HOUSE OF FINANCE

WORKING PAPER SERIES

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Technology Trade with Asymmetric Tax Regimes and Heterogeneous Labor Markets: Implications for Macro Quantities and Asset Prices

SAFE Working Paper No. 163

SAFE | Sustainable Architecture for Finance in Europe
A cooperation of the Center for Financial Studies and Goethe University Frankfurt

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Non-Technical Summary

Early empirical works provide evidence of a positive relationship between cross-country technology diffusion and international growth. In particular, it has been shown that trading patents internationally contributes to world productivity. Moreover, adopting foreign technologies might be more beneficial than producing new technologies internally. Therefore, international knowledge diffusion represents an important source of global productivity growth.

Using a newly available dataset on technology, more recent empirical analyses indicate a positive association between economies' expenditure for the acquisition of foreign technologies (i.e. adoption) and labor productivity growth. In addition, they show that investments in the adoption of foreign technologies and goods appear to be – on average – a stronger contributor than domestic investments in R&D. However, being successful in adopting new technologies may depend on country-specific fundamentals.

Based on these findings, we examine the equilibrium effects of technology and adoption shocks on international macroeconomic aggregates and asset prices in the presence of heterogeneous economies. Following the most recent literature on international endogenous growth, we develop a two-country model where economic growth is driven by internal production of new technology (via R&D) and international technology trade (via adoption). Given that economies tend to differ in their fundamentals, cross-country heterogeneity is accounted for. Specifically, it is assumed that the two countries are heterogeneous in their fiscal policy and in the flexibility of their labor market. To be closer to the current European scenario, we rely on (i) a fiscally weak country that employs a zero deficit fiscal rule and has, at the same time, a relatively rigid labor market, and (ii) a fiscally strong country that is allowed to run a small deficit temporarily in bad macroeconomic conditions and has a relatively flexible labor market.

Our quantitative analysis shows that country heterogeneity has non-negligible effects on international technology diffusion. First, a positive adoption probability shock in the fiscally constrained economy leads to increases in all macroeconomic aggregates but consumption domestically. The foreign fiscally flexible economy displays an initial decline in all macroeconomic aggregates but investment and labor which, however, turns positive in the long run. On the contrary, investment and labor in the foreign economy increases for over 80 quarters after the domestic adoption probability shock. The effects on the foreign economy are smaller in magnitude but more persistent than the effects on the domestic economy.

Second, a positive productivity shock in the fiscally constrained economy increases the availability of new technology and stimulates economic growth in both countries. However, in the foreign economy which can run a deficit the beneficial effect of the shock is weaker but more long lasting. Labor market rigidities impair the ability of wages to counteract the effects of macroeconomic shocks. Therefore, a more rigid labor market is more exposed to macroeconomic shocks than a frictionless labor market. These structural differences affect the future growth prospects of the two countries and are reflected in asset returns. In our model, investors command a return premium to invest in the country characterized by a zero-deficit fiscal policy and rigid labor markets, consistent with empirical evidence. Moreover, the country with a zero-deficit fiscal policy and relatively rigid labor markets displays higher volatilities of major macroeconomic aggregates than the country which can run deficits and has a relatively flexible labor market, exactly as in the data.

Technology Trade with Asymmetric Tax Regimes and Heterogeneous Labor Markets: Implications for Macro Quantities and Asset Prices

Giuliano Curatola* Michael Donadelli* Patrick Grüning**

This version: January 9, 2017

Abstract

The international diffusion of technology plays a key role in stimulating global growth and explaining co-movements of international equity returns. Existing empirical evidence suggests that countries are heterogeneous in their attitude toward innovation: Some countries rely more on technology adoption while other countries rely more on internal technology production. European countries that rely more on adoption are also typically characterized by lower fiscal policy flexibility and higher labor market rigidity. We develop a two-country model – where both countries rely on R&D and adoption – to study the short-run and long-run effects of aggregate technology and adoption probability shocks on economic growth in the presence of the aforementioned asymmetries. Our framework suggests that an increase in the ability to adopt technology from abroad stimulates economic growth in the country that benefits from higher adoption rates but the beneficial effects also spread to the foreign country. Moreover, it helps explaining the differences in macro quantities and equity returns observed in the international data.

Keywords: Technology Adoption, R&D Investment, Asymmetric Tax Regimes, Asset Prices

JEL: E3, F3, F4, G12

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We thank Fulvio Corsi, Alessandro Gioffré, Marcus Jüppner, Alexander Ludwig, Roberto Pancrazi, and Christian Schlag and seminar participants at the Bank of Lithuania for helpful comments and suggestions. We gratefully acknowledge research and financial support from the Research Center SAFE, funded by the State of Hessen initiative for research LOEWE. The views expressed herein are solely those of the authors and do not necessarily reflect the views of the Bank of Lithuania or the Eurosystem. All remaining errors are our own.

1 Introduction

The seminal work of Romer (1990) illustrates the fundamental role of technological innovation for economic growth. Building on the argument that asset prices reflect changes in the growth opportunities of the economy, the recent asset pricing literature has analyzed the link between technological innovation and stock returns (Garleanu, Panageas, and Yu, 2012; Kung and Schmid, 2015; Bena, Garlappi, and Grüning, 2016). Given that technological innovation is not only based on internal production but can also be imported from abroad, Gavazzoni and Santacreu (2015) and Croce, Nguyen, and Schmid (2015) argue that technological innovation can help to explain the correlation across international stock markets and the co-movement of macroeconomic quantities across different countries.

Traditional models that aim at explaining the link between technological innovation and the comovement of international capital markets and macro quantities typically assume that countries are homogeneous, that is, they feature identical fundamentals. However, countries tend to exhibit structural differences. Importantly, such differences show up also across countries belonging to the same region. Moreover, the relative contribution of technology adoption as compared to the internal technology production differs across countries. For instance Choi, González, and Gray (2013) show that fiscally weak European countries and Eastern European countries exhibit low level of investment in research and development (R&D) and thus rely more on technology adoption from abroad to sustain economic growth. Differently, fiscally strong countries are closer to the technology frontier and sustain economic growth with a sizable amount of R&D investments. In addition, fiscally weak and fiscally strong European countries typically differ in their economic fundamentals. For instance, fiscally weak countries tend to exhibit less flexible labor markets (Nickell, 1997). This suggests that the country's characteristics may affect the link between the diffusion of technology and international stock returns. In this respect, Jahan-Parvar, Liu, and Rothman (2013) suggest that cross-country heterogeneity helps to match the observed differences in the equity risk premium between developed and emerging markets.

