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 framework, MP serves as the channel of international idea diffusion: when firms operate in a foreign country, they contribute to the local stock of knowledge. By embedding this mechanism into a quantitative model of trade and MP, we characterize the evolution of bilateral MP flows, trade flows, and technology dynamics across 54 economies. Counterfactual analysis reveals that reduction in MP costs boosted economic growth, especially in developing economies. We show that a 10-year MP sanction on Russia would reduce the welfare by 9.11%, although the immediate effect is small. We find that increasing outward MP costs for U.S. firms has immediate positive wage effects but negative growth implications. Additionally, a 10% increase in U.S. inward trade costs results in a 0.2% decline in the country's present value of welfare.

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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 this process, as hosts of MP, believe that it 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 dynamic implications of MP in the global economy.

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 and welfare implications of sanctions on Russia? How would reshoring policies of the United States affect economic growth and welfare?

We consider a world with multiple countries and technology diffusion through multinational production in host countries. 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 all countries. Firms can choose to locate their plants in different countries in the world, the choice depending on the relative costs of MP, labor, and transportation. We assume perfect competition. A single price-taking firm from a given headquarter location supplies a given variety at minimum cost to markets where one of its plants is the lowest cost supplier. We will interpret that single firm as multinational.

Our model introduces a novel and crucial element, which is the endogenous evolution of productivity driven by innovation and technology diffusion. We model innovation and diffusion as follows. A firm is essentially an idea of production. These new ideas of production arrive stochastically, and the their efficiency is a combination of two components:

an original component with the potential for production in all countries (represented as a vector) and an insight observed from an existing plant within the firm's headquarter country (represented as a scalar). The insight is drawn from an active producer within the country, a plant either owned domestically or by a foreign firm. 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 has important policy implications for attracting MP. Our model yields 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 operating in 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, represented as 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. Broadly speaking, the static gains of openness are from two sources: higher labor demand and competition from both MP and trade. The former results in higher wages for the host country of MP, and the later reduces the price level. The static gains are larger than classical gains from openness in the quantitative trade literature when we take MP into consideration. When it comes to the dynamic implications, idea diffusion means that opening up to MP boosts the growth rate, especially for countries 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 hinders 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 (2025)), but we manage to make progress. We first measure the knowledge stock using patent stock data across countries over time. 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 an instrumented 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.

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 wages. 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 9.11%. When the sanction is imposed, real consumption in Russia immediately drops by 1.5%. During the sanction, the annual growth rate in Russia decreases by 3.15 percentage points. 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 implications of potential MP and trade strategies by the US, considering a permanent twenty-percent increase in outward MP costs from the United States to the rest of the world, as well as an ten-percent increase in inward trade costs to the United States. With the the first policy, the United States remains the global technology leader. While such a policy increases consumption in the US in the short run by 0.52%, 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 0.01 percentage points. As a result, the present value of welfare increases by 0.04% in the United States. When the United States increase its inward trade costs by 10%, the present value of welfare decreases by 0.2% 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 (2023) presents a development accounting framework leveraging micro-level data on MP to measure firm-embedded productivity across countries. Li (2023) develops a multi-sector trade and MP framework to study global shock propagation through MP during the great recession. These papers use 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 the 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 (2025) 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. Xiang (2023) develops a model that incorporates MP and endogenous technical change, while abstracting from technology diffusion. Fan (2025) embeds offshore R&D into a general equilibrium model of MP and trade. 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), Fons-Rosen, Kalemli-Ozcan, Sorensen, Villegas-Sanchez, and Volosovych (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 if the firm were to set up a plant in country j. The firm suffers 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.

[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.

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*

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

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 appendix B.2.

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 appendix B.1.

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 producing that variety 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.

It is worth noting that (2) is the distribution of state-of-the-art efficiencies, not individual ideas. 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).

[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.

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

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

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

[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.

expenditure share) is

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

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

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

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 $\pi^T_{ij} = \sum_{h=1}^N \pi_{ijh}$. 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]

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, we assume that the MP costs γ doesn't affect spillovers: if the plant sampled is from country k, the observed efficiency q' is the actual efficiency of the plant before discounted, $q' = q_{hk}$.

[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.

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:*

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

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 $\pi_{hhn}, \pi^{E}_{hj}, \psi_{hhj}$ 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 $\frac{\lambda_{j,t}}{\pi^{E}_{hj,t}\psi^{1-\eta}_{hhj,t}}$, which results from competition among firms. For a given level of $\lambda_{j,t}$, a smaller $\pi^{E}_{hj,t}$ 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

[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.

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 $(\pi_{ijh}, \pi^E_{ih}, \psi_{ijh})$ stay constant, and the growth rate of the knowledge stock is $g_\lambda = \frac{g_\alpha}{1-\rho}$.

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

$$\pi_{ijh} = \frac{\kappa_{ijh}^{-\frac{\theta}{1-\eta}}}{\sum_{k=1}^N \kappa_{ikh}^{-\frac{\theta}{1-\eta}}} \frac{\tilde{\lambda}_h \left(\sum_{k=1}^N \kappa_{ikh}^{-\frac{\theta}{1-\eta}}\right)^{1-\eta}}{\sum_{n=1}^N \tilde{\lambda}_n \left(\sum_{k=1}^N \kappa_{ikn}^{-\frac{\theta}{1-\eta}}\right)^{1-\eta}}, \tag{9}$$

$$w_j L_j = \sum_{i=1}^N \sum_{h=1}^N \pi_{ijh} w_i L_i, \tag{10}$$

$$\tilde{\lambda}_i = \frac{1}{g_\lambda} \tilde{\alpha}_i \Gamma(1-\rho) \sum_{h=1}^N \frac{\pi_{iih}}{\sum_{n=1}^N \pi_{iin}} \left(\frac{\tilde{\lambda}_h}{\pi^E_{ih} \psi_{iih}^{1-\eta}}\right)^\rho, \tag{11}$$

where κ, π^E, ψ are defined in (3), (4), and (5) respectively.

2.5 Welfare Implications

We now look into the model's implications of how MP and trade affect welfare in each country. Following the existing literature, we use income per worker as our measure of welfare. 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

[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 (2025).

[8]Normalization for wage rates is needed here. We choose to normalize the US wage to be 1.

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 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. As we show in appendix B.5, aggregate real income per worker ω can be summarized by the aggregate shares and the stock of knowledge:

$$\omega_{i,t} = B\left(\frac{\lambda_{i,t}}{\pi_{iii,t}}\left(\psi_{iii,t}\right)^{\eta}\right)^{\frac{1}{\theta}}, \tag{12}$$

where B is a constant. This equation demonstrates that welfare is determined by the productivity of domestic firms, trade, and MP. To better understand the role of productivity, consider the special case of autarky, where $\pi_{iii,t} = \psi_{iii,t} = 1$. Under autarky, welfare is given by $\omega_{i,t}^{\text{Aut}} = B\left(\lambda_{i,t}^{\text{Aut}}\right)^{1/\theta}$. In this case, real wage is proportional to the average productivity of all domestic firms on the frontier, which is proportional to $\lambda_{i,t}^{1/\theta}$. In autarky, there is no trade or MP, but learning from domestic producers is still possible. The detrended knowledge stock in the steady state in autarky satisfies

$$\tilde{\lambda}_i^{\text{Aut}} = \left(\frac{1}{g_\lambda}\tilde{\alpha}_i\Gamma(1-\rho)\right)^{\frac{1}{1-\rho}}, \tag{13}$$

which follows from (11) by setting $\pi_{ijh} = 0$ if either $i \neq j$ or $i \neq h$, and $\pi_{iii} = 1$.[9]

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.

[9] In autarky where no trade or MP is possible, the only non-zero term in the summation in (11) is when $h = i$.

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

$$GO_i := \frac{\omega_i}{\omega_i^{\text{Aut}}} = \underbrace{\left(\pi_{ii}^E\right)^{-\frac{1}{\theta}} \psi_{iii}^{-\frac{1-\eta}{\theta}}}_{\text{static}} \underbrace{\left(\sum_{h=1}^{N} \frac{\pi_{iih}}{\sum_{n=1}^{N} \pi_{iin}} \left[\frac{\tilde{\lambda}_h}{\tilde{\lambda}_i} \frac{1}{\pi_{ih}^E} \left(\frac{1}{\psi_{iih}}\right)^{1-\eta}\right]^{\rho}\right)^{\frac{1}{1-\rho}\frac{1}{\theta}}}_{\text{learning}}, \tag{14}$$

where the learning part is the relative level of the knowledge stock, derived from taking ratios between (11) and (13). 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).[10] 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 $i \neq j$.

[10]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 (14) becomes:

$$GO_i = \underbrace{\left(\pi^E_{ii}\right)^{-\frac{1}{\theta}}}_{\text{static}} \underbrace{\left(\sum_{h=1}^{N} \pi^E_{ih} \left[\frac{\tilde{\lambda}_h}{\tilde{\lambda}_i} \frac{1}{\pi^E_{ih}}\right]^{\rho}\right)^{\frac{1}{1-\rho}\frac{1}{\theta}}}_{\text{learning}}. \tag{15}$$

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 learning 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.

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 (14) becomes:

$$GO_i = \underbrace{\left(\pi^E_{ii}\right)^{-\frac{1}{\theta}}}_{\text{static}} \underbrace{\left(\pi^E_{ii}\right)^{-\frac{\rho}{1-\rho}\frac{1}{\theta}}}_{\text{learning}}. \tag{16}$$

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 learning 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. Our model shares a similar insight with Sampson (2016): trade causes technology diffusion by shifting the domestic productivity distribution. 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 learning effect comes from selection through trade, a feature of the extreme value distribution is that the size of the learning 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 learning effect is larger. All else equal, the learning 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 the manufacturing sector in 54 economies where we have good data for trade and MP from 2005 to 2016. Note that we calibrate our model without assuming it is on a balanced growth path. 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).[11]

[11]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

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. [12] Note that this growth rate will pin down the long-run growth rate of our semi-endogenous growth model, it doesn't dictate the growth rate of our model in the transition dynamics. 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.

For trade data, we use manufacturing trade flows from 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.[13] 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 (manufacturing) expenditures $X_{i,t}$. To get the empirical counterpart of bilateral MP data in the model, we use the Analytical AMNE database from OECD.[14] For each year, we construct the $N \times N$ matrix of MP shares, $\pi^M_{jh,t}$.

Next, we demonstrate how our model can be used to infer the trilateral shares π_{ijh} with trade and MP data. We construct a measure of knowledge stock for each country each year based on patent data. Using the recovered aggregate shares and knowledge stocks, we then estimate the learning intensity ρ.

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 $\pi^M_{jh,t}$. However, our model provides enough structure to do so. We relegate the details to appendix B.7.[15]

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.

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

[13] 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 manufacturing trade flows $X^T_{ij,t}$ from the Gravity database, and $\pi^T_{ii,t}$ and from MRIO.

[14] 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. We focus on MP flows within the manufacturing sector, consistent with our analysis of trade flows.

[15] Arkolakis et al. (2018) deals with a similar problem in a setting where each firm produces a unique variety.

From the trilateral shares, we can also back out which countries are the top manufacturing suppliers of the world, measured by either the source of production of exports or by the source of technology used for that production. For the remainder of this section, unless otherwise noted, all statements and comments refer to the manufacturing sectors. 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.[16] The blue bar (on the left) shows the export of the country as a share of the total world consumption. For example, in 2005, German exports accounted for 3.36% of total world consumption, followed by the United States (2.72%) and China (2.68%). The orange bar (on the right) shows a different statistic, measuring exports by the source of technology rather than production location. In 2005, foreign consumption of goods produced with US technology — whether produced in the United States or elsewhere — accounted for 7.81% of total world consumption.

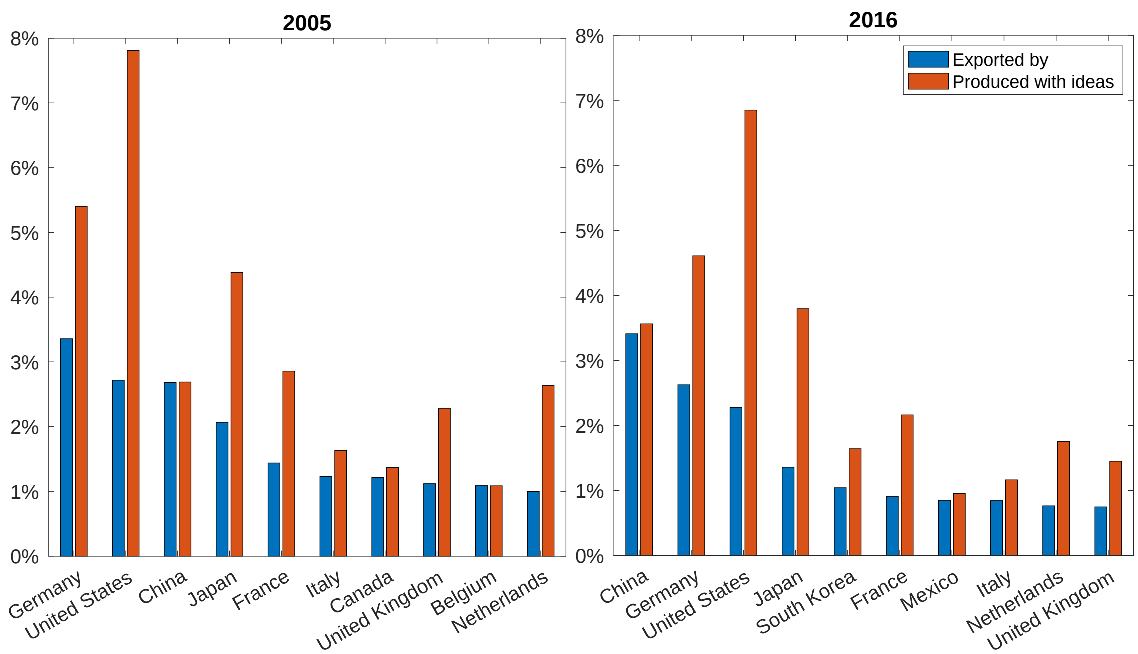

Figure 1: Top Exporting Countries

Notes: This figure shows the manufacturing export by different countries in 2005 and in 2016. The blue bar (on the left) shows the export of the country as a share of the total world consumption. For example, in 2005, German exports accounted for 3.36% of total world consumption. The orange bar (on the right) measures exports by the source of technology rather than production location. In 2005, foreign consumption of goods produced with U.S. technology — regardless of production location — accounted for 7.81% of total world consumption.

