International R&D Spillovers and Asset Prices

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Abstract

We study the international propagation of long-run risk in the context of a general equilibrium model with endogenous growth. Innovation and international diffusion of technologies are the channels at the core of our mechanism. A calibrated version of the model matches several asset pricing and macroeconomic quantity moments, alleviating some of the puzzles highlighted in the international macro-finance literature. Our model predicts that country-pairs that share more R&D have less volatile exchange rates and more correlated stock market returns. Using data from a sample of 19 developed countries, we provide suggestive empirical evidence in favor of our model's predictions.

Keywords: international asset pricing, recursive preferences, long-run risk, innovation, international diffusion

JEL classification: F3, F4, O3

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1 Introduction

The cross-country correlation in aggregate consumption growth is low. Sharpe ratio estimates of the stock market are large implying substantial variability in stochastic discount factors. These two simple facts represent a significant challenge to international equilibrium economic models with complete financial markets. On the one hand, aggregate consumption growth is too smooth and does not covary enough with stock returns. On the other hand, in a frictionless economy, agents should share risk perfectly and equalize their marginal rates of substitution: the cross-country correlation in consumption growth should be equal to one. In the data, it is almost always below 0.4 (see, among others, Brandt, Cochrane, and Santa-Clara 2006).

A growing empirical literature in international finance has proposed a potential explanation of the above puzzles (see, among others, Colacito and Croce 2011 and Lustig, Roussanov, and Verdelhan 2011). The explanation relies on the presence of a common component in the stochastic discount factors of domestic and foreign investors which substantially drives up risk premia but has a minor impact on equilibrium macroeconomic quantities. In this paper, we present a general equilibrium model that *endogenously* generates this common component, with an emphasis on its international aspects.

We build a two-country endogenous growth model of innovation and international technology diffusion. Growth in each country is driven by the accumulation of technology through endogenous innovation. Innovation is the result of research and development (R&D) and it diffuses across countries through two channels. First, technology embodied in intermediate goods spreads across countries via international trade. We assume that domestically developed varieties must be adopted before being used in the foreign economy. We call this mechanism *international adoption* and we model it as an endogenous process in which a foreign adopter buys the right to sell the domestic technology in the foreign country. As a result, the aggregate expected productivity of a country depends not only on its own innovation but also on the foreign innovations embodied in imported intermediate products. Second, within each country, innovators are more productive when they learn about the existence of a foreign technology, even if such technology has not yet been adopted by the domestic economy. We call this mechanism *international diffusion of ideas*. Preferences are recursive and agents fear variation in the economy's long-run future growth prospects. Endogenous

innovation and international adoption and diffusion of ideas make the equilibrium growth path risky through their effect on the present discounted value of future profits of all firms in the economy.

Our endogenous growth mechanism works as follows. Within countries, R&D drives a small and persistent component of equilibrium growth rates. International adoption and diffusion of ideas render this component common across countries. The intuition is that a technology shock in the home country affects the incentives to innovate not only in that country but also abroad, and in turn affects the prospects of global growth. The final effect is that a short-run technology shock in the home country has a long-run impact on the dynamics of future growth rates in both the home and the foreign economy. We study the effect of varying degrees of international adoption and diffusion of ideas and find that both channels contribute positively to the diffusion of long-run risk.

With recursive preferences, variations in the economy's future prospects have a significant effect on asset prices and on the cross-country correlation of equilibrium economic quantities. As technological innovation diffuses across countries, it generates a sizable common component in discount rates that drives up the correlation in stock market returns while reducing the volatility of exchange rates. Our model can replicate these international asset pricing facts together with a realistic calibration of other macroeconomic quantities. More specifically, the model predicts—in line with the data—that realized consumption growth is only somewhat correlated across countries.

In essence, domestic innovation and the international adoption and diffusion of ideas generate long-run fluctuations that affect the prospects of future growth. These long-run fluctuations are priced and have a substantial impact on equilibrium asset prices. Our setting is of particular interest given its documented ability to account for several empirical regularities of the joint dynamics of international asset prices and quantities in a two-country setting. We extend it by developing an international general equilibrium model in which long-run fluctuations in growth prospects are the endogenous outcome of agents' investment in innovation and international adoption.

We calibrate the model to data on macroeconomic quantities and asset prices. Two parameters directly affect the speed of international adoption of R&D and the intensity of international diffusion of ideas. The first governs the speed at which a novel technology developed in the home country is adopted by the foreign country. We carefully calibrate this

parameter using disaggregated bilateral trade data and R&D expenditures for a panel of 19 developed countries and the 1996-2013 period. The value we find implies that the average country adopts a new foreign technology approximately every 6 years. The second parameter determines the positive effect of foreign ideas on the productivity of domestic innovators. We find that a small degree of international diffusion and adoption of ideas generates sufficiently strong comovement in the stochastic discount factors.

Our calibrated model predicts that country-pairs that share more R&D, that is the countries with a faster speed of international adoption, have more correlated stock market returns and less volatile exchange rates. These results imply that, holding trade intensity constant, country-pairs that share more R&D have more correlated stock market returns and less volatile exchange rates. In an empirical section at the end of the paper, we provide suggestive empirical evidence in favor of these model's predictions.

The model generates substantial deviations from uncovered interest parity (UIP). The international risk sharing mechanism implied by recursive preferences makes the equilibrium (pseudo-) Pareto weights time-varying and, in turn, induces variation in the higher moments of the stochastic discount factors (see, for instance, Backus, Foresi, and Telmer 2001). The model cannot, however, generate a sizable return for the currency carry trade strategy of Lustig, Roussanov, and Verdelhan (2011). As described in Colacito, Croce, Gavazzoni, and Ready (2018) and Hassan and Mano (2014), large average returns for the currency carry strategy require the presence of permanent (or almost permanent) asymmetries, which are absent in our two-country symmetric model.

Our paper is related to several strands of the literature. First, our analysis sheds light on the economic foundation of long-run risk and is therefore related to the literature that began with the seminal one-country model of Bansal and Yaron (2004) and was then applied to the international setting by Bansal and Shaliastovich (2013), Colacito and Croce (2011), Colacito and Croce (2013), Colacito, Croce, Ho, and Howard (2018), and Colacito, Croce, Liu, and Shaliastovich (2015). Whereas these papers specify long-run risk exogenously, our model shows how such risk arises endogenously through innovation and the international diffusion of R&D.

The macroeconomic mechanism is related to the literature on endogenous growth through innovation. Technological innovation is a fundamental source of sustained economic growth (Romer 1990, Comin and Gertler (2006)). Comin, Gertler, and Santacreu (2009) study the

dynamics of the stock market in a one-country model with endogenous growth. Kung and Schmid (2015) extend the one-country model to include recursive preferences. We develop our model along those lines and extend it to an international setting in which technology diffuses across countries trough international trade in varieties (e.g., Broda, Greenfield, and Weinstein 2006; Santacreu 2015).

Our analysis helps to shed light on the connection between risk premia, country-level characteristics and international trade, and provides general equilibrium foundations to the reduced-form analysis of international asset risk premia of Della Corte, Riddiough, and Sarno (2016), Hassan and Mano (2014), Lustig, Roussanov, and Verdelhan (2014), Mueller, Stathopoulos, and Vedolin (2017), and Zviadadze (2017). Our study is also related to the growing body of literature that has investigated the macroeconomic foundations of international financial markets fluctuations (see, among others, Farhi and Gabaix 2016, Stathopoulos 2017, Heyerdahl-Larsen 2014, and Verdelhan 2010). Unlike those papers, which focus on disaster risk or habit formation, we examine the foundations of of long-run economic fluctuations and analyze their effects on equilibrium asset pricing .

Although our model features symmetric countries, short-term asymmetries arise due to the realization of imperfectly correlated productivity shocks. In this sense, our study can be seen as providing a benchmark relative to those papers emphasizing the role of quasi-permanent asymmetries across countries, such as country size (Hassan 2013), commodity intensity (Ready, Roussanov, and Ward 2017), monetary policy (Backus, Gavazzoni, Telmer, and Zin 2010), and financial development (Maggiori 2017). Finally, although our attention is focused on a frictionless risk-sharing setting, we regard the introduction of frictions in our model as an important direction for future research in this area (see, for example, Gabaix and Maggiori 2015).

The rest of our paper is organized as follows. Section 2 introduces the main model. In Section 3 we describe the economic mechanism at work, and Section 4 presents the calibration and our quantitative analysis. Section 5 looks at the empirical evidence, and Section 6 concludes.

2 Model

In this section, we present a model of innovation and international technology diffusion in which long-run risk arises endogenously within a country and is shared internationally through the adoption of foreign technologies and the diffusion of ideas. Each country has a representative household, with recursive preferences, who consumes a final good. A final good producer uses labor, capital, and a composite of intermediate goods—which we call materials—to produce a non-traded final good that is used for consumption, investment in physical capital, and investment in R&D and adoption. Materials are produced using traded intermediate goods (varieties), both domestic and foreign, which are produced by monopolistic competitive firms. The production of materials reflects a love-of-variety effect: if expenditures are held constant, a higher number of varieties increases the country's aggregate productivity. New varieties are introduced in each country through an endogenous process of innovation, after which they spread endogenously across countries through a slow process of adoption. Endogenous innovation and adoption, along with recursive preferences, are the key features at the core of our mechanism. Financial markets are assumed to be internationally complete.

Next, we describe the domestic economy d; the foreign economy f is defined analogously. Throughout the paper, a variable's subscript refers to the origin country—the exporter—while its superscript refers to the destination country–the importer. Unless otherwise specified, we use upper case letters to denote variables in levels, lower case letters to denote variables in logs, and $\Delta x_{t+1} = x_{t+1} - x_t$ to denote the log-growth of variable X between time t and time $t+1$.

2.1 Households

The domestic representative household has Epstein and Zin (1989) recursive preferences over consumption:

$$U_{d,t} = \{(1-\beta)C_{d,t}^{\theta} + \beta(E_t[U_{d,t+1}^{1-\gamma}])^{\theta/(1-\gamma)}\}^{1/\theta}. \tag{1}$$

In this expression, U_d is utility, t denotes time, β is the subjective discount factor, C_d denotes consumption, E is the expectations operator, γ is the constant relative risk aversion (CRRA), $\theta = \frac{1-\gamma}{1-1/\psi}$, and $\psi \equiv \frac{1}{1-\theta}$ is the intertemporal elasticity of substitution (IES). We assume that

$\psi > 1/\gamma$, so that the representative agent has a preference for early resolution of uncertainty and fears variations in the economy's long-run prospects.

The stochastic discount factor (SDF) is given by

$$M_{d,t+1} = \beta \left(\frac{C_{d,t+1}}{C_{d,t}} \right)^{\theta-1} \left(\frac{U_{d,t+1}}{E_t[U_{d,t+1}^{1-\gamma}]^{1/(1-\gamma)}} \right)^{1-\gamma-\theta}. \tag{2}$$

The first term of the right-hand side, $\beta \left(\frac{C_{d,t+1}}{C_{d,t}} \right)^{\theta-1}$, captures short-run risk. We refer to it as the short-run component of the SDF, M_d^{SR}. The second term, $\left(\frac{U_{d,t+1}}{E_t[U_{d,t+1}^{1-\gamma}]^{1/(1-\gamma)}} \right)^{1-\gamma-\theta}$, captures the agent's concerns about uncertainty in future growth. We refer to it as the long-run component of the SDF, M_d^{LR}. The household consumes, supplies labor to the final good producer, and makes investment and savings decisions while participating in complete international financial markets. Accordingly, her budget constraint is

$$C_{d,t} + E_t\Big[M_{d,t+1}\mathcal{A}_{d,t+1}\Big] = W_{d,t}L_{d,t} + \mathcal{A}_{d,t},$$

where $W_{d,t}$ is the wage rate, $L_{d,t}$ denotes hours worked, and $\mathcal{A}_{d,t}$ is the state-contingent value of the household's financial wealth. Since there is no disutility of labor, the household supplies its entire endowment, which is normalized to one.

2.2 Final Good Producer

Domestic final producers are perfectly competitive. They use capital ($K_{d,t}$), labor ($L_{d,t}$), and a composite of domestic and foreign intermediate goods, which we call materials ($G_{d,t}$), to produce a non-traded final good ($Y_{d,t}$) in accordance with the following Cobb–Douglas production function:

$$Y_{d,t} = \left(K_{d,t}^{\alpha} \left(\Omega_{d,t} L_{d,t} \right)^{(1-\alpha)} \right)^{(1-\xi)} G_{d,t}^{\xi}. \tag{3}$$

Materials $G_{d,t}$ are defined as

$$G_{d,t} = \left[h \left(\sum_{i=1}^{N_{d,t}^d} (X_{d,i,t}^d)^{\nu} \right) + (1-h) \left(\sum_{i=1}^{N_{f,t}^d} (X_{f,i,t}^d)^{\nu} \right) \right]^{1/\nu}. \tag{4}$$

Here $X^d_{d,i,t}$ (resp. $X^d_{f,i,t}$) is the amount of domestically (resp. foreign) produced intermediate good i that is used for final production in the domestic economy, $N^d_{d,t}$ (resp. $N^d_{f,t}$) is the mass of domestic (resp. foreign) intermediate goods that is used by domestic final producers, and $1/(1-\nu)$ is the elasticity of substitution across intermediate goods (with $\nu < 1$). Intermediate goods are aggregated according to a constant elasticity of substitution production function. The parameter h captures the degree of home bias. The parameter α represents the physical capital share, and ξ is the share of materials in final production.

The exogenous process $\Omega_{d,t}$ is the only source of exogenous uncertainty in our model. We assume that $\Omega_{d,t} = e^{a_{d,t}}$, where $a_{d,t}$ follows the following process:

$$a_{d,t} = \varphi\ a_{d,t-1} + \rho_{ec}(a_{f,t-1} - a_{d,t-1}) + \varepsilon_{d,t},$$

where $|\varphi| < 1$ and $\varepsilon_{d,t} \sim N(0, \sigma^2)$. We allow for cross-country correlation in the exogenous technology shocks and let $\rho = \text{corr}(\varepsilon_{d,t}, \varepsilon_{f,t})$. The parameter $\rho_{ec} \in (0,1)$ is a small error correction term calibrated to generate moderate cointegration. It ensures the stability of our solution method, yet has virtually no effect on the results (see, for instance, Colacito and Croce 2013).

Final producers choose capital, labor, investment, and intermediate goods to maximize shareholder's value subject to the production technology (3). Formally, we have

$$\max_{\{I_{d,t}, L_{d,t}, K_{d,t+1}, X^d_{d,i,t}, X^d_{f,i,t}\}_{t\geq 0,}} E_0 \left[\sum_{t=0}^{\infty} M_{d,t} D_{d,t} \right], \tag{5}$$

where the firm's dividends are given by

$$D_{d,t} = Y_{d,t} - I_{d,t} - W_{d,t} L_{d,t} - \sum_{i=1}^{N^d_{d,t}} P^d_{d,i,t} X^d_{d,i,t} - \sum_{i=1}^{N^d_{f,t}} P^d_{f,i,t} X^d_{f,i,t}. \tag{6}$$

Here, $I_{d,t}$ is investment in physical capital, $P^d_{d,i,t}$ is the price of a domestically produced intermediate good, and $P^d_{f,i,t}$ is the price of a foreign-produced intermediate good that is used for domestic production. Both prices are expressed in units of the domestic producer's final good. The law of motion for physical capital is given by

$$K_{d,t+1} = (1-\delta) K_{d,t} + \Lambda \left(\frac{I_{d,t}}{K_{d,t}} \right) K_{d,t}, \tag{7}$$

where $\delta \in (0,1)$ is the depreciation rate and where $\Lambda\left(\frac{I_{d,t}}{K_{d,t}}\right)$ captures convex capital adjustment costs.[1]

2.3 Intermediate Good Producers

In each country, a set of monopolistic competitive firms produces a differentiated good using final output according to a constant returns to scale production function: one unit of the final output is used to produce one unit of the intermediate good. All intermediate producers produce with the same efficiency and for both the domestic and foreign market. Every period, each domestic intermediate producer solves the following static profit maximization problem:

$$\begin{aligned}
\max_{P^d_{d,t},P^{f*}_{d,t}} \Pi_{d,t} &\equiv \max_{P^d_{d,t},P^{f*}_{d,t}} (\pi^d_{d,t} + \pi^f_{d,t}) \\
&= \max_{P^d_{d,t}} \quad P^d_{d,t} \cdot X^d_{d,t}(P^d_{d,t}) \; - X^d_{d,t}(P^d_{d,t}) \\
&+ \max_{P^{f*}_{d,t}} \; (\underbrace{P^f_{d,t}\mathcal{E}_t}_{P^{f*}_{d,t}}) \cdot X^f_{d,t}(\underbrace{P^f_{d,t}\mathcal{E}_t}_{P^{f*}_{d,t}}) - X^f_{d,t}(\underbrace{P^f_{d,t}\mathcal{E}_t}_{P^{f*}_{d,t}}),
\end{aligned} \tag{8}$$

where $\pi^d_{d,t}$ (resp. $\pi^f_{d,t}$) are the profits from selling the domestic product at home (resp. abroad) and where $P^{f*}_{d,t} = P^f_{d,t}\mathcal{E}_t$ is the price (in units of the domestic good) of a domestically produced intermediate good that is being exported. We use $\mathcal{E}_t$ to denote the real exchange rate, defined as the number of domestic final goods per unit of foreign final good.[2]

2.4 Innovation and International Technology Diffusion

So far, we have described the production process of the economy, while assuming a given set of available technologies or intermediate goods. Yet the number of intermediate goods evolves over time according to endogenous innovation and adoption. New technologies are introduced through innovation, and each new technology is then used to produce an intermediate good under monopolistic competition. Domestic intermediate goods can immediately be sold to the domestic final producer; however, for the good to be sold in the foreign market, it must

[1] As in Jermann (1998), $\Lambda_{d,t} \equiv (I_{d,t}/K_{d,t}) = (\alpha_1/\zeta)(I_{d,t}/K_{d,t})^{\zeta} + \alpha_2$. The parameters α_1 and α_2 are chosen so that there are no adjustments costs in the steady state, and $1/(1-1/\zeta)$ is the elasticity of the investment rate with respect to Tobin's Q.