Motivated by these observations, we develop a two-country general equilibrium model where economic growth is driven by internal production of new technology (via R&D) and international technology trade (via adoption). Most importantly, the two countries are heterogeneous in their fiscal policy and in the flexibility of their labor market. To be close to the current European scenario, we assume that the fiscally weak country employs a zero-deficit fiscal rule and, at the same time, has a rigid labor market. Contrarily, the fiscally strong country is allowed to temporarily run a small fiscal deficit when macroeconomic conditions deteriorate and has a less rigid labor market. In this framework, a positive macroeconomic shock in one country (both in terms of productivity and in terms of adoption possibilities) increases the availability of new technology and stimulates economic growth in both countries. In the foreign country, the effect is naturally smaller and initially even negative in the case of a shock to the domestic adoption probability. Even if smaller, the effects are more long-lasting due to the slow but persistent adoption process and unambiguously positive in the long run. The structural differences among countries have clear implications for macroeconomic quantities and asset prices: Labor market rigidities and the zero-deficit policy impair the country's ability to counteract the effects of macroeconomic shocks. Therefore, a country characterized by rigid labor market or by a zero-deficit fiscal policy is more exposed to macroeconomic shocks than a frictionless market. These structural differences affect the future growth prospects of the two countries and are reflected in asset returns. In our model, investors command a return premium to invest in the country characterized by a zero-deficit fiscal policy and a rigid labor market, consistent with empirical evidence. Moreover, macroeconomic fundamentals are more volatile in this country relative to the country characterized by a flexible fiscal rule and less rigid labor markets, as in the data. In other words, we build a realistic framework where structural differences across countries are used to explain observed differences in macroeconomic quantities and asset prices. We then use our framework to analyze the implications of technology trade for macroeconomic growth. Our analysis suggests that an increase in the ability to adopt technology from abroad stimulates economic growth in the country that benefits from higher adoption rates but the beneficial effects also spread to the foreign country that experiences a positive growth in the long run.

The remainder of the paper is organized as follows. Section 2 discusses the most relevant literature focusing on international endogenous growth models and their implications for business cycles and asset prices. Section 3 presents our international endogenous growth model featuring asymmetric tax regimes and heterogeneous labor market rigidities. The calibration and quantitative implications of our model are discussed in Section 4. Finally, Section 5 concludes.

2 Background and Motivation

The goal of this paper is to study the link between international asset returns and technological innovation in a world where countries exhibit structural differences. In our model, economic growth is induced by (i) internal production of newly developed intermediate goods and (ii) adoption of new technology from abroad. The production function depends on four elements: a stochastic productivity process (i.e. disembodied technology), the endogenous amount of capital, the endogenous supply of labor, as well as domestically developed and internationally adopted intermediate goods.

Our theoretical framework is closely related to Croce, Nguyen, and Schmid (2015) and Gavazzoni and Santacreu (2015). However, we differ from them in several important aspects. Croce, Nguyen, and Schmid (2015) focus on the uncertainty (in the sense of entropy) about economic shocks and its effect on the international technology diffusion. Our utility function does not account for investors' aversion to model uncertainty. Moreover, in our model the total production of final goods depends on both labor and capital while in Croce, Nguyen, and Schmid (2015) it depends on labor only. As we will see later, capital accumulation is important because, via the investment channel, it makes the total output and consumption of one country more sensitive to productivity shocks of the other country. Note also that the inclusion of both R&D and physical capital allows firms to choose between two different investment opportunities, a trade-off absent in Croce, Nguyen, and Schmid (2015). In addition, we assume that the probability of adopting technologies from the foreign quantities is a stochastic process while in Croce, Nguyen, and Schmid (2015) this probability is modeled as a function of the country's total output. These differences enable us to study the short-run and long-run effects of shocks to the adoption probability and their welfare implications.

The main focus of Gavazzoni and Santacreu (2015) is to analyze the effects of endogenous technology adoption on international asset prices. Their international endogenous growth model produces a high correlation of equity returns while fundamentals are moderately correlated, as in the data. Moreover, they provide empirical evidence that countries that trade more (goods and technologies) with each other display higher cross-country correlations of equity returns. As in their study, we concentrate on international trade of technology to explain the co-movement of macroeconomic quantities and stock returns. Differently from our economy and Croce, Nguyen, and Schmid (2015), the model developed by Gavazzoni and Santacreu (2015) has no government sector. Therefore, international differences in fiscal policy and potential spillover effects from those are not studied. Additionally, they allow for full risk-sharing for households by imposing a complete international capital markets structure, whereas the households in our model face incomplete markets because they can only invest in the local financial assets. Given that the macroeconomic implications of financial integration are extensively studied, we assume market incompleteness to isolate the effects of heterogeneous fiscal policies and labor markets on macroeconomic quantities and asset prices.[1] Moreover, Gavazzoni and Santacreu (2015) include iceberg transaction costs in the international trade of intermediate goods, whereas we allow for frictionless trade. Finally, we differ from both Croce, Nguyen, and Schmid (2015) and Gavazzoni and Santacreu (2015) because we account for labor market frictions and, most importantly, because we allow the two countries to differ in terms of labor market frictions and fiscal policies. Country heterogeneity is crucial in our framework because it implies that, in equilibrium, the unconditional moments of stock returns and macroeconomic quantities differ across the two countries. Therefore, heterogeneity in international business cycle moments and equity returns' characteristics arises endogenously in our model.

More broadly, our paper also expands on the growing literature on international technology diffusion and its effect on productivity, growth, and cross-country income differences. Using a novel dataset on technology trade, Choi, González, and Gray (2013) find evidence of a positive association between technology adoption and productivity growth. Comin and Hobijn (2004) observe that the countries' ability in adopting technologies depends on the level of human capital, government characteristics, degree of trade openness, and on the former adoption process. In this respect, cross-country macroeconomic heterogeneity matters a lot for the international diffusion of technologies. Moreover, they show that the adoption of foreign technologies contributes more strongly to the countries' productivity than domestic investment in R&D. Therefore, technology adoption is key for stimulating growth and should be publicly subsidized. Using data on international patents, Peri (2005) shows that knowledge flows within and across countries tend to have positive effects on productivity and innovation. Eaton and Kortum (1996) observe that international trade in ideas is a major factor in world growth. In particular, they find that the majority of OECD members other than the United States obtains more than 50% of its productivity growth from ideas that originated abroad. It turns out that positive (negative) shocks to the adoption process may boost (undermine) global growth.[2] We contribute to this literature by showing that the benefits of the economic expansion in the home country caused by an increase

[1] The effects of financial integration on the international transmission of shocks, exchanges rates, and welfare have been already extensively analyzed. See, for instance, Bodenstein (2008), Devereux and Yetman (2010), Devereux and Sutherland (2011), Colacito and Croce (2013), Kollmann (2015), Colacito, Croce, Ho, and Howard (2016), and Kollmann (2016) and the references therein.

