhn,t}}\left(\frac{\lambda_{j,t}}{\pi_{hj,t}^{E}\psi_{hhj,t}^{1-\eta}}\right)^{\rho}$$

for $h = 1, \ldots, N$, where $\Gamma(\cdot)$ is the Gamma function.

C Additional Quantitative Results

This appendix includes tables listing additional results for all countries.

Tables C.1 - C.3 complement results in Section 4.1. Table C.1 presents results on TFP growth for all countries, holding MP costs constant at their levels in 2005. Table C.2 presents results on TFP growth for all countries, holding trade costs constant at their levels in 2005. Table C.3 presents results on TFP growth under different values of learning intensity, ρ.

Tables C.4 - C.5 complement results in Section 4.2. Table C.4 reports the gains from openness for all countries. This table reports the welfare, the static gains, and the effect of openness in growth rates. Table C.5 reports the gains from MP for all countries.

Table C.6 reports the effects of a 10-year MP sanction on Russia on all countries, and Table C.7 reports the effects of a 10-year economic sanction where Russia is completely isolated from the global economy, i.e., no MP or trade is allowed between Russia and the rest of the world.

Table C.8 reports the welfare effects for all countries in the counterfactual with US reshoring policy.

Table C.1: TFP Growth with Constant MP Costs

	Data (1)	Constant MP Costs (2)	Ratio (3)
Argentina	0.31	0.29	0.93
Australia	0.15	0.17	1.14
Austria	0.21	0.20	0.95
Belgium	0.22	0.17	0.79
Bulgaria	0.51	0.35	0.68
Brazil	0.42	0.32	0.77
Canada	0.03	0.08	2.91
Switzerland	0.28	0.22	0.79
Chile	0.39	0.29	0.73
China	0.96	0.56	0.58
Colombia	0.37	0.27	0.73
Costa Rica	0.39	0.31	0.80
Czech Republic	0.34	0.24	0.70
Germany	0.17	0.16	0.93
Denmark	0.28	0.23	0.84
Spain	0.30	0.23	0.78
Estonia	0.54	0.38	0.71
Finland	0.16	0.16	1.01
France	0.16	0.17	1.04
United Kingdom	0.13	0.13	1.01
Greece	0.02	0.04	2.11
Croatia	0.34	0.25	0.76
Hungary	0.26	0.20	0.77
Indonesia	1.02	0.59	0.58
India	1.16	0.56	0.48
Ireland	0.31	0.25	0.81
Iceland	0.09	0.12	1.33
Israel	0.11	0.16	1.45
Italy	0.14	0.15	1.08
Japan	-0.02	0.00	-0.08
South Korea	0.17	0.18	1.03
Lithuania	0.57	0.39	0.68
Latvia	0.58	0.42	0.71
Morocco	0.69	0.45	0.66
Mexico	0.20	0.18	0.90
Malta	0.28	0.22	0.80
Malaysia	0.24	0.24	1.02
Netherlands	0.13	0.12	0.96
Norway	0.05	0.12	2.28
New Zealand	0.23	0.21	0.93
Philippines	0.51	0.36	0.72
Poland	0.49	0.32	0.66
Portugal	0.23	0.19	0.83
Romania	1.06	0.50	0.47
Russia	0.57	0.39	0.69
Slovak Republic	0.36	0.26	0.71
Slovenia	0.20	0.17	0.84
Sweden	0.28	0.24	0.87
Thailand	0.56	0.38	0.68
Turkey	0.54	0.38	0.70
Chinese Taipei	0.11	0.13	1.12
United States	0.13	0.13	0.98
Vietnam	0.89	0.61	0.69
South Africa	0.02	0.06	3.49

Notes: This table presents TFP growth for all countries. Column (1) reports the TFP growth between 2005 and 2016 in the data. Column (2) reports the TFP growth during the same period with MP costs constant at the 2005 level. Column (3) reports the ratio between Column (2) and Column (1).