Two implications of the Figure 1 stand out. First, the distribution of export measured by MP is more concentrated than the distribution of export measured by production. In a world with no MP the two bars would be the same for each country as, in that case,

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

all export from a country could only use ideas originated from the same country. The differences between the two bars indicates the prominence of MP in the global economy. Second, from 2005 to 2016, export measured by MP became 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 Initial Knowledge Stocks

It is essential to estimate the initial knowledge stock across countries for our subsequent counterfactual analysis of TFP growth. To estimate the initial knowledge stock 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

$$\omega_{i,t} = B\left(\frac{\lambda_{i,t}}{\pi_{iii,t}}\left(\psi_{iii,t}\right)^{\eta}\right)^{\frac{1}{\theta}}, \tag{17}$$

where B is a constant. Real GDP is thus equal to

$$\text{Real GDP}_{i,0} = \frac{w_{i,0}L_{i,0}}{P_{i,0}} = B\left(\frac{\lambda_{i,0}\psi^{\eta}_{iii,0}}{\pi_{iii,0}}\right)^{\frac{1}{\theta}} L_{i,0}, \tag{18}$$

where the term $B\left(\frac{\lambda_{i,0}\psi^{\eta}_{iii,0}}{\pi_{iii,0}}\right)$ captures the measured TFP. It increases with $\lambda_{i,0}$, which is proportional to the average productivity of all domestic firms. It also reflects selection in the open economy, as indicated by $\psi_{iii,0}$ and $\pi_{iii,0}$, where only the most productive domestic firms survive the competition from trade and MP.

We can solve for the initial stock of knowledge as

$$\lambda_{i,0} = B^{-\theta}\omega^{\theta}_{i,0}\pi_{iii,0}\psi^{-\eta}_{iii,0}. \tag{19}$$

The intuition for (19) 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 construct the real output per worker in the manufacturing sector as the empirical counterpart of ω_i, using information from the Penn World Table 10.0 (PWT, Feenstra, Inklaar, and Timmer (2015)), the UNU-WIDER Economic Transformation Database (ETD, de Vries et al. (2021)), World Bank's World Development Indicators (WDI), and UN Statistics.[17] We calculate $\psi_{iii,0}$ using our constructed measure of trilateral shares as described in the previous section.

Note that (17) and (19) 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 $\lambda_{i,0}$'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 C.7 shows the heterogeneity in knowledge stocks and measured TFP on a log scale.

3.3 An Alternative Measure of Knowledge Stocks

As in Cai, Caliendo, Parro, and Xiang (2025), an alternative measure for knowledge stock is the accumulated number of patents (patent stock). We first explain how we construct this measure, and in the following section, we discuss why it is particularly useful for our estimation. Country-level patent data is sourced from the *International Patent and Citations across Sectors* (INPACT-S) database, compiled by LaBelle, Martinez-Zarzoso, Santacreu, and Yotov (2023). The original dataset includes information on the countries where patents are filed and the countries of origin of the assignees.

To construct our measure of patent stock, we aggregate the number of filed patents in manufacturing sectors at the country level. Specifically, we compute the cumulative number of patents filed in manufacturing sectors since 1980 as a proxy for patent stock. We compile country-level manufacturing patent stocks from 2005 to 2016 as our measure for λ's.[18] We now proceed with the estimation of our diffusion parameters using all the data we have constructed thus far.

3.4 Estimation of Learning Intensity

In our model, parameters ρ and $\{\alpha_{i,t}\}$ govern productivity growth and technology diffusion across countries. In this section, we show how we discipline these parameters.

[17]We obtain expenditure-side real GDP at chained PPPs (rgdpe) and total persons engaged (emp) from the Penn World Tables (PWT). Manufacturing value-added shares and manufacturing employment shares are sourced from the ETD. For countries not covered in the ETD, we supplement with data from the WDI and UN Statistics. We construct real manufacturing output per worker by combining these data sources.

[18]The estimation is based on 50 economies due to data availability constraints for patent data. The quantitative exercise extends the analysis to the full sample of 54 economies, which additionally includes Indonesia, Malta, Thailand, and Vietnam, for which sufficient trade and MP data are available.

We start from the discrete-time counterpart of the law of motion (8) in Proposition 2:[19]

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

which provides a structural relationship between the evolution of knowledge stock, the arrival rate and shares related to trade and MP. We use this structural equation to identify the diffusion parameters. Although we have constructed all the shares, we still face a challenge regarding the measurement of knowledge stock. On one hand, we could use equation (19) to invert the λ's, but this approach requires trade and MP data to calculate λ's, which may bias our estimates of ρ. On the other hand, patent stocks can serve as proxies for knowledge stock. While this measure is subject to fewer endogeneity concerns, the $\{\alpha_{i,t}\}$ may be estimated in incorrect units. Notably, the magnitude of $\{\alpha_{i,t}\}$ is related to the size of the change in λ's. To address these issues, we adopt an iterative procedure. First, we estimate ρ using the cumulative number of patents filed in each country. Once we have the estimate for ρ, we back out $\{\alpha_{i,t}\}$ by by precisely matching our inverted λ's from equation (19). We now turn to detailing the estimation procedure.

For expositional purpose, we define some notations for this subsection only. We define the detrended knowledge stock change, $y_{i,t} = (\lambda_{i,t+1} - \lambda_{i,t})/(1+g_\alpha)^t$. We pack all the shares in this equation into $\mathbf{s}'_{i,t} = (\pi_{ii1,t}, ..., \pi_{iiN,t}, \pi^E_{i1,t}, ..., \pi^E_{iN,t}, \psi_{ii1,t}, ..., \psi_{iiN,t})$, and as before, we use bold letter to denote the vector, $\boldsymbol{\lambda}_t = (\lambda_{1,t}, ..., \lambda_{N,t})$. So we can write the model compactly as

$$y_{i,t} = \alpha_{i,0} \cdot \Gamma(1-\rho) \cdot f(\mathbf{s}_{i,t}, \boldsymbol{\lambda}_t, \rho),$$

f being the remaining part of the right-hand side, $f(\mathbf{s}_{it}, \boldsymbol{\lambda}_t, \rho) = \sum_{h=1}^{N} \frac{\pi_{iih,t}}{\sum_{n=1}^{N} \pi_{iin,t}} \left(\frac{\lambda_{h,t}}{\pi^E_{ih,t} \psi^{1-\eta}_{iih,t}} \right)^\rho$.

We face two econometric issues in our nonlinear panel data setting. The first issue is that we have a relatively short panel with 12 years of data on 54 economies, and our model has country-specific effects. This may cause the incidental parameter problem (Cameron (2005) Chapter 23). To address this issue, we use the quasi-difference transformation to eliminate $\alpha_{i,0}$,

$$y_{i,t} = \frac{f(\mathbf{s}_{it}, \boldsymbol{\lambda}_t, \rho)}{f(\mathbf{s}_{i,t-1}, \boldsymbol{\lambda}_{t-1}, \rho)} y_{i,t-1}.$$

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

Our nonlinear least square (NLLS) estimator is defined as the solution to

$$\min_{\rho} \quad \sum_{i=1}^{N}\sum_{t=2}^{T}\frac{1}{N(T-1)}\left(y_{i,t}-\frac{f(\mathbf{s}_{it},\boldsymbol{\lambda}_t,\rho)}{f(\mathbf{s}_{i,t-1},\boldsymbol{\lambda}_{t-1},\rho)}y_{i,t-1}\right)^2,$$

Equivalently, the NLLS corresponds to the following moment condition

$$\mathbb{E}\left[\left(y_{i,t}-\frac{f(\mathbf{s}_{it},\boldsymbol{\lambda}_t,\rho)}{f(\mathbf{s}_{i,t-1},\boldsymbol{\lambda}_{t-1},\rho)}y_{i,t-1}\right)\frac{\partial\frac{f(\mathbf{s}_{it},\boldsymbol{\lambda}_t,\rho)}{f(\mathbf{s}_{i,t-1},\boldsymbol{\lambda}_{t-1},\rho)}y_{i,t-1}}{\partial\rho}\right]=0. \tag{20}$$

This is related to the second potential issue, which is about endogeneity of the trade and MP shares. In our model, firms are not forward looking in choosing MP. A firm does 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. Consider the following example. If a country with a higher MP exposure also implement complementing innovation policy, and in our specification, this policy would generate positive correlation between MP exposure and the error term. To deal with this issue, we use instrumented NLLS, using the initial shares as instrument for current shares. Parallel to the moment condition for NLLS estimator (20), the moment condition for the instrumented NLLS estimator is

$$\mathbb{E}\left[\left(y_{i,t}-\frac{f(\mathbf{s}_{it},\boldsymbol{\lambda}_t,\rho)}{f(\mathbf{s}_{i,t-1},\boldsymbol{\lambda}_{t-1},\rho)}y_{i,t-1}\right)\frac{\partial\frac{f(\mathbf{s}_{it}^{(IV)},\boldsymbol{\lambda}_t,\rho)}{f(\mathbf{s}_{i,t-1}^{(IV)},\boldsymbol{\lambda}_{t-1},\rho)}y_{i,t-1}}{\partial\rho}\right]=0. \tag{21}$$

Table 1 presents the results of our NLLS estimation with and without IV. When we continue to the quantitative exercise, we will use $\hat{\rho}=0.728$ as our benchmark of learning parameter and discuss the implication for other values where appropriate. Finally, with $\hat{\rho}$, we match our inverted λ's from equation (19) to infer α's. The structural interpretation of these estimates are $\hat{\alpha}$'s plus the residuals.

	NLLS	With IV
	(1)	(2)
$\hat{\rho}$	0.651 ***	0.728 **
	(0.213)	(0.329)

Table 1: Estimation Results

Notes: This table shows the nonlinear least squares estimation results with and without IV. Standard errors clustered by country are reported in parentheses, and *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively.

4 Quantitative Exercises

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

First, we use our model to decompose the sources of growth from 2005 to 2016 into three drivers: MP costs, trade costs, and learning. Furthermore, we break down learning-driven growth into two components: learning from foreign producers and learning from domestic producers. We also examine the role of key headquarter countries and host countries in fostering learning and driving growth.

Second, we turn to our analysis of gains from openness. 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. As our paper nests the mechanisms of a set of trade and growth papers, we compare our findings with results in those papers.

Third, motivated by recent developments in international geopolitics, we consider a counterfactual economic sanction where all foreign MP exits Russia for ten years. We then shift our attention to the United States through an analysis of trade and multinational production policies. We consider two counterfactuals, both having the effect of discouraging US firms from producing in other countries. In the first counterfactual, outward MP costs from the United States increase by 20% permanently. In the second one, inward trade costs increases by 10% permanently.

In appendix C, we also provide a more detailed discussion on quantitative results, additional figures and tables, as well as an extended model where learning can happen both through production and through products.

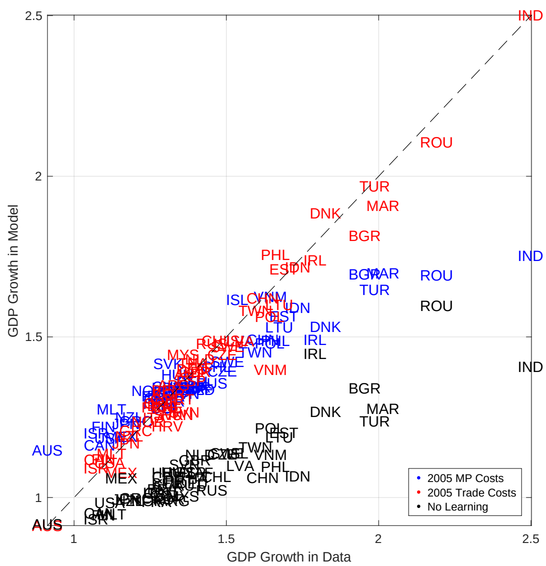

Figure 2: GDP Growth

Notes: This figure shows the ratio of 2016 GDP to 2005 GDP for each country under three counterfactual scenarios. The blue dots represent the ratio when MP costs remain constant at 2005 levels, the red dots show the ratio when trade costs remain constant at 2005 levels, and the black dots display the ratio in the absence of learning. The dashed line represents a 45-degree line.

4.1 Sources of Growth

In this section, we use our model to decompose the sources of growth from 2005 to 2016 into three key drivers: MP costs, trade costs, and learning. Inspired by Alviarez, Cravino, and Ramondo (2023), we further break down growth from learning into two components: learning from foreign producers and learning from domestic producers.

If MP costs had remained at their 2005 levels, aggregate GDP in 2016 would have been 5% lower, and GDP growth between 2005 and 2016 would have been 15.3% lower. Similarly, if trade costs had remained constant at their 2005 levels, aggregate GDP growth over the same period would have been 0.7% lower.

While these aggregate numbers are informative, we show how each country's GDP is affected in figure 2, which shows the model predicted GDP growth if MP costs had remained at their 2005 levels, if trade costs had remained at their 2005 levels, and if there is no learning, respectively. We observe that learning explains a lot of GDP growth during this period for countries in our sample.

While these aggregate numbers are informative, we how how changes in MP costs affect growth in different countries. We show GDP growth gains due to changes in MP costs in each country in Figure 3.[20] We construct a measure for changes in MP costs as

[20]We define GDP growth lost as the difference of GDP ratio in model versus data. Visually, it's the vertical difference in figure 2 of each point to the 45 degree line.

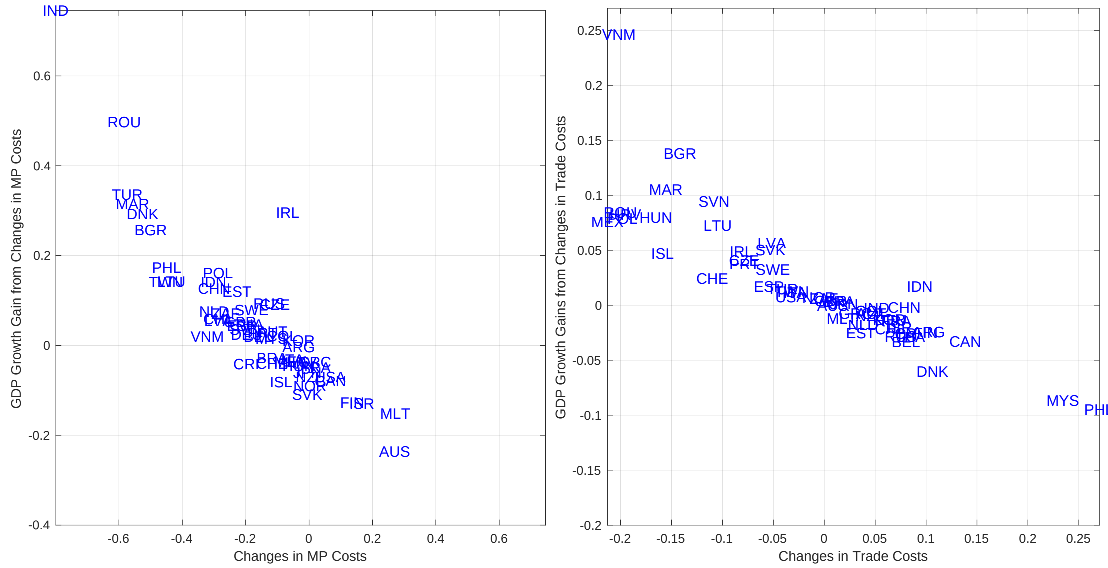

Figure 3: Growth Gains Versus Changes in MP and Trade Costs

Notes: This figure shows the effect of GDP growth from changes in MP and trade costs respectively. GDP growth gains from changes in MP (trade) costs are the difference of the ratio of 2016 GDP to 2005 GDP between data and the counterfactual scenario where MP (trade) costs are held constant at 2005 level. Changes in MP (trade) costs are measured as the inward MP share differences with 2005 MP (trade) costs (data in 2005) versus 2016 MP (trade) costs, holding other factors constant.

follows. We first compute what a country's inward MP shares would be, if knowledge stocks and trade costs are at their *2005* level, while MP costs are at their *2016* level. We plot the gap between actual inward MP share in 2005 and the constructed share. A positive gap means that inward MP costs increased for this country. Changes in trade costs are similarly defined (by holding MP costs the same while having 2016 trade costs). We construct GDP growth gains from MP (or trade) costs changes by calculating GDP growth in data relative to counterfactual GDP growth keeping MP (or trade) costs at their 2005 level.