[2] We express real prices of the intermediate goods in units of the importer's final good. This means that, when the domestic (resp. foreign) intermediate good is used for the production of the foreign (resp. domestic) final output, $P^f_{d,t} \equiv (1/\nu)\mathcal{E}_t^{-1}$ and $P^d_{f,t} \equiv (1/\nu)\mathcal{E}_t$.

be adopted first. In our model, adoption is equivalent to importing a foreign intermediate good. We model it as a slow and costly endogenous process in which domestic adopters invest resources to purchase the rights to sell a foreign intermediate good in the domestic economy.

2.4.1 Innovation

In each country, innovators invest resources (final output) to introduce new prototypes of a product. A successful innovator starts producing the new good as an intermediate producer. Domestic innovators choose $S_{d,t}$ units of final output to maximize the present discounted value of future profits that they expect to obtain from selling the good to both domestic and foreign producers.

The law of motion for new prototypes is

$$N^d_{d,t+1} = \vartheta_{d,t} S_{d,t} + (1-\phi) N^d_{d,t}; \tag{9}$$

where $N^d_{d,t}$ is the mass of new technologies arriving in country d at time t, ϕ is the exogenous probability that a new variety becomes obsolete, and $\vartheta_{d,t}$ is the productivity of innovation. Following Santacreu (2015), we assume that this productivity takes the functional form:

$$\vartheta_{d,t} = \frac{\chi(N^d_{d,t} + \iota N^f_{f,t})}{S^{1-\eta}_{d,t}(N^d_{d,t})^{\eta}}. \tag{10}$$

The parameter η denotes the elasticity of innovation with respect to R&D, and χ is a scaling parameter. The term $N^d_{d,t} + \iota N^f_{f,t}$ captures an externality on the innovation process of country d. It stems from two sources: (i) the total number of ideas that have already been invented by country d up to time t; (ii) a fraction of the foreign ideas that have been invented up to time t and that the domestic innovator has learned about, regardless of whether they have been adopted by the domestic economy or not. Here, $\iota \in (0,1)$ represents the strength at which this international diffusion of ideas positively affects the productivity of domestic innovation. In other words, an innovator can learn from its own past innovations but also from innovations done elsewhere. The underlying assumption is that innovators benefit from all foreign knowledge regardless of whether or not it has been adopted through trade. Finally, in our specification for innovation, $\vartheta_{d,t}$ is taken as given in the choice of optimal investment in R&D.

2.4.2 International Adoption

Each intermediate good produced with the new technology must be adopted before it can be used by the final producer. Adoption is assumed to be instantaneous and free within countries but slow and costly across countries. We assume that the international adoption process is undertaken by foreign adopters who buy the right to sell an an idea developed by a domestic innovator. Adopters fund the expenses of adoption with loans from households and pay the innovators for the right to use the technology. Adopters then make the product usable for final producers in their economy by investing resources. Once the good has been adopted, it is sold to the final producers who use it as an input. An adopter in country f becomes successful in making a product developed by country d usable for final production in country f in any given period t with a probability $\vartheta^f_{d,t}$, which is increasing in the amount of final output that the adopter spends, $h^f_{d,t}$. An adopter who is not successful may try again in the subsequent period. The probability $\vartheta^f_{d,t}$ governs the speed of adoption and is a key driver of our mechanism.

Following Santacreu (2015), we assume that the stochastic rate of adoption has the following functional form:

$$\vartheta^f_{d,t} = \chi_a \left(\frac{h^f_{d,t}(N^d_{d,t+1} - N^f_{d,t})}{N_{f,t}} \right)^{\eta_a}, \tag{11}$$

where $\chi_a > 0$ is a scaling parameter and $\eta_a \in (0, 1)$ is the elasticity with respect to investment in adoption. Note that the probability of adoption has the same microfoundations as productivity of the innovation process.

The law of motion for domestic intermediate goods that can be used by the foreign final producer evolves according to

$$N^f_{d,t+1} - (1-\phi)N^f_{d,t} = \vartheta^f_{d,t}(1-\phi)(N^d_{d,t+1} - N^f_{d,t}), \tag{12}$$

where $N^f_{d,t}$ is the number of domestic goods imported by the foreign economy. If follows that the mass of domestic varieties not yet adopted by the foreign country is equal to $N^d_{d,t+1} - N^f_{d,t}$. Adoption is not instantaneous but follows a slow moving process, as it has been documented by Keller (2004).

2.4.3 Value Functions

Innovation and adoption are both endogenous processes. Let $V_{d,t}^f$ be the value to an adopter in country f of successfully adopting a technology developed in country d. This value is the present discounted value of profits from selling that good in country f:

$$V_{d,t}^f = \pi_{d,t}^f + (1-\phi)E_t[M_{f,t+1}V_{d,t+1}^f], \tag{13}$$

where $\pi_{d,t}^f$ denote profits. The value of technologies invented in country d at time t that have yet to be adopted by country f is

$$J_{d,t}^f = \max_{h_{d,t}^f} \left\{ -h_{d,t}^f + \{(1-\phi)E_t\left[M_{f,t+1}\left(\vartheta_d^f V_{d,t+1}^f + (1-\vartheta_d^f)J_{d,t+1}^f\right)\right]\right\}. \tag{14}$$

At time t, the adopter in country f invests $h_{d,t}^f$ to adapt a technology that has been invented by country d. At $t+1$, adoption is successful with probability $\vartheta_{d,t}^f$ and the adopter obtains the value of an adopted technology, $V_{d,t+1}^f$; with probability $1-\vartheta_{d,t}^f$, adoption is not successful and the adopter obtains the continuation value $J_{d,t+1}^f$.

Note that $J_{d,t}^f$ is also the price that adopters in country f are willing to pay to innovators in country d for the right to use the technology. Therefore, the value of a domestic innovation, $V_{d,t}$, is given by the present discounted value of the profits that innovator i expects to obtain from selling the good domestically, $V_{d,t}^d$, and the price paid by adopters in country f:

$$V_{d,t} = V_{d,t}^d + J_{d,t}^f, \tag{15}$$

where

$$V_{d,t}^d = \pi_{d,t}^d + (1-\phi)E_t[M_{d,t+1}V_{d,t+1}^d], \tag{16}$$

Discounted future profits on innovations are the payoff to innovators. Because the R&D sector is competitive, the free-entry condition for R&D investment–in the symmetric equilibrium under which all firms are identical–is

$$S_{d,t} = E_t\left[M_{d,t+1}V_{d,t+1}\right]\left(N_{d,t+1}^d - (1-\phi)N_{d,t}^d\right) \tag{17}$$

or, equivalently,

$$\frac{1}{\vartheta_{d,t}} = E_t\left[M_{d,t+1}V_{d,t+1}\right]. \tag{18}$$

Finally, the first order condition for investment in adoption is given by

$$H^f_{d,t} = \eta_a(1-\phi)\vartheta^f_{d,t}E_t\left[M_{f,t+1}\left(V^f_{d,t+1} - J^f_{d,t+1}\right)\right] \tag{19}$$

with $H^f_{d,t} = h^f_{d,t}(N^d_{d,t+1} - N^f_{d,t})$.

2.5 Resource Constraint

Final output is used for consumption, investment in physical capital, intermediate goods production, and investment in R&D and adoption. Hence the resource constraint is

$$Y_{d,t} = C_{d,t} + I_{d,t} + S_{d,t} + H^d_{f,t} + N^d_{d,t}X^d_{d,t} + N^f_{d,t}X^f_{d,t} \ .$$

2.6 Equilibrium conditions

We define a symmetric equilibrium as a set of equations according to which all firms within a country behave symmetrically.

A *general symmetric equilibrium* is defined as an exogenous stochastic sequence of technology shocks $\{\Omega_{d,t}, \Omega_{f,t}\}_{t=0}^{\infty}$, an initial vector $\{N^d_{d,0}, N^f_{d,0}, N^f_{f,0}, N^d_{f,0},, K_{d,0}, K_{f,0}\}$, a set of parameters $\{\beta, \theta, \gamma, \alpha, \xi, \varphi, \sigma, \rho, \delta, \zeta, \nu, \chi, \iota, \phi, \eta, h, \vartheta^f_d, \eta_a, \chi_a\}$, a sequence of aggregate prices $\{W_{d,t}, W_{f,t}, V_{d,t}, V_{f,t}, q_{d,t}, q_{f,t}, \mathcal{E}_t\}_{t=0}^{\infty}$, where q is the Tobin's Q, value functions $\{V^d_{d,t}, V^f_{f,t}, J^f_{d,t}, J^d_{f,t}, V^f_{d,t}, V^d_{f,t}\}_{t=0}^{\infty}$, a sequence of intermediate good prices $\{P^d_{d,t}, P^f_{d,t}, P^f_{f,t}, P^d_{f,t}\}_{t=0}^{\infty}$, a sequence of aggregate quantities $\{Y_{d,t}, Y_{f,t}, G_{d,t}, G_{f,t}, C_{d,t}, C_{f,t}, I_{d,t}, I_{f,t}, L_{d,t}, L_{f,t}, S_{d,t}, S_{f,t}, H^f_{d,t}, H^d_{f,t}\}_{t=0}^{\infty}$, quantities of intermediate goods $\{X^d_{d,t}, X^f_{d,t}, X^f_{f,t}, X^d_{f,t}\}_{t=0}^{\infty}$, a sequence of profits $\{\Pi_{d,t}, \Pi_{f,t}, \pi^d_{d,t}, \pi^f_{d,t}, \pi^f_{f,t}, \pi^d_{f,t}\}_{t=0}^{\infty}$, and laws of motion $\{N^d_{d,t+1}, N^f_{d,t+1}, N^f_{f,t+1}, N^d_{f,t+1}, K_{d,t+1}, K_{f,t+1}\}_{t=0}^{\infty}$ such that the following conditions hold:

(i) The state variables satisfy their respective laws of motion.

(ii) The endogenous variables solve the producers', innovators', and representative households' problems.

(iii) The resource constraint is satisfied.

(iv) Prices are such that all markets clear.

The equilibrium conditions are given in Appendix A.

2.7 Aggregate Productivity

Domestic aggregate productivity can be expressed as

$$Z_{d,t} \equiv \Omega_{d,t} \left(\tilde{A}\right)^{\frac{1}{1-\alpha}} \left[hN^d_{d,t} + \left(\frac{h}{1-h}\mathcal{E}_t\right)^{\frac{\nu}{\nu-1}} N^d_{f,t} \right], \tag{20}$$

where $\tilde{A} \equiv (\xi\nu)^{\xi/(1-\xi)}$. Taking logarithms, we have

$$\log Z_{d,t} = \log \Omega_{d,t} + \log \left\{ \left(\tilde{A}\right)^{1/(1-\alpha)} \left[hN^d_{d,t} + \left(\frac{h}{1-h}\mathcal{E}_t\right)^{\frac{\nu}{\nu-1}} N^d_{f,t} \right] \right\}.$$

Thus aggregate productivity has both an exogenous and an endogenous component, that is

$$\log(Z_{d,t}) = \log(Z^{EXO}_{d,t}) + \log(Z^{ENDO}_{d,t}).$$

where

$$\log(Z^{EXO}_{d,t}) \equiv \log \Omega_{d,t},$$

and

$$\log(Z^{ENDO}_{d,t}) \equiv \log \left\{ \left(\tilde{A}\right)^{1/(1-\alpha)} \left[hN^d_{d,t} + \left(\frac{h}{1-h}\mathcal{E}_t\right)^{\frac{\nu}{\nu-1}} N^d_{f,t} \right] \right\} \quad .$$

The exogenous component of aggregate productivity is given by the stochastic process $\Omega_{d,t}$. The endogenous component, which is the driver of growth in our model, depends on the number $N^d_{d,t}$ of varieties produced domestically, the number $N^d_{f,t}$ of varieties produced in the foreign country and that have been already adopted in the home country, and the real exchange rate, $\mathcal{E}_t$.

2.8 Dividends and the Stock Market Return

Stocks are viewed as claims on all the production sectors: the final good sector, the intermediate good sector, the innovation sector, and the international adoption sector. The aggregate dividend is defined as the net payout from these production sectors; formally,

$$\mathcal{D}_{d,t} = D_{d,t} + N^d_{d,t}\pi^d_{d,t} + N^d_{f,t}\pi^d_{f,t} - S_{d,t} - H^d_{f,t} \quad . \tag{21}$$

Optimality implies the following asset pricing condition:

$$\mathcal{P}^m_{d,t} = E_t[M_{d,t+1}(\mathcal{P}^m_{d,t+1} + \mathcal{D}_{d,t+1})],$$

where $\mathcal{P}^m_{d,t}$ is the domestic stock market price and $\mathcal{D}_{d,t}$ is the aggregate market dividend. Finally, the return on the stock market is defined as: $R^m_{t+1} = (\mathcal{P}^m_{d,t+1} + \mathcal{D}_{d,t+1})/\mathcal{P}^m_{d,t}$.

2.9 Exchange Rate, and Risk Sharing

Since we assume that financial markets are complete, the exchange rate depreciation is given by the ratio of foreign to domestic SDFs. Thus,

$$\frac{\mathcal{E}_{t+1}}{\mathcal{E}_t} = \frac{M_{f,t+1}}{M_{d,t+1}}. \tag{22}$$

Because of recursive preferences, the risk-sharing mechanism is non-standard. In particular, agents fear not only current shocks but also variation in future utility. Formally, let $\Upsilon_t = \mathcal{E}_t \left(\frac{C_{d,t}}{C_{f,t}}\right)^{\theta-1}$ be the ratio of marginal utilities, expressed in the same units. We refer to it as the (pseudo-) Pareto weight. Using the SDF from equation (2) together with the no-arbitrage condition (22), we can express Υ_t recursively as follows:

$$\Upsilon_{t+1} = \Upsilon_t \, \frac{M_{f,t+1}}{M_{d,t+1}} \, \frac{e^{(\theta-1)\Delta c_{d,t+1}}}{e^{(\theta-1)\Delta c_{f,t+1}}} \quad . \tag{23}$$

The variable Υ_t is constant in the CRRA case. With recursive preferences, however, it evolves as a function of the cross-country realizations of agents' continuation utilities.

3 The Mechanism

We illustrate the model's main mechanism by analyzing the effect of an increase in domestic exogenous productivity on asset prices and quantities. After a positive exogenous productivity shock, final producers demand more intermediate goods–both domestic and foreign. The resulting higher demand for intermediate goods increases the value of domestic innovations, with more resources being allocated to domestic R&D. In order to understand the effect on the foreign economy, we need to consider the international adoption of intermediate goods and the international risk sharing mechanism at work.

Recall that optimal R&D spending equals the present discounted value of an innovation (equation 17). Likewise, optimal spending in international adoption equals the present value of the right to sell a foreign technology in the domestic country (equation 19). When a positive domestic exogenous productivity shock hits the economy, both countries shift resources from consumption to investment in R&D and international adoption. Future expected growth becomes riskier and more correlated across countries. The SDFs are more volatile and share a sizable common component. The result is a first order effect on the international correlation structure of stock market returns and on the volatility of exchange rates. Stock market returns are highly correlated across countries and exchange rates are relatively smooth.

While recursive preferences have a large effect on asset prices, their impact on realized consumption growth within each country is limited. This is the combined result of two channels. The first is the well-known result that, in a standard real business cycle model, decoupling risk aversion from the elasticity of intertemporal substitution significantly improves a model's ability to replicate asset pricing moments while leaving quantity moments virtually unaltered (see Tallarini 2000 and Kaltenbrunner and Lochstoer 2010). Unlike those papers, our model features endogenous growth, so that we observe *some* effects on quantities.