[2] Other studies aimed at quantifying the benefits of international technology diffusion to productivity growth include Benhabib and Spiegel (1994), Parente and Prescott (1994), Coe and Helpman (1995), and Eaton and Kortum (1999).

in the probability of adoption are transmitted to the foreign country through the channel of trade in intermediate goods. In particular, our international endogenous growth framework suggests that these benefits are long-lasting, and that it depends on the countries' structural heterogeneity to what extent macroeconomic shocks spill over to the other country. Therefore, we confirm that adoption is a key channel in short-run and (more importantly) long-run global growth.

3 Model

In this section, we introduce a model of technology trade between two economies—a domestic and a foreign economy—that differ from each other both in the severity of the labor market friction and the tax regime. In what follows, we first introduce the household behavior, then we present the production sector, and the government policy regimes. Households and production technology are fairly standard in this literature. Therefore, we put more emphasis on the description of the innovation process, on the country-specific fiscal policy, and on the labor market specifications. Unless specified differently, in the sections below all equations labeled by index $j \in \{H, F\}$ refer to both countries. We use H to refer to the home country and F to refer to the foreign country. When needed, to denote the country different from country j we use the symbol $-j$. Hence, $-j = H$ if $j = F$ and $-j = F$ if $j = H$.

3.1 Households

Preferences. In each country, there is a representative household that has recursive preferences in the spirit of Epstein and Zin (1989):

$$U_{j,t} = \left[(1-\beta) u_{j,t}^{1-\frac{1}{\psi}} + \beta \mathbb{E}_t [U_{j,t+1}^{1-\gamma}]^{\frac{1-\frac{1}{\psi}}{1-\gamma}} \right]^{\frac{1}{1-\frac{1}{\psi}}},$$

where $C_{j,t}$ represents consumption and $\bar{L}_j - L_{j,t}$ leisure. Consumption and leisure enter the utility function by means of the CES aggregator $u_{j,t}$ defined as:

$$u_{j,t} = \left[\kappa C_{j,t}^{1-\frac{1}{\sigma}} + (1-\kappa)[N_{j,t}(\bar{L}_j - L_{j,t})]^{1-\frac{1}{\sigma}} \right]^{\frac{1}{1-\frac{1}{\sigma}}}.$$

The parameters γ, ψ, and σ denote the relative risk aversion, the elasticity of intertemporal substitution, and the degree of complementarity between leisure and consumption, respectively. $\bar{L}_j$ is the total time endowment, $L_{j,t}$ is the labor supply, while the parameter κ measures the weight on consumption in the utiliy bundle $u_{j,t}$. Finally, $N_{j,t}$ is the available technology in the economy, i.e. the total number of patents either developed domestically or adopted from abroad up to period t.

Financial markets. In each country $j \in \{H, F\}$, there are two financial markets: the stock market and the bond market. The representative household maximizes preferences by choosing, in each period t, labor $L_{j,t}$, consumption $C_{j,t}$, equity shares $Z_{j,t}$, and bond holdings $B_{j,t}$. Therefore, the budget constraint must satisfy the following condition:

$$C_{j,t} + S_{j,t} + (V^a_{j,t} - D^a_{j,t})Z_{j,t} + B_{j,t} = (1 - \tau_{j,t})W^u_{j,t}L_{j,t} + V^a_{j,t}Z_{j,t-1} + (1 + r^f_{j,t-1})B_{j,t-1},$$

where $V^a_{j,t} - D^a_{j,t}$ is the ex-dividend market value of the equity share and $D^a_{j,t}$ is its dividend, while $W^u_{j,t}$ represents the frictionless wage, which is taxed at the rate $\tau_{j,t}$. Finally, the total R&D expenditure in country j is given by $S_{j,t}$, and $r^f_{j,t-1}$ is the risk-free interest rate.

Optimality conditions. In the spirit of Uhlig (2007), we assume that wages are sticky and only a fraction of them is determined by the intratemporal optimality condition:

$$\frac{1-\kappa}{\kappa} N_{j,t}^{(1-1/\sigma)} \left(\frac{C_{j,t}}{\bar{L}_j - L_{j,t}} \right)^{1/\sigma} = (1 - \tau_{j,t})W^u_{j,t}. \tag{1}$$

The remaining part of the wage is set to last period's wage:

$$W_{j,t} = \left(e^{\Delta a_{j,t}} W_{j,t-1} \right)^{\mu_j} \left(W^u_{j,t} \right)^{1-\mu_j}, \tag{2}$$

where the country-specific parameter $\mu_j > 0$ determines the fraction of the wage that is sticky, while $\Delta a_{j,t}$ captures the domestic technology growth rate as defined in Equation (21) and the assumption that the wage is indexed to aggregate productivity growth when it cannot be chosen optimally.[3] In this setting, the stochastic discount factor in economy j is given by:

$$\mathbb{M}_{j,t+1} = \beta \left(\frac{u_{j,t+1}}{u_{j,t}} \right)^{\frac{1}{\sigma} - \frac{1}{\psi}} \left(\frac{C_{j,t+1}}{C_{j,t}} \right)^{-\frac{1}{\sigma}} \left(\frac{U_{j,t+1}^{1-\gamma}}{E_t[U_{j,t+1}^{1-\gamma}]} \right)^{\frac{\frac{1}{\psi} - \gamma}{1-\gamma}}, \tag{3}$$

where the last factor captures aversion to continuation utility risk (i.e. long-run risk). Bond holdings and equity shares are chosen optimally and thus satisfy the usual Euler conditions:

$$\begin{aligned} V^a_{j,t} &= D^a_{j,t+1} + \mathbb{E}_t[\mathbb{M}_{j,t+1} V^a_{j,t+1}], \\ 1 &= \mathbb{E}_t[\mathbb{M}_{j,t+1}(1 + r^f_{j,t})]. \end{aligned} \tag{4}$$

3.2 Production

Final goods. In each country $j \in \{H, F\}$ a non-traded final good, whose total output is denoted by $Y_{j,t}$, is produced by a representative perfectly competitive firm. Production of the final output takes place by employing capital $K_{j,t}$, labor $L_{j,t}$, and a basket of intermediate goods $\Sigma_{j,t}$, whose technology (i.e. patent) has been either developed domestically or adopted from abroad. As will be explained later, we assume that the foreign adopted intermediate goods employed by the representative firm in country j are bought from country $-j$ whereas the domestically developed intermediate goods are purchased by the local firm. Therefore, we denote by $X_{j,i,t}$ the time-t units of intermediate good i,

[3] Donadelli and Grüning (2016) show using a one-country endogenous growth model that this simple form of modeling wage rigidities performs quantitatively very similar to a more complex setting, in which wage rigidities arise from a Calvo-type of wage stickiness.