Figure 3 shows the relationship. The negative correlation is consistent with our intuition. During this period countries where MP (or trade) costs decreased more experienced higher growth gains. Also, the size of costs change is quite different across countries. We see that India, Romania and Turkey experienced the largest reduction in MP costs, while many developed countries, including the USA, didn't see too much MP costs change. Similarly, changes in trade costs are heterogenous as well, with Vietnam and Mexico getting the largest reduction. Overall, by our measure, the reduction in MP costs are larger than in trade costs.

If we shut down technology diffusion ($\rho = 0$), aggregate GDP growth between 2005 and 2016 would have been 82.23% lower. Given the crucial role of learning in economic growth, we further examine its contribution by distinguishing between learning from domestic and foreign producers. If learning were allowed only from domestic producers, aggregate GDP growth between 2005 and 2016 would have been 11.3% lower. In contrast, if learning were allowed only from foreign producers, GDP growth would have been 73.8% lower.

It is important to note that this result does not imply that MP by foreign producers is unimportant for growth. Foreign MP intensifies domestic competition, which, in turn, improves the domestic technology frontier through selection. A more advanced domestic technology frontier fosters better new insights, ultimately driving further economic growth.

We further examine the role of key headquarter and host countries in global growth by analyzing the impact of multinational production (MP). Specifically, we ask: How much aggregate GDP growth would there be, if knowledge stocks of key headquarter countries were kept at their 2005 levels? Conversely, how would aggregate GDP evolve if key host countries' knowledge stocks were fixed at their 2005 levels? [21] If the knowledge stocks of top headquarter countries had remained at their 2005 levels, GDP growth would have been 25.3% lower. Similarly, if the knowledge stocks of top host countries had been fixed, GDP growth would have been 46.9% lower. This highlights the significant contribution of learning in top host countries to GDP growth.

4.2 Gains from Openness

In this part, we examine a question frequently asked in the quantitative trade literature: What are the gains from openness?

We consider the overall welfare effect, measured in terms of annual consumption equivalent variation,

$$(1-\beta)\sum_{t=1}^{\infty}\beta^{t-1}\log\left(\frac{C'_{it}}{C_{it}}\right), \tag{22}$$

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. Essentially, we ask: What percentage of consumption must be removed from the benchmark economy *annually* to equalize the discounted utility with the counterfactual?

We present both static and dynamic effects from openness. The static effect is defined as the immediate change in real consumption after a shock in trade and/or MP costs, consistent with welfare definition in static models (e.g., Ramondo and Rodríguez-Clare

[21] According to Li (2023), as of 2007, the top ten global headquarters were USA, JPN, GBR, DEU, FRA, NLD, CHE, ITA, ROW, and CAN, while top ten global host countries were USA, DEU, GBR, CHN, FRA, CAN, ITA, AUS, ESP, and NLD.

(2013)). For dynamic effects, we show the change in average growth rate of real consumption and the overall welfare effect defined in (22), including transitional dynamics. This complements our long-run welfare analysis in Section 2.5.[22]

Gains from Openness

Taking 2016 as our base year, we run the economy forward with parameters at the 2016 level, allowing knowledge stock to evolve endogenously (our benchmark). We then run a counterfactual where there is no trade or MP from 2016 onward. We compare the difference between the counterfactual and the benchmark to understand the gains from openness.[23]

Table 2 presents results for selected countries. Column (1) shows welfare gains as annual consumption equivalent variation. Compared to autarky, openness provides equivalent annual consumption increases of 35.77% for the United States and 46.24% for China. These substantial figures combine immediate effects with long-term growth impacts. Column (2) shows static gains from openness, defined as the immediate gap in real consumption levels. These gains vary considerably across countries, ranging from 6.17% in China to 59.65% in Ireland. Small, open economies like Hungary, Ireland, and Vietnam experience the largest static gains. Column (3) displays the annual growth rate of real consumption over a 50-year period in the benchmark model, while Column (4) shows the difference between this benchmark rate and the autarky scenario. All countries show higher growth rates compared to autarky, with increases ranging from 1.08 percentage points for Ireland to 2.12 percentage points for Vietnam.

Gains from MP

To isolate MP's role in openness gains, we run a counterfactual where MP costs approach infinity from 2016 onward, while leaving trade costs unchanged. We denote the difference between this "MP autarky" and the benchmark as gains from MP.

In this exercise, with increased MP costs but unchanged trade costs, trade flows increase since trade and MP are substitutes for firms selling to markets.[24] When MP costs rise, trade

[22]Our model abstracts from capital accumulation, intermediate goods, and non-tradable goods, which may bias our quantitative welfare results. As shown in Cai, Caliendo, Parro, and Xiang (2025), capital accumulation tends to complement TFP growth, amplifying welfare effects. In static models, intermediate goods increase welfare gains, while non-tradable goods decrease them. We conjecture these factors do not significantly affect the dynamic patterns or cross-country distribution of gains.

[23]The expenditure-side real GDP at chained PPP in PWT shows an implausible 39.8% increase from 2014 to 2015, likely reflecting accounting relocations rather than genuine growth. To maintain consistency in our knowledge stock estimates, we therefore extrapolate Ireland's values for 2015 and 2016 based on pre-2015 trends rather than calculate them directly.

[24]When considering "bridge MP" (a firm producing in a foreign country and exporting to a third country),

	Welfare (1)	Static Gain (2)	Growth Rate (3)	Δg (4)
Australia	53.00%	16.94%	1.90	1.75
Brazil	58.96%	10.66%	2.18	2.09
Canada	68.45%	33.86%	1.83	1.73
China	46.24%	6.17%	1.97	1.94
France	54.86%	20.27%	1.85	1.70
United Kingdom	71.32%	34.20%	1.92	1.81
Hungary	128.17%	87.54%	1.96	1.95
India	48.79%	8.87%	1.95	1.94
Ireland	82.75%	59.65%	1.89	1.08
Mexico	76.52%	36.64%	1.95	1.92
United States	35.77%	11.03%	1.87	1.18
Vietnam	92.67%	47.84%	2.12	2.12

Table 2: Gains from Openness: Selected Countries

Notes: This table presents the gains from openness for a subset of countries in the sample. Column (1) presents overall welfare gains in terms of annual consumption equivalent variation, as defined in (22). 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) presents the annualized growth rate in the following 50 years in the benchmark economy. Column (4) presents the difference between the annualized growth rate between benchmark and autarky in the following 50 years.

becomes relatively more cost-efficient, increasing aggregate trade flows. This partially offsets the reduction in MP flows, mitigating immediate consumption impacts. However, reduced MP flows lead to less international learning, producing significant dynamic effects despite increased trade.

Table 3 presents selected country results. Column (1) reports welfare gains from MP as annual consumption equivalent variation. As expected, these are smaller than gains from openness. Column (2) reports static MP gains, defined as immediate real consumption gaps between MP autarky and benchmark. For China, Vietnam, and India, immediate consumption effects from MP reduction are largely offset by trade increases. Vietnam's negative static gains may seem surprising but reflect general equilibrium effects on relative wages. Countries hosting more foreign MP in the base year experience decreased relative wages in MP autarky due to reduced labor demand from foreign firms. With relatively small MP presence, India and Vietnam experience smaller labor demand reductions, resulting in relative real wage increases and potentially higher immediate consumption through cheaper imports.

Regarding dynamic effects, Column (4) shows growth rate changes, revealing that

trade and MP are complements. Since bridge MP flows represent a small portion of total MP, we focus on the substitution effect to highlight the intuition.

	Welfare (1)	Static Gain (2)	Growth Rate (3)	Δg (4)
Australia	44.52%	9.47%	1.90	1.70
Brazil	50.70%	3.22%	2.18	2.05
Canada	42.61%	11.21%	1.83	1.56
China	40.37%	0.83%	1.97	1.91
France	34.41%	2.50%	1.85	1.56
United Kingdom	39.67%	6.71%	1.92	1.59
Hungary	59.56%	21.23%	1.96	1.83
India	39.40%	0.03%	1.95	1.91
Ireland	11.16%	12.62%	1.89	0.06
Mexico	39.97%	2.99%	1.95	1.77
United States	25.47%	3.53%	1.87	1.04
Vietnam	41.67%	-0.96%	2.12	2.01

Table 3: Gains from MP: Selected Countries

Notes: This table presents the gains from MP openness for a subset of countries in the sample. Column (1) presents overall welfare gains in terms of annual consumption equivalent variation, as defined in (22). 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) presents the annualized growth rate in the following 50 years in the benchmark economy. Column (4) presents the difference between the annualized growth rate between benchmark and autarky in the following 50 years.

openness's dynamic effects are largely explained by MP's dynamic effects. Even countries with minimal static MP gains experience substantial long-run effects. Going to MP autarky, annual real consumption growth rate is higher in the benchmark. Complete MP gains for all countries appear in the appendix.

Discussion on Quantitative Results

Our paper calculates static and dynamic gains from trade, MP, and openness. Since our model nests mechanisms from several trade and growth papers, Table C.1 summarizes gains across different models and provides a detailed cross-paper comparison.

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. Relatedly, de Souza, Hu, Li, and Mei (2024) investigates a similar question by focusing on international trade sanctions, here we use our model to highlight the role of MP.

We consider the counterfactual exercise where a group of countries impose MP sanction

	Welfare	Static Gain	Δ Growth Rate (Percentage Points)
	(1)	(2)	(3)
China	-0.05%	0.00%	-0.01
Czech Republic	-0.07%	0.01%	-0.02
Lithuania	-0.19%	0.03%	-0.07
Latvia	-0.09%	0.15%	-0.04
Russia	-9.11%	-1.50%	-3.15

Table 4: Economic Sanction on Russia: Selected Countries

Notes: This table shows the 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.

on Russia. In this scenario, Russia's inward MP costs from these countries increase to infinity (i.e., $\gamma_{RUS,h} = \infty$ for all h in the group).[25] 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 largely cutoff from global production. The *ten-year* MP sanction on Russia causes an welfare effect equivalent to a 9.11% annual reduction in real consumption *perpetually*. Real consumption decreases by 1.50% in Russia immediately, and during the period of economic sanction the annual growth rate of real consumption is lower by 3.15 percentage points compared to autarky. Figure 4 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.[26]

[25] We borrow the list of countries that impose sanction on Russia from de Souza, Hu, Li, and Mei (2024): Australia, Austria, Belgium, Bulgaria, Canada, Switzerland, Czech Republic, Germany, Denmark, Spain, Estonia, Finland, France, United Kingdom, Greece, Croatia, Hungary, Ireland, Iceland, Israel, Italy, Japan, South Korea, Lithuania, Latvia, Morocco, Malta, Netherlands, Norway, New Zealand, Poland, Portugal, Romania, Slovak Republic, Slovenia, Sweden, Chinese Taipei, United States.

[26] At the same time, Figure 4 also illustrates a property of the model that the (detrended) steady-state levels are not affected by transitory changes in parameters after the reversal of changes. This is different from models where even transitory changes may lead to changes in steady state levels. See Peters (2022) for an example of influx of immigration leads to long-run economic development, and Allen and Donaldson (2020) for a more general discussion on persistence and path dependence.

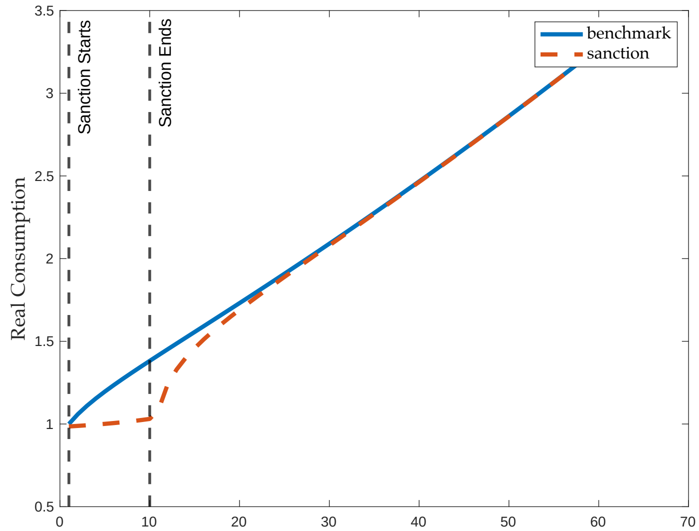

Figure 4: Real Consumption in Russia

Notes: This figure shows the paths of real consumption in Russia with and without MP Sanction. The solid blue line depicts the path of real consumption in Russia in the benchmark economy where trade and MP costs stay constant at 2016 level. The dashed red line shows the path with 10-year MP sanction. The real consumption in base year in the benchmark is normalized to 1.

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 Table C.7 we report the results for all countries.[27] [28]

4.4 US Strategies in MP and Trade

Relocating 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 two types of US policies that may encourage US multinational firms to locate

[27] In Table C.8, we also present 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.

[28] We report what the welfare loss in Russia would be for different lengths of MP sanctions in Figure C.8. If the duration of the MP sanction increases from 5 years to 15 years, the welfare loss in Russia increase from 4.4% to 13.5%.

	Benchmark (1)	Increased MP Costds (2)	Base Year (3)
USA / Median	1.73	1.77	1.78
USA / Median of High Income	1.42	1.49	1.46
USA / Median of Low & Middle Income	2.86	2.92	3.13
USA / China	3.87	3.94	4.06

Table 5: US Technological Dominance

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 Malta. New Zealand's TFP is the median among high-income economies. Brazil'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.

their production within the US.

Increasing Outward MP Costs

We first consider 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. 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 C.9, the positive effects dominate, and US real consumption level goes up by 0.52% 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. If we look at the dynamics of the US economy, the US growth rate mildly decreases as a result of the policy: annualized growth rate in the next 50 years is 0.01 percentage point lower. The overall effect on the US welfare is the result of the two effects (immediately increased real wage and slower growth), and it turns out to be positive - 0.04% welfare increase.