Table C.2: TFP Growth with Constant Trade Costs

	Data (1)	Constant Trade Costs (2)	Ratio (3)
Argentina	1.31	1.32	1.01
Australia	1.15	1.15	1.00
Austria	1.21	1.22	1.01
Belgium	1.22	1.24	1.02
Bulgaria	1.51	1.49	0.99
Brazil	1.42	1.40	0.99
Canada	1.03	1.04	1.01
Switzerland	1.28	1.28	1.00
Chile	1.39	1.40	1.01
China	1.96	1.95	1.00
Colombia	1.37	1.41	1.02
Costa Rica	1.39	1.40	1.01
Czech Republic	1.34	1.32	0.99
Germany	1.17	1.17	1.00
Denmark	1.28	1.29	1.00
Spain	1.30	1.29	1.00
Estonia	1.54	1.55	1.01
Finland	1.16	1.17	1.01
France	1.16	1.17	1.00
United Kingdom	1.13	1.13	1.00
Greece	1.02	1.02	1.00
Croatia	1.34	1.32	0.99
Hungary	1.26	1.22	0.97
Indonesia	2.02	2.01	1.00
India	2.16	2.17	1.00
Ireland	1.31	1.30	0.99
Iceland	1.09	1.08	0.99
Israel	1.11	1.12	1.01
Italy	1.14	1.14	1.00
Japan	0.98	0.98	1.00
South Korea	1.17	1.18	1.01
Lithuania	1.57	1.57	1.00
Latvia	1.58	1.56	0.99
Morocco	1.69	1.65	0.98
Mexico	1.20	1.18	0.98
Malta	1.28	1.24	0.97
Malaysia	1.24	1.28	1.04
Netherlands	1.13	1.13	1.01
Norway	1.05	1.06	1.01
New Zealand	1.23	1.23	1.00
Philippines	1.51	1.53	1.02
Poland	1.49	1.48	0.99
Portugal	1.23	1.23	1.00
Romania	2.06	2.05	0.99
Russia	1.57	1.58	1.00
Slovak Republic	1.36	1.34	0.99
Slovenia	1.20	1.18	0.99
Sweden	1.28	1.28	1.00
Thailand	1.56	1.58	1.01
Turkey	1.54	1.55	1.00
Chinese Taipei	1.11	1.11	0.99
United States	1.13	1.13	1.00
Vietnam	1.89	1.70	0.90
South Africa	1.02	1.01	1.00

Notes: This table presents results for all countries. Column (1) reports the TFP growth between 2005 and 2016 in the data. Column (2) reports the TFP growth during the same period with trade costs constant at the 2005 level. Column (3) reports the ratio between Column (2) and Column (1).

Table C.3: TFP Growth with Different ρ's

	Data (1)	$\rho = 0.45$ (2)	Ratio (3)	$\rho = 0$ (4)	Ratio (5)
Argentina	1.31	1.07	0.82	0.99	0.76
Australia	1.15	1.02	0.89	0.99	0.86
Austria	1.21	1.05	0.86	1.01	0.83
Belgium	1.22	1.06	0.87	1.02	0.83
Bulgaria	1.51	1.23	0.81	1.15	0.76
Brazil	1.42	1.16	0.82	1.06	0.75
Canada	1.03	0.97	0.94	0.96	0.93
Switzerland	1.28	1.11	0.86	1.06	0.83
Chile	1.39	1.13	0.81	1.04	0.75
China	1.96	1.50	0.77	1.22	0.63
Colombia	1.37	1.11	0.81	1.02	0.74
Costa Rica	1.39	1.12	0.80	1.03	0.74
Czech Republic	1.34	1.16	0.86	1.11	0.83
Germany	1.17	1.04	0.89	1.00	0.86
Denmark	1.28	1.08	0.84	1.02	0.80
Spain	1.30	1.11	0.85	1.05	0.81
Estonia	1.54	1.22	0.79	1.11	0.72
Finland	1.16	1.03	0.88	0.99	0.85
France	1.16	1.03	0.88	0.99	0.85
United Kingdom	1.13	1.02	0.91	1.00	0.89
Greece	1.02	1.00	0.98	1.00	0.98
Croatia	1.34	1.13	0.85	1.07	0.80
Hungary	1.26	1.14	0.90	1.11	0.88
Indonesia	2.02	1.57	0.78	1.25	0.62
India	2.16	1.64	0.76	1.30	0.60
Ireland	1.31	1.13	0.86	1.08	0.82
Iceland	1.09	1.03	0.95	1.01	0.93
Israel	1.11	1.00	0.90	0.98	0.88
Italy	1.14	1.03	0.90	1.00	0.88
Japan	0.98	0.99	1.01	0.99	1.01
South Korea	1.17	1.04	0.89	1.00	0.85
Lithuania	1.57	1.25	0.79	1.13	0.72
Latvia	1.58	1.25	0.79	1.12	0.71
Morocco	1.69	1.32	0.78	1.16	0.68
Mexico	1.20	1.07	0.89	1.04	0.86
Malta	1.28	1.11	0.87	1.07	0.83
Malaysia	1.24	1.03	0.83	0.97	0.78
Netherlands	1.13	1.03	0.91	1.00	0.89
Norway	1.05	0.98	0.93	0.95	0.90
New Zealand	1.23	1.06	0.86	1.01	0.82
Philippines	1.51	1.19	0.79	1.04	0.69
Poland	1.49	1.22	0.82	1.13	0.76
Portugal	1.23	1.07	0.87	1.02	0.83
Romania	2.06	1.65	0.80	1.50	0.73
Russia	1.57	1.24	0.79	1.07	0.68
Slovak Republic	1.36	1.17	0.86	1.12	0.82
Slovenia	1.20	1.06	0.89	1.03	0.86
Sweden	1.28	1.09	0.85	1.03	0.80
Thailand	1.56	1.27	0.81	1.16	0.74
Turkey	1.54	1.21	0.78	1.07	0.69
Chinese Taipei	1.11	1.03	0.92	1.01	0.90
United States	1.13	1.03	0.91	1.00	0.89
Vietnam	1.89	1.48	0.79	1.26	0.67
South Africa	1.02	0.99	0.98	0.99	0.97