employed in country j, whose patent is domestically developed (i.e. domestic intermediate goods). Similarly, we denote by $X^*_{j,l,t}$ the time-t units of good l used by the firm of country j, whose patent is developed abroad (i.e. adopted intermediate goods).[4] The representative firm of country j is endowed with the following technology:

$$Y_{j,t} = \left(K^{\alpha}_{j,t} \left(\Omega_{j,t} L_{j,t}\right)^{1-\alpha}\right)^{1-\xi} \Sigma^{\xi}_{j,t}, \tag{5}$$

where $\Omega_{j,t}$ is an exogenous stochastic productivity process given by:

$$\log(\Omega_{j,t}) = \rho_{\Omega} \log(\Omega_{j,t-1}) + \epsilon^{\Omega}_{j,t}, \quad \epsilon^{\Omega}_{j,t} \sim N(0, \sigma^2_{\Omega}), \tag{6}$$

while

$$\Sigma_{j,t} = \left[\int_0^{A_{j,t}} \left(X_{j,i,t}\right)^{\frac{1}{\nu}} di + \int_0^{A^*_{j,t}} \left(X^*_{j,l,t}\right)^{\frac{1}{\nu}} dl\right]^{\nu}$$

denotes an aggregate composite of intermediate goods. Here, we use $A_{j,t}$ and $A^*_{j,t}$ to label the number of intermediate goods available at date t, whose patents have been domestically developed and adopted from abroad, respectively. Furthermore, the parameter $\nu > 1$ determines the elasticity of substitution between domestic intermediate goods and adopted intermediate goods. Capital evolves according to the following dynamics:

$$K_{j,t+1} = (1-\delta)K_{j,t} + \Lambda(I_{j,t}/K_{j,t})K_{j,t}, \tag{7}$$

and it is subject to convex adjustment costs specified as in Jermann (1998) by means of the following adjustment cost function:

$$\Lambda_{j,t} := \Lambda\left(\frac{I_{j,t}}{K_{j,t}}\right) = \frac{\alpha_1}{1-\frac{1}{\zeta}}\left(\frac{I_{j,t}}{K_{j,t}}\right)^{1-\frac{1}{\zeta}} + \alpha_2, \text{ where } \alpha_1 = \left(\overline{\alpha} + \delta - 1\right)^{\frac{1}{\zeta}}, \ \alpha_2 = \frac{1}{1-\zeta}\left(\overline{\alpha} + \delta - 1\right).$$

The constant $\overline{\alpha}$ is chosen such that there are no adjustment costs in the deterministic steady state, while the parameter ζ determines the elasticity of investment.

The final goods firm takes prices as given and chooses the demand for domestic and adopted intermediate goods, capital, investment, and labor, in order to maximize the present value of its future dividends, subject to

$$D_{j,t} = Y_{j,t} - W_{j,t}L_{j,t} - I_{j,t} - \int_0^{A_{j,t}} P_{j,i,t}X_{j,i,t} di - \int_0^{A^*_{j,t}} P^*_{j,l,t}X^*_{j,l,t} dl$$

and the capital accumulation equation (7). We use $P_{j,i,t}$ and $P^*_{j,l,t}$ to denote the prices of the domestic and the adopted intermediate goods at time t, respectively. Taking these prices as given, the optimal

[4] In other words, we are assuming that any patent may give rise to two different goods, of which both are used in the production of the final good: When we consider production in country j, then $X_{j,i,t}$ represents the units of good i whose patent is developed in country j, while $X^*_{j,i,t}$ represents the units of good i whose patent is adopted from country $-j$. In the sense specified above, the superscript * refers to adopted goods.

demands for the domestic intermediate goods i and for the adopted intermediate good l, are given by:

$$X_{j,i,t} = \left(\frac{\xi \left(K_{j,t}^{\alpha} \left(\Omega_{j,t} L_{j,t} \right)^{1-\alpha} \right)^{1-\xi} \left(\Sigma_{j,t} \right)^{\xi - \frac{1}{\nu}}}{P_{j,i,t}} \right)^{\frac{\nu}{\nu-1}}, \tag{8}$$

$$X_{j,l,t}^{*} = \left(\frac{\xi \left(K_{j,t}^{\alpha} \left(\Omega_{j,t} L_{j,t} \right)^{1-\alpha} \right)^{1-\xi} \left(\Sigma_{j,t} \right)^{\xi - \frac{1}{\nu}}}{P_{j,l,t}^{*}} \right)^{\frac{\nu}{\nu-1}}. \tag{9}$$

The first-order condition with respect to labor, instead, gives rise to the following equation in the labor market:

$$W_{j,t} = \frac{(1-\alpha)(1-\xi) Y_{j,t}}{L_{j,t}}. \tag{10}$$

Finally, the first-order condition with respect to next period's capital implies:

$$1 = \mathbb{E}_t \left[\mathbb{M}_{j,t+1} \Lambda_{j,t}' \left\{ \frac{\alpha(1-\xi) Y_{j,t+1} - I_{j,t+1}}{K_{j,t+1}} + \left(\frac{1 - \delta + \Lambda_{j,t+1}}{\Lambda_{j,t+1}'} \right) \right\} \right]. \tag{11}$$

Intermediate goods. The production of intermediate goods takes place in infinitesimally small and monopolistically competitive firms. Following Gavazzoni and Santacreu (2015), we assume that the foreign adopted intermediate goods used in country j are produced in country $-j$ and sold abroad where the goods' prices are denoted in importer's final goods units. This means that in each country j the representative final goods firm employs the intermediate goods produced by a monopolistically competitive, specialized domestic firm that produces good i, with $i \in [0, A_{j,t}]$, and it employs the goods from monopolistically competitive, specialized domestic firm in country $-j$ that produces good l, with $l \in [0, A_{j,t}^{*}]$. In order to produce one unit of each intermediate good, firms must employ one unit of the final good. Hence, profit maximization in the intermediate goods' sector takes the following form:

$$\Pi_{j,i,t} = \max_{\{P_{j,i,t}\}} \left\{ P_{j,i,t} X_{j,i,t}(P_{j,i,t}) - X_{j,i,t}(P_{j,i,t}) \right\}, \qquad i \in [0, A_{j,t}],$$

$$\Pi_{j,l,t}^{*} = \max_{\{P_{j,l,t}^{*}\}} \left\{ P_{j,l,t}^{*} / Q_{j,t} X_{j,l,t}^{*}(P_{j,l,t}^{*} / Q_{j,t}) - X_{j,l,t}^{*}(P_{j,l,t}^{*} / Q_{j,t}) \right\}, \qquad l \in [0, A_{j,t}^{*}],$$

where $\Pi_{j,i,t}$ and $\Pi_{j,i,t}^{*}$ are the profits from producing the domestic intermediate good i and the adopted intermediate good l, respectively. The exchange rate is denoted by $Q_{j,t}$ and defined below in Equation (14). At the optimal demand for intermediate goods, given by Equations (8) and (9), intermediate goods firms charge a constant markup over marginal cost subject only to exchange rate risk:

$$P_{j,i,t} \equiv P_j = \nu, \tag{12}$$

$$P_{j,l,t}^{*} \equiv P_j^{*} = \nu Q_{j,t}, \tag{13}$$

where $Q_{j,t}$ denotes the exchange rate or terms of trade, i.e. the price of country j's goods in units of country $-j$'s goods. The exchange rate is determined by:

$$Q_{j,t} = \frac{C_{j,t}}{C_{-j,t}}. \tag{14}$$

To ensure balanced growth, we impose the following parametric restriction:

$$\frac{(\nu-1)\xi}{1-\xi} = 1-\alpha, \tag{15}$$

which implies the following conditions for the intermediate goods sector:

$$X_{j,i,t} \equiv X_{j,t} = \left(\frac{\xi}{\nu}\right)^{\frac{\nu}{\nu-1}} K_{j,t}^{\alpha} \left(\Omega_{j,t} L_{j,t}\right)^{1-\alpha} \left(\left(\frac{\xi}{\nu}\right)^{\frac{1}{\nu-1}} A_{j,t} + \left(\frac{\xi}{\nu Q_{j,t}}\right)^{\frac{1}{\nu-1}} A_{j,t}^{*}\right)^{-\alpha}, \tag{16}$$

$$X_{j,i,t}^{*} \equiv X_{j,t}^{*} = \left(\frac{\xi}{\nu Q_{j,t}}\right)^{\frac{\nu}{\nu-1}} K_{j,t}^{\alpha} \left(\Omega_{j,t} L_{j,t}\right)^{1-\alpha} \left(\left(\frac{\xi}{\nu}\right)^{\frac{1}{\nu-1}} A_{j,t} + \left(\frac{\xi}{\nu Q_{j,t}}\right)^{\frac{1}{\nu-1}} A_{j,t}^{*}\right)^{-\alpha}, \tag{17}$$

$$\Pi_{j,i,t} \equiv \Pi_{j,t} = (\nu-1)\, X_{j,t}, \tag{18}$$

$$\Pi_{j,i,t}^{*} \equiv \Pi_{j,t}^{*} = (\nu-1)\, X_{j,t}^{*}. \tag{19}$$

Using Equations (16), (17), and (15) in Equation (5) yields the equilibrium final output:

$$Y_{j,t} = K_{j,t}^{\alpha} \left[\Omega_{j,t} L_{j,t} \left(\left(\frac{\xi}{\nu}\right)^{\frac{1}{\nu-1}} A_{j,t} + \left(\frac{\xi}{\nu Q_{j,t}}\right)^{\frac{1}{\nu-1}} A_{j,t}^{*}\right)\right]^{1-\alpha}. \tag{20}$$

In each country, the variety of new intermediate goods may expand either by means of their own innovation activities (i.e. R&D) or by importing technology from abroad (i.e. adoption). In the next section, we describe how these two activities take place in our international production economy.

3.3 Technology innovation

R&D. Developers of new patents (innovators) sell their intellectual property to monopolistically competitive firms that buy these patents and produce new intermediate goods. To accomplish their projects in period $t+1$, innovators invest $S_{j,t}$ units of the final good in R&D in period t. We assume that the total mass of domestic variety of patents developed in country j evolves according to the following law of motion:

$$A_{j,t+1} = \upsilon_{j,t} S_{j,t} + (1-\delta_v) A_{j,t}, \qquad e^{\Delta a_{j,t+1}} = \frac{A_{j,t+1}}{A_{j,t}}, \tag{21}$$

where, in each period, a new variety becomes obsolete with probability δ_v, while $\upsilon_{j,t}$ is the time-varying probability to develop new patents. Following Comin and Gertler (2006), we assume that $\upsilon_{j,t}$ evolves as

$$\upsilon_{j,t} = \chi \left(\frac{S_{j,t}}{N_{j,t}}\right)^{\eta-1}, \quad \eta \in (0,1),$$

where η denotes the elasticity of new intermediate goods with respect to R&D investments, χ is a scale parameter, while

$$N_{j,t} = A_{j,t} + A^*_{j,t} \tag{22}$$

represents the technological frontier of country j at date t (i.e. the total mass of patents available at a given time t).

Adoption. The total mass of foreign variety adopted by country j instead evolves according to the following law of motion:

$$A^*_{j,t+1} = (1-\delta_v)A^*_{j,t} + \upsilon^A_{j,t}(1-\delta_v)[A_{-j,t} - A^*_{j,t}]. \tag{23}$$

where $A_{-j,t} - A^*_{j,t}$ is the mass of foreign technology that has not been adopted yet by country j at date t, and $\upsilon^A_{j,t}$ is the probability that a new technology is adopted by country j in period t. With probability $1-\upsilon^A_{j,t}$, the adopter j gets nothing. We assume that $\upsilon^A_{j,t}$ evolves according to the following stochastic process:

$$\begin{aligned} \upsilon^A_{j,t} &= \frac{1}{1+e^{-\theta_{j,t}}}, \\ \theta_{j,t} &= (1-\rho_\theta)\overline{\theta} + \rho_\theta \theta_{j,t-1} + \epsilon^\theta_{j,t}, \quad \epsilon^\theta_{j,t} \sim N(0,\sigma^2_\theta). \end{aligned} \tag{24}$$

This specification ensures that $\upsilon^A_{j,t} \in (0,1)$. Note that (23) does not allow country j to adopt in period $t+1$ the new varieties made available in period $t+1$ in country $-j$ in period t. This captures the idea that technology adoption may incur time delays, which may be due to legal, institutional, logistic and other local barriers.

language or logistic barriers, for instance.

Technology value. We assume that patents are intangible assets. Therefore, they can be sold either domestically or abroad in a competitive market. In each country j, the representative firm uses the patent i to create new intermediate goods. Accordingly, the value $V_{j,i,t}$ of a new patent i at time t is equal to the sum of discounted expected profits the firm is able to make by exploiting the patent, both domestically and abroad. Formally, let $W^V_{j,i,t}$ be the expected value of firms in country j using patent i at time t, and $J_{j,i,t}$ be the expected value of firms in country j with patent i that can potentially be adopted by the foreign country starting from $t+1$. When the adoption is successful, the value of an adopted patent is denoted by $W^{V,*}_{j,t,t}$. We have:

$$V_{j,i,t} = W^V_{j,i,t} + J_{j,i,t}, \tag{25}$$

where

$$W^V_{j,i,t} = \Pi_{j,i,t} + (1-\delta_v)\mathbb{E}_t[\mathbb{M}_{j,t+1}W^V_{j,i,t+1}], \tag{26}$$

$$W^{V,*}_{j,i,t} = \Pi^*_{-j,i,t} + (1-\delta_v)E_t[\mathbb{M}_{j,t+1}W^{V,*}_{j,i,t+1}], \tag{27}$$

$$J_{j,i,t} = (1-\delta_v)\mathbb{E}_t\Big[\mathbb{M}_{j,t+1}\Big(\upsilon^A_{-j,t}W^{V,*}_{j,i,t+1} + (1-\upsilon^A_{-j,t})J_{j,i,t+1}\Big)\Big]. \tag{28}$$