Some may argue that increasing outward MP costs could help maintain U.S. technological dominance. Table 5 compares the TFP ratio between the United States and other countries. Column (1) presents the TFP ratio over 50 years without such a policy, while Column (2) shows the ratio with the policy in place. The results suggest that this policy partially achieves its goal, as the TFP ratio is higher when outward MP costs are increased.

Increasing Inward Trade Costs

We consider a second scenario in which U.S. inward trade costs increase by 10% (i.e., $\tau'_{USA,j}/\tau_{USA,j} = 1.1$ for all $j \neq USA$), simulating a rise in U.S. tariffs. In our model, higher inward trade costs encourage firms to serve the U.S. market through multinational production (MP) rather than trade, allowing them to bypass the additional costs.

In the short run, U.S. welfare is influenced by two opposing forces: a positive effect from increased labor demand and a negative effect from higher price levels due to elevated trade costs. Our findings indicate that the negative effects dominate initially, leading to a 0.79% decline in U.S. real consumption.

Turning to the long-term dynamics, we find that the U.S. annualized growth rate over the next 50 years rises modestly by 0.004 percentage points. However, the overall impact on U.S. welfare remains negative, with a small decline of 0.2%. Table C.10 presents the effects of this policy on all countries in our sample.

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 these policies can have different short-run and long-run effects on wages and consumption, 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}	Combination of MP cost, wage cost, and trade cost.
$\pi_{ijh}, \pi_{ij}^T, \pi_{ih}^E$	Trilateral share, trade share and expenditure share.
π_{jh}^{MP}	Bilateral MP *production* share. Directly observable from data.
π_{jh}^{M}	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

We discuss two special cases regarding the value of η in Assumption 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 this 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. We illustrate the reason in the simple case where $N = 2$.[29] Note that for all $x_2 > x_1 \geq 0$, $y_2 > y_1 \geq 0$, the arrival rate of ideas with original component $\mathbf{z}$ such that $z_1 \in (x_1, x_2]$, $z_2 \in (y_1, y_2]$ is

$$A_{h,t}\left(\begin{bmatrix} x_1 \\ y_2 \end{bmatrix}\right) - A_{h,t}\left(\begin{bmatrix} x_1 \\ y_1 \end{bmatrix}\right) - A_{h,t}\left(\begin{bmatrix} x_2 \\ y_2 \end{bmatrix}\right) + A_{h,t}\left(\begin{bmatrix} x_2 \\ y_1 \end{bmatrix}\right) = 0.\text{[30]}$$

[29] The same logic can be extended to more general cases where $n > 2$. We set $N = 2$ in the main text only to save on notations.

[30] The arrival rate of ideas with original component $\mathbf{z}$ such that $z_1 \leq x$, $z_2 \leq y$ is $1 - A_{h,t}([x\ y]')$. So the arrival rate of ideas with original component $\mathbf{z}$ such that $z_1 \in (x_1, x_2]$, $z_2 \in (y_1, y_2]$ is $(1 - A_{h,t}([x_2, y_2]')) - (1 - A_{h,t}([x_1, y_2]')) - (1 - A_{h,t}([x_2, y_1]')) + (1 - A_{h,t}([x_1, y_1]'))$.

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

Now we look at the other special case as $\eta \to 1$. Note that as $\eta \to 1$, $A_{h,t}(\mathbf{z}) \to \alpha_{h,t} \max\{z_1^{-\theta}, \ldots, z_n^{-\theta}\}$. In this case, the only possible arrivals of $\mathbf{z}$ have the same value in all dimensions. Again, we set $N = 2$ to save on notations, but the same logic applies to more general cases where $N > 2$. Consider a vector (x, y) where $x \neq y$. Without loss of generality, assume $y < x$. Let $\delta = (x - y)/3$. The arrival rate of ideas with original component such that $z_1 \in (x - \delta, x + \delta]$, $z_2 \in (y - \delta, y + \delta]$ is

$$A_{h,t}\left(\begin{bmatrix} x-\delta \\ y+\delta \end{bmatrix}\right) - A_{h,t}\left(\begin{bmatrix} x-\delta \\ y-\delta \end{bmatrix}\right) - A_{h,t}\left(\begin{bmatrix} x+\delta \\ y+\delta \end{bmatrix}\right) + A_{h,t}\left(\begin{bmatrix} x+\delta \\ y-\delta \end{bmatrix}\right) = 0.$$ [31]

That is to say, when $\eta \to 1$, there will be no ideas whose original component do not have the same value in all dimensions.

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.

[31] The equation holds because $A_{h,t}([x-\delta, y+\delta]') = A_{h,t}([x+\delta, y+\delta]')$, and $A_{h,t}([x-\delta, y-\delta]') = A_{h,t}([x+\delta, y-\delta]')$.

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

$$\begin{aligned}
\Pr[\mathbf{Q}_{h,t}^{(1)}(v) \leq \mathbf{q}] &= \exp\left(-\int_{-\infty}^{t} \tilde{A}_{h,\tau}(\mathbf{q}) d\tau\right) \\
&= \exp\left(-\int_{-\infty}^{t} \alpha_{h,\tau}\Lambda_{h,\tau} \left(\sum_{n=1}^{N} q_n^{-\frac{\theta}{1-\eta}}\right)^{1-\eta} d\tau\right) \\
&= \exp\left(-\int_{-\infty}^{t} \alpha_{h,\tau}\Lambda_{h,\tau} d\tau \left(\sum_{n=1}^{N} q_n^{-\frac{\theta}{1-\eta}}\right)^{1-\eta}\right) \\
&= \exp\left(-\lambda_{h,t} \left(\sum_{n=1}^{N} q_n^{-\frac{\theta}{1-\eta}}\right)^{1-\eta}\right)
\end{aligned}$$

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 specifies 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:*

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

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,

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

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

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

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

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

$$
\begin{aligned}
&= \int_0^q (-\lambda_h) \left(\sum_k (\frac{\kappa_{ikh}}{\kappa_{ijh}})^{-\frac{\theta}{1-\eta}} \right)^{-\eta} \exp\left(\sum_{n=1}^N -\lambda_n \left(\sum_{k=1}^N \left(\frac{\kappa_{ikn}}{\kappa_{ijh}} \right)^{-\frac{\theta}{1-\eta}} \right)^{1-\eta} x^{-\theta} \right) dx^{-\theta} \\
&= \frac{\lambda_h \left(\sum_k (\frac{\kappa_{ikh}}{\kappa_{ijh}})^{-\frac{\theta}{1-\eta}} \right)^{-\eta}}{\sum_{n=1}^N \lambda_n \left(\sum_{k=1}^N \left(\frac{\kappa_{ikn}}{\kappa_{ijh}} \right)^{-\frac{\theta}{1-\eta}} \right)^{1-\eta}} \exp\left(\sum_{n=1}^N -\lambda_n \left(\sum_{k=1}^N \left(\frac{\kappa_{ikn}}{\kappa_{ijh}} \right)^{-\frac{\theta}{1-\eta}} \right)^{1-\eta} q^{-\theta} \right) \\
&= \kappa_{ijh}^{-\frac{\theta}{1-\eta}} \frac{\lambda_h \left(\sum_k (\kappa_{ikh})^{-\frac{\theta}{1-\eta}} \right)^{-\eta}}{\sum_{n=1}^N \lambda_n \left(\sum_{k=1}^N (\kappa_{ikn})^{-\frac{\theta}{1-\eta}} \right)^{1-\eta}} \exp\left(\sum_{n=1}^N -\lambda_n \left(\sum_{k=1}^N \left(\frac{\kappa_{ikn}}{\kappa_{ijh}} \right)^{-\frac{\theta}{1-\eta}} \right)^{1-\eta} q^{-\theta} \right) \\
&= \pi_{ijh} \exp\left(\sum_{n=1}^N -\lambda_n \left(\sum_{k=1}^N \left(\frac{\kappa_{ikn}}{\kappa_{ijh}} \right)^{-\frac{\theta}{1-\eta}} \right)^{1-\eta} q^{-\theta} \right).
\end{aligned}
$$

Note that

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

So we have

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

and

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

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). $\square$

B.5 Real Income

We derive equation (12) here. Equation (12) indicates that the real income per worker can be summarized by the stock of knowledge and aggregate self shares. This relationship holds at any time period. In this section we omit the time subscript unless possible confusion arises.

The real income per worker is

$$\omega_i = \frac{w_i}{P_i}.$$

We derive the price index here. Let us first consider the probability that country i can buy a variety v produced with ideas from country h for a price less than p, regardless of the production location, denoted as

$$G_{ih}^{(p)}(p) = \Pr\left(\min_j p_{ijh}(v) \leq p\right).$$

Using the joint distribution of $(q_{1h}, ..., q_{Nh})$, we have

$$\begin{aligned}
G_{ih}^{(p)}(p) &= \Pr\left(\min_j p_{ijh}(v) \leq p\right) \\
&= 1 - \Pr\left(p_{ijh}(v) \geq p, \forall j\right) \\
&= 1 - \Pr\left(\frac{\kappa_{ijh}}{q_{jh}(v)} \geq p, \forall j\right) \\
&= 1 - \Pr\left(q_{jh}(v) \leq \frac{\kappa_{ijh}}{p}, \forall j\right) \\
&= 1 - F_h(\frac{\kappa_{i1h}}{p}, ..., \frac{\kappa_{iNh}}{p}) \\
&= 1 - \exp\left(-\lambda_h \left(\sum_{j=1}^{N} \left(\kappa_{ijh}\right)^{-\frac{\theta}{1-\eta}}\right)^{1-\eta} p^{\theta}\right).
\end{aligned}$$

Next we derive the price distribution in country i. The probability that country i can buy a variety v for a price less than p is

$$G_i^{(p)}(p) = \Pr\left(p_i(v) \leq p\right).$$

We can write

$$\begin{aligned}
G_i^{(p)}(p) &= \Pr\left(p_i(v) \leq p\right) \\
&= \Pr\left(\min_h p_{ih}(v) \leq p\right) \\
&= 1 - \Pr\left(\min_h p_{ih}(v) \geq p\right) \\
&= 1 - \Pr\left(p_{ih}(v) \geq p, \forall h\right) \\
&= 1 - \prod_{h=1}^{N}\left(1 - G_{ih}^{(p)}(p)\right) \\
&= 1 - \exp\left(-\sum_{h=1}^{N}\lambda_h\left(\sum_{j=1}^{N}\left(\kappa_{ijh}\right)^{-\frac{\theta}{1-\eta}}\right)^{1-\eta} p^{\theta}\right) \\
&= 1 - \exp\left(-\Phi_i p^{\theta}\right),
\end{aligned}$$

where $\Phi_i = \sum_{h=1}^{N}\lambda_h\left(\sum_{j=1}^{N}\left(\kappa_{ijh}\right)^{-\frac{\theta}{1-\eta}}\right)^{1-\eta}$.

Then the price index in country i is

$$\begin{aligned}
P_i &= \left(\int_0^1 p_i(v)^{1-\sigma} dv\right)^{1/(1-\sigma)} \\
&= \left(\int_0^{\infty} p^{1-\sigma} dG_i^{(p)}(p)\right)^{1/(1-\sigma)} \\
&= \left(\theta\Phi_i\int_0^{\infty} p^{\theta-\sigma}\exp\left(-\Phi_i p^{\theta}\right)dp\right)^{1/(1-\sigma)} \\
&= \Phi_i^{-\frac{1}{\theta}}\Gamma\left(\frac{\theta+1-\sigma}{\theta}\right)^{\frac{1}{1-\sigma}},
\end{aligned}$$

where $\Gamma(t) = \int_0^{\infty} x^{t-1}e^{-x}dx$ is the Gamma function.

From (4), and the definition of Φ_i, we have

$$\pi_{ii}^{E} = \frac{\lambda_i\left(\sum_{k=1}^{N}\kappa_{iki}^{-\frac{\theta}{1-\eta}}\right)^{1-\eta}}{\Phi_i},$$

and from (5) , we have

$$\psi_{iii} = \frac{w_i^{-\frac{\theta}{1-\eta}}}{\sum_{k=1}^{N}\kappa_{iki,t}^{-\frac{\theta}{1-\eta}}}.$$

Combining these expressions together, it follows immediately that

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

where $B = \Gamma\left(\frac{\theta+1-\sigma}{\theta}\right)^{-\frac{1}{1-\sigma}}$ is a constant.

B.6 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.

B.7 Trilateral Shares

In this appendix, we show that our model provides enough structure to back out the N^3 trilateral shares $\pi_{ijh,t}$ from the $N \times N$ matrices of trade shares $\pi_{ij,t}^{T}$ and MP shares $\pi_{jh,t}^{M}$.

To see this, define $\xi_{jh,t}^{M} = \lambda_{h,t}\gamma_{jh,t}^{-\theta}$ and $\xi_{ij,t}^{T} = (\tau_{ij,t}w_{j,t})^{-\theta}$. We can rewrite (6) as

$$\pi_{ijh,t} = \frac{(\xi_{ij,t}^{T}\xi_{jh,t}^{M})^{1/(1-\eta)}}{\sum_{k=1}^{N}(\xi_{ik,t}^{T}\xi_{kh,t}^{M})^{1/(1-\eta)}}\frac{\left(\sum_{k=1}^{N}(\xi_{ik,t}^{T}\xi_{kh,t}^{M})^{1/(1-\eta)}\right)^{1-\eta}}{\sum_{n=1}^{N}\left(\sum_{k=1}^{N}(\xi_{ik,t}^{T}\xi_{kn,t}^{M})^{1/(1-\eta)}\right)^{1-\eta}}. \tag{23}$$

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

$$\pi_{ij,t}^{T} = \sum_{h=1}^{N}\frac{(\xi_{ij,t}^{T}\xi_{jh,t}^{M})^{1/(1-\eta)}}{\sum_{k=1}^{N}(\xi_{ik,t}^{T}\xi_{kh,t}^{M})^{1/(1-\eta)}}\frac{\left(\sum_{k=1}^{N}(\xi_{ik,t}^{T}\xi_{kh,t}^{M})^{1/(1-\eta)}\right)^{1-\eta}}{\sum_{n=1}^{N}\left(\sum_{k=1}^{N}(\xi_{ik,t}^{T}\xi_{kn,t}^{M})^{1/(1-\eta)}\right)^{1-\eta}}, \tag{24}$$

$$\pi_{jh,t}^{M} = \sum_{i=1}^{N}\frac{X_{i,t}}{Y_{j,t}}\frac{(\xi_{ij,t}^{T}\xi_{jh,t}^{M})^{1/(1-\eta)}}{\sum_{k=1}^{N}(\xi_{ik,t}^{T}\xi_{kh,t}^{M})^{1/(1-\eta)}}\frac{\left(\sum_{k=1}^{N}(\xi_{ik,t}^{T}\xi_{kh,t}^{M})^{1/(1-\eta)}\right)^{1-\eta}}{\sum_{n=1}^{N}\left(\sum_{k=1}^{N}(\xi_{ik,t}^{T}\xi_{kn,t}^{M})^{1/(1-\eta)}\right)^{1-\eta}}, \tag{25}$$

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 (24) and (25) uniquely determine $\xi_{jh,t}^{M}$ and $\xi_{ij,t}^{T}$ up to a constant scale.