The second channel comes from complete financial markets. After a positive domestic productivity shock, the domestic economy becomes more innovative and expected future productivity increases. In turn, the long-run growth prospects of the economy improve. Endogenous growth transforms a short-run transitory shock into a long-run shock with persistent effects on future growth. With recursive preferences, the domestic consumer experiences a substantial drop in her marginal utility. These are very good times for the domestic economy, not only because of the current technological environment, but also because the future looks bright. As a result, domestic final producers demand more intermediate goods, both domestic and foreign. The higher demand for foreign intermediate goods induces agents in the foreign economy to divert resources from consumption towards investment in R&D and adoption. The outcome is a cross-country correlation in consumption that is lower than what we would obtain in the absence of our recursive risk-sharing mechanism. In contrast, stock market returns become even more highly correlated, since they reflect the present discounted value of future growth prospects. These prospects are shared across countries, as captured by the high cross-country correlation of the long-run components of the SDFs.

4 Quantitative Implications

In this section, we discuss the quantitative implications of our model and explore its ability to replicate key international moments for macroeconomic quantities and asset prices. We put particular emphasis on the endogenous creation of long-run risk and its international diffusion. Our baseline model is calibrated at a quarterly frequency to the median country of our panel.

4.1 Calibration

We need to specify a total of 19 parameters, whose values are reported in Table 1. We start by discussing those that are relatively more standard. Values for the preference parameters are set in the spirit of the long-run risk literature (e.g., Bansal and Yaron 2004; Colacito and Croce 2013). In particular, we set the coefficient γ of relative risk aversion equal to 10 and the coefficient θ equal to 1/3, which implies an intertemporal elasticity of substitution of $\psi = 1.5$. Under this calibration of the preference parameters, agents in the economy fear shocks to expected future growth. The subjective discount factor is chosen to pin down the mean of the risk-free rate; thus, $\beta = 0.984^{1/4}$.

The parameters relating to the technology for final good production are obtained from Comin and Gertler (2006) and Kung and Schmid (2015). The capital share α is set to 0.35 to match the average capital share, and the share ξ of intangible capital is set to 0.5. The depreciation rate of physical capital is set to 0.02 to match the average capital investments rate and the parameter ζ is chosen to fix an elasticity of the investment rate with respect to Tobin's Q of 0.3. We follow the literature and use a value of 0.4 for ν; this parameter is related to the elasticity of substitution across intermediate goods and fixes the intermediate good markup in our model. The home bias parameter, h is set to 0.985, in line with the international estimates of Colacito and Croce (2013). We set the autocorrelation of the exogenous technology shock to $0.95^{1/4}$ and the volatility parameter σ at 1.82% in order to obtain a realistic volatility for consumption and output growth. Finally, we calibrate the cross-country correlation of the exogenous technology shocks, ρ, to 0.35, so that in equilibrium our model delivers a cross-country correlation of total factor productivity (TFP) growth of roughly 0.3, which is consistent with the empirical estimate of our sample of countries.

We now discuss the less standard parameters that govern the process of innovation and

Table 1: Parameters for the Baseline model.

Description	**Parameter**	**Value**
Preferences:		
Risk aversion	γ	10
IES	$\psi = 1/(1-\theta)$	1.5
Subjective discount factor	β^4	0.984
Final Production:		
Capital share	α	0.35
Share of materials	ξ	0.5
Autocorrelation of $\Omega = e^a$	φ^4	0.95
Volatility of exogenous shock ε	σ	1.82%
Cross-correlation of exogenous shock	ρ	0.35
Depreciation of capital stock	δ	0.02
Investment adjustment cost	$1/(1-1/\zeta)$	0.3
Inverse markup	ν	0.4
Home bias	h	0.985
Innovation and International Adoption:		
Scale of innovation	χ	0.4240
Scale of adoption	χ_a	1.428
Innovation obsolesce rate	ϕ	0.0375
Elasticity of innovation w.r.t. R&D	η	0.50
International diffusion of ideas	$\iota = 1-h$	0.015
International adoption (s.s.)	ϑ_d^f	0.0415
Elasticity of adoption w.r.t. R&D	η_a	0.3

technology adoption. The parameter χ is a pure scaling parameter; we set its value such that the steady-state growth rate of consumption has an annualized mean of 1.90%. Together with the calibrated parameter ν, χ gives us a value $\tilde{A} = (\xi\nu)^{\frac{\xi}{1-\xi}}$ that is consistent with balanced growth. The parameter η governs the elasticity of new varieties with respect to R&D and is set to 0.5, a number within the range of estimates given by Griliches (1990). We set $\phi = 0.0375$, which corresponds to a 15% annualized depreciation rate of the R&D stock.

We have three remaining parameters to calibrate: ι, ϑ_d^f, and η_a. We proceed sequentially. The parameter ι governs the intensity of international diffusion of ideas and makes the productivity of domestic R&D depend not only on domestic ideas, N_d^d, but also on foreign ideas, N_f^f, regardless of whether they have been adopted or not by the domestic economy. When domestic innovators learn about a newly developed foreign idea, they can use their

knowledge of such idea to become more productive in their innovative efforts. Formally, the parameter ι captures the level of substitutability across domestic and foreign ideas on the efficiency of innovation. To our knowledge, there are no direct measures of the effect of foreign ideas on the domestic efficiency of innovation. For parsimony, we calibrate it to the value of $\iota = 1 - h = 0.015$, akin to our home bias specification for intermediate goods in aggregate materials in equation (4). Quantitatively, we find that our model performs better with small values of ι.[3]

Next, we calibrate ϑ_d^f, which governs the speed of international adoption in steady state. We use annual data on R&D and disaggregated bilateral trade for 19 countries from 1996 to 2013. In total, we have a panel of 190 unique country-pairs and 26 years.[4] To calibrate this parameter, we use equation (12) together with equations (9) and (10) in the model. Equation (12) describes the law of motion of the number of varieties traded between countries d and f (i.e, the so-called extensive margin of trade), $N_{d,t}^f$, as a function of the stock of R&D of country d, $N_{d,t}^d$. After rearranging it, we obtain

$$N_{d,t+1}^f = \vartheta_{d,t}^f N_{d,t+1}^d + (1 - \vartheta_{d,t}^f)(1 - \phi) N_{d,t}^f \quad . \tag{24}$$

For each unique country-pair, we then compute the extensive margin of trade $N_{d,t}^f$. To compute the stock of R&D, $N_{d,t}^d$, we combine equations (9) and (10) as follows:

$$N_{d,t+1}^d = \chi \frac{N_{d,t}^d + \iota N_{f,t}^f}{N_{d,t}^d} \left(\frac{S_{d,t}}{N_{d,t}^d} \right)^{\eta - 1} + (1 - \phi) N_{d,t}^d \quad . \tag{25}$$

Using data on R&D expenditures ($S_{d,t}$) from the OECD for each country-pair and time period, the calibrated values for χ, η, ϕ, and ι, and the perpetual inventory method, we obtain a time series for the stock of R&D, $N_{d,t+1}^d$. Finally, we regress the extensive margin of trade, $N_{d,t+1}^f$, against its lagged value and the stock of R&D computed above, $N_{d,t}^d$, including year fixed effects (equation 24). The estimated coefficient captures the effect of a country-pair R&D expenditure on the rate at which its product can be adopted. Our estimates for this parameter range from 0.03 to 0.05, which imply that innovations take between 5 and 8 years to be adopted internationally. In our benchmark calibration, we use a quarterly value of $\vartheta_d^f = 0.0415$. This value implies that, consistently with the data, the share of traded

[3]See discussion in Section 4.3.

[4]Details on the data are described in Section 5.

varieties, N_d^f/N_d^d, is 0.36, and the steady-state R&D intensity, S_d/N_d^d, is 5%.[5]

The last parameter we need to calibrate is the elasticity of the probability of adoption with respect to adoption expenditures, η_a. In steady state, equation (11) can be expressed in logs as

$$\log(\vartheta_d^f) = \log(\chi_a) + \eta_a \log(H_d^f) \quad . \tag{26}$$

The left-hand-side variable is pinned down by the calibration of ϑ_d^f explained above. Data on the right hand side requires information on adoption expenditures incurred by each country f to use a technology developed in country d. To our knowledge, there are no direct measures of adoption expenditures, let alone adoption rates.[6] Given the specification of the adoption process in our model, a proxy for adoption expenditures is given by royalty payments from country f (i.e., the adopter) to country d (i.e, the innovator). Royalty payments reflect payments from a domestic adopter to a foreign innovator for the use of intellectual property. We collect data on bilateral royalty payments for the countries in our sample and the period of analysis from the OECD International Trade in Services database. Royalty payments are measured as charges for the use of intellectual property and they are recorded as a trade in service in the balance of payments of the country. We compute the average of that variable over time for each country pair d and f and obtain a measure of H_d^f. We then perform the regression in equation (26) and obtain an estimate for η_a of 0.31, with a 95% confidence interval of $[0.28, 0.34]$. Finally, we choose the value of the scale parameter χ_a to guarantee that the process of endogenous adoption is consistent with balanced growth.

The model is solved using perturbation methods. We compute a third-order approximation of our policy functions using the Dynare++ package. All variables included in our code are expressed in log-units.[7]

[5] As described above, our calibration procedure for ϑ_d^f depends on the parameter ι. We conduct a series of robustness exercises in which we vary the magnitude of ι to analyze its impact on our calibrated value of ϑ_d^f. We find that the implied dynamics of N_d^d in equation (25) are not particularly sensitive to the use of different values for the parameter ι. Therefore, the estimated ϑ_d^f coefficient that we obtain when we run regression (24) is not significantly affected by the value of ι.

[6] Comin and Gertler (2006) calibrate this parameter in a closed economy using development costs incurred by manufacturing firms trying that make new capital goods usable. As they acknowledge in their paper, the value they obtain is a rough estimate.

[7] For additional details on the solution and on the approximation of recursive economies with multiple agents see, Colacito and Croce (2012, 2013), Rabitsch, Stepanchuk, and Tsyrennikov (2015), and Colacito, Croce, Gavazzoni, and Ready (2018).

4.2 Results

In this section, we describe the main results for the dynamics of macroeconomic quantities and asset prices. Later, in Section 4.3, we analyze the endogenous sources of long-run risk and conduct a sensitivity analysis of its international diffusion. Table 2 reports simulated moments of four different calibrations: Baseline, Fast Adoption, EXO and CRRA. For the Fast Adoption calibration, we increase ϑ_d^f by 10%. The EXO calibration corresponds to a model in which innovation and adoption are exogenous. In this version of the model, new ideas arrive exogenously according to a Poisson process so that the steady-state growth rate of consumption does not change and international adoption is exogenous. For the CRRA calibration, we impose $\psi = 1/\gamma$ and leave all other parameters unaltered. Consistently with our empirical analysis, the length of our sample is 72 quarters and results are averaged across 5,000 simulations. Table 2 contains the main moments of our four calibrations, together with their empirical counterparts.

Macroeconomic Quantities. Our Baseline model performs fairly well in terms of moments for both output and consumption growth. Their respective standard deviations are 2.20% and 2.39%. The model generates a cross-country correlation of consumption growth of 0.23. The relatively low correlation is in line with our empirical estimates and with previous studies. This value is lower than the calibrated cross-country correlation of exogenous productivity shocks (0.35)—a consequence of the risk-sharing mechanism implied by recursive preferences. When a positive short-run shock hits the domestic economy, innovation and endogenous growth generate long-term growth effects that propagate to the rest of the world. Under recursive preferences, foreign marginal utility drops substantially and results in a reallocation of resources toward the production of foreign intermediate goods. The overall effect is a slight reduction in foreign consumption growth, which puts downward pressure in the cross-country correlation.

Our model performs quite well in terms of the dynamics of R&D expenditure. The volatility of R&D intensity, S/N, is 0.52% (0.49% in the data), the volatility of the growth rate of R&D intensity, $\Delta \log S/N$, is 2.93% (2.19% in the data) and its cross-country correlation is 0.30, also in line with the data.

Asset pricing implications. The volatility of exchange rate depreciation is 7.18%. This re-

sult is a direct consequence of the joint presence of recursive preferences and a sizable amount of endogenous long-run growth uncertainty. The model generates a substantial amount of risk, as confirmed by its Sharpe ratio of 0.33, but SDFs are highly correlated across countries as a consequence of the international diffusion of long-run risk. Given such a large correlation in SDFs, stock market returns are also highly correlated across countries, with a correlation of 0.70, consistently with the empirical evidence.

The model generates a low and persistent risk-free rate, as observed in the data. However, as is common in international production models, its volatility is lower than what we observe in the data. Another limitation of our model, which is also common in the literature, is that the equity premium is low unless we assume the presence of financial leverage. Following Boldrin, Christiano, and Fisher (2001), we lever equity returns with a financial leverage of 5 and obtain $E(r^m - r^f) = 2.14$ and $Std(r^m - r^f) = 14.28$.

The role of international adoption–Fast adoption case. When we increase ϑ_d^f by 10%, long-run risk diffuses faster across countries. Faster adoption of foreign R&D has a mild impact on macroeconomic quantities, but a significant impact on the dynamics of international asset prices. Relative to our baseline calibration, stock market returns become more correlated (0.82 vs 0.70) and exchange rates less volatile (6.83% vs. 7.18%). In addition, in line with our model's risk-sharing mechanism induced by recursive preferences, faster adoption generates more common variation in the economy's future prospects, i.e. $corr(m_d^{LR}, m_f^{LR})$ increases. As a result, the difference between the cross-country correlation of consumption growth and that of stock market returns increases. In Section 5 we provide suggestive empirical evidence to support this mechanism.

Why endogenous growth?–the EXO case. When growth is exogenous, the risk propagation mechanism at the core of our baseline calibration is muted. Put simply: short-run risk, which results from the exogenous productivity process, does not have significant long-run effects on growth. In this case, the power of recursive preferences is limited. Even though recursive preferences make agents fear variations in future utility, such variation is too small to have significant quantitative effects on equilibrium quantities and asset prices. Indeed, the volatility of the long-run component of the SDF is only about 4.5%, roughly seven times smaller than what is obtained from the baseline model with endogenous growth. Similarly,

Table 2: Simulated moments for macroeconomic quantities and asset prices. Subscripts d (domestic) and f (foreign) are suppressed when there is no ambiguity. 'Baseline' refers to our baseline calibration in Table 1. 'Fast Adoption' refers to a calibration with a 10% increase in the value of ϑ_d^f relative to the Baseline model. 'EXO' refers to the model with exogenous growth. 'CRRA' refers to the case of constant relative risk aversion case and is obtained by setting $\psi = 1/\gamma$. The risk premium, $r^m - r^f$, is levered following Boldrin, Christiano, and Fisher (2001). For the R&D variables (S/N), we report moments of their low-frequency components, which are obtained using the bandpass filter from Christiano and Fitzgerald (2003) and isolating frequencies between 120 and 200 quarters. Data and standard errors are for the 1996-2013 period for our panel of countries. The UIP slope coefficient (β^{UIP}) is obtained after rescaling the volatility of the interest rate differential to match its empirical counterpart. Means and standard deviations are reported as annualized percentages.