Since we assume that the there are no frictions in selling a new technology in the country where the new technology is developed, say country j, once the new patent enters the market, then it is sold domestically with certainty. Conversely, a new patent may be sold abroad—equivalently, adopted from abroad—one period later, and this occurs with uncertainty, according to the process (23). Accordingly, the expected profits realized by selling adopted intermediate goods enter the value of a new patent with probability $v^A_{-j,t}$, starting from period $t+1$ as specified in Equation (28).[5]

Developers invest $S_{j,t}$ units of the final good in each period t to produce a new technology available in period $t+1$. Their payoff is given by the expected discounted value of future profits obtained by selling the patents to the intermediate goods sector. From Equation (21), the new technology produced in period $t+1$ is given by:

$$A_{j,t+1} - (1-\delta_v)A_{j,t} = \upsilon_{j,t} S_{j,t},$$

and the expected payoff that developers obtain by selling this new technology is:

$$\upsilon_{j,t} S_{j,t} \mathbb{E}_t \left[\mathbb{M}_{j,t+1} V_{j,t+1} \right],$$

where, due to the symmetry of the problem, we have dropped the subscript i since all firms in the intermediate goods sector are identical. Since the R&D sector is a competitive market with free entry, the following zero-profit condition holds in equilibrium:

$$S_{j,t} = \upsilon_{j,t} S_{j,t} \mathbb{E}_t \left[\mathbb{M}_{j,t+1} V_{j,t+1} \right],$$

or, equivalently,

$$\frac{1}{\upsilon_{j,t}} = \mathbb{E}_t \left[\mathbb{M}_{j,t+1} V_{j,t+1} \right]. \tag{29}$$

The left-hand side represents the marginal cost of producing an extra variety in t, while the right-hand side is the marginal revenue by selling an extra variety in $t+1$.

3.4 Government

Expenditure. In each country, the public expenditure $G_{j,t}$ over total production $Y_{j,t}$ evolves stochastically as follows:

$$\frac{G_{j,t}}{Y_{j,t}} = \frac{1}{1+e^{-g_{j,t}}},$$

where we assume that:

$$g_{j,t} = (1-\rho_G)\overline{g} + \rho_G g_{j,t-1} + \epsilon^G_{j,t}, \quad \epsilon^G_{j,t} \sim N(0, \sigma^2_G). \tag{30}$$

The government has two fiscal instruments to finance its public spending: It can either tax labor income, i.e. $T_{j,t} = \tau_{j,t} W_{j,t} L_{j,t}$, or use public debt $B_{j,t}$. Put together, these two measures must satisfy

[5] In the intermediate goods sector, the purchase of a new technology and the development of a new intermediate good are processes that occur intratemporal, i.e. at the start of the period and at the end of the period, respectively.

the following budget constraint:

$$B_{j,t} = (1 + r^f_{j,t-1})B_{j,t-1} + G_{j,t} - T_{j,t}. \tag{31}$$

However, as will be explained next, we focus on a situation in which one country—a fiscally weak country—is committed to a zero-deficit rule (due to austerity measures, for instance). Therefore, it can only tax labor income to finance its expenditure. On the contrary, the other country—a fiscally strong country—by virtue of its financial discipline might run a temporary fiscal deficit in addition to taxing labor income. As will become clear from the description of the tax policy below, the fiscal deficit will be progressively reduced by means of higher future taxes.

Asymmetric tax regimes. We assume that the two governments adopt two different tax regimes. The government of the home country ($j = H$) is committed to a zero-deficit rule, so that Equation (31) simply becomes $G_{H,t} = T_{H,t}$. To guarantee that the zero-deficit budget constraint holds in each period, the government fixes a labor tax rate equal to:

$$\tau^0_{H,t} = \frac{G_{H,t}/Y_{H,t}}{(1-\alpha)(1-\xi)}, \tag{32}$$

where α and ξ are, respectively, the share of physical capital, and the share of patents in the production technology of the final goods sector as specified in Equation (5). Such a choice on $\tau_{H,t}$ implies that the tax rate perfectly follows the path of the exogenous government expenditure process.

Conversely, the government of the foreign country ($j = F$) is not committed to a zero-deficit rule, and it can finance its public expenditure also by running deficits. Following Croce, Nguyen, and Schmid (2013), we assume that the debt to output ratio is driven by the following dynamics:

$$\frac{B_{F,t}}{Y_{F,t}} = \rho_{B,F}\frac{B_{F,t-1}}{Y_{F,t-1}} + \phi_{B,F} \cdot (\log L_{F,ss} - \log L_{F,t}), \tag{33}$$

where $\rho_F \in (0,1)$ captures the delay of debt repayment, $\phi_B \geq 0$ is a scale parameter, and $L_{F,ss}$ is the steady-state level of labor. Using (31) and (33), the tax rate for the foreign country becomes:

$$\tau_{F,t} = \tau^0_{F,t} + \frac{1}{(1-\alpha)(1-\xi)}\left(\frac{1 + r^f_{F,t-1}}{Y_{F,t}/Y_{F,t-1}} - \rho_{B,F}\right)\frac{B_{F,t-1}}{Y_{F,t-1}} + \phi_{B,F}\frac{\log L_{F,t} - \log \bar{L}_F}{(1-\alpha)(1-\xi)}, \tag{34}$$

where $\tau^0_{F,t}$ is the zero-deficit tax rate, similarly to (32). Following Croce, Nguyen, and Schmid (2013), we choose $\phi_{B,F} > 0$ to model an employment-oriented tax rule. In bad times, i.e. labor below the steady state level, the government cuts taxes on labor income (i.e. increases debt). In good times instead, it increases taxes (i.e. reduces debt). Note that the second term on the right-hand side of Equation (34) accounts also for the long-lasting effect on taxes caused by debt repayment and that by imposing $\rho_F \in (0,1)$ we rule out unstable fluctuations of the debt to output ratio.

3.5 Resource constraint

Final output is used for consumption, capital investment, R&D investment, production of domestically developed and foreign adopted intermediate goods, and public expenditure:

$$Y_{j,t} = C_{j,t} + I_{j,t} + S_{j,t} + A_{j,t}X_{j,t} + A^*_{-j,t}X^*_{-j,t} + G_{j,t}. \tag{35}$$

4 Quantitative Analysis

In this section, we first present the benchmark calibration of our model followed by the discussion of the unconditional moments of our model and their fit to international macroeconomic and financial data. Finally, we analyze the impulse response functions of the key macroeconomic shocks of the model.