C Additional Results and Discussion

C.1 Discussion on Quantitative Results

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 C.1. 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 C.1, 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.

	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							
Sampson (2016)	✓	✓		✓	✓		✓
Buera and Oberfield (2020)	✓	✓		✓	✓		✓
Cai, Li, and Santacreu (2022)	✓	1.109		1.109	1.226		1.226
This Paper	✓	1.087	1.047	1.285	1.094	1.373	1.650

Table C.1: Gains from Openness

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.

C.2 The Role of MP Costs, Trade Costs, and Learning

We first use our model to examine the role of MP costs, trade costs, and learning in the evolution of TFP over time. Specifically, we address the following questions: How is TFP growth shaped by MP costs? How do changes in trade costs impact TFP? And how much growth would occur in the absence of 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 $\rho = 0.728$, the model can pin down the paths of $\alpha_{i,t}$ and residual terms for each country that perfectly match the time series of shares and stocks of knowledge from 2005 to 2016.[32] 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 $\rho = 0.728$, we perfectly match the time series of the stock of knowledge. We compare the baseline scenario with a counterfactual in which MP costs are increased or decreased by 10% to assess the impact of changes in MP costs. Similarly, to evaluate the effect of trade cost variations, we conduct a counterfactual analysis by increasing or decreasing trade costs by 10%. Finally, we simulate the economy with different values of ρ, to show the role

[32] 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.

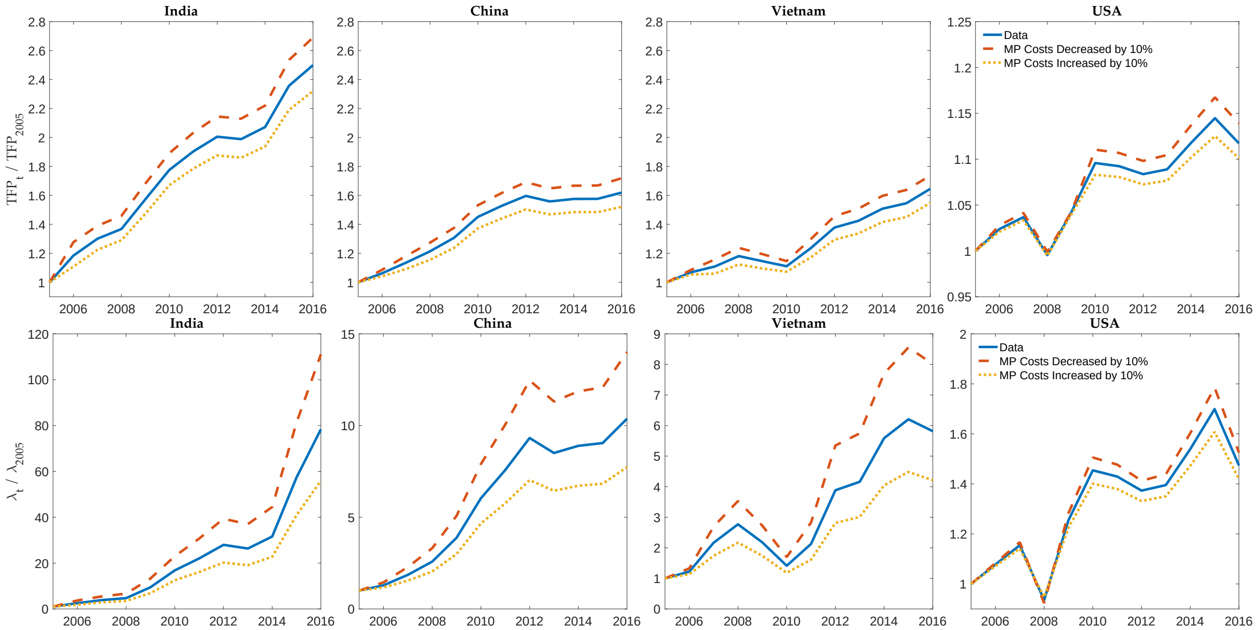

Figure C.1: Growth with Different MP Costs

Notes: This figure shows the results for three developing countries - India, China, Vietnam - and the USA. The first row presents the changes in measured TFP, which is calculated as $(\lambda_{i,t}\psi_{iii,t}^{\eta}/(B\pi_{iii,t}))^{1/\theta}$. The second row presents the changes in knowledge stock, which is $\lambda_{i,t}$. In each panel, we plot three lines. The solid line represents the changes of the measured TFP or knowledge stock from the data. The dashed (dotted) line represents the scenario where MP costs are decreased (increased). A table with results for all economies is in the appendix.

of learning in the dynamics of productivity.

MP Costs

We begin by studying what the dynamics of TFP would have been if we increase or decrease MP costs by 10%. The first row of Figure C.1 presents the dynamics of measured TFP for India, China, Vietnam, and the United States, while the second row presents the result of knowledge stock. In each panel, we plot three 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 increased or decreased by 10%. The dashed (dotted) line represents the scenario where MP costs are decreased (increased). We interpret the difference between the dashed/dotted and solid 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.

An immediate implication is that changes in MP costs significantly impact the growth of measured TFP and knowledge stock in India, China, and Vietnam, with India being the most affected. In contrast, TFP growth in the United States is overall less affected by changes in MP costs. This pattern is common among developed economies, partly because their technology levels are already high and their MP costs are relatively low.

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 foreign 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.[33] 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 C.2 presents the result for the same set of selected countries, and we put a table for all countries in the appendix. The first row illustrates the dynamics of measured TFP, while the second row depicts changes in knowledge stock. As before, the solid line represents the actual data, while the dashed/dotted line indicates the counterfactual scenario. In the counterfactual, we increase or decrease the trade costs τ_{ij} by 10% while keeping others the same as indicated by data. The dashed (dotted) line represents the scenario where trade costs are decreased (increased).

Interestingly, we find that an increase of trade costs results in a higher growth. When trade costs increase, MP acts as a substitute for trade, displacing less productive domestic firms and enhancing the technology frontier from which new ideas are drawn. Consequently, higher trade costs intensify learning from more productive producers, leading to stronger TFP growth.

Among the four countries, Vietnam's knowledge stock is the most affected by changes in trade costs. The impact of trade costs on TFP growth in the U.S. remains limited, in part due to its already high technology level. While trade cost changes significantly influence these economies, their impact is slightly smaller than that of MP cost changes, reinforcing our argument that trade costs have mixed effects on TFP growth.

[33] This is not saying that a reduction in import costs leads to less *employment* within the affected country. It is a model with inelastic labor supply so there will be firms producing and employing workers in any case. The consequence of reduction in importing costs is that *less productive production plants* would be producing in this country.

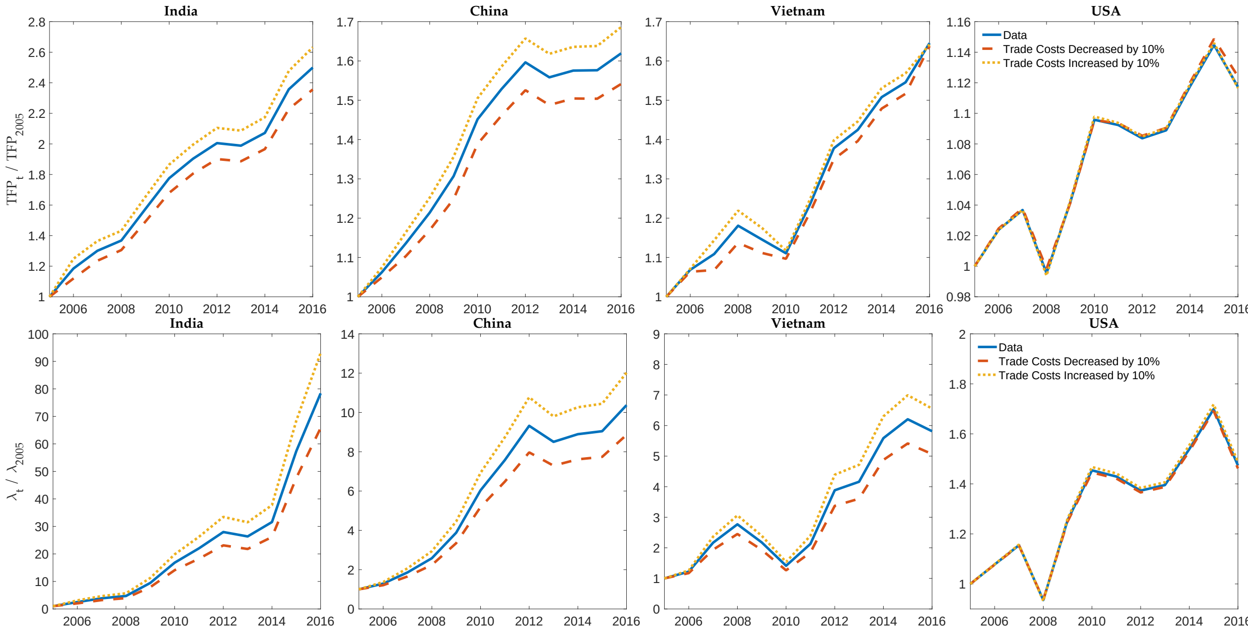

Figure C.2: TFP Growth with Different Trade Costs

Notes: This figure shows the counterfactual measured TFP in the first row and knowledge stock in the second row. In each panel, we plot three lines. The solid line represents the changes of the measured TFP or knowledge stock from the data. The dashed (dotted) line represents the scenario where trade costs are decreased (increased). A table with results for all economies is in the appendix.

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.[34] Figure C.3 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 $\rho = 0.728$, 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 56% of the data level; the statistic is 68% for China and 70% for Vietnam.

[34]We simply impose different values of ρ while keeping all other parameters unaffected. This is not a recalibration of the model, but more a display of whether different values of ρ may lead to very different growth implications.

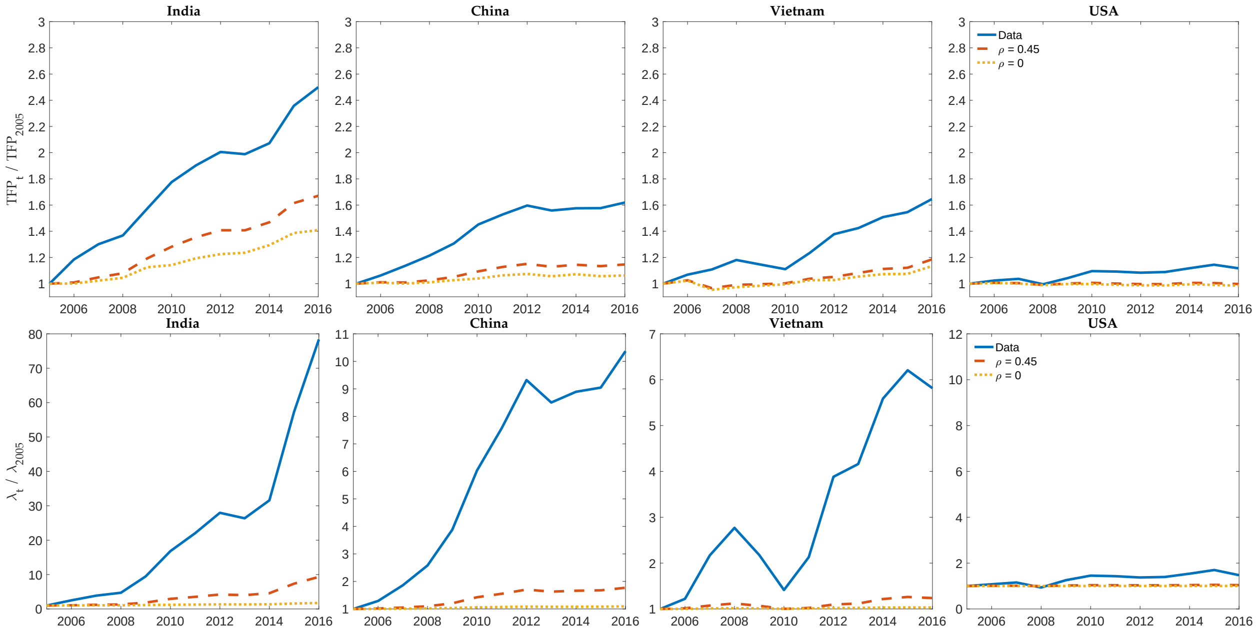

Figure C.3: TFP Growth with Different Learning Intensity

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 $(\lambda_{i,t}\psi_{iii,t}^{\eta}/(B\pi_{iii,t}))^{1/\theta}$. 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 56% of the data level; if $\rho = 0.45$, it would be at 68% of the data level.

C.3 Slowdown in MP growth

Our model also helps identify the drivers behind the recent slowdown in MP growth. Specifically, we compute counterfactual total MP flow as a percentage of total GDP under three scenarios: (1) fixing knowledge stocks in key headquarter countries, (2) fixing knowledge stocks in other countries, and (3) fixing MP costs at their 2005 levels. We then compare these counterfactual shares with the observed data. Figure C.4 presents the results. We find that between 2005 and 2016, changes in MP costs played a significant role in shaping MP patterns over time. If MP costs had remained at their 2005 levels, foreign affiliate sales relative to GDP would have been more than 5 percentage points lower. Knowledge stocks in top headquarter countries also played a crucial role, becoming

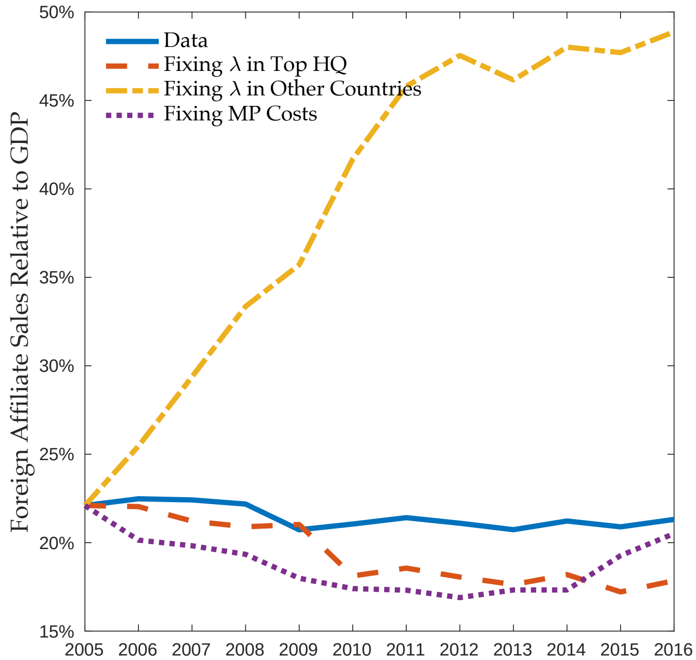

Figure C.4: Evolution of Aggregate MP Shares

Notes: The figure illustrates the evolution of MP shares, measured by foreign affiliate sales relative to GDP. The blue line represents the observed data, while the red line shows the counterfactual shares when we fix knowledge stocks in key headquarter countries at their 2005 levels. The yellow line represents the counterfactual shares when knowledge stocks in other countries are fixed at their 2005 levels, and the purple line depicts the counterfactual shares when MP costs are fixed at their 2005 levels.

increasingly important after 2009. Failing to account for changes in productivity in these top headquarter countries would have resulted in a reduction of foreign affiliate sales relative to GDP by 5 percentage points annually from 2010 to 2016. Interestingly, during the recession in 2009, as MNEs from top headquarter countries faced negative TFP shocks, keeping their productivity at 2005 levels would have resulted in an increase in their TFP, thereby boosting MP shares. Moreover, if the productivity levels of the rest of the countries had remained at their 2005 levels, the productivity growth of top headquarter countries would have driven an expansion of MP.