Notes: Results of TFP growth with different values of the learning intensity, ρ. Column (1) is the TFP ratio between 2016 and 2005 for each country, with benchmark $\rho = 0.64$, which also matches the data. Columns (2) and (4) report the same statistic with $\rho = 0.45$ and $\rho = 0$ respectively. Columns (3) and (5) report the ratio of Columns (2) and (4) to Column (1).

Table C.4: Gains from Openness

	Welfare	Static Gain	Δ Growth Rate (Percentage Points)
	(1)	(2)	(3)
Argentina	28.41%	4.91%	1.15
Australia	20.02%	5.89%	0.71
Austria	26.83%	11.97%	0.77
Belgium	29.76%	15.92%	0.72
Bulgaria	40.59%	16.17%	1.22
Brazil	33.81%	4.95%	1.32
Canada	25.90%	10.86%	0.84
Switzerland	31.15%	16.50%	0.75
Chile	29.72%	6.91%	1.08
China	28.18%	4.17%	1.21
Colombia	29.84%	4.44%	1.24
Costa Rica	28.51%	7.27%	1.07
Czech Republic	49.03%	27.85%	1.12
Germany	26.43%	9.74%	0.85
Denmark	25.55%	9.59%	0.79
Spain	24.22%	8.08%	0.77
Estonia	38.56%	16.56%	1.10
Finland	24.04%	7.94%	0.79
France	20.54%	6.61%	0.72
United Kingdom	27.04%	10.53%	0.87
Greece	23.19%	4.70%	0.86
Croatia	35.23%	11.49%	1.10
Hungary	57.95%	36.48%	1.15
Indonesia	29.17%	4.84%	1.21
India	29.53%	4.22%	1.26
Ireland	43.16%	29.22%	0.70
Iceland	11.21%	5.29%	0.24
Israel	16.97%	4.86%	0.63
Italy	21.68%	6.98%	0.76
Japan	14.91%	2.45%	0.70
South Korea	17.50%	4.20%	0.65
Lithuania	39.62%	15.75%	1.14
Latvia	38.61%	14.65%	1.18
Morocco	37.12%	11.62%	1.26
Mexico	34.75%	13.18%	1.12
Malta	38.41%	19.59%	0.91
Malaysia	35.58%	13.42%	1.12
Netherlands	33.53%	16.88%	0.89
Norway	24.37%	10.26%	0.61
New Zealand	22.65%	5.76%	0.85
Philippines	33.27%	10.27%	1.19
Poland	34.57%	12.96%	1.07
Portugal	30.42%	10.39%	1.01
Romania	42.17%	17.52%	1.21
Russia	26.93%	3.49%	0.94
Slovak Republic	54.43%	29.28%	1.21
Slovenia	35.86%	15.76%	1.01
Sweden	27.89%	11.97%	0.78
Thailand	35.73%	12.50%	1.20
Turkey	23.93%	5.63%	0.85
Chinese Taipei	22.84%	9.53%	0.66
United States	11.74%	3.09%	0.47
Vietnam	57.93%	33.72%	1.25
South Africa	32.21%	10.32%	1.14

Notes: Column (1) presents overall welfare gains in terms of annual consumption equivalent variation, as defined in the paper. Column (2) shows the static gains from openness, i.e., changes in real consumption level between autarky and the benchmark economy in 2016. Column (3) shows the dynamic effect of openness on the average growth rate of real consumption in the following 50 years.