	Data	(s.e.)	Baseline	Fast adoption	EXO	CRRA
A. Macro Quantities:						
$Std(\Delta c)$	1.611	(0.140)	2.195	2.198	2.475	2.236
$Corr(\Delta c_d, \Delta c_f)$	0.192	(0.095)	0.232	0.226	0.396	0.736
$Std(\Delta y)$	2.236	(0.207)	2.389	2.389	2.336	2.244
$Corr(\Delta y_d, \Delta y_f)$	0.213	(0.103)	0.305	0.305	0.383	0.493
$Std(\Delta z)$	1.261	(0.225)	3.685	3.685	3.602	3.459
$Corr(\Delta z_d, \Delta z_f)$	0.373	(0.160)	0.305	0.305	0.383	0.492
$Std(\Delta \log(S/N))$	2.187	(0.145)	2.927	2.925	n.a.	2.974
$Corr(\Delta \log(S_d/N_d), \Delta \log(S_f/N_f))$	0.207	(0.100)	0.299	0.301	n.a.	-0.150
$Std(S/N)$	0.489	(0.041)	0.522	0.522	n.a.	0.154
B. Asset prices:						
$E(r^f)$	2.020	(0.120)	2.004	2.307	2.787	20.042
$Std(r^f)$	1.229	(0.082)	0.112	0.112	0.081	0.439
$corr(r_d^f, r_f^f)$	0.746	(0.039)	0.675	0.681	0.077	0.852
$Std(\Delta q)$	8.386	(1.006)	7.180	6.825	5.167	16.147
$E(r^m - r^f)$	6.050	(1.962)	2.140	2.137	0.517	1.2819
$Std(r^m - r^f)$	24.332	(2.982)	14.276	13.630	9.051	6.1527
$corr(r_d^m - r_d^f, r_f^m - r_d^f)$	0.738	(0.096)	0.702	0.821	0.443	0.898
$corr(\Delta e_{t+1}, r_{d,t}^f - r_{f,t}^f)$	-0.049	(0.031)	-0.026	-0.027	0.139	0.184
β^{UIP}	-0.655	(0.426)	-0.150	-0.154	0.641	0.794
C. Long-run risk:						
$ACF_1\ E_t(\Delta c_{t+1})$			0.912	0.912	0.396	0.913
$StdE_t(\Delta c_{t+1})$			0.174	0.172	0.121	0.046
$CorrE_t(\Delta c_{d,t+1}), E_t(\Delta c_{f,t+1})$			0.602	0.610	0.081	0.622
$ACF_1\ E_t(\Delta z_{t+1})$			0.915	0.915	0.909	0.907
$Std(E_t(\Delta z_{t+1}))$			0.084	0.084	0.270	0.028
$Corr(E_t(\Delta z_{d,t+1}), E_t(\Delta z_{f,t+1}))$			0.600	0.607	0.196	0.470
$Corr(m_d, m_f)$			0.975	0.978	0.640	0.737
$Std(M)/E(M)$			32.593	32.562	6.117	22.402
$corr(m_d^{SR}, m_f^{SR})$			0.232	0.226	0.396	0.736
$corr(m_d^{LR}, m_f^{LR})$			0.959	0.962	0.718	n.a.
$Std(m^{SR})$			1.464	1.465	1.650	22.356
$Std(m^{LR})$			31.383	31.339	4.490	n.a.

the Sharpe Ratio declines to 0.06, and both the volatility of the exchange rate (5.17%) and the cross-country correlation in stock market returns (0.44) are lower than their empirical counterparts.

Why recursive preferences?–the CRRA case. Recursive preferences are crucial to our mechanism because they allow for realistic dynamics of asset prices without compromising the model's performance with respect to macroeconomic quantities. The last column of Table 2 reports the results obtained in the standard CRRA case. The dynamics of macroeconomic quantities within each country are only marginally changed, but the reported cross-country moments reveal some serious shortcomings: in particular, the CRRA case cannot account for the sizable wedge observed in the data between cross-country correlations in consumption growth and stock market returns. The cross-country correlation in consumption growth is too high (0.74), and the cross-country correlation in the stock market excess returns is 0.90. Finally, the average of the risk-free rate is too high (20.05%)—a manifestation of the well-known risk-free rate puzzle.

Uncovered Interest Rate Parity and Currency Carry Trade. Following the literature on the violations of UIP, we consider the regression

$$\Delta e_{t+1} = \alpha^{UIP} + \beta^{UIP}(r^f_{d,t} - r^f_{f,t}) + \epsilon^{UIP}_{t+1} \quad , \tag{27}$$

where Δe_{t+1} is the log depreciation rate of the domestic currency and $\beta^{UIP} = \frac{cov(\Delta e_{t+1}, r^f_{d,t} - r^f_{f,t})}{var(r^f_{d,t} - r^f_{f,t})}$ is the well known Bilson-Fama-Tryon UIP coefficient. Under the null hypothesis of uncovered interest rate parity, $\beta^{UIP} = +1$. In the data, estimates of the slope coefficient are typically negative. Backus, Foresi, and Telmer (2001) show that, in order to obtain deviations from UIP (i.e. $\beta^{UIP} < 1$), higher order moments of the SDFs must be time-varying. In our model, this variation comes from the time-varying nature of the (pseudo-) Pareto weights (see equation 23) and the third order approximation solution method that we use is able to capture it.

We notice that our model cannot replicate the *magnitude* of the UIP slope coefficient observed in the data. As is clear from equation 27, the UIP slope coefficient depends on four endogenous moments: i) the volatility of the depreciation rate, ii) the volatility of the

domestic and foreign risk free rates, iii) the correlation between the depreciation rate and the interest rate differential and iv) the correlation between the domestic and foreign risk free rates. Our model performs well in all but one of the moments above: the volatility of the risk free rate (see Table 2). We find that the risk free rate is too smooth, hence the absolute magnitude of the UIP slope coefficient is too high. Next, we explore the reason behind this result.

Following Colacito and Croce (2013), the risk free rate in our model is approximately equal to

$$\begin{aligned} r^f_{d,t} &\approx \frac{1}{\psi}E_t[\Delta c_{d,t+1}] - \frac{1}{2}\left(\frac{1}{\psi}\right)^2 Var_t[\Delta c_{d,t+1}] + \frac{1}{2}\left(1-\frac{1}{\psi}\right)\left(\frac{1}{\psi}-\gamma\right) Var_t[\log \tilde{U}_{d,t+1}] \\ &+ \frac{1}{\psi}\left(\frac{1}{\psi}-\gamma\right) Cov_t\left[\Delta c_{d,t+1}, \log \tilde{U}_{d,t+1}\right] \end{aligned}$$

where $\tilde{U}_d = U_d/C_d$ is the rescaled utility.[8] Quantitatively, the term involving the conditional mean of future consumption growth, $E_t(\Delta c_{t+1})$, is the main factor explaining the low volatility of the risk-free rate (see Table 2). This term reflects variation in future growth prospects of the economy, which measures the amount of long-run risk generated by our model. We compare the predictions of our model for $E_t(\Delta c_{t+1})$ to those of a two-country production economy in which long-run risk is exogenous (see for instance, Colacito, Croce, Ho, and Howard 2018). The fundamental difference between our model and the exogenous long-run risk literature is that, in our model, long-run risk is an equilibrium outcome: it is driven by our endogenous growth mechanism. Instead, in the traditional long-run risk literature, it is modeled as an exogenous shock. To shed more light on the implications of a model of endogenous long-run risk, we modify our baseline model and consider a production economy in which: (i) growth is exogenous, and (ii) the productivity shocks explicitly contain long-run risk. Following the exogenous long-run risk literature, the law of motion of the domestic productivity shock is modified as follows:

$$\begin{aligned} a_{d,t} &= \varphi\ a_{d,t-1} + l_{d,t-1} + \rho_{ec}(a_{f,t-1} - a_{d,t-1}) + \sigma_a \varepsilon_{d,t} \\ l_{d,t} &= \varphi_l\ l_{d,t-1} + \sigma_l \varepsilon^l_{d,t} \end{aligned}$$

[8] In Appendix B, we provide the details of this derivation, which assumes lognormality of utility. We verified numerically that the volatility of the risk free rate obtained with this approximation is very close to what we obtain in our benchmark model.

where $l_{d,t}$ represents the long-run risk component and ε_d and ε_d^l are independent $(0,1)$ normally distributed innovations. Foreign productivity is specified analogously. Details can be found in Appendix C.

We then perform two calibration exercises in which we keep the overall volatility of productivity to be the same as in our benchmark model but choose the σ_l/σ_a ratio in two different ways. First, we choose it so that the size of the long-run shock — relative to the short-run shock — is consistent with the estimates of the exogenous long-run risk literature (see, among others, Bansal and Yaron 2004, Colacito and Croce 2013, and Colacito, Croce, Ho, and Howard 2018). Second, we choose it to match the volatility of expected consumption growth generated by our baseline model with endogenous growth. We find that, in this second exercise, the long-run risk component is relatively smaller, implying that the variation in expected consumption growth generated by our benchmark model is less than what is commonly found in the exogenous long-run risk literature. Quantitatively, we can only generate a third of this variation. As a result, all else equal, risk free rates are too smooth. Thus the UIP slope coefficient is too large (in absolute value).

In light of this limitation of our model, and to facilitate comparison with the magnitude of the UIP coefficient reported in the literature, we conduct the following exercise. First, we rescale the volatility of the risk free rates to match their empirical counterpart. Then, we run the UIP regressions in equation (27) for a long simulation of our economy. Panel B of Table 2 reports the UIP slope coefficients together with the correlation between the future depreciation of the exchange rate and the interest rate differential.

The UIP slope coefficient of the Baseline and Fast Adoption models are *negative* and very similar in magnitude (-0.15). In each country, endogenous growth generates long-run risk which then spreads internationally through our mechanism of endogenous adoption of varieties. The risk sharing mechanism of recursive preferences generates variation in higher order moments of the SDFs, which result in substantial deviations from UIP. The UIP slope coefficient of the EXO model is *positive* and equal to $+0.64$. Despite the presence of recursive preferences, when growth is exogenous the amount of long-run risk is limited and deviations from UIP are smaller. Finally, as is well known, the CRRA model fails to generate substantial deviations from UIP for its inability to capture long-run risk. The estimated coefficient is $+0.80$.

In the spirit of Lustig, Roussanov, and Verdelhan (2011), we also consider a zero-cost

HML currency carry trade strategy in which, at each quarter t, the investor borrows money from the country with a low risk-free rate and invests in the country with a high risk-free rate. The per-period realized excess return is:

$$rx_{t+1}^{HML} = I_t \cdot (r_{d,t}^f - r_{f,t}^f - \Delta q_{t+1}) \qquad I_t = \begin{cases} +1 & \text{if } r_{d,t}^f > r_{f,t}^f \\ -1 & \text{otherwise} \end{cases} .$$

In the data, estimates of the average return of the HML strategy are as high as 6%. We notice that, while our Baseline model can generate substantial deviations from UIP, it cannot deliver a sizable return for the HML carry trade strategy. The average return is only $E(rx^{HML}) = 0.04\%$. This result is consistent with the findings of Colacito, Croce, Gavazzoni, and Ready (2018) and Hassan and Mano (2014) who show that deviations from UIP and returns of the HML strategy are two distinct phenomena which are only partially related. In particular, large average returns for the HML strategy require the presence of permanent (or almost permanent) asymmetries, which are absent in our two-country symmetric model.

4.3 Long-Run Risk Within and Across Countries

In this section, we investigate the mechanism at the heart of the model: the endogenous generation of long-run risk and its international diffusion. In Appendix D, we show how our general equilibrium mechanism can be captured by a reduced form model of long-run risk.

Endogenous long-run risk. Growth within a country is risky as it is tied to discounted future profits of innovations. Iterating forward equation (9), the economy's growth rate can be expressed as the present discounted value of domestic and foreign profits as follows

$$\Delta N_{d,t+1}^d = (1-\phi) + E_t \left[\chi^{\frac{1}{\eta}} \sum_{j=1}^{\infty} M_{d,t+j} (1-\phi)^{j-1} (\pi_{d,t+j}^d + \pi_{d,t+j}^f) \right]^{\frac{\eta}{1-\eta}} ,$$

where $M_{d,t+j} \equiv \prod_s^j M_{d,t+s}$ is the j-period SDF.

In our international setting, intermediate producers can sell new varieties both to domestic final producers and, once they have been adopted, to foreign final producers. The profits from selling these varieties are discounted at the SDF from equation (2) and determine the characteristics of equilibrium growth in our model. With recursive preferences and a prefer-

ence for early resolution of risk, agents fear variations on the economy's future prospects. The entire future distribution of risk matters. The more productivity and consumption growth are predictable, the more volatile the SDF. The result is a volatile endogenous growth path, which exhibits a quantitatively substantial long-run risk. In our baseline calibration expected productivity and consumption growth are highly persistent, with an autocorrelation coefficient of 0.915 and 0.912, respectively. The SDF is volatile, resulting in an annualized Sharpe ratio of roughly one third. The success of our model in generating large long-run risk does not come at the expense of other moments. Indeed, our model matches quite well the implied dynamics of realized macroeconomic quantities, such as consumption and productivity growth, R&D expenditures and the number of varieties. Means, standard deviations, and cross-country correlations of these variables are in line with their empirical counterparts. This is due to the mechanism of international diffusion described below.

International diffusion of long-run risk. In our model, long-run risk diffuses internationally through trade in intermediate goods. When financial markets are complete, long-run risk must be highly correlated across countries. To see this, consider the risk-sharing condition in equation (22). In logs, $\Delta \log \mathcal{E}_{t+1} = m_{f,t+1} - m_{d,t+1}$. That is, the currency depreciation rate is equal to the difference between the foreign and domestic SDFs. In the data, the volatility of the currency depreciation is about 8%. Hansen and Jagannathan (1991) show that the SDFs must have a volatility of, at least, 30-40%. Therefore, the correlation between the domestic and foreign SDFs must be close to one. Unfortunately, in the data, realized consumption growth is neither volatile enough nor highly correlated across countries. Therefore, the required high volatility and high correlation of the SDFs cannot come from its short-run components, but must come from the components capturing the continuation utility and the riskiness of future growth, i.e, $M_{t+1}^{LR} = \left(\frac{U_{t+1}}{E_t[U_{t+1}^{1-\gamma}]^{\frac{1}{1-\gamma}}} \right)^{1-\gamma-\theta}$.

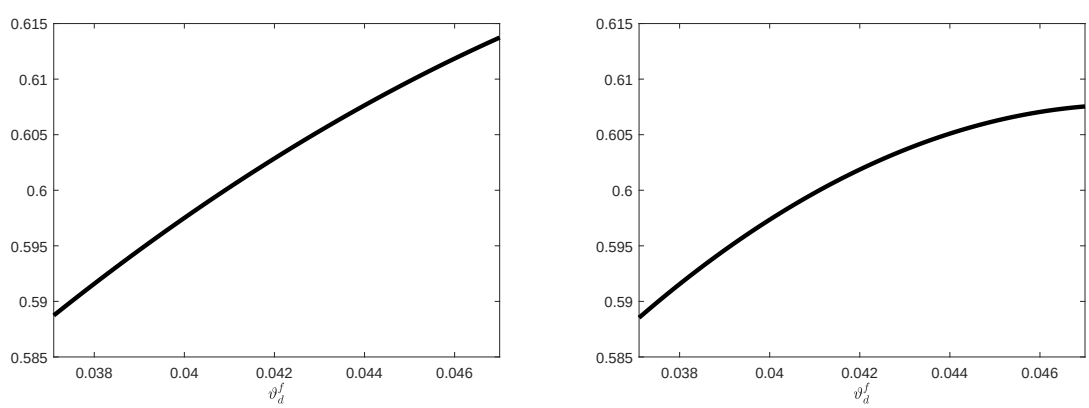
In our baseline calibration, the cross-country correlation of the SDFs is as high as 0.98 and is almost exclusively due to long-run risk. Indeed, the short-run component of the SDFs has a low cross-country correlation of 0.23, matching the cross-country correlation observed in the data for consumption growth. The sizable cross-country correlation in the long-run component of the SDFs manifests itself in a large and positive cross-country correlation of expected consumption growth and expected productivity growth (0.6). While actual consumption and productivity profiles are only mildly correlated across countries, future expected growth rates

feature a sizable common component. As a result, the equilibrium dynamics of the SDFs imply a volatility of the currency depreciation rate in our baseline calibration of 7.18%, which is consistent with its empirical estimates. In the remaining part of this section, we conduct a sensitivity analysis of the model for the two key parameters governing the (steady-state) speed of international adoption (ϑ_d^f) and the intensity of diffusion of ideas (ι).

Speed of international adoption. We conduct the following exercise. We consider a range of values for ϑ_d^f centered around the mean of our empirical estimates and simulate the model over that range. Then, we focus on the effect of increasing the speed of adoption on the moments that are most affected by the international diffusion of long-run risk. Figure 1a shows how the cross-country correlation of expected consumption growth changes as we vary ϑ_d^f. We find that it is increasing and it ranges from roughly 0.59, with a $\vartheta_d^f = 0.0370$, to more than 0.61, with $\vartheta_d^f = 0.0475$. That is, the faster the speed of adoption, the more long-run risk diffuses across countries, making the prospects of future growth more correlated across countries.

Figure 1: Cross-country correlations of $E_t(\Delta c_{t+1})$ and $E_t(\Delta z_{t+1})$ as a function of the speed of international adoption ϑ_d^f.

(a) Cross-country corr. of future cons. growth (b) Cross-country corr. of future prod. growth



In Figure 1b, we show that the cross-country correlation in expected productivity growth is also increasing in ϑ_d^f. Faster adoption allows for a greater diffusion of long-run risk. To see this, we derive the following expression for the expected growth of the endogenous component of productivity (see Appendix E for details):

$$E_t \Delta \log(Z^{ENDO}_{d,t+1}) \approx \left[h\chi \left(\frac{S_{d,t}}{N^d_{d,t}} \right)^{\eta} + \left(\frac{h}{1-h} \right)^{\frac{\nu}{\nu-1}} \frac{\bar{N}^d_f}{\bar{N}^d_d} \left(\frac{\nu}{\nu-1} E_t \Delta \log(\mathcal{E}_{t+1}) + (1-\phi)\vartheta^f_d \chi \left(\frac{S_{f,t}}{N^f_{f,t}} \right)^{\eta} \frac{N^f_{f,t}}{N^d_{f,t}} \right) \right]$$

Expected productivity growth in the domestic economy depends on: i) domestic R&D intensity, ii) foreign R&D intensity, and iii) expected changes in the real exchange rate. When the elasticity of substitution between domestic and foreign varieties is large enough—as is the case in our baseline calibration—the exchange rate channel is quantitatively weak so that the cross-country correlation of future expected productivity growth increases with ϑ^f_d. In Figure 2 we look at this relation and plot simulated paths of expected domestic productivity growth together with domestic R&D intensity, S_d/N_d, and foreign R&D intensity, S_f/N_f. Consistently with the expression above, the two graphs reveal that expected domestic productivity growth tracks closely both domestic and foreign R&D intensity.