C.4 Extended Model with Learning From Trade

We extend the model by allowing for learning from trade (sellers). Producers combine insights from other producers and sellers. Hence, the new insight becomes

$$\boldsymbol{Q} = \boldsymbol{Z} \cdot \left(Q_p'\right)^{\rho_1} \left(Q_s'\right)^{\rho_2},$$

where Q_p' is the quality of an new idea drawn from producers, and Q_s' is the quality of an new idea drawn from sellers. The parameter ρ_1 and ρ_2 govern the learning intensities. The law of motion of knowledge stock becomes:

$$\dot{\lambda}_{h,t} = \alpha_{h,t} \int_0^\infty \int_0^\infty \left(q_p^{\rho_1} q_s^{\rho_2}\right)^\theta dG_{h,t}^p\left(q_p\right) dG_{h,t}^s\left(q_s\right),$$

where $G_{h,t}^p\left(q_p\right)$ and $G_{h,t}^s\left(q_s\right)$ are technology frontiers of producers and selles, respectively. It follows that

$$G_{h,t}^s\left(q\right) = \sum_j \sum_n \frac{\pi_{hjn}}{\sum_j \sum_n \pi_{hjn}} \exp\left(-\frac{\lambda_n}{\pi_{hn}^E \psi_{hjn}^{1-\eta}} q^{-\theta}\right).$$

We thus have our updated law of motion of knowledge stock:

$$\dot{\lambda}_{h,t} = \alpha_{h,t} \Gamma_{\rho_1,\rho_2} \left[\sum_n \frac{\pi_{hhn,t}}{\sum_n \pi_{hhn,t}} \left(\frac{\lambda_{n,t}}{\pi_{hn,t}^E \psi_{hhn,t}^{1-\eta}}\right)^{\rho_1}\right] \left[\sum_n \sum_j \frac{\pi_{hjn,t}}{\sum_j \sum_n \pi_{hjn,t}} \left(\frac{\lambda_{n,t}}{\pi_{hn,t}^E \psi_{hjn,t}^{1-\eta}}\right)^{\rho_2}\right].$$

Using a similar instrumented NLLS estimation strategy, we obtain $\hat{\rho}_1 = 0.629$ and $\hat{\rho}_2 = 0.488$. [35]

Next, we analyze the contribution of different learning channels to growth. We find that without learning from trade ($\rho_2 = 0$), aggregate GDP growth between 2005 and 2016 would be 87.2% lower; without learning from MP ($\rho_1 = 0$), it would be 81.4% lower. In the absence of any learning, GDP growth would be 94.1% lower. These results highlight the critical role of learning, particularly learning from MP. Figure C.5 shows the effect for each country. In most countries, without learning from trade would have a large impact on growth, possibly due to high trade shares. Mexico and Ireland are examples where learning from MP is more important.

We also find that in this extended model, if MP costs had remained at their 2005 levels, GDP growth between 2005 and 2016 would have been 17.23% lower. Similarly, if trade costs had remained constant at their 2005 levels, aggregate GDP growth over the same period would have been 0.02% lower. Figure C.6 shows the effect for each country. As we can see, the results are very similar to those in our baseline model.

[35] Note that the sum of the two estimated values of ρ exceeds 1. This suggests that the estimated parameters based on data from 2005 to 2016 do not allow for a BGP in the long run in this extended model. While this does not affect the validity of our model, it reflects the characteristics of the data during this period.

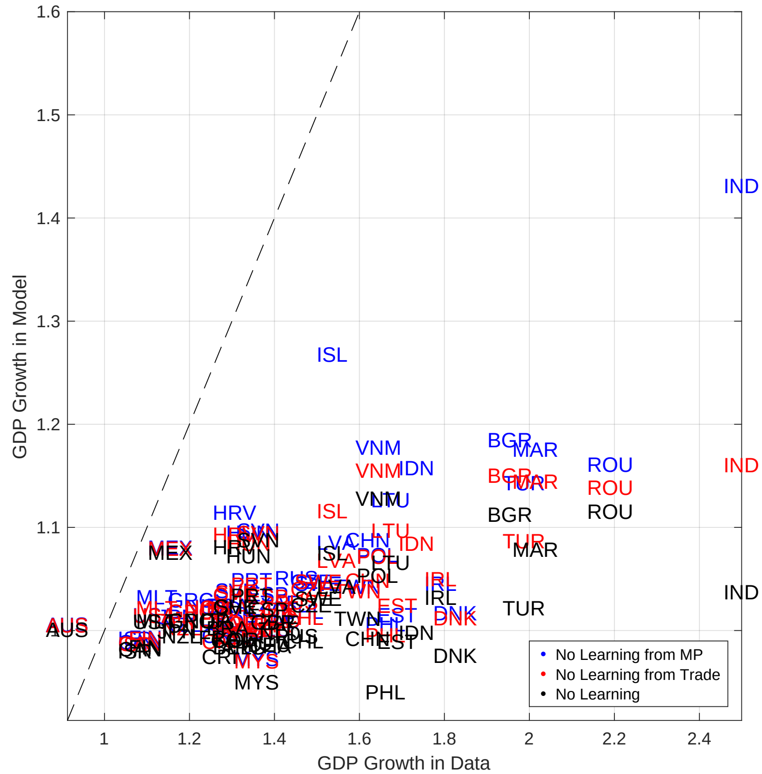

Figure C.5: GDP Growth

Notes: This figure shows the ratio of 2016 GDP to 2005 GDP for each country under three counterfactual scenarios. The blue dots represent the ratio when there is no learning from MP, the red dots show the ratio when no learning from trade is allowed, and the black dots display the ratio in the absence of either learning. The dashed line represents a 45-degree line.

C.5 Additional Tables and Figures

This appendix includes additional tables and figures to provide more detailed information on data and quantitative results.

Figure C.7 shows the heterogeneity in knowledge stocks (calibrated in Section 3.2) and measured TFP on a log scale. The left panel presents knowledge stocks in 2005 and the right panel presents measured TFP in the same year. The dashed line is the simple average of knowledge stocks and measured TFP across economies. Countries with the highest knowledge stocks in manufacturing are the United States, Switzerland and South Korea, while countries with the lowest knowledge stocks are Vietnam, India and Bulgaria.

Figure C.8 report what the welfare loss in Russia would be for different lengths of MP sanctions for the exercise in Section 4.3.

Tables C.2 - C.4 complement results in Section C.2. Table C.2 presents results on TFP growth for all countries, holding MP costs constant at their levels in 2005. Table C.3 presents results on TFP growth for all countries, holding trade costs constant at their

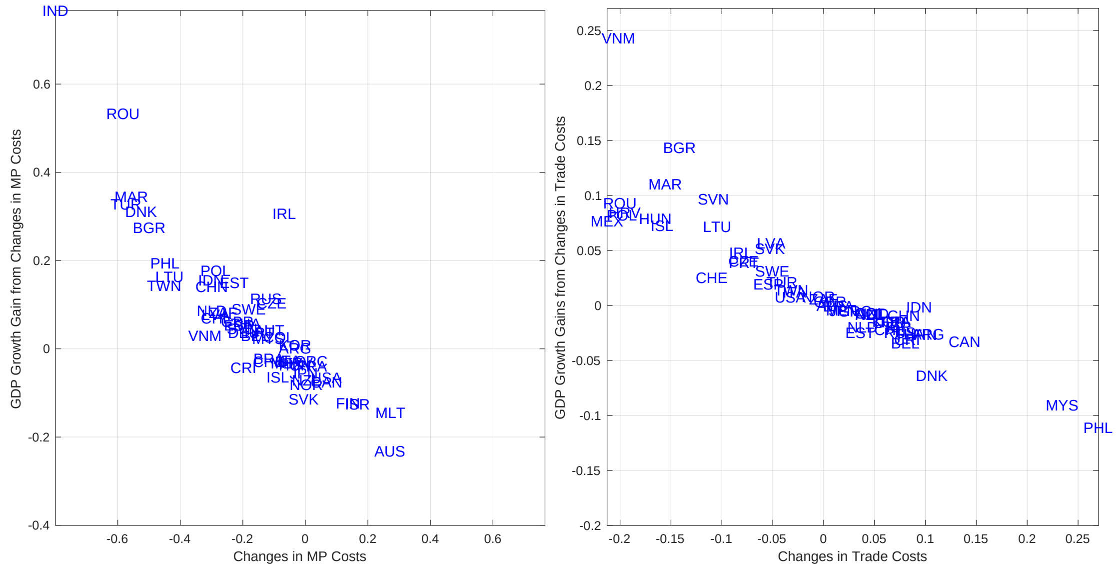

Figure C.6: Growth Gains Versus Changes in MP and Trade Costs

Notes: This figure shows the effect of GDP growth from changes in MP and trade costs in the extended model. GDP growth gains from changes in MP (trade) costs are the difference of the ratio of 2016 GDP to 2005 GDP between data and the counterfactual scenario where MP (trade) costs are held constant at 2005 level. Changes in MP (trade) costs are measured as the inward MP share differences with 2005 MP (trade) costs (data in 2005) versus 2016 MP (trade) costs, holding other factors constant.

levels in 2005. Table C.4 presents results on TFP growth under different values of learning intensity, ρ.

Tables C.5 - C.6 complement results in Section 4.2. Table C.5 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.6 reports the gains from MP for all countries.

Table C.7 reports the effects of a 10-year MP sanction on Russia on all countries, and Table C.8 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.9 reports the welfare effects for all countries in the counterfactual with US reshoring policy.

	Data	Constant MP Costs	Ratio
	(1)	(2)	(3)
Argentina	0.33	0.33	1.01
Australia	-0.09	0.15	-1.70
Austria	0.38	0.34	0.91
Belgium	0.30	0.28	0.93
Bulgaria	0.95	0.70	0.73
Brazil	0.29	0.32	1.09
Canada	0.09	0.16	1.92
Switzerland	0.31	0.35	1.13
Chile	0.47	0.41	0.87
China	0.62	0.49	0.79
Colombia	0.30	0.28	0.93
Costa Rica	0.27	0.31	1.15
Czech Republic	0.49	0.39	0.81
Germany	0.39	0.36	0.93
Denmark	0.83	0.53	0.64
Spain	0.38	0.34	0.88
Estonia	0.69	0.56	0.82
Finland	0.10	0.22	2.32
France	0.27	0.32	1.18
United Kingdom	0.40	0.34	0.87
Greece	0.20	0.24	1.18
Croatia	0.31	0.34	1.12
Hungary	0.34	0.38	1.13
Indonesia	0.73	0.59	0.81
India	1.50	0.75	0.50
Ireland	0.79	0.49	0.62
Iceland	0.54	0.62	1.15
Israel	0.07	0.20	2.80
Italy	0.26	0.29	1.12
Japan	0.17	0.23	1.35
South Korea	0.31	0.30	0.96
Lithuania	0.67	0.53	0.79
Latvia	0.54	0.49	0.90
Morocco	1.01	0.70	0.69
Mexico	0.15	0.19	1.23
Malta	0.13	0.28	2.20
Malaysia	0.36	0.34	0.95
Netherlands	0.41	0.34	0.81
Norway	0.24	0.33	1.37
New Zealand	0.18	0.25	1.38
Philippines	0.66	0.49	0.74
Poland	0.64	0.48	0.75
Portugal	0.34	0.32	0.92
Romania	1.19	0.69	0.58
Russia	0.45	0.36	0.79
Slovak Republic	0.31	0.42	1.35
Slovenia	0.36	0.32	0.90
Sweden	0.50	0.42	0.84
Thailand	0.39	0.34	0.88
Turkey	0.99	0.65	0.66
Chinese Taipei	0.59	0.45	0.76
United States	0.12	0.19	1.59
Vietnam	0.65	0.63	0.97
South Africa	0.41	0.34	0.82

Table C.2: TFP Growth with Constant MP Costs

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).

	Data (1)	Constant Trade Costs (2)	Ratio (3)
Argentina	0.33	0.35	1.07
Australia	-0.09	-0.09	1.00
Austria	0.38	0.38	1.02
Belgium	0.30	0.33	1.11
Bulgaria	0.95	0.82	0.86
Brazil	0.29	0.29	0.99
Canada	0.09	0.12	1.39
Switzerland	0.31	0.28	0.92
Chile	0.47	0.49	1.05
China	0.62	0.62	1.00
Colombia	0.30	0.31	1.02
Costa Rica	0.27	0.29	1.09
Czech Republic	0.49	0.45	0.92
Germany	0.39	0.40	1.03
Denmark	0.83	0.89	1.07
Spain	0.38	0.36	0.95
Estonia	0.69	0.71	1.04
Finland	0.10	0.12	1.26
France	0.27	0.28	1.05
United Kingdom	0.40	0.39	0.99
Greece	0.20	0.21	1.04
Croatia	0.31	0.22	0.73
Hungary	0.34	0.26	0.76
Indonesia	0.73	0.72	0.98
India	1.50	1.50	1.00
Ireland	0.79	0.74	0.94
Iceland	0.54	0.49	0.91
Israel	0.07	0.09	1.28
Italy	0.26	0.25	0.95
Japan	0.17	0.17	0.99
South Korea	0.31	0.32	1.04
Lithuania	0.67	0.60	0.89
Latvia	0.54	0.49	0.90
Morocco	1.01	0.91	0.90
Mexico	0.15	0.08	0.51
Malta	0.13	0.14	1.09
Malaysia	0.36	0.45	1.24
Netherlands	0.41	0.43	1.04
Norway	0.24	0.24	0.97
New Zealand	0.18	0.19	1.05
Philippines	0.66	0.76	1.14
Poland	0.64	0.56	0.88
Portugal	0.34	0.31	0.89
Romania	1.19	1.11	0.93
Russia	0.45	0.48	1.06
Slovak Republic	0.31	0.26	0.84
Slovenia	0.36	0.27	0.74
Sweden	0.50	0.47	0.93
Thailand	0.39	0.42	1.07
Turkey	0.99	0.97	0.98
Chinese Taipei	0.59	0.58	0.98
United States	0.12	0.11	0.93
Vietnam	0.65	0.40	0.62
South Africa	0.41	0.40	0.98

Table C.3: TFP Growth with Constant Trade Costs

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).