Table C.5: Gains from MP

	Welfare (1)	Static Gain (2)	Δ Growth Rate (Percentage Points) (3)
Argentina	25.22%	1.91%	1.13
Australia	16.29%	2.72%	0.68
Austria	16.65%	3.23%	0.68
Belgium	15.88%	4.21%	0.59
Bulgaria	28.57%	4.60%	1.18
Brazil	29.69%	1.05%	1.30
Canada	18.01%	3.73%	0.79
Switzerland	14.99%	2.96%	0.59
Chile	23.62%	1.38%	1.04
China	24.21%	0.34%	1.19
Colombia	26.00%	0.76%	1.22
Costa Rica	21.58%	0.88%	1.03
Czech Republic	30.74%	10.53%	1.04
Germany	17.43%	1.95%	0.77
Denmark	16.17%	1.72%	0.70
Spain	17.85%	2.75%	0.71
Estonia	23.97%	3.25%	1.01
Finland	16.72%	1.79%	0.72
France	14.29%	1.30%	0.67
United Kingdom	20.01%	4.31%	0.82
Greece	18.90%	1.06%	0.82
Croatia	26.22%	3.41%	1.04
Hungary	31.92%	11.35%	1.07
Indonesia	24.59%	0.40%	1.19
India	25.05%	-0.16%	1.25
Ireland	14.70%	6.10%	0.41
Iceland	2.13%	-1.30%	0.12
Israel	11.20%	0.05%	0.57
Italy	16.00%	2.10%	0.71
Japan	11.89%	-0.20%	0.67
South Korea	12.81%	0.29%	0.61
Lithuania	25.76%	3.22%	1.05
Latvia	26.97%	3.91%	1.11
Morocco	25.78%	0.62%	1.23
Mexico	22.54%	1.66%	1.07
Malta	21.32%	5.05%	0.75
Malaysia	24.05%	2.62%	1.06
Netherlands	17.73%	2.88%	0.77
Norway	15.47%	3.34%	0.50
New Zealand	18.04%	1.72%	0.82
Philippines	23.29%	0.46%	1.17
Poland	24.89%	4.14%	1.01
Portugal	21.80%	2.64%	0.95
Romania	30.93%	6.92%	1.16
Russia	23.07%	0.29%	0.90
Slovak Republic	33.28%	9.82%	1.09
Slovenia	21.87%	3.14%	0.92
Sweden	16.83%	2.74%	0.68
Thailand	25.53%	2.54%	1.17
Turkey	18.64%	1.14%	0.80
Chinese Taipei	13.66%	1.91%	0.57
United States	9.40%	1.15%	0.45
Vietnam	23.78%	-0.19%	1.20
South Africa	24.18%	2.56%	1.12

Notes: Column (1) presents overall welfare gains in terms of annual consumption equivalent variation, as defined in the paper. Column (2) shows the static gains from openness, i.e., changes in real consumption level between autarky and the benchmark economy in 2016. Column (3) shows the dynamic effect of openness on the average growth rate of real consumption in the following 50 years.

Table C.6: Economic Sanctions On Russia (MP Only)