Figure 2: Expected productivity growth $E_t(\Delta z_{t+1})$ and domestic and foreign R&D intensity.

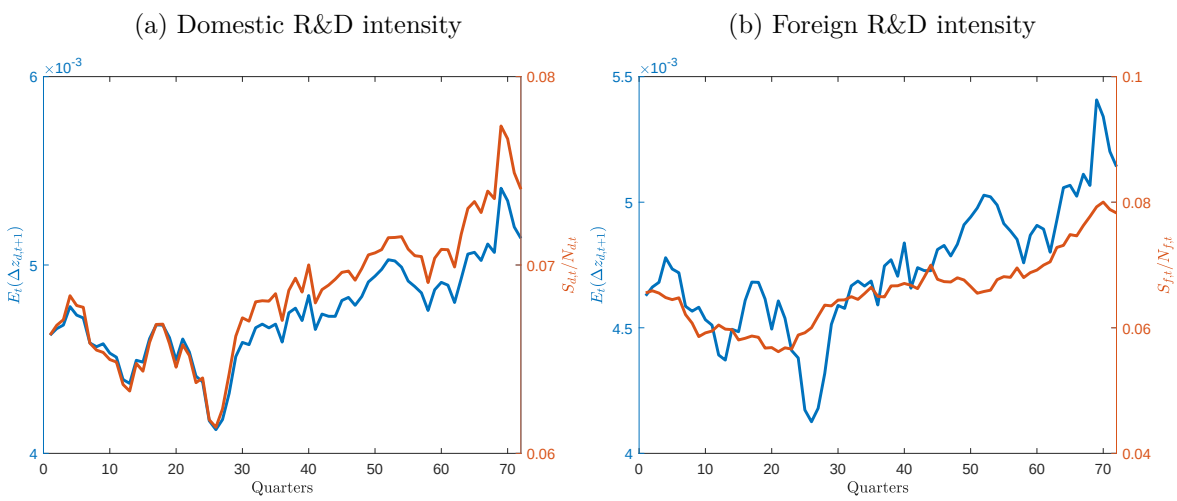
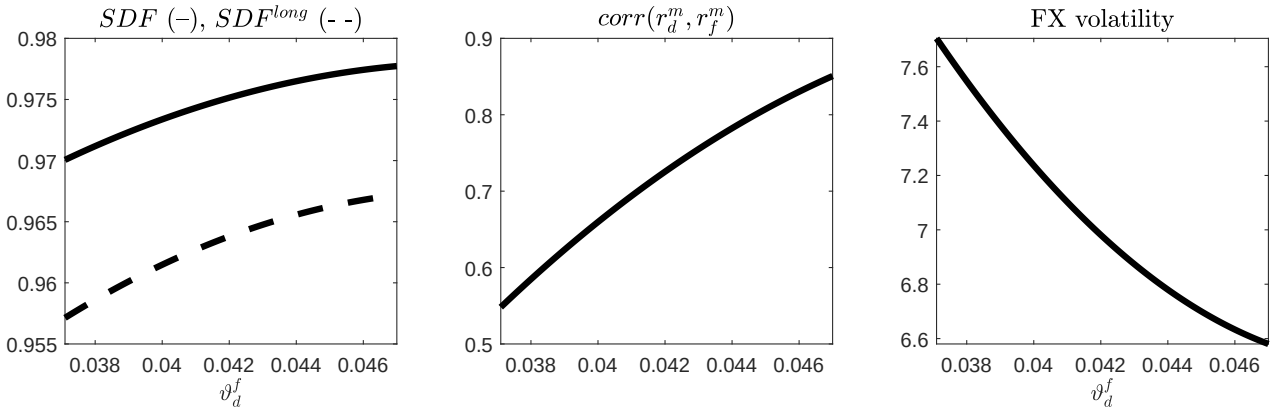


Figure 3 confirms that, when international adoption is stronger, more long-run risk diffuses across countries. Indeed, the SDFs become more correlated, stock market returns are more correlated, and exchange rates are less volatile. For the range of our estimated speed of adoption, the correlation of stock market returns increases from 0.55 to 0.85 and the standard deviation of the currency depreciation rate drops from 7.71% to 6.54%.

Figure 3: Sensitivity to speed of international adoption (ϑ_d^f). Cross-country correlation of SDFs, stock market correlation and volatility of currency depreciation rate.



International diffusion of ideas. We conduct the same exercise with respect to the intensity of international diffusion of ideas across countries, which is governed by the parameter ι. Figures 4a and 4b show that the cross-country correlation of expected consumption and productivity growth are increasing in ι. Figure 5 shows that, as there is more international diffusion of ideas, the SDFs and the returns of the stock markets are more correlated and the exchange rate depreciation is less volatile. When more ideas spread worldwide, innovators in each country are more productive and the amount of long-run risk that is internationally shared is higher.

This exercise shows why our model performs better with small values of ι. The intuition is the following. When ι is large, domestic and foreign technologies enter symmetrically in the productivity of domestic innovators. The international diffusion of ideas is essentially frictionless so that the long-run risk created by the endogenous innovation mechanism spreads *too fast* across countries. Future growth prospects for the domestic and foreign economy are too similar to each other, SDFs become too correlated across countries and, as a consequence, exchange rates are too smooth. Indeed, the volatility of the currency depreciation rate drops below 4% for values of ι larger than 0.02.

Figure 4: Cross-country correlations of $E_t(\Delta c_{t+1})$ and $E_t(\Delta z_{t+1})$ as a function of the intensity of diffusion of ideas ι.

(a) Cross-country corr. of future cons. growth (b) Cross-country corr. of future prod. growth

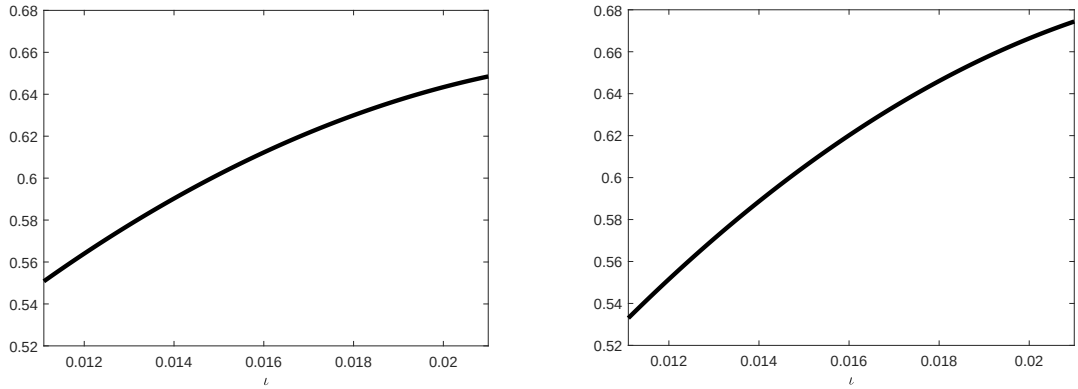
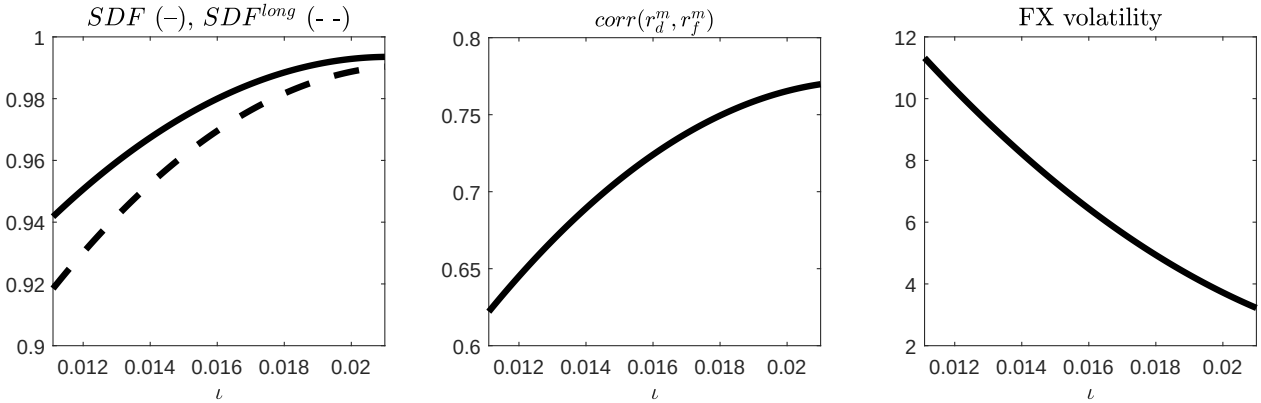


Figure 5: Sensitivity to intensity of diffusion of ideas (ι). Cross-country correlation of SDFs, stock market correlation and volatility of currency depreciation rate.



5 Innovation, Trade, and Asset Prices: Empirical Evidence

In this section, we provide suggestive empirical evidence of our proposed mechanism: country-pairs that share more R&D thorough trade in varieties have more correlated stock market returns and less volatile exchange rates. Importantly, we show that *both* R&D *and* trade generate the asset pricing implications that we propose in our paper, suggesting that the international diffusion of R&D plays a distinct role in this mechanism.

Data. We begin by constructing a measure of R&D embodied in international trade. There is a large empirical literature studying the role that R&D embodied in intermediate goods has on the productivity of a country. The main idea behind these studies is that technology transfers across countries contribute to increases in productivity of the country receiving such technologies. Technology can transfer across countries in various ways: through international trade, multinational production, human capital accumulation, and other channels. We focus on the diffusion of technology through international trade. Several studies have found that technology embodied in intermediate traded goods is an important channel for international technology diffusion. On the theory side, Romer (1990) and Grossman and Helpman (1991) have developed models in which both domestic and foreign intermediate goods increases productivity, which is the mechanism at work in our model. On the empirical side, research has found a tight link between R&D embodied in trade and total factor productivity (Keller 1998, Coe and Helpman 1995, and Nishioka and Ripoll 2012). The mechanism proposed in our paper is based on these studies.

Our main data sources are as follows: for international trade, the UN COMTRADE; for R&D, the OECD Science and Technology Indicators (Business Enterprise R&D (BERD) as a % of GDP); and for asset prices, Global Financial Data and Ken French's website.[9] Our main data set covers the 1996–2013 period for a sample of 19 countries.[10] The choice of countries and time period was determined based on the availability of data for asset pricing, trade, and R&D. Details on these sources–and on the construction of measures used in our analysis–are given in Appendix F.

We focus on two moments: the cross-country correlation in stock market returns and the volatility of the exchange rate. We start with monthly observations and construct annual, non-overlapping measures of cross-country correlation—for stock market returns—and volatility—for the exchange rate depreciation—for each country-pair. We then use data on R&D and bilateral trade flows to construct a measure of the R&D content of trade. This is the key measure of our mechanism and it reflects how R&D is shared across countries though international trade. For this purpose, we start by constructing the R&D stock for each country in our sample. Given a country's R&D intensity—defined as R&D expenditures

[9] http://mba.tuck.dartmouth.edu/pages/faculty/ken.french/data_library.html

[10] The countries are Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Ireland, Italy, Japan, the Netherlands, New Zealand, Norway, Spain, Sweden, Switzerland, the United Kingdom, and the United States. For exchange rates, we use the same period but eliminate all Eurozone countries (save Germany) and Denmark, which has instituted a managed exchange rate versus the Euro.

over gross domestic product (GDP)—we apply the so-called perpetual inventory method using an annual depreciation rate of 15% (as in Coe and Helpman 1995). Next, we follow the empirical literature and obtain a measure of the R&D content of international trade for a particular pair of countries i and j ($X_{i,j}^{\text{R\&D}}$), as

$$X_{i,j}^{\text{R\&D}} = \frac{X_{i,j}}{GDP_j} R\&D_j + \frac{X_{j,i}}{GDP_i} R\&D_i \tag{28}$$

where $X_{i,j}$ is total trade between exporter j and importer i, $R\&D_i$ is the stock of R&D in country i, and GDP_i is the gross domestic product of country i. This measure is constructed for each year in our sample.

Scatter plots. We analyze the relation between our estimated moments of asset prices and measures of international trade and R&D. The goal is to determine whether the mechanism that we propose (i.e., R&D embodied in trade) plays any role in determining the equilibrium dynamics of asset prices. Figure 6 reveals that pairs of countries whose trade is characterized by greater R&D content exhibit more highly correlated stock market returns and less volatile exchange rates. In the graphs, each solid circle represents the time-series average over the 1996-2013 period of each country pair in our sample. We have 171 unique country pairs for the stock market correlation (left panel) and 108 unique country pairs for the exchange rate volatility (right panel).

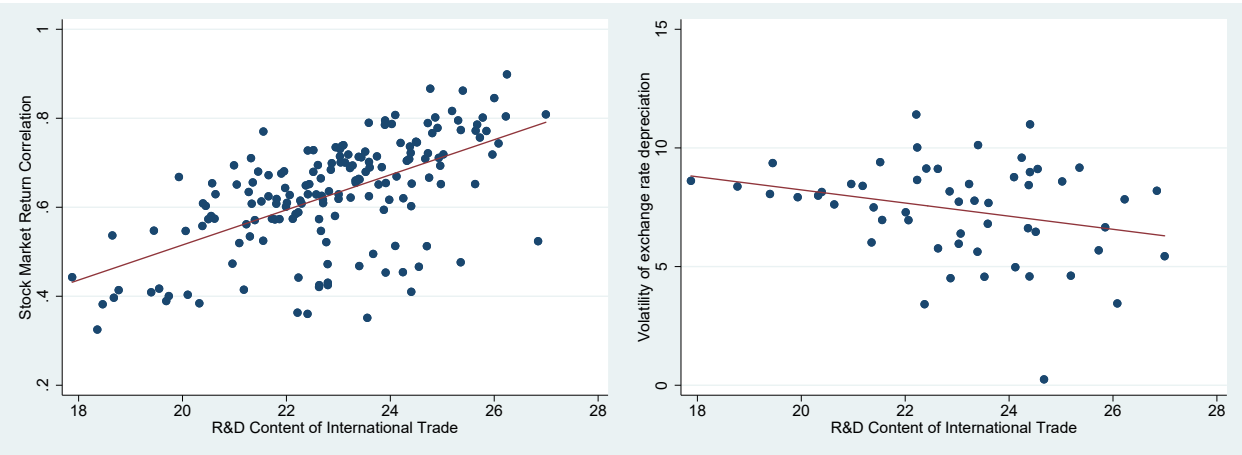


Figure 6: R&D content of trade and asset prices: time-series average for each country pair. each solid circle represents the time-series average over the 1996-2013 period of each country pair in our sample.

The empirical literature on productivity and trade has typically used country-level aggregate data of R&D and bilateral trade flows to analyze the impact of the R&D content of international trade on aggregate variables. A limitation of this approach is that it cannot capture good-specific R&D characteristics. Ideally, we would like to use highly disaggregated data at the product level. However, these data is not available for a large sample of countries and time period. Nishioka and Ripoll (2012) use trade and R&D data at the industry-level, which is the highest level of disaggregation available for our panel. Following their work closely, we conduct a robustness analysis in which our measure of R&D embodied in intermediate inputs, $X_{i,j}^{\text{R\&D}}$, is calculated at the industry level. We use OECD input-output data for R&D spending and bilateral trade flows for seven manufacturing industries, our sample of countries and the 1996-2013 period. We then evaluate the extent to which this new measure correlates with our moments of asset prices. As Figure 7 shows, the results are broadly in line with those obtained using more aggregated measures. Country pairs that share more R&D through trade, using the input-output structure of the data, have more correlated stock market returns and less volatile exchange rates. Taken together, these graphs provide suggestive evidence that R&D and international trade can provide some useful insights on the international dynamics of asset prices.