	Data	$\rho = 0.45$	Ratio	$\rho = 0$	Ratio
	(1)	(2)	(3)	(4)	(5)
Argentina	1.33	1.03	0.78	0.99	0.75
Australia	0.91	0.92	1.00	0.92	1.00
Austria	1.38	1.07	0.78	1.04	0.75
Belgium	1.30	1.07	0.82	1.05	0.80
Bulgaria	1.95	1.40	0.72	1.34	0.69
Brazil	1.29	1.05	0.82	1.03	0.80
Canada	1.09	0.96	0.89	0.95	0.88
Switzerland	1.31	1.09	0.83	1.07	0.82
Chile	1.47	1.11	0.76	1.07	0.73
China	1.62	1.15	0.71	1.06	0.66
Colombia	1.30	1.03	0.79	1.01	0.77
Costa Rica	1.27	1.03	0.81	1.01	0.80
Czech Republic	1.49	1.17	0.79	1.14	0.76
Germany	1.39	1.08	0.78	1.05	0.75
Denmark	1.83	1.33	0.73	1.27	0.69
Spain	1.38	1.11	0.80	1.08	0.78
Estonia	1.69	1.25	0.74	1.20	0.71
Finland	1.10	0.96	0.88	0.95	0.86
France	1.27	1.01	0.80	0.99	0.78
United Kingdom	1.40	1.14	0.82	1.12	0.80
Greece	1.20	1.02	0.85	1.00	0.83
Croatia	1.31	1.10	0.84	1.08	0.83
Hungary	1.34	1.10	0.82	1.08	0.81
Indonesia	1.73	1.19	0.69	1.07	0.62
India	2.50	1.67	0.67	1.41	0.56
Ireland	1.79	1.48	0.83	1.45	0.81
Iceland	1.54	1.27	0.83	1.14	0.74
Israel	1.07	0.94	0.88	0.93	0.87
Italy	1.26	1.04	0.82	1.02	0.80
Japan	1.17	1.02	0.87	1.00	0.85
South Korea	1.31	1.04	0.79	1.00	0.76
Lithuania	1.67	1.25	0.75	1.19	0.71
Latvia	1.54	1.15	0.75	1.10	0.71
Morocco	2.01	1.39	0.69	1.28	0.63
Mexico	1.15	1.07	0.93	1.06	0.92
Malta	1.13	0.97	0.86	0.95	0.84
Malaysia	1.36	1.05	0.77	1.00	0.74
Netherlands	1.41	1.16	0.82	1.13	0.80
Norway	1.24	1.02	0.82	0.99	0.80
New Zealand	1.18	1.00	0.85	0.99	0.84
Philippines	1.66	1.19	0.71	1.10	0.66
Poland	1.64	1.26	0.77	1.22	0.74
Portugal	1.34	1.08	0.80	1.05	0.78
Romania	2.19	1.66	0.76	1.60	0.73
Russia	1.45	1.07	0.74	1.02	0.71
Slovak Republic	1.31	1.06	0.81	1.04	0.79
Slovenia	1.36	1.12	0.83	1.10	0.81
Sweden	1.50	1.18	0.78	1.14	0.76
Thailand	1.39	1.10	0.79	1.06	0.76
Turkey	1.99	1.36	0.68	1.24	0.62
Chinese Taipei	1.59	1.21	0.76	1.16	0.73
United States	1.12	1.00	0.89	0.98	0.88
Vietnam	1.65	1.18	0.72	1.13	0.69
South Africa	1.41	1.11	0.79	1.08	0.77

Table C.4: TFP Growth with Different ρ's

Notes: This table presents 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).

	Welfare (1)	Static Gain (2)	Growth Rate (3)	Δg (4)	BGP Ratio (5)
Argentina	35.00%	9.20%	1.96	1.18	3.38
Australia	53.00%	16.94%	1.90	1.75	16.14
Austria	74.88%	39.83%	1.88	1.70	17.03
Belgium	81.93%	46.95%	1.85	1.72	24.01
Bulgaria	87.35%	44.41%	2.01	2.00	248.39
Brazil	58.96%	10.66%	2.18	2.09	26.69
Canada	68.45%	33.86%	1.83	1.73	24.94
Switzerland	59.47%	33.62%	1.93	1.21	4.61
Chile	45.09%	13.78%	2.03	1.40	4.54
China	46.24%	6.17%	1.97	1.94	47.48
Colombia	48.19%	7.41%	1.99	1.93	32.52
Costa Rica	58.90%	21.37%	1.89	1.83	35.06
Czech Republic	103.10%	63.06%	1.94	1.93	191.67
Germany	53.13%	19.09%	1.97	1.61	7.90
Denmark	67.80%	31.90%	1.98	1.72	12.26
Spain	56.29%	20.85%	1.93	1.67	10.54
Estonia	105.21%	64.20%	1.97	1.96	280.90
Finland	49.64%	16.85%	2.04	1.49	5.38
France	54.86%	20.27%	1.85	1.70	15.79
United Kingdom	71.32%	34.20%	1.92	1.81	24.52
Greece	47.51%	13.37%	1.89	1.63	9.40
Croatia	77.30%	31.94%	2.09	2.04	47.63
Hungary	128.17%	87.54%	1.96	1.95	404.85
Indonesia	47.70%	7.21%	2.00	1.93	27.68
India	48.79%	8.87%	1.95	1.94	111.79
Ireland	82.75%	59.65%	1.89	1.08	5.20
Iceland	34.05%	19.15%	3.02	0.37	1.40
Israel	37.88%	12.95%	1.78	1.23	4.50
Italy	51.76%	15.63%	1.94	1.70	10.84
Japan	24.55%	4.47%	2.01	0.91	2.32
South Korea	19.65%	4.83%	1.89	0.67	1.92
Lithuania	80.74%	38.11%	2.07	1.96	27.85
Latvia	89.92%	42.84%	2.22	2.18	77.82
Morocco	63.84%	22.78%	1.99	1.96	77.63
Mexico	76.52%	36.64%	1.95	1.92	71.68
Malta	75.52%	30.84%	2.12	1.97	19.96
Malaysia	60.53%	22.54%	1.97	1.81	17.27
Netherlands	80.12%	44.06%	1.90	1.74	19.76
Norway	61.08%	25.66%	1.99	1.63	8.62
New Zealand	40.31%	9.83%	1.81	1.53	8.46
Philippines	53.11%	15.56%	1.90	1.85	43.34
Poland	80.51%	39.95%	1.97	1.93	59.31
Portugal	73.25%	32.86%	1.96	1.91	54.39
Romania	94.77%	48.04%	2.15	2.08	47.36
Russia	51.54%	5.60%	2.17	2.02	15.98
Slovak Republic	136.63%	81.72%	2.36	2.33	128.25
Slovenia	93.63%	54.04%	1.93	1.90	100.84
Sweden	73.19%	40.03%	2.00	1.53	7.75
Thailand	68.44%	23.83%	2.11	2.03	32.33
Turkey	48.34%	12.97%	1.97	1.70	9.55
Chinese Taipei	42.27%	15.48%	1.97	1.23	3.88
United States	35.77%	11.03%	1.87	1.18	3.72
Vietnam	92.67%	47.84%	2.12	2.12	632.88
South Africa	57.19%	18.71%	1.94	1.86	28.58

Table C.5: Gains from Openness

Notes: This table shows the gains from openness for all countries in the sample. 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 baseline growth rates, and (4) shows the dynamic effect of openness on the average growth rate of real consumption in the following 50 years. (5) shows the ratio of real consumption level in BGP.

	Welfare (1)	Static Gain (2)	Growth Rate (3)	Δg (4)	BGP Ratio (5)
Argentina	27.58%	3.88%	1.96	1.08	2.57
Australia	44.52%	9.47%	1.90	1.70	6.66
Austria	35.04%	6.18%	1.88	1.38	3.86
Belgium	39.30%	10.14%	1.85	1.42	4.32
Bulgaria	46.58%	4.99%	2.01	1.93	9.44
Brazil	50.70%	3.22%	2.18	2.05	8.39
Canada	42.61%	11.21%	1.83	1.56	5.57
Switzerland	24.71%	9.29%	1.93	0.72	2.10
Chile	30.19%	2.80%	2.03	1.21	2.82
China	40.37%	0.83%	1.97	1.91	9.14
Colombia	42.02%	1.77%	1.99	1.90	8.57
Costa Rica	37.78%	2.23%	1.89	1.72	6.69
Czech Republic	57.77%	19.77%	1.94	1.82	9.47
Germany	32.72%	2.81%	1.97	1.39	3.61
Denmark	31.53%	2.55%	1.98	1.37	3.45
Spain	38.99%	6.38%	1.93	1.52	4.54
Estonia	40.73%	2.44%	1.97	1.82	7.67
Finland	30.11%	2.32%	2.04	1.24	2.89
France	34.41%	2.50%	1.85	1.56	4.99
United Kingdom	39.67%	6.71%	1.92	1.59	5.09
Greece	32.26%	0.61%	1.89	1.50	4.28
Croatia	46.40%	3.29%	2.09	1.92	7.25
Hungary	59.56%	21.23%	1.96	1.83	9.57
Indonesia	40.49%	0.64%	2.00	1.89	8.08
India	39.40%	0.03%	1.95	1.91	9.73
Ireland	11.16%	12.62%	1.89	0.06	1.45
Iceland	-7.14%	-3.89%	3.02	-0.15	0.94
Israel	21.66%	0.88%	1.78	1.02	2.57
Italy	36.11%	2.47%	1.94	1.57	4.65
Japan	16.83%	-0.67%	2.01	0.79	1.88
South Korea	13.72%	0.94%	1.89	0.58	1.64
Lithuania	43.50%	5.17%	2.07	1.73	5.35
Latvia	48.35%	4.01%	2.22	2.04	7.82
Morocco	41.31%	1.43%	1.99	1.90	8.65
Mexico	39.97%	2.99%	1.95	1.77	6.78
Malta	41.70%	1.76%	2.12	1.72	4.74
Malaysia	40.03%	4.72%	1.97	1.67	5.46
Netherlands	31.72%	3.23%	1.90	1.35	3.56
Norway	30.60%	1.85%	1.99	1.29	3.11
New Zealand	28.68%	0.13%	1.81	1.43	4.23
Philippines	38.30%	1.99%	1.90	1.79	7.86
Poland	46.89%	8.71%	1.97	1.80	7.33
Portugal	41.88%	3.61%	1.96	1.80	7.14
Romania	58.10%	14.44%	2.15	1.92	7.32
Russia	46.32%	0.99%	2.17	1.98	7.24
Slovak Republic	67.57%	17.65%	2.36	2.06	7.42
Slovenia	41.87%	5.16%	1.93	1.75	6.77
Sweden	29.70%	7.56%	2.00	1.00	2.55
Thailand	49.10%	6.48%	2.11	1.93	7.48
Turkey	34.86%	1.73%	1.97	1.58	4.57
Chinese Taipei	25.14%	3.30%	1.97	1.00	2.40
United States	25.47%	3.53%	1.87	1.04	2.60
Vietnam	41.67%	-0.96%	2.12	2.01	9.62
South Africa	42.23%	5.04%	1.94	1.79	7.37

Table C.6: Gains from MP

Notes: This table shows the gains from MP openness for all countries in the sample. 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 baseline growth rates, and (4) shows the dynamic effect of openness on the average growth rate of real consumption in the following 50 years. (5) shows the ratio of real consumption level in BGP.

	Welfare	Static Gain	Δ Growth Rate (Percentage Points)
	(1)	(2)	(3)
Argentina	-0.02%	0.00%	-0.00
Australia	-0.01%	0.00%	-0.00
Austria	-0.01%	0.01%	-0.00
Belgium	-0.03%	0.01%	-0.01
Bulgaria	-0.03%	0.02%	-0.01
Brazil	-0.02%	0.00%	-0.00
Canada	-0.02%	0.00%	-0.00
Switzerland	-0.02%	0.01%	-0.01
Chile	-0.01%	-0.00%	-0.00
China	-0.05%	0.00%	-0.01
Colombia	-0.01%	0.00%	-0.00
Costa Rica	-0.01%	0.00%	-0.00
Czech Republic	-0.07%	0.01%	-0.02
Germany	-0.01%	0.01%	-0.00
Denmark	-0.01%	0.03%	-0.01
Spain	-0.01%	0.00%	-0.00
Estonia	-0.08%	0.20%	-0.04
Finland	-0.03%	0.04%	-0.01
France	-0.01%	0.01%	-0.00
United Kingdom	-0.01%	0.01%	-0.00
Greece	-0.01%	0.06%	-0.01
Croatia	-0.03%	0.01%	-0.01
Hungary	-0.01%	0.01%	-0.00
Indonesia	-0.01%	0.00%	-0.00
India	-0.02%	0.01%	-0.01
Ireland	-0.01%	0.00%	-0.00
Iceland	-0.00%	0.01%	-0.00
Israel	-0.01%	0.01%	-0.00
Italy	-0.06%	0.01%	-0.02
Japan	-0.04%	0.00%	-0.01
South Korea	-0.01%	0.00%	-0.00
Lithuania	-0.19%	0.03%	-0.07
Latvia	-0.09%	0.15%	-0.04
Morocco	-0.02%	0.01%	-0.00
Mexico	-0.01%	0.00%	-0.00
Malta	-0.01%	0.01%	-0.00
Malaysia	-0.01%	0.00%	-0.00
Netherlands	-0.01%	0.03%	-0.01
Norway	-0.01%	0.01%	-0.00
New Zealand	-0.01%	-0.00%	-0.00
Philippines	-0.01%	0.00%	-0.00
Poland	-0.01%	0.02%	-0.00
Portugal	-0.01%	0.00%	-0.00
Romania	-0.04%	0.00%	-0.01
Russia	-9.11%	-1.50%	-3.15
Slovak Republic	-0.02%	0.01%	-0.01
Slovenia	-0.02%	0.03%	-0.01
Sweden	-0.01%	0.02%	-0.00
Thailand	-0.02%	0.00%	-0.00
Turkey	-0.04%	0.02%	-0.01
Chinese Taipei	-0.02%	0.00%	-0.00
United States	-0.02%	0.00%	-0.00
Vietnam	-0.02%	0.02%	-0.01
South Africa	-0.02%	-0.00%	-0.00

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

Notes: This table shows the 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.