	Welfare	Static Gain	Δ Growth Rate (Percentage Points)
	(1)	(2)	(3)
Argentina	-0.03%	-0.00%	-0.00
Australia	-0.03%	0.00%	-0.01
Austria	-0.03%	0.00%	-0.01
Belgium	-0.03%	0.00%	-0.01
Bulgaria	-0.06%	0.02%	-0.01
Brazil	-0.04%	0.00%	-0.01
Canada	-0.02%	0.00%	-0.00
Switzerland	-0.03%	0.01%	-0.00
Chile	-0.02%	-0.00%	-0.00
China	-0.10%	0.00%	-0.02
Colombia	-0.03%	0.00%	-0.00
Costa Rica	-0.01%	-0.00%	-0.00
Czech Republic	-0.07%	0.00%	-0.02
Germany	-0.06%	0.00%	-0.01
Denmark	-0.02%	0.01%	-0.00
Spain	-0.01%	0.00%	-0.00
Estonia	-0.10%	0.03%	-0.03
Finland	-0.04%	0.02%	-0.01
France	-0.02%	0.00%	-0.00
United Kingdom	-0.02%	0.00%	-0.00
Greece	-0.04%	0.02%	-0.01
Croatia	-0.05%	0.00%	-0.01
Hungary	-0.03%	0.01%	-0.01
Indonesia	-0.03%	-0.00%	-0.00
India	-0.04%	0.00%	-0.01
Ireland	-0.01%	0.00%	-0.00
Iceland	-0.02%	0.00%	-0.00
Israel	-0.03%	0.01%	-0.00
Italy	-0.05%	0.00%	-0.01
Japan	-0.05%	0.00%	-0.01
South Korea	-0.02%	0.01%	-0.00
Lithuania	-0.16%	0.01%	-0.04
Latvia	-0.25%	0.07%	-0.07
Morocco	-0.04%	0.00%	-0.01
Mexico	-0.03%	0.00%	-0.00
Malta	-0.09%	0.07%	-0.03
Malaysia	-0.04%	0.00%	-0.01
Netherlands	-0.03%	0.02%	-0.01
Norway	-0.02%	0.00%	-0.00
New Zealand	-0.03%	-0.00%	-0.00
Philippines	-0.04%	-0.00%	-0.00
Poland	-0.04%	0.01%	-0.01
Portugal	-0.01%	0.00%	-0.00
Romania	-0.06%	0.00%	-0.01
Russia	-7.25%	-0.63%	-2.16
Slovak Republic	-0.04%	0.01%	-0.01
Slovenia	-0.09%	0.00%	-0.02
Sweden	-0.02%	0.01%	-0.00
Thailand	-0.04%	0.00%	-0.01
Turkey	-0.05%	0.01%	-0.01
Chinese Taipei	-0.03%	0.00%	-0.00
United States	-0.02%	0.00%	-0.00
Vietnam	-0.07%	0.00%	-0.01
South Africa	-0.03%	0.00%	-0.00

Notes: Result of an counterfactual exercise where the MP frictions from the rest of the world to Russia increase to infinity for 10 years. All economies are listed above. Column (1) presents the overall welfare effects. Column (2) presents the immediate impact on real consumption in each country. The last column shows the differences between the annual growth rates during the sanction versus the benchmark case.

Table C.7: Economic Sanctions On Russia (MP and Trade)

	Welfare	Static Gain	Δ Growth Rate (Percentage Points)
	(1)	(2)	(3)
Argentina	-0.04%	-0.02%	-0.01
Australia	-0.04%	-0.02%	-0.01
Austria	-0.04%	-0.05%	-0.01
Belgium	-0.06%	-0.11%	-0.01
Bulgaria	-0.18%	-0.39%	-0.04
Brazil	-0.05%	-0.05%	-0.01
Canada	-0.02%	-0.01%	-0.00
Switzerland	-0.04%	-0.07%	-0.01
Chile	-0.03%	-0.01%	-0.00
China	-0.12%	-0.11%	-0.03
Colombia	-0.03%	-0.01%	-0.01
Costa Rica	-0.02%	-0.01%	-0.00
Czech Republic	-0.11%	-0.22%	-0.02
Germany	-0.08%	-0.14%	-0.02
Denmark	-0.04%	-0.06%	-0.01
Spain	-0.02%	-0.02%	-0.00
Estonia	-0.31%	-0.87%	-0.05
Finland	-0.12%	-0.28%	-0.02
France	-0.03%	-0.03%	-0.01
United Kingdom	-0.02%	-0.02%	-0.00
Greece	-0.09%	-0.12%	-0.02
Croatia	-0.08%	-0.15%	-0.02
Hungary	-0.08%	-0.19%	-0.01
Indonesia	-0.03%	-0.03%	-0.00
India	-0.06%	-0.06%	-0.01
Ireland	-0.02%	-0.03%	-0.00
Iceland	-0.03%	-0.02%	-0.01
Israel	-0.04%	-0.06%	-0.01
Italy	-0.07%	-0.11%	-0.02
Japan	-0.05%	-0.04%	-0.01
South Korea	-0.04%	-0.07%	-0.01
Lithuania	-0.40%	-1.26%	-0.06
Latvia	-0.63%	-1.67%	-0.13
Morocco	-0.08%	-0.15%	-0.02
Mexico	-0.04%	-0.02%	-0.01
Malta	-0.37%	-0.92%	-0.08
Malaysia	-0.06%	-0.06%	-0.01
Netherlands	-0.11%	-0.29%	-0.02
Norway	-0.03%	-0.02%	-0.01
New Zealand	-0.03%	-0.01%	-0.01
Philippines	-0.04%	-0.02%	-0.01
Poland	-0.09%	-0.19%	-0.02
Portugal	-0.03%	-0.03%	-0.00
Romania	-0.10%	-0.20%	-0.02
Russia	-4.53%	-3.49%	-3.06
Slovak Republic	-0.12%	-0.30%	-0.03
Slovenia	-0.12%	-0.26%	-0.02
Sweden	-0.04%	-0.07%	-0.01
Thailand	-0.05%	-0.04%	-0.01
Turkey	-0.11%	-0.16%	-0.03
Chinese Taipei	-0.05%	-0.06%	-0.01
United States	-0.02%	-0.01%	-0.00
Vietnam	-0.11%	-0.22%	-0.02
South Africa	-0.04%	-0.03%	-0.01