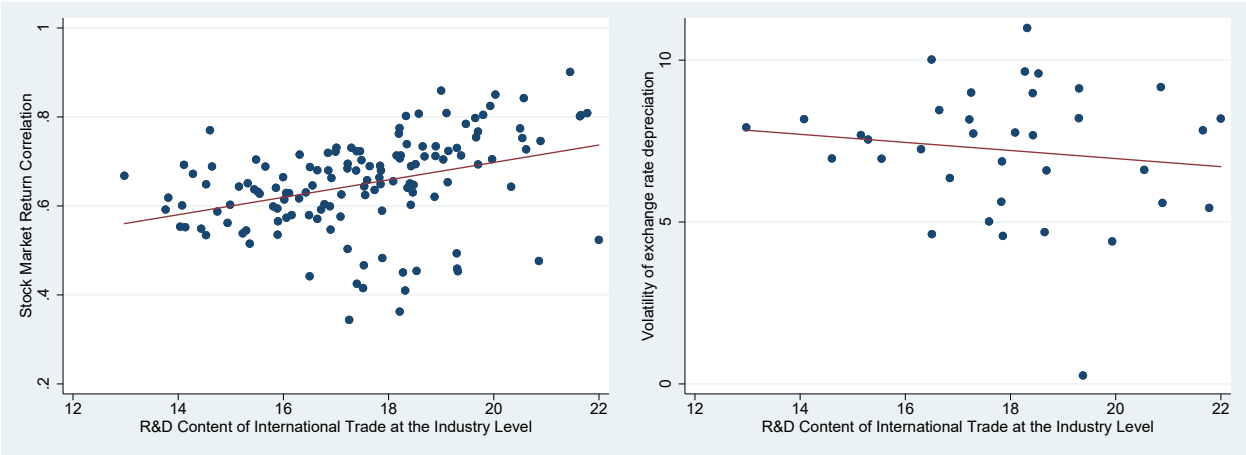


Figure 7: R&D content of trade and asset prices (industry measure): time-series average for each country pair. Each solid circle represents the time-series average over the 1996-2013 period of each country pair in our sample.

Regression Analysis. We now undertake a formal regression analysis in order to address the economic and statistical significance of the results presented in Figures 6 and 7. We regress the asset pricing moments of interest—namely, the cross-country correlation of stock

market returns and the volatility of exchange rate—on our measure the R&D embodied in trade. To preserve the data time series aspect, we report the regression results for unique country pairs over the entire 1996 to 2013 period. Results are reported in Table 3. We find that the coefficients are significant. More specifically, a 1% increase in the log R&D content of international trade increases the correlation of asset returns by 0.11% and decreases the volatility of the exchange rate by 0.32%.[11]

Table 3: Asset prices and R&D embodied in international trade. Standard errors in parentheses. *, **, and *** denote statistical significance at the 10%, 5%, and 1% level, respectively.

	(1)	(2)
	Stock Market Correlation	Volatility of Exchange Rate Depreciation
$\log(X_{ij}^{R\&D})$	0.111^{***}	-0.321^{**}
	(0.007)	(0.150)
N	3078	990
R^2	0.087	0.005

Next, we further explore the role of trade in diffusing technology across countries. Recall that we assume technology is embodied in products and diffuses across countries through trade. One can therefore decompose the total value of trade into the number of different products traded across each country-pair—the so called extensive margin of trade—and the amount of each good traded across countries–the so called intensive margin of trade. Our conjecture is that if R&D is transmitted across countries through trade in the varieties of products that embody such R&D, then the extensive margin (N_d^f) should have a larger effect (than the intensive margin) on asset pricing moments. In Table 4, we report the results of regressing those asset pricing moments on both the extensive margin (EM) and intensive margin (IM) of each country pair's respective international trade.

[11]The left-hand-side variables in our regressions are subject to sampling uncertainty. In Appendix G, we report the results using robust standard errors and feasible generalized least squares (FGLS). Our main conclusions remain unchanged.

Table 4: Asset prices and the margins of international trade. Standard errors in parentheses. *, **, and *** denote statistical significance at the 10%, 5%, and 1% level, respectively.

	(1)	(2)
	Stock Market Correlation	Volatility of Exchange Rate Depreciation
$\log(\mathrm{EM_{ij}})$	0.142***	-4.453***
	(0.016)	(0.387)
$\log(\mathrm{IM_{ij}})$	0.015***	0.940***
	(0.006)	(0.125)
N	3078	990
R^2	0.109	0.129

We find that both the extensive and intensive margins have a positive and statistically significant effect on the correlation of stock market returns. However, the effect of the extensive margin of trade is one order of magnitude larger than that of the intensive margin of trade. In particular, all else equal, a 1% increase in the log of the extensive margin of trade increases the correlation of stock market returns between the trading partners by 0.142%, whereas a 1% increase of the log of the intensive margin increases the correlation by 0.015%. In the case of the volatility of the exchange rate, the extensive margin has a negative and statistically significant effect, whereas the intensive margin has a positive and statistically significant effect. That is, countries-pairs that trade a larger number of varieties with each other have a larger correlation of stock market returns and a lower volatility of the exchange rate.

To further corroborate our results, we next consider the two components of the R&D intensity of trade separately: (i) our measure of trade intensity ($X_{i,j}$), and (ii) a measure of R&D given by the stock of R&D in the two country pairs ($\mathrm{R\&D_{i,j}}$). We then regress our moments of asset pricing moments on these two components. The goal is to investigate whether including the total value of international trade across countries removes the significance of R&D. We report the regression results in Table 5, which shows that this is not the case. In fact, we find that R&D remains a significant driver of asset price comovement even when the regression incorporates the total value of international trade. These results imply that, for the same trade intensity, country-pairs that share more R&D have more correlated

stock market returns and less volatile exchange rates. In particular, holding trade intensity constant a 1% increase in the log of R&D between country i and country j, increases the correlation of stock market returns between these countries by 0.019% and decreases the volatility of exchange rate between these two countries by 0.151%.

Table 5: Asset prices, innovation and international trade. Standard errors in parentheses. *, **, and *** denote statistical significance at the 10%, 5%, and 1% level, respectively.

	(1)	(2)
	Stock Market Correlation	Volatility of Exchange Rate Depreciation
$\log(\mathrm{R\&D_{ij}})$	0.019***	-0.151***
	(0.003)	(0.048)
$\log(\mathrm{X_{i,j}})$	0.060***	-0.246***
	(0.003)	(0.058)
N	3078	990
R^2	0.105	0.034

Our results are robust to using disaggregated data at the industry-level. When we regress our asset pricing moments on the measure for R&D embodied in trade that we computed from industry level data, we find that R&D embodied in trade has a positive and statistically significant effect on the correlation of stock market returns and a negative and statistically significant effect on the volatility of exchange rate (see Table 6). In particular, holding trade intensity constant a 1% increase in the log of R&D between country i and country j, increases the correlation of stock market returns between these countries by 0.020 and decreases the volatility of exchange rate between these two countries by 0.192.

Table 6: Asset prices and R&D embodied in international trade at the industry level. Standard errors in parentheses. *, **, and *** denote statistical significance at the 10%, 5%, and 1% level, respectively.

	(1)	(2)
	Stock Market Correlation	Exchange Rate Volatility
$\log(\mathrm{X^{R\&D}_{ijh}})$	0.020***	-0.192***
	(0.001)	(0.019)
N	21058	5978

The speed of international adoption, international trade, and asset prices. Finally, we construct an empirical proxy for the speed of international adoption using a similar approach to the one used in Section 4.1. Specifically, for each country-pair, we regress the log of the extensive margin of trade against the average stock of R&D expenditures among the two countries including year fixed effects.[12] We then analyze the correlation between the estimated speed of adoption for each country-pair with: (i) international trade; and (ii) asset prices. Figure 8 shows that country-pairs with faster speed of adoption have a higher trade intensity and a higher extensive margin of trade. Figure 9 shows that, consistently with our suggestive evidence presented previously, country-pairs with a faster speed of adoption also have a larger cross-country correlation of stock market returns and a lower volatility of the exchange rate. In all, our empirical analysis suggests that the mechanism of the international diffusion of R&D proposed by our model is an important driver of the joint dynamics of international macro quantities and asset prices.

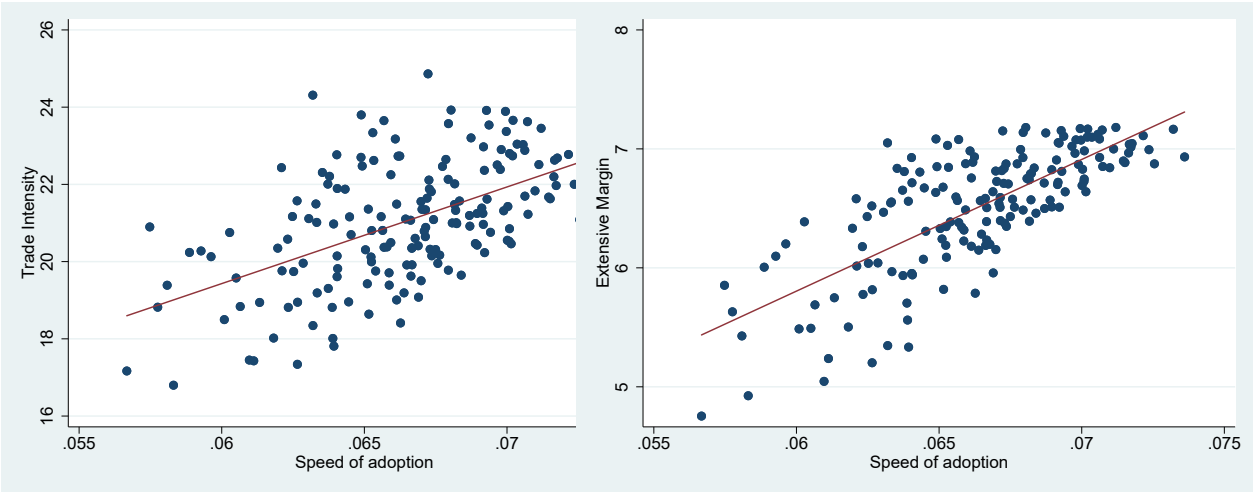


Figure 8: International trade and the speed of adoption. Each solid circle represents the time-series average over the 1996-2013 period of each country pair in our sample.

[12]This is slightly different from what we do in our calibration section as we compute one estimate of ϑ_d^f for each country pair, to be consistent with our empirical analysis.

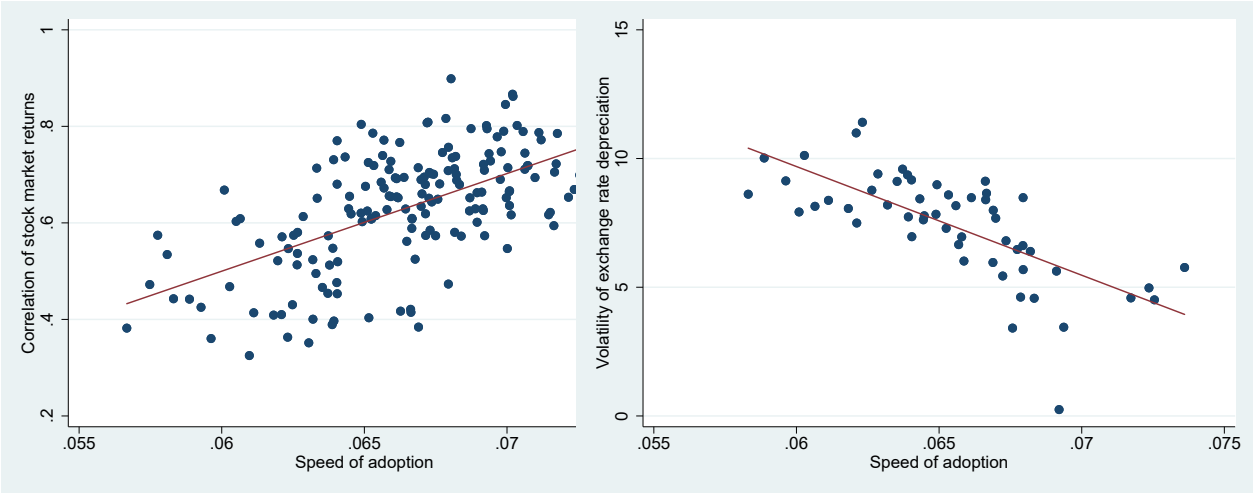


Figure 9: Asset prices and the speed of adoption. Each solid circle represents the time-series average over the 1996-2013 period of each country pair in our sample.

6 Conclusion

In this paper, we develop a multicountry general equilibrium model in which long-run risk arises endogenously in each country and then diffuses internationally. Specifically, we conduct a quantitative analysis of a symmetric, two-country, endogenous growth model of innovation, international adoption of foreign varieties, and international diffusion of ideas. We have shown—both theoretically and by way of a calibration exercise—that the joint presence of endogenous growth and recursive preferences has a significant impact on the equilibrium dynamics of both quantities and asset prices. In particular, we have seen that when both ingredients are present, the model generates expected consumption growth processes that are volatile, highly autocorrelated within country and highly correlated across countries. This is consistent with what has been advocated by the exogenous long-run risk literature in order to rationalize several international macroeconomic and asset pricing puzzles. Specifically, our model generates a low and smooth risk-free rate, large Sharpe ratios, and exchange rate volatility and cross-country correlation of macroeconomic quantities that are consistent with the data. Moreover, the model can generate substantial deviations from uncovered interest parity.

We provide suggestive empirical evidence of our proposed mechanism. In particular, we show that country pairs with a higher R&D content of international trade have more highly correlated stock market returns and less volatile exchange rates. Furthermore, we show that,

keeping the level of trade intensity constant, the more country-pairs are innovative the more correlated their stock market returns and the less volatile their exchange rates. In all, our results lend support to the hypothesis that international diffusion of R&D through trade in varieties is a powerful channel through which long-run risk spreads across countries.

The model developed in this paper features two symmetric countries. Thus it cannot directly be used to investigate the cross sectional aspects of countries featuring substantial asymmetries. Our model cannot, for instance, account for the cross section of currency risk premia. Future developments should relax the symmetry assumption and study the diffusion of innovation among countries with, for instance, different ability to innovate and different levels of financial development. More realistic trading frictions offer another promising direction for future research. We leave this issues to future work.

References

Backus, D. K., S. Foresi, and C. I. Telmer (2001, 02). Affine term structure models and the forward premium anomaly. *Journal of Finance 56*(1), 279–304.

Backus, D. K., F. Gavazzoni, C. Telmer, and S. E. Zin (2010, July). Monetary policy and the uncovered interest parity puzzle. Working Paper 16218, National Bureau of Economic Research.

Bansal, R., D. Kiku, and A. Yaron (2016). Risks for the long run: Estimation with time aggregation. *Journal of Monetary Economics 82*(Supplement C), 52 – 69.

Bansal, R. and I. Shaliastovich (2013). A long-run risks explanation of predictability puzzles in bond and currency markets. *Review of Financial Studies 26*(1), 1–33.

Bansal, R. and A. Yaron (2004, 08). Risks for the long run: A potential resolution of asset pricing puzzles. *Journal of Finance 59*(4), 1481–1509.

Boldrin, M., L. J. Christiano, and J. D. M. Fisher (2001, March). Habit persistence, asset returns, and the business cycle. *American Economic Review 91*(1), 149–166.

Brandt, M. W., J. H. Cochrane, and P. Santa-Clara (2006, May). International risk sharing is better than you think, or exchange rates are too smooth. *Journal of Monetary Economics 53*(4), 671–698.

Broda, C., J. Greenfield, and D. Weinstein (2006, September). From groundnuts to globalization: A structural estimate of trade and growth. NBER Working Papers 12512, National Bureau of Economic Research, Inc.

Christiano, L. J. and T. J. Fitzgerald (2003). The band pass filter. *international economic review 44*(2), 435–465.

Coe, D. T. and E. Helpman (1995, May). International R&D spillovers. *European Economic Review 39*(5), 859–887.

Colacito, R., M. Croce, S. Ho, and P. Howard (2018, November). Bkk the ez way: International long-run growth news and capital flows. *American Economic Review 108*(11), 3416–49.

Colacito, R. and M. M. Croce (2011). Risks for the long run and the real exchange rate. *Journal of Political Economy 119*(1), 153 – 181.

Colacito, R. and M. M. Croce (2013). International asset pricing with recursive preferences. *The Journal of Finance 68*(6), 2651–2686.

Colacito, R., M. M. Croce, F. Gavazzoni, and R. Ready (2018). Currency risk factors in a recursive multicountry economy. *The Journal of Finance 73*(6), 2719–2756.

Colacito, R., M. M. Croce, Y. Liu, and I. Shaliastovich (2015). Volatility risk pass-through. Working Paper.

Comin, D. and M. Gertler (2006, June). Medium-term business cycles. *American Economic Review 96*(3), 523–551.

Comin, D. A., M. Gertler, and A. M. Santacreu (2009). Technology innovation and diffusion as sources of output and asset price fluctuations.

Della Corte, P., S. J. Riddiough, and L. Sarno (2016). Currency premia and global imbalances. *The Review of Financial Studies 29*(8), 2161–2193.

Epstein, L. G. and S. E. Zin (1989, July). Substitution, risk aversion, and the temporal behavior of consumption and asset returns: A theoretical framework. *Econometrica 57*(4), 937–69.