	Welfare	Static Gain	Δ Growth Rate (Percentage Points)
	(1)	(2)	(3)
Argentina	-0.04%	0.00%	-0.01
Australia	-0.04%	-0.00%	-0.01
Austria	-0.06%	-0.06%	-0.01
Belgium	-0.10%	-0.12%	-0.01
Bulgaria	-0.21%	-0.32%	-0.02
Brazil	-0.05%	0.01%	-0.01
Canada	-0.05%	-0.02%	-0.01
Switzerland	-0.08%	-0.09%	-0.01
Chile	-0.03%	0.01%	-0.01
China	-0.08%	0.02%	-0.02
Colombia	-0.04%	0.00%	-0.01
Costa Rica	-0.03%	0.01%	-0.00
Czech Republic	-0.17%	-0.22%	-0.02
Germany	-0.06%	-0.05%	-0.01
Denmark	-0.08%	-0.09%	-0.01
Spain	-0.04%	-0.02%	-0.00
Estonia	-0.90%	-1.56%	-0.06
Finland	-0.20%	-0.27%	-0.02
France	-0.04%	-0.03%	-0.00
United Kingdom	-0.05%	-0.04%	-0.01
Greece	-0.13%	-0.15%	-0.02
Croatia	-0.13%	-0.17%	-0.01
Hungary	-0.09%	-0.11%	-0.01
Indonesia	-0.04%	0.01%	-0.01
India	-0.06%	0.00%	-0.01
Ireland	-0.05%	-0.04%	-0.01
Iceland	-0.05%	-0.04%	-0.00
Israel	-0.05%	-0.04%	-0.01
Italy	-0.13%	-0.16%	-0.01
Japan	-0.09%	-0.05%	-0.01
South Korea	-0.04%	-0.02%	-0.00
Lithuania	-0.99%	-2.06%	-0.03
Latvia	-0.85%	-1.48%	-0.06
Morocco	-0.10%	-0.13%	-0.01
Mexico	-0.03%	0.02%	-0.01
Malta	-0.09%	-0.10%	-0.01
Malaysia	-0.04%	0.01%	-0.01
Netherlands	-0.12%	-0.17%	-0.01
Norway	-0.06%	-0.05%	-0.01
New Zealand	-0.04%	-0.01%	-0.01
Philippines	-0.04%	0.00%	-0.01
Poland	-0.12%	-0.17%	-0.01
Portugal	-0.04%	-0.02%	-0.00
Romania	-0.14%	-0.22%	-0.01
Russia	-10.54%	-4.52%	-3.27
Slovak Republic	-0.14%	-0.17%	-0.02
Slovenia	-0.14%	-0.20%	-0.01
Sweden	-0.07%	-0.07%	-0.01
Thailand	-0.05%	0.01%	-0.01
Turkey	-0.07%	0.02%	-0.02
Chinese Taipei	-0.07%	-0.05%	-0.01
United States	-0.05%	-0.03%	-0.01
Vietnam	-0.05%	0.03%	-0.01
South Africa	-0.04%	0.01%	-0.01

Table C.8: Economic Sanctions On Russia (MP and Trade)

Notes: This table shows the 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.

	Welfare	Static Gain	Δ Growth Rate (Percentage Points)
	(1)	(2)	(3)
Argentina	-0.49%	-0.76%	-0.02
Australia	-0.89%	-2.03%	-0.00
Austria	-0.38%	-0.67%	-0.01
Belgium	-0.98%	-2.46%	-0.01
Bulgaria	-0.56%	-0.27%	-0.02
Brazil	-0.98%	-1.13%	-0.02
Canada	-1.68%	-4.38%	-0.00
Switzerland	-0.83%	-2.85%	0.01
Chile	-0.50%	-0.80%	-0.01
China	-0.79%	-0.06%	-0.04
Colombia	-0.89%	-0.51%	-0.03
Costa Rica	-1.32%	-1.19%	-0.04
Czech Republic	-0.61%	-0.96%	-0.01
Germany	-0.49%	-1.04%	-0.01
Denmark	-0.47%	-0.85%	-0.01
Spain	-0.62%	-0.91%	-0.02
Estonia	-0.45%	-0.23%	-0.02
Finland	-0.39%	-0.68%	-0.01
France	-0.60%	-1.08%	-0.01
United Kingdom	-0.71%	-1.90%	0.01
Greece	-0.74%	-0.16%	-0.04
Croatia	-0.46%	-0.21%	-0.02
Hungary	-0.84%	-1.66%	-0.01
Indonesia	-0.77%	-0.00%	-0.04
India	-1.00%	-0.04%	-0.04
Ireland	-0.86%	-4.47%	0.05
Iceland	-0.23%	-0.03%	-0.01
Israel	-0.71%	-1.08%	-0.03
Italy	-0.55%	-0.68%	-0.02
Japan	-0.61%	-0.24%	-0.04
South Korea	-0.54%	-0.35%	-0.05
Lithuania	-0.50%	-0.49%	-0.02
Latvia	-0.31%	-0.04%	-0.02
Morocco	-0.48%	-0.09%	-0.02
Mexico	-0.75%	-1.76%	0.01
Malta	-0.27%	0.10%	-0.02
Malaysia	-0.80%	-1.33%	-0.02
Netherlands	-1.10%	-3.35%	0.01
Norway	-0.59%	-0.95%	-0.02
New Zealand	-0.74%	-0.50%	-0.04
Philippines	-0.90%	-0.50%	-0.04
Poland	-0.55%	-0.97%	-0.01
Portugal	-0.59%	-0.42%	-0.02
Romania	-0.48%	-0.79%	-0.01
Russia	-0.76%	-0.23%	-0.03
Slovak Republic	-0.47%	-0.97%	-0.00
Slovenia	-0.46%	-0.31%	-0.02
Sweden	-0.40%	-0.88%	-0.01
Thailand	-0.77%	-0.78%	-0.02
Turkey	-0.43%	-0.14%	-0.03
Chinese Taipei	-0.55%	-0.78%	-0.03
United States	0.04%	0.52%	-0.01
Vietnam	-0.74%	0.47%	-0.03
South Africa	-0.75%	-1.05%	-0.02

Table C.9: Higher Outward MP Costs for US

Notes: This table shows 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.

	Welfare	Static Gain	Δ Growth Rate (Percentage Points)
	(1)	(2)	(3)
Argentina	0.00%	-0.06%	0.00
Australia	-0.02%	-0.07%	-0.00
Austria	-0.04%	-0.14%	-0.00
Belgium	-0.05%	-0.22%	0.00
Bulgaria	0.00%	-0.03%	0.00
Brazil	0.02%	-0.13%	0.00
Canada	-0.34%	-1.07%	0.00
Switzerland	-0.05%	-0.18%	-0.00
Chile	-0.05%	-0.24%	0.00
China	0.05%	-0.15%	0.01
Colombia	0.03%	-0.22%	0.01
Costa Rica	-0.35%	-1.00%	0.01
Czech Republic	-0.00%	-0.03%	-0.00
Germany	-0.05%	-0.13%	-0.00
Denmark	-0.04%	-0.15%	-0.00
Spain	-0.00%	-0.05%	0.00
Estonia	-0.04%	-0.13%	0.00
Finland	-0.02%	-0.07%	-0.00
France	-0.04%	-0.11%	-0.00
United Kingdom	-0.08%	-0.22%	-0.00
Greece	0.03%	-0.09%	0.00
Croatia	-0.02%	-0.08%	-0.00
Hungary	-0.02%	-0.07%	-0.00
Indonesia	0.10%	-0.11%	0.01
India	0.01%	-0.28%	0.01
Ireland	-0.23%	-0.72%	-0.01
Iceland	-0.05%	-0.23%	0.00
Israel	-0.13%	-0.44%	-0.00
Italy	-0.02%	-0.10%	0.00
Japan	0.06%	-0.12%	0.01
South Korea	0.04%	-0.09%	0.01
Lithuania	-0.01%	-0.06%	-0.00
Latvia	-0.03%	-0.06%	-0.00
Morocco	-0.03%	-0.11%	0.00
Mexico	-1.11%	-2.31%	-0.01
Malta	-0.17%	-0.45%	0.00
Malaysia	-0.05%	-0.23%	0.00
Netherlands	-0.03%	-0.12%	-0.00
Norway	-0.02%	-0.11%	0.00
New Zealand	-0.00%	-0.18%	0.00
Philippines	0.01%	-0.22%	0.01
Poland	-0.02%	-0.04%	-0.00
Portugal	-0.01%	-0.06%	0.00
Romania	-0.01%	-0.01%	-0.00
Russia	0.07%	-0.04%	0.00
Slovak Republic	-0.03%	-0.03%	-0.00
Slovenia	-0.00%	-0.05%	0.00
Sweden	-0.04%	-0.13%	-0.00
Thailand	-0.02%	-0.17%	0.00
Turkey	0.01%	-0.08%	0.00
Chinese Taipei	-0.04%	-0.23%	0.00
United States	-0.20%	-0.80%	0.00
Vietnam	-0.66%	-0.73%	0.00
South Africa	-0.03%	-0.12%	0.00

Table C.10: Higher Inward Trade Costs for US

Notes: This table shows welfare and growth implications for all countries of an counterfactual exercise where the inward trade costs to the United States increase by 10%. 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.

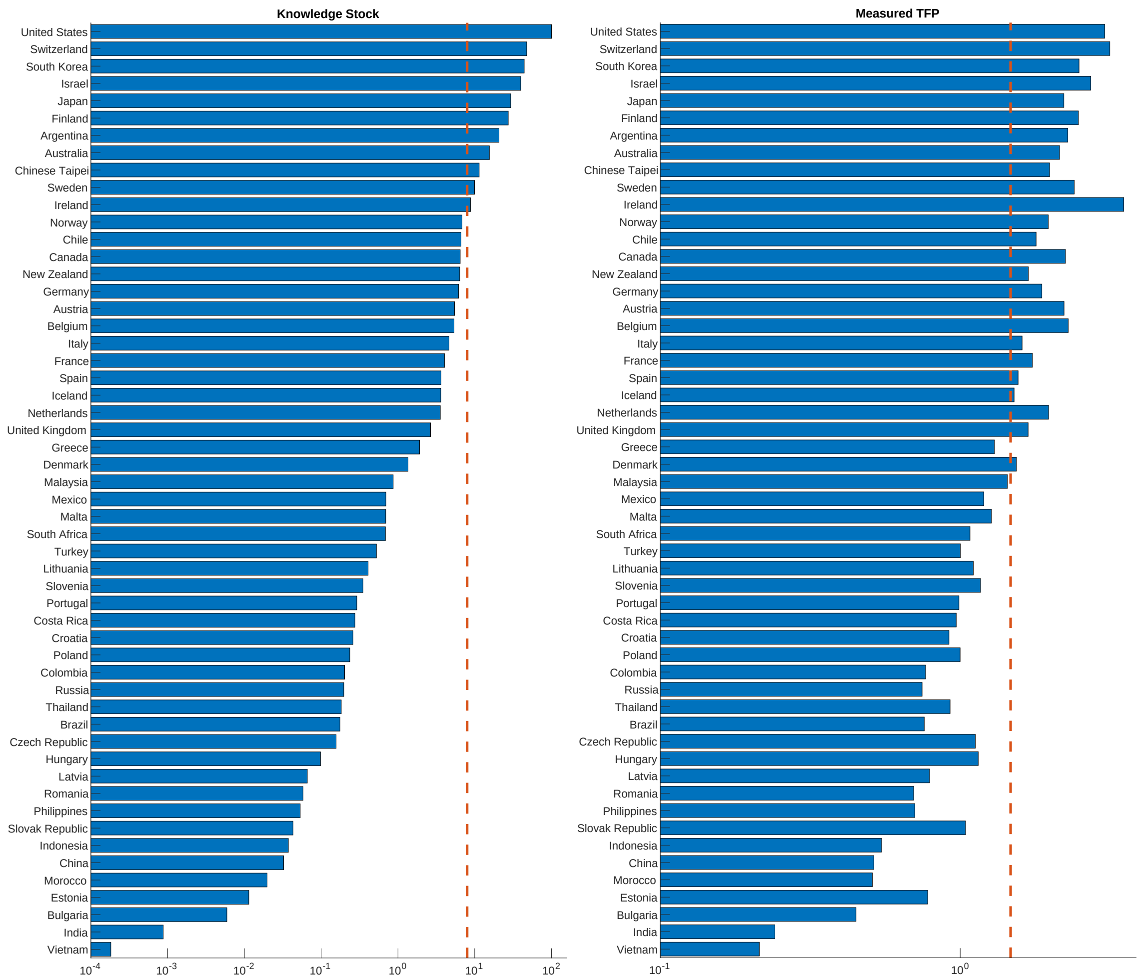

Figure C.7: Knowledge Stocks and Measured TFP

Notes: By authors' calculation. This figure shows the calibrated knowledge stocks (left) and TFP level (right) in each country in 2005 on a log scale. The dashed line shows the simple average of knowledge stocks across economies.

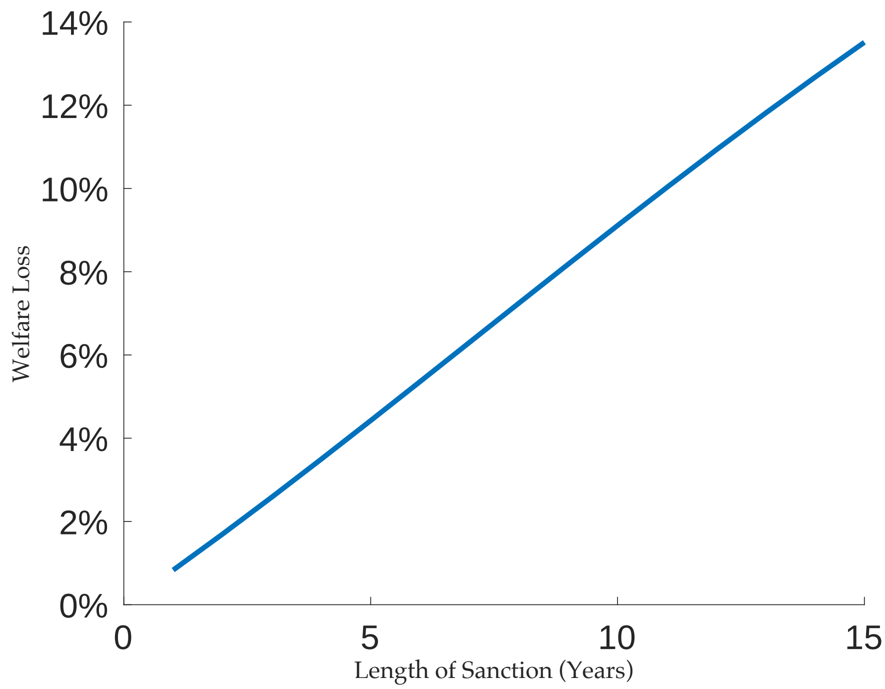

Figure C.8: Welfare Loss in Russia

Notes: This figure shows welfare loss in Russia resulted from an MP sanction with various duration.