4.1 Benchmark calibration

Panel A of Table 1 summarizes all the parameters used in our benchmark calibration. Panel B reports those parameter values for three other calibrations ([1], [2], and [3]) which are different from the benchmark calibration [4]. In order to calibrate the model, we rely on German and Italian data.[6]. The home country in our model represents Italy and the foreign country Germany. In our benchmark calibration countries exhibit asymmetric fiscal policies and different labor market frictions. Italy has been severely affected by the fiscal crisis. Therefore, it is forced to save and reduce its deficit due to both internal and external constraints. Hence, the opportunities for Italy to increase fiscal spending by means of increasing its deficit are limited. To capture this, we assume Italy to be committed to a zero-deficit policy in the model. Germany, on the other hand, does not have this enormous pressure to save and reduce its fiscal deficit. Thus, it can finance additional expenditure by means of additional debt relatively easily. Hence, Germany can run fiscal deficits via a tax-smoothing policy in the model.[7] In this respect, we set the intensity of the foreign country's smoothing policy $\phi_{B,F}$ and the related inverse of the speed of debt repayment $\rho_{F,B}$ to values of 0.0025 and $\sqrt[4]{0.95}$, respectively. Both values are similar to the calibration reported in Croce, Nguyen, and Schmid (2013). Heterogeneous labor market frictions are then captured by different wage rigidities parameters. Specifically, we assume Italy to have a less flexible labor market than Germany. In this respect, we set $\mu_H = 0.35$ and $\mu_F = 0.20$.[8] These values are similar in magnitude to the values used in the recent asset pricing literature that employ wage rigidities (see, for example, Uhlig, 2007; Donadelli and Grüning, 2016).

To understand the role of country heterogeneity, we also study three other calibrations whose values different from the benchmark calibration are reported in Table 1, Panel B. Specification [1] refers to the case when both countries are committed to a zero-deficit rule and have homogeneous labor market frictions ($\mu_H = \mu_F = 0.2$). Specification [2] features symmetric tax regimes but labor

[6]Although Germany and Italy are both part of a currency union and have the Euro as a joint currency, there is real exchange rate risk and, therefore, one generally has $Q_{j,t} \neq 1$ in Equation (14)

[7]This assumption reflects the current EU situation imposed by the set of common guidelines for the management of public debt for countries in the Euro zone (i.e. European Stability and Growth Pact).

[8]Note that our international endogenous growth framework applies to any pair of countries exhibiting differences in fiscal budgets and labor market conditions (e.g., Canada vs. Unites States or France vs. Spain).

market frictions are heterogeneous as in the benchmark calibration ($\mu_H = 0.35$ and $\mu_F = 0.2$). Finally, specification [3] considers asymmetric tax regimes as in the benchmark calibration but homogeneous labor market frictions ($\mu_H = \mu_F = 0.2$).

In order to obtain an average output growth rate compatible with the data for Italy and Germany, the R&D productivity parameter χ is chosen to produce an expected output growth rate of about 1.9 percentage points in both countries and across all four calibrations. The consumption share in the utility bundle κ is set so that the steady-state labor supply is one third of the total time endowment of the household across all calibrations. Hence, these two parameter values vary slightly across the four calibrations.

Preference parameters are set in line with the long-run risk literature (see, e.g., Bansal and Yaron, 2004; Kung and Schmid, 2015; Gavazzoni and Santacreu, 2015). Thus, the risk aversion parameter γ is set to 10 and the elasticity of intertemporal substitution ψ to 1.5. Hence, the households exhibit preferences for early resolution of uncertainty as observed by recent experimental studies (see Brown and Kim, 2014). As in Gavazzoni and Santacreu (2015), we set the discount factor β to $\sqrt[4]{0.984}$. Finally, the elasticity between consumption and leisure σ is set to 0.7, which is a standard value used in the literature and, for example, also used by Croce, Nguyen, and Schmid (2013).

The choices of the technology parameters in the final goods sector are quite standard in the macroeconomics literature. We set α, the capital share, δ, the quarterly depreciation rate of capital, and ξ, the intermediate goods share, to values of 0.35, 0.02, and 0.3939, respectively. In order to obtain in the model that investment is about twice more volatile than output (as observed in the data), we impose relatively low investment adjustment costs and set $\zeta = 3.33$.

Values for the productivity shock volatility σ_Ω and persistence ρ_Ω are chosen similarly to the values used by Kung and Schmid (2015). Specifically, we set $\sigma_\Omega = 0.017$ and $\rho_\Omega = \sqrt[4]{0.95}$. To replicate the observed correlation between Italian and German output growth rates (i.e. 0.73), we assume cross-country productivity shocks to be positively correlated. Specifically, we impose $\rho(\varepsilon_H^\Omega, \varepsilon_F^\Omega) = 0.7$.

In the intermediate goods sector, the monopoly markup parameter ν and the R&D elasticity are chosen as in Gavazzoni and Santacreu (2015): $\nu = 2$ and $\eta = 0.60$. The patent quarterly obsolescence rate, i.e. the depreciation rate of the R&D stock δ_v is equal to 0.03, as in Croce, Nguyen, and Schmid (2013).

We now turn to the adoption probability parameters. We calibrate the probability of a successful adoption to 0.01 in the steady state in order to feature a rather slow adoption process. This implies $\bar{\theta} = -4.5951$. Gavazzoni and Santacreu (2015) also apply a value of 0.01 for the adoption probability. However, in their model the adoption probability is a constant. The volatility of shocks to the adoption probability σ_θ is set to 0.001 to allow for small but quantitatively relevant deviations from the adoption probability long-run mean. For parsimony, we assume that the persistence of adoption probability shocks ρ_θ is equal to the persistence of aggregate productivity. Therefore, $\rho_\theta = \sqrt[4]{0.95}$.

Finally, we discuss the parameters related to government expenditure. We set $\overline{g} = -1.3863$ to obtain a government expenditure to GDP ratio of 20%.[9] Once again, for parsimony, we let the persistence of government spending shocks ρ_G be equal to the persistence of the productivity and

[9]This value corresponds to the average government spending to GDP ratio observed in Italy (i.e. 20.58%) and Germany (i.e. 19.34%) over the period 1970–2015 (source: OECD National Accounts).

Table 1: Quarterly Calibrations

This table reports the parameters used in the quarterly calibrations of our model. Panel A reports the parameters of our benchmark calibration, i.e. specification [4], featuring asymmetric tax regimes and different degrees of labor market frictions. Panel B reports the parameters for three other calibrations that are different from the benchmark calibration, i.e. specifications [1], [2], and [3]. Specification [1]: symmetric tax regimes and homogeneous labor market rigidities. Specification [2]: symmetric tax regimes and heterogeneous labor market rigidities. Specification [3]: asymmetric tax regimes and homogeneous labor market rigidities. Specification [4]: asymmetric tax regimes and heterogeneous labor market rigidities (benchmark calibration). Parameters' sources: 1=Gavazzoni and Santacreu (2015), 2=Uhlig (2007), 3=Croce, Nguyen, and Schmid (2013), 4=own calibration.