Farhi, E. and X. Gabaix (2016). Rare disasters and exchange rates. *The Quarterly Journal of Economics 131*(1), 1–52.

Gabaix, X. and M. Maggiori (2015). International liquidity and exchange rate dynamics *. *The Quarterly Journal of Economics 130*(3), 1369–1420.

Griliches, Z. (1990, December). Patent Statistics as Economic Indicators: A Survey. *Journal of Economic Literature 28*(4), 1661–1707.

Grossman, G. M. and E. Helpman (1991). Trade, knowledge spillovers, and growth. *European economic review 35*(2-3), 517–526.

Hansen, L. P. and R. Jagannathan (1991). Implications of security market data for models of dynamic economies. *Journal of Political Economy 99*(2), 225–262.

Hanushek, E. A. (1974). Efficient estimators for regressing regression coefficients. *The American Statistician 28*(2), 66–67.

Hassan, T. and R. Mano (2014). Forward and spot exchange rates in a multi-currency world. Working paper, IMF and University of Chicago Working Paper.

Hassan, T. A. (2013). Country size, currency unions, and international asset returns. *The Journal of Finance 68*(6), 2269–2308.

Heyerdahl-Larsen, C. (2014). Asset prices and real exchange rates with deep habits. *The Review of Financial Studies 27*(11), 3280–3317.

Jermann, U. J. (1998). Asset pricing in production economies. *Journal of Monetary Economics 41*(2), 257–275.

Kaltenbrunner, G. and L. A. Lochstoer (2010). Long-Run Risk through Consumption Smoothing. *Review of Financial Studies 23*(8), 3190–3224.

Keller, W. (1998, September). Are international R&D spillovers trade-related?: Analyzing spillovers among randomly matched trade partners. *European Economic Review 42*(8), 1469–1481.

Keller, W. (2004). International technology diffusion. *Journal of economic literature 42*(3), 752–782.

Kung, H. and L. Schmid (2015). Innovation, growth, and asset prices. *The Journal of Finance 70*(3), 1001–1037.

Lewis, J. B. and D. A. Linzer (2005). Estimating regression models in which the dependent variable is based on estimates. *Political analysis 13*(4), 345–364.

Lustig, H., N. Roussanov, and A. Verdelhan (2011). Common risk factors in currency markets. *Review of Financial Studies 24*(11), 3731–3777.

Lustig, H., N. Roussanov, and A. Verdelhan (2014). Countercyclical currency risk premia. *Journal of Financial Economics 111*(3), 527–553.

Maggiori, M. (2017, October). Financial intermediation, international risk sharing, and reserve currencies. *American Economic Review 107*(10), 3038–71.

Mueller, P., A. Stathopoulos, and A. Vedolin (2017). International correlation risk. *Journal of Financial Economics 126*(2), 270 – 299.

Nishioka, S. and M. Ripoll (2012). Productivity, trade and the R&D content of intermediate inputs. *European Economic Review 56*(8), 1573–1592.

Rabitsch, K., S. Stepanchuk, and V. Tsyrennikov (2015). International portfolios: A comparison of solution methods. *Journal of International Economics*, –.

Ready, R., N. Roussanov, and C. Ward (2017). Commodity trade and the carry trade: A tale of two countries. *The Journal of Finance 72*(6), 2629–2684.

Romer, P. M. (1990). Endogenous technological change. *Journal of political Economy*, S71–S102.

Santacreu, A. M. (2015). Innovation, diffusion, and trade: Theory and measurement. *Journal of Monetary Economics 75*, 1–20.

Stathopoulos, A. (2017). Asset prices and risk sharing in open economies. *The Review of Financial Studies 30*(2), 363–415.

Tallarini, T. D. (2000, June). Risk-sensitive real business cycles. *Journal of Monetary Economics 45*(3), 507–532.

Verdelhan, A. (2010, 02). A habit-based explanation of the exchange rate risk premium. *Journal of Finance 65*(1), 123–146.

White, H. (1980). A heteroskedasticity-consistent covariance matrix estimator and a direct test for heteroskedasticity. *Econometrica: Journal of the Econometric Society*, 817–838.

Zviadadze, I. (2017). Term structure of consumption risk premia in the cross section of currency returns. *The Journal of Finance 72*(4), 1529–1566.

Appendix

A Model Equations

This appendix consists of all the equations used to characterize the domestic economy. The foreign economy is represented by a set of analogous equations.

Preferences

$$U_{d,t} = \left\{ (1-\beta) C_{d,t}^{\theta} + \beta \left(E_t \left(U_{d,t+1}^{1-\gamma} \right) \right)^{\frac{\theta}{1-\gamma}} \right\}^{\frac{1}{\theta}}$$

Stochastic discount factor

$$M_{d,t+1} = \beta \left(\frac{C_{d,t+1}}{C_{d,t}} \right)^{\theta-1} \left(\frac{U_{d,t+1}}{E_t \left(U_{d,t+1}^{1-\gamma} \right)^{\frac{1}{1-\gamma}}} \right)^{1-\gamma-\theta}$$

Final producers

$$Y_{d,t} = (Z_{d,t} L_{d,t})^{1-\alpha} K_{d,t}^{\alpha}$$

Labor

$$L_{d,t} = 1$$

Aggregate productivity

$$Z_{d,t} \equiv \Omega_{d,t} \left(\tilde{A} \right)^{\frac{1}{1-\alpha}} \left[h N_{d,t}^{d} + \left(\frac{h}{1-h} \mathcal{E}_t \right)^{\frac{\nu}{\nu-1}} N_{f,t}^{d} \right]$$

$$\tilde{A} = (\xi \nu)^{\frac{\xi}{1-\xi}}$$

$$\Omega_{d,t} = e^{a_{d,t}}$$

$$a_{d,t} = \varphi \; a_{d,t-1} + \varepsilon_{d,t}$$

First order condition of labor

$$W_{d,t} = (1-\alpha)(1-\xi)\frac{Y_{d,t}}{L_{d,t}}$$

First order condition of investment

$$q_{d,t} = \frac{1}{\Lambda'_{d,t}}$$

$$1 = E_t\left[M_{d,t+1}\left\{\frac{1}{q_{d,t}}\left(\alpha(1-\xi)\frac{Y_{d,t+1}}{K_{d,t+1}} + q_{d,t+1}(1-\delta) - \frac{I_{d,t+1}}{K_{d,t+1}} + q_{d,t+1}\Lambda_{d,t+1}\right)\right\}\right]$$

Law of motion of capital

$$K_{d,t+1} = (1-\delta)K_{d,t} + \Lambda_{d,t}K_{d,t}$$

Investment adjustment costs

$$\Lambda_{d,t} \equiv \Lambda\left(\frac{I_{d,t}}{K_{d,t}}\right) = \frac{\alpha_1}{\zeta}\left(\frac{I_{d,t}}{K_{d,t}}\right)^{\zeta} + \alpha_2$$

$$\Lambda'_{d,t} = \alpha_1\left(\frac{I_{d,t}}{K_{d,t}}\right)^{\zeta-1}$$

Demand for domestic intermediate goods

$$X^d_{d,t} = (h\xi\nu Y_{d,t}G^{-\nu}_{d,t})^{\frac{1}{1-\nu}}$$

Demand for foreign intermediate goods (imports)

$$X^d_{f,t} = (\mathcal{E}_t^{-1}\nu Y_{d,t}G^{-\nu}_{d,t}\xi(1-h))^{\frac{1}{1-\nu}} = X^d_{d,i,t}\left(\mathcal{E}_t\frac{h}{1-h}\right)^{\frac{1}{\nu-1}}$$

Materials (intermediate goods)

$$G_{d,t} = \xi\nu Y_{d,t}\left[hN^d_{d,t} + \left(\frac{h}{1-h}\mathcal{E}_t\right)^{\frac{\nu}{\nu-1}} N^d_{f,t}\right]^{\frac{1-\nu}{\nu}}$$

Profits of intermediate producers

$$\Pi_{d,t}N^d_{d,t} = \pi^d_{d,t}N^d_{d,t} + \pi^f_{d,t}N^f_{d,t}$$

Profits of domestic producers in the domestic market

$$\pi^d_{d,t} = \left(\frac{1}{\nu} - 1\right) X^d_{d,t}$$

Profits of domestic producers in the foreign market

$$\pi^f_{d,t} = \left(\frac{1}{\nu} - 1\right) X^f_{d,t}$$

Present Discounted Value (PDV) of a domestic producers selling in the domestic market

$$V^d_{d,t} = \pi^d_{d,t} + (1-\phi)E_t[M_{d,t+1}V^d_{d,t+1}]$$

PDV of a domestic producers selling in the domestic market

$$V^f_{d,t} = \pi^f_{d,t} + (1-\phi)E_t[M_{d,t+1}V^f_{d,t+1}]$$

PDV of a domestic producers not-yet selling in the domestic market

$$J^f_{d,t} = -H^f_{d,t} + (1-\phi)E_t\left[M_{d,t+1}\left(\vartheta^f_d V^f_{dt+1} + (1-\vartheta^f_d)J^f_{d,t+1}\right)\right]$$

Value of an innovation

$$V_{d,t} = V^d_{d,t} + J^f_{d,t}$$

Law of motion of new technologies

$$N^d_{d,t+1} = \vartheta_{d,t}S_{d,t} + (1-\phi)N^d_{d,t}$$

$$\vartheta_{d,t} = \frac{\chi(N^d_{d,t} + \iota N^d_{f,t})}{S^{1-\eta}_{d,t}(N^d_{d,t})^\eta}$$

Free entry condition of innovation

$$S_{d,t} = E_t\left[M_{d,t+1}V_{d,t+1}\right]\left(N^d_{d,t+1} - (1-\phi)N^d_{d,t}\right)$$

Law of motion of adopted technologies

$$N^f_{d,t+1} = \vartheta^f_d(1-\phi)(N^d_{d,t} - N^f_{d,t}) + (1-\phi)N^f_{d,t}$$

Probability of adoption

$$\vartheta^f_{d,t} = \chi_a \left(\frac{H^f_{d,t}}{N_{f,t}}\right)^{\eta_a}$$

First order condition of adoption

$$H^f_{d,t} = \eta_a(1-\phi)\vartheta^f_{d,t}E_t\left[M_{f,t+1}\left(V^f_{d,t+1} - J^f_{d,t+1}\right)\right]$$

Resource constraint

$$Y_{d,t} = C_{d,t} + I_{d,t} + S_{d,t} + N^d_{d,t}X^d_{d,t} + N^f_{d,t}X^f_{d,t} + H^d_{f,t}$$

Dividends

$$\mathcal{D}_{d,t} = D_{d,t} + N^d_{d,t}\pi^d_{d,t} + N^d_{f,t}\pi^d_{f,t} - S_{d,t}$$

International risk sharing

$$\frac{\mathcal{E}_{t+1}}{\mathcal{E}_t} = \frac{M_{f,t+1}}{M_{d,t+1}}$$

B Analytical Approximation of the Risk-Free Rate

In this Appendix, we follow Colacito and Croce (2013) and derive an approximate analytical expression for the risk-free rate. Define $\tilde{U}_{d,t} \equiv U_{d,t}/C_{d,t}$. The log SDF is

$$\log M_{d,t+1} = \log \beta - \frac{1}{\psi}\Delta c_{d,t+1} + \left(\frac{1}{\psi} - \gamma\right) \log \tilde{U}_{d,t+1} - \frac{1/\psi - \gamma}{1-\gamma} \log E_t \left[e^{(1-\gamma)\log \tilde{U}_{d,t+1}}\right]$$

Assume $\tilde{U}_{d,t}$ is approximately log-normally distributed. The log SDF can be approximated as

$$\begin{aligned} \log M_{d,t+1} &= \log \beta - \frac{1}{\psi}\Delta c_{d,t+1} + \left(\frac{1}{\psi} - \gamma\right) \log \tilde{U}_{d,t+1} - (1/\psi - \gamma) E_t \left[\tilde{U}_{d,t+1}\right] \\ &- \frac{1}{2}(1-\gamma)\left(\frac{1}{\psi} - \gamma\right) Var_t \left[\tilde{U}_{d,t+1}\right] \end{aligned}$$

Therefore, the risk free rate is

$$\begin{aligned} r^f_{d,t} &= -\log E_t \left[e^{\log M_{d,t+1}}\right] \\ &= \frac{1}{\psi} E_t[\Delta c_{d,t+1}] - \frac{1}{2}\left(\frac{1}{\psi}\right)^2 Var_t[\Delta c_{d,t+1}] + \frac{1}{2}\left(1 - \frac{1}{\psi}\right)\left(\frac{1}{\psi} - \gamma\right) Var_t[\log \tilde{U}_{d,t+1}] \\ &+ \frac{1}{\psi}\left(\frac{1}{\psi} - \gamma\right) Cov_t \left[\Delta c_{d,t+1}, \log \tilde{U}_{d,t+1}\right] \end{aligned}$$

From our simulations, the main contribution to the overall volatility of the risk-free rate comes from the first term, $(1/\psi)E_t[\Delta c_{d,t+1}]$.

C A Model with Exogenous Long-Run Risk

In this appendix, we modify our baseline model to highlight the differences with a production model of exogenous long-run risk. In the spirit of Colacito, Croce, Ho, and Howard (2018), we consider a production economy in which: (i) growth is exogenous, and (ii) the productivity shocks explicitly contain long-run risk. First, we shut down the endogenous growth mechanism: new ideas arrive exogenously according to a Poisson process so that the steady-state growth rate of consumption does not change and international adoption is exogenous. Second, following the exogenous long-run risk literature, we modify the law of motion of the domestic productivity shock as follows:

$$\begin{aligned} a_{d,t} &= \varphi\ a_{d,t-1} + l_{d,t} + \rho_{ec}(a_{f,t-1} - a_{d,t-1}) + \sigma_a \varepsilon_{d,t} \\ l_{d,t} &= \varphi_l\ l_{d,t-1} + \sigma_l \varepsilon^l_{d,t} \end{aligned}$$

where $l_{d,t}$ represents the long-run risk component, $\varphi_l = 0.97$ as it is commonly found in the long-run risk literature, and ε_d and ε^l_d are independent $(0, 1)$ normally distributed innovations.

We perform two calibration exercises. In both of them we keep the overall volatility of the productivity process and the volatility of the depreciation rate equal to their values in our benchmark model. We choose the σ_l/σ_a ratio in two ways. First, we calibrate it so that the size of the long-run shock — relative to the short-run shock — is consistent with the estimates of the exogenous long-run risk literature (see, among others, Bansal and Yaron 2004, Colacito and Croce 2013, and Colacito, Croce, Ho, and Howard 2018). Second, we choose the σ_l/σ_a ratio to match the volatility of expected consumption growth generated by our baseline model with endogenous growth.[13] We find that, in this second exercise, the long-run risk component is relatively smaller, implying that the variation in expected consumption growth generated by our benchmark model is less than what is commonly found in the exogenous long-run risk literature. Quantitatively, we can only generate one third of this variation (i.e., 0.014 vs. 0.042). Table A1 shows the results for the two calibration of the model with exogenous long-run risk and compare them with those of our benchmark model with endogenous growth.

[13] A calibration targeting the volatility of expected future productivity, another measure of long-run risk in the model, delivers similar results.

Table A1: Simulated moments for our baseline model of Section 4.2 and the exogenous long-run risk model of this Appendix. While conducting the two calibration exercises, we modify the cross-country correlation in the long-run shocks to keep the volatility of the depreciation rate in line with what we obtain in our baseline model.

	Baseline	EXO-LRR $\sigma_l/\sigma_a = 0.014$	EXO-LRR $\sigma_l/\sigma_a = 0.042$
$Std(\Delta z)$	3.685	3.686	3.686
$Std(r^f)$	0.112	0.142	0.411
$Std(E_t(\Delta c_{t+1}))$	0.174	0.178	0.573

D A Reduced-Form Model of Long-Run Risk Spillovers

Following the seminal paper of Bansal and Yaron (2004), the long-run risk literature has forcefully argued in favor of the existence of a small, predictable news component driving the future prospects of the economy. For this component to have important quantitative implications for asset prices it must be priced — hence the use of recursive preferences — but it also needs to be: i) highly autocorrelated *within* a country, and ii) highly correlated *across* countries. Where does long-run risk come from? Previous studies have investigated how, in the context of a one-country general equilibrium model, long-run risk can arise endogenously from agent's consumption and investment decisions. Our paper proposes a mechanism to understand the drivers of the high cross-country correlation of the long-run risk across countries: international technology diffusion. In this section, we describe a reduced-form model that captures our novel mechanism of international diffusion of long-run risk. In Section 2, we introduce our benchmark general equilibrium model, in which we endogenize such mechanism.