Notes: Result of an counterfactual exercise where Russia is completely cut off from global economy for 10 years. We increase the MP costs and trade costs associated with Russia to infinity during the sanction. All economies are listed above. Column (1) presents the overall welfare effects. Column (2) presents the immediate impact on real consumption in each country. The last column shows the differences between the annual growth rates during the sanction versus the benchmark case.

Table C.8: US Reshoring

	Welfare	Static Gain	Δ Growth Rate (Percentage Points)
	(1)	(2)	(3)
Argentina	-0.81%	-0.39%	-0.05
Australia	-0.51%	-0.60%	-0.04
Austria	-0.36%	-0.25%	-0.04
Belgium	-0.60%	-1.05%	-0.03
Bulgaria	-0.57%	-0.16%	-0.04
Brazil	-1.06%	-0.42%	-0.05
Canada	-0.88%	-1.58%	-0.04
Switzerland	-0.66%	-1.43%	-0.03
Chile	-0.83%	-0.49%	-0.05
China	-1.15%	-0.03%	-0.06
Colombia	-1.06%	-0.23%	-0.05
Costa Rica	-1.31%	-0.49%	-0.07
Czech Republic	-0.54%	-0.57%	-0.04
Germany	-0.48%	-0.50%	-0.04
Denmark	-0.39%	-0.29%	-0.04
Spain	-0.45%	-0.36%	-0.04
Estonia	-0.46%	-0.15%	-0.04
Finland	-0.39%	-0.24%	-0.04
France	-0.42%	-0.38%	-0.04
United Kingdom	-0.66%	-1.12%	-0.03
Greece	-0.47%	-0.09%	-0.04
Croatia	-0.48%	-0.10%	-0.04
Hungary	-0.78%	-1.25%	-0.03
Indonesia	-1.38%	-0.04%	-0.06
India	-2.04%	-0.05%	-0.06
Ireland	-0.91%	-3.11%	-0.00
Iceland	-0.21%	0.02%	-0.02
Israel	-0.76%	-0.31%	-0.07
Italy	-0.44%	-0.33%	-0.04
Japan	-0.65%	-0.18%	-0.06
South Korea	-0.70%	-0.18%	-0.06
Lithuania	-0.46%	-0.13%	-0.04
Latvia	-0.42%	-0.06%	-0.04
Morocco	-0.76%	-0.00%	-0.04
Mexico	-0.93%	-0.83%	-0.04
Malta	-0.37%	-0.04%	-0.04
Malaysia	-0.81%	-0.59%	-0.05
Netherlands	-0.82%	-1.67%	-0.03
Norway	-0.40%	-0.45%	-0.03
New Zealand	-0.56%	-0.30%	-0.05
Philippines	-1.64%	-0.11%	-0.06
Poland	-0.56%	-0.51%	-0.04
Portugal	-0.52%	-0.28%	-0.04
Romania	-0.53%	-0.30%	-0.04
Russia	-0.72%	-0.09%	-0.05
Slovak Republic	-0.52%	-0.56%	-0.03
Slovenia	-0.46%	-0.18%	-0.04
Sweden	-0.37%	-0.30%	-0.04
Thailand	-1.10%	-0.33%	-0.05
Turkey	-0.46%	-0.10%	-0.04
Chinese Taipei	-0.52%	-0.36%	-0.05
United States	-0.10%	0.14%	-0.03
Vietnam	-1.31%	0.34%	-0.05
South Africa	-0.80%	-0.35%	-0.05

Notes: Welfare and growth implications for all countries of an counterfactual exercise where the outward MP costs from the United States increase by 20%. Column (1) presents the overall welfare effects. Column (2) presents the immediate impact on real consumption in each country. The last column shows the differences between the annual growth rates in this counterfactual versus the benchmark case.