Let the home and foreign long-run risk be described by the following two-dimensional autoregressive process $x_t \equiv (x_t^H, x_t^F)'$:

$$x_t = \Phi x_{t-1} + \varepsilon_t \quad . \tag{29}$$

We restrict our attention to a symmetric calibration in which the autocorrelation matrix Φ is given by

$$\Phi = \begin{pmatrix} \varphi & \varphi_H^F \\ \varphi_H^F & \varphi \end{pmatrix}$$

and the $\varepsilon \equiv (\varepsilon^H, \varepsilon^F)'$ innovations are *i.i.d.* and normally distributed as follows:

$$\begin{pmatrix} \varepsilon^H \\ \varepsilon^F \end{pmatrix} \sim \left(\begin{bmatrix} 0 \\ 0 \end{bmatrix}, \begin{bmatrix} \sigma_\varepsilon^2 & \rho_\varepsilon \sigma_\varepsilon^2 \\ \rho_\varepsilon \sigma_\varepsilon^2 & \sigma_\varepsilon^2 \end{bmatrix} \right) \quad .$$

For stationarity, the eigenvalues of Φ must lie within the unit circle. To showcase the mechanism of our paper, we analyze two versions of equation (29), both of which generate the required correlation structure of long-run risk.

First, we consider a *univariate* long-run risk specification, in which we shut down the off-diagonal elements of the autocorrelation matrix Φ, by imposing $\varphi_H^F = 0$. In this case, lagged values of x^F (x^H) *do not* affect current values of x^H (x^F). With this restriction in place, it is straightforward to show that $Corr(x_t^H, x_{t-1}^H) = Corr(x_t^F, x_{t-1}^F) = \varphi$ and $Corr(x_t^H, x_t^F) = \rho_\varepsilon$. Therefore, for long-run risk to be highly correlated both *within* and *across* countries, it must be that $\varphi \approx +1$ and $\rho_\varepsilon \approx +1$. Many papers have studied the nature of the autocorrelation coefficient φ and its effect on asset prices (see, among others, Bansal and Yaron 2004 and Bansal, Kiku, and Yaron 2016). In this paper, we focus on the cross-country correlation and notice that in this univariate specification it can be as high as prescribed by the literature only if we assume a high cross-country correlation in the long-run innovations, ε^H and ε^F. This is the solution adopted by Bansal and Shaliastovich (2013) and Colacito and Croce (2011). In sum, for a univariate specification to work, one must assume both a high autocorrelation coefficient and a high cross-country correlation in long-run innovations.

The second specification we consider is a *bivariate* long-run risk process which is closer in spirit to the mechanism of our general equilibrium model. This specification features an international spillover effect, which we capture by allowing for non-zero off-diagonal elements of Φ ($\varphi_H^F \neq 0$). Therefore, lagged values of x^F (x^H) *do* affect current realizations of x^H (x^F). In order to isolate the effect of the interaction term on the correlation structure of home and foreign long-run risk, we shut down the cross-country correlation in the ε shocks and impose $\rho_\varepsilon = 0$.[14] We ask the following question: How strong must the spillover effect be in order to obtain a high cross-country correlation between x^H and x^F? The answer is: *not much*. To see this, we conduct a simple sensitivity exercise in which we change, gradually, the intensity of the international spillover effect. What is striking is that a small international spillover is enough to generate a large cross-country correlation of long-run risk. For example, for values as small as $\varphi_H^F = 0.05$, the cross-country correlation is as high as 0.80.

While the magnitude of the spillover effects is hard to interpret in this reduced-form setting, in the next section we present a general equilibrium model in which they are tightly connected

[14] This restriction is relaxed in the full model of Section 2.

with the international diffusion of technologies, generating a strong comovement between home and foreign long-run growth prospects.

A bivariate VAR model of international long-run risk: Calibration. The high cross-country correlation of expected consumption growth that we obtain in our baseline calibration is a consequence of the spillover effect introduced by the adoption of foreign technologies. We conduct the same exercise using simulated data and, for each of the 5,000 simulations of 72 quarters from our baseline calibration, we estimate the following two-dimensional VAR(1) process

$$\begin{pmatrix} E_t(\Delta c^d_{t+1} - \mu) \\ E_t(\Delta c^f_{t+1} - \mu) \end{pmatrix} = \Phi \begin{pmatrix} E_{t-1}(\Delta c^d_t - \mu) \\ E_{t-1}(\Delta c^f_t - \mu) \end{pmatrix} + \Sigma \begin{pmatrix} \varepsilon^d_{t+1} \\ \varepsilon^f_{t+1} \end{pmatrix} \quad ,$$

where μ is the unconditional mean of consumption growth, Φ is the autocorrelation matrix and Σ is the variance-covariance matrix associated with the innovation $(\varepsilon^d_{t+1}, \varepsilon^f_{t+1})$. We let the model tell us the correlation structure in the innovations. We obtain the following results:

$$\Phi = \begin{pmatrix} 0.89 & 0.01 \\ 0.01 & 0.89 \end{pmatrix} \quad ; \qquad \Sigma = 10^{-8} \begin{pmatrix} 2.16 & 1.24 \\ 1.24 & 2.16 \end{pmatrix} \quad .$$

Expected consumption growth is volatile and its international correlation structure depends not only on the cross-country correlation in the innovations but also on the spillover effect. Indeed, the off-diagonal elements of the autocorrelation matrix are positive and statistically different from zero. We can also estimate moments associated with this VAR specification. We find that expected consumption growth, our measure of long-run risk, is highly persistent *within* a country ($corr(E_t(\Delta c_{t+1}), E_{t-1}(\Delta c_t)) = 0.93$) and *across* countries ($corr(E_t(\Delta c^d_{t+1}), E_t(\Delta c^f_{t+1})) = 0.51$).

E Future productivity growth

From equation (20),

$$Z_{d,t}^{ENDO} \propto \left[hN_{d,t}^{d} + \left(\frac{h}{1-h} \mathcal{E}_t \right)^{\frac{\nu}{\nu-1}} N_{f,t}^{d} \right], \tag{30}$$

Log-linearizing the expression around the steady state, taking growth rates and expectations, we have

$$\frac{\bar{Z}_d}{\bar{N}_d^d} E_t \Delta \log(Z_{d,t+1}^{ENDO}) \propto \left[hE_t \Delta \log(n_{d,t+1}^{d}) + \left(\frac{h}{1-h} \right)^{\frac{\nu}{\nu-1}} \frac{\bar{N}_f^d}{\bar{N}_d^d} \left(\frac{\nu}{\nu-1} E_t \Delta \log(\mathcal{E}_{t+1}) + E_t \Delta \log(n_{f,t+1}^{d}) \right) \right], \tag{31}$$

where $\bar{X}$ reflect the steady-state value of variable X.

Now we need to obtain $E_t \Delta \log(n_{d,t+1}^{d})$ and $E_t \Delta \log(n_{f,t+1}^{d})$. From equation (9),

$$E_t \Delta \log(n_{d,t+1}^{d}) \approx (1-\phi) + \chi \left(\frac{S_{d,t}}{N_{d,t}^{d}} \right)^{\eta}$$

and from equation (12),

$$E_t \Delta \log(n_{f,t+1}^{d}) \approx (1-\phi)(1-\vartheta) + (1-\phi)\vartheta E_t \Delta \log(n_{f,t+1}^{f}) \frac{N_{f,t}^{f}}{N_{f,t}^{d}}$$

which can also be written as

$$E_t \Delta \log(n_{f,t+1}^{d}) \approx (1-\phi)(1-\vartheta_d^f) + (1-\phi)\vartheta_d^f \chi \left(\frac{S_{f,t}}{N_{f,t}^{f}} \right)^{\eta} \frac{N_{f,t}^{f}}{N_{f,t}^{d}}$$

Substituting into equation (31)

$$E_t \Delta \log(Z_{d,t+1}^{ENDO}) \approx \left[h\chi \left(\frac{S_{d,t}}{N_{d,t}^{d}} \right)^{\eta} + \left(\frac{h}{1-h} \right)^{\frac{\nu}{\nu-1}} \frac{\bar{N}_f^d}{\bar{N}_d^d} \left(\frac{\nu}{\nu-1} E_t \Delta \log(\mathcal{E}_{t+1}) + (1-\phi)\vartheta_d^f \chi \left(\frac{S_{f,t}}{N_{f,t}^{f}} \right)^{\eta} \frac{N_{f,t}^{f}}{N_{f,t}^{d}} \right) \right] \tag{32}$$

F Trade Data, Asset Prices, and Comovements

In this appendix, we describe the relevant trade data and asset prices, after which we construct the measures used in our analysis.

Trade Data

The source of our trade data is UN COMTRADE. We collect product data at the 6-digit level of disaggregation; these data are annual and cover the period 1996-2013. Our focus is on the trade that occurs between importer i (identified by its IISCODE) and exporter j (identified by its EISCODE). We therefore collect data on the product types being traded (using their 6-digits identifiers it) and the dollar value of the trade in each product (i.e., the per-product trade value).

To derive our preliminary statistics, we calculate the fraction of world trade and world GDP accounted for by the countries in our sample (those countries are listed in footnote 5).

From this data, we construct the following measures:

- Trade Intensity (i, j): $\tilde{X}_{i,j}$, the sum of the trade value of all traded products from country j to country i
- Extensive margin (i, j): $EM_{i,j}$, the number (the"count") of different types of goods imported by country i from country j
- Intensive Margin (i, j): $IM_{i,j}$, "how much", in US dollars, country i is trading on average for each product imported from country j

In order to compare these numbers across pairs of countries, we normalize them while accounting for each country's GDP. These normalized measures are defined as

$$X_{i,j} = \frac{\tilde{X}_{i,j} + \tilde{X}_{j,i}}{GDP_i + GDP_j}$$

Each country pair is ordered: i is the importer and j is the exporter, i.e., $X_{i,j}$ will usually be different from $X_{j,i}$. We want to make sure that the relationship $X_{i,j} = EM_{i,j}IM_{i,j}$ holds, so that, taking logs, we can easily run linear regressions.

Industry-Level Data

- R&D data: We use R&D spending data from the OECD STAN database at industry level (ISIC REV.4 classification). We use the 7 most aggregated manufacturing industries: D10T12, D13T15, D16T18, D19T23, D24T25, D26T30, D31T33 for the year 1996-2013.

- Trade data: We bilateral trade data from the OECD STAN database at industry level (ISIC REV.4 classification), and aggregate them to the same 7 industries as R&D data above for the year 1996-2013.

Asset Prices

We consider two main statistics for asset prices: the cross-country correlation in stock market returns and the volatility of the currency depreciation rate. We start from monthly observations of stock market returns (from Ken French's website) and exchange rates (from Global Financial Data). Then, using twelve monthly observation for each year of our sample, we construct the following measures:

Stock Market

- Annual cross-country stock market return correlations between country i and country j, $corr(r^s_{i,t}, r^s_{j,t})$, for each year t.

Exchange Rate

- Annual volatility of currency i depreciation rate with respect to currency j, $vol(\Delta q^j_{i,t})$, for each year t. The log depreciation rate for currency i with respect to currency j is defined as $\Delta e^j_{i,t} = e^j_{i,t} - e^j_{i,t-1}$, where $e^j_{i,t}$ is the log exchange rate level at time t for country i (in units of currency i per one unit currency j).

G Estimated Dependent Variable: Robust Standard Errors and FGLS

In our regression analysis in Section 5, the left-hand-side variables (i.e. the exchange rate volatility and the stock market correlation) are subject to sampling uncertainty and are therefore measured with error. Variation in the sampling variance of the observations on the dependent variable induces heteroskedasticity and, when the sampling error represents a significant fraction of the variation in the dependent variable, the estimated coefficients are inefficient and the standard errors are too small. In this appendix, we follow Lewis and Linzer (2005) and correct for sampling uncertainty in two ways. First, we run OLS regressions using White (1980)'s robust standard errors clustered by country pairs. Second, we use the feasible generalized least squares (FGLS) first suggested by Hanushek (1974).

OLS with robust standard errors leave the estimated coefficients unchanged while addressing the potential heteroskedasticity of the measurement error. The results are reported in the third column of Tables E.1-E.6. Compared to the case in which we use standard OLS standard errors (first column), the estimated coefficients remain statistically significant, despite generating wider confidence intervals.[15]

FGLS has the ability to improve the efficiency of the estimates, in particular when the sampling error represents a significant fraction of the variation in the dependent variable. First, we compute Newey-West standard errors for each observation of the dependent variable and use them as our estimate for the true sampling variance. Then, we follow the procedure described in Lewis and Linzer (2005) to estimate our regressions using FGLS: we run a first-step standard OLS regression and use the obtained residuals and our estimated standard errors of the dependent variable to construct the weights for a second stage weighted least square regression. Coefficients estimated with FGLS are more efficient than those estimated with OLS, especially when the fraction of total regression error variance is due to sampling error. Moreover, standard errors produce less overconfidence than what is usually found with OLS. The results are reported in the second column of Tables E.1-E.6. The estimated coefficients are similar to those estimate using OLS and in some cases they even generate stronger results in favor of our mechanism. Moreover, they remain statistically significant.[16]

Finally, we show that our regression results using more disaggregated data (i.e., industry-level data) are also robust to the use of robust standard errors and FGLS (see Tables E.7 and E.8).

[15] An exception to this result is in Table E.4, where the coefficient is no longer significant. However, as we show next, when we use FGLS, the coefficient is more efficient and statistically significant.

[16] An exception to this result is in Table E.6, where the coefficient is no longer significant. However, in the case of robust standard errors the coefficient is statistically significant.

Table E.1: Stock market correlation and R&D embodied in international trade. Standard errors in parentheses. *, **, and *** denote statistical significance at the 10%, 5%, and 1% level, respectively.

	(1)	(2)	(3)
	OLS	FGLS	Robust SE
$\log(X_{ij}^{R\&D})$	0.111***	0.116***	0.111***
	(0.006)	(0.007)	(0.012)
N	3060	3060	3060

Table E.2: Stock market correlation and the margins of international trade. Standard errors in parentheses. *, **, and *** denote statistical significance at the 10%, 5%, and 1% level, respectively.

	(1)	(2)	(3)
	OLS	FGLS	Robust SE
$\log(EM_{ij})$	0.142***	0.138***	0.142***
	(0.016)	(0.018)	(0.025)
$\log(IM_{ij})$	0.0148***	0.0186***	0.015
	(0.006)	(0.005)	(0.009)
N	3060	3060	3060

Table E.3: Stock market correlation, innovation and international trade. Standard errors in parentheses. *, **, and *** denote statistical significance at the 10%, 5%, and 1% level, respectively.

	(1)	(2)	(3)
	OLS	FGLS	Robust SE
$\log(R\&D_{ij})$	0.019***	0.023***	0.019***
	(0.003)	(0.003)	(0.006)
$\log(X_{ij})$	0.060***	0.059***	0.060***
	(0.087)	(0.089)	(0.179)
N	3060	3060	3060

Table E.4: Volatility of exchange rate depreciation and R&D embodied in international trade. Standard errors in parentheses. *, **, and *** denote statistical significance at the 10%, 5%, and 1% level, respectively.

	(1)	(2)	(3)
	OLS	FGLS	Robust SE
$\log(X_{ij}^{R\&D})$	-0.321**	-0.567***	-0.321
	(0.150)	(0.143)	(0.313)
N	990	990	990

Table E.5: Volatility of exchange rate depreciation and the margins of international trade. Standard errors in parentheses. *, **, and *** denote statistical significance at the 10%, 5%, and 1% level, respectively.

	(1)	(2)	(3)
	OLS	FGLS	Robust SE
$\log(\mathrm{EM_{ij}})$	-4.453***	-5.329***	-4.453***
	(0.387)	(0.503)	(0.958)
$\log(\mathrm{IM_{ij}})$	0.940***	0.797***	0.940***
	(0.125)	(0.125)	(0.287)
N	990	990	990

Table E.6: Volatility of exchange rate depreciation, innovation and international trade.Standard errors in parentheses. *, **, and *** denote statistical significance at the 10%, 5%, and 1% level, respectively.

	(1)	(2)	(3)
	OLS	FGLS	Robust SE
$\log(\mathrm{R\&D_{ij}})$	-0.151***	-0.0843	-0.151**
	(0.0477)	(0.0725)	(0.0574)
$\log(\mathrm{X_{ij}})$	-0.246***	-0.573***	-0.246**
	(0.0585)	(0.0782)	(0.114)
N	990	990	990

Table E.7: Exchange rate volatility and R&D embodied in international trade at the industry level

	(1)	(2)	(3)
	OLS	FGLS	Robust SE
$\log(\mathrm{X_{ijh}^{R\&D}})$	-0.192***	-0.482***	-0.192
	(0.019)	(0.026)	(0.096)
N	5978	5978	5978

Table E.8: Stock market correlation and R&D embodied in international trade at the industry level

	(1)	(2)	(3)
	OLS	FGLS	Robust SE
$\log(X_{ijh}^{R\&D})$	0.020^{***}	0.022^{***}	0.020^{***}
	(0.001)	(0.001)	(0.003)
N	21058	21058	21058