(a) Panel A: Benchmark calibration [4]

Parameter	Description	Source	Home Country	Foreign Country
PREFERENCE PARAMETERS				
β	Subjective discount factor	1	$\sqrt[4]{0.984}$	
γ	Risk aversion	1	10	
ψ	Elasticity of intertemporal substitution	1	1.5	
κ	Consumption share in utility bundle	4	0.1598	
σ	Elasticity between consumption and leisure in utility bundle	3	0.7	
FINAL GOODS SECTOR				
Technology parameters				
α	Capital share in final goods production	1	0.35	
ξ	Intermediate good share in final goods production	1	0.3939	
δ	Depreciation rate of physical capital	1	0.02	
ζ	Capital adjustment cost parameter	4	3.33	
Productivity parameters				
σ_Ω	Volatility of productivity shocks	3	0.017	
ρ_Ω	Persistence of productivity shocks	1	$\sqrt[4]{0.95}$	
$\rho(\varepsilon_H^\Omega, \varepsilon_F^\Omega)$	Correlation of productivity shocks	4	0.7	
INTERMEDIATE GOODS SECTOR AND PATENT DEVELOPMENT				
Technology parameters				
ν	Elasticity of intermediate goods / monopoly markup	1	2.00	
δ_v	Patent obsolescence probability	3	0.03	
R&D and Adoption parameters				
χ	Productivity of R&D expenditure	4	0.1059	
η	Elasticity of R&D expenditure	1	0.60	
$\bar{\theta}$	Long-run mean of process controlling adoption probability	1	-4.5951	
σ_θ	Volatility of shocks to the adoption probability	4	0.001	
ρ_θ	Persistence of shocks to the adoption probability	4	$\sqrt[4]{0.95}$	
GOVERNMENT				
$\bar{g}$	Long-run mean of process controlling government expenditure to GDP ratio	4	-1.3863	
σ_G	Volatility of shocks to the government expenditure to GDP ratio	4	0.0076	
ρ_G	Persistence of shocks to the government expenditure to GDP ratio	4	$\sqrt[4]{0.95}$	
$\phi_{B,j}$	Intensity of debt repayment policy	4	0	0.0025
$\rho_{B,j}$	Inverse of the speed of debt repayment	4	–	$\sqrt[4]{0.95}$
LABOR MARKET				
μ_j	Wage rigidities parameter	2/4	0.35	0.20

(b) Panel B: Other calibrations

Parameter	[1]	[2]	[3]	[4]
κ	0.1605	0.1605	0.1604	0.1598
χ	0.1054	0.1054	0.1055	0.1059
μ_H	0.2	0.35	0.2	0.35
μ_F	0.2	0.2	0.2	0.2
$\phi_{B,F}$	0	0	0.0025	0.0025
$\rho_{B,F}$	—	—	$\sqrt[4]{0.95}$	$\sqrt[4]{0.95}$

adoption shocks (i.e. $\sqrt[4]{0.95}$). This value is in line with Croce, Nguyen, and Schmid (2013). To obtain a volatility of the government expenditure to GDP ratio of slightly above one percentage point—as observed in the data—we set the volatility of government expenditure shocks σ_G to 0.0076.

The model is solved using a third-order perturbation around the stochastic steady state implemented in Dynare++ 4.4.3.

4.2 Cross-country heterogeneity, macro quantities, and asset returns

In Table 2 we report the moments of macroeconomic quantities and those of asset prices. Specification [1] in Table 2 refers to the economy where the two countries feature identical labor market frictions and the same fiscal rule (i.e. the zero-deficit policy). Hence, the moments of macro quantities and asset prices are identical across countries. However, thanks to the trade channel, the cross-country correlation of consumption growth is slightly lower than the correlation of output growth and stock market returns, consistent with international macroeconomic and financial data. Therefore, our model accounts partially for the international consumption correlation puzzle (see Bodenstein, 2008). Using their related international endogenous growth model, Gavazzoni and Santacreu (2015) show in detail how the adoption channel is capable of creating highly correlated equity returns while keeping fundamentals moderately correlated.

Macro and asset pricing moments diverge when we introduce heterogeneous wage rigidities (Specification [2]): The country with higher rigidities features more volatile macroeconomic aggregates and, at the same time, higher excess stock returns, consistent with empirical evidence. An exception is consumption which is still equally volatile across both countries. Our model, therefore, suggests that a fraction of the international difference between stock returns can be explained by different labor market rigidities. Precisely, the introduction of heterogeneous labor market frictions explains about 21% of the observed cross-country equity return gap.

Specification [3] introduces asymmetric fiscal policies when the two countries exhibit similar labor market characteristics (i.e. moderate wage rigidities with $\mu_H = \mu_F = 0.20$). Thanks to the tax-smoothing mechanism, the foreign country features less volatile macro quantities. Concerning asset prices, we observe that investors require a higher return premium to invest in the country with the zero-deficit fiscal rule, i.e. the equity premium is about 5 basis points higher in the home country than in the foreign country. Thus, the international differences in stock returns can also be explained, at least partially, by different fiscal policies. As discussed above, similar dynamics are induced by heterogeneous wage rigidities. It turns out that countries employing a strict fiscal policy pay higher returns than countries employing tax-smoothing policies, consistent with empirical data. This is again explained by more volatile fundamentals that are reflected in the asset prices. Quantitatively, the compensation risk for a stringent tax regime accounts for about 12% of the total equity return gap of 42 basis points observed between Germany and Italy. Hence, the effects of asymmetric tax regimes are quantitatively less important than the effects of heterogeneous labor markets. This observation holds as well with respect to the heterogeneity in the volatilities of excess returns and macroeconomic growth rates.

Specification [4] refers to our benchmark international endogenous growth economy where it is

Table 2: Model vs. Data: International Macro Quantities and Asset Prices

This table reports the results of simulating 1,000 economies for 200 quarters by drawing sequences of normally distributed random numbers for all shocks in the model. The moments are computed by removing the initial 40 quarters of the simulated data ("burn-in" period). The reported moments are annualized. Means and volatilities are reported in percentage points. Note that the equity return in country $j \in \{H, F\}$ is the return on the claim on the aggregate dividend $D^a_{j,t}$, which is defined by $D^a_{j,t} = D_{j,t} + A_{j,t}\Pi_{j,t} + A^*_{-j,t}\Pi^*_{-j,t}$. As in Croce (2014), the aggregate excess returns, $R_H - R^f_H$ and $R_F - R^f_F$, are levered using a leverage parameter of 2.

Moments for asset prices and macroeconomic quantities are reported for the benchmark calibration (specification [4]) and for three other calibrations. Specification [1]: symmetric tax regimes and homogeneous labor market rigidities. Specification [2]: symmetric tax regimes and heterogeneous labor market rigidities. Specification [3]: asymmetric tax regimes and homogeneous labor market rigidities. Specification [4]: asymmetric tax regimes and heterogeneous labor market rigidities (benchmark calibration).

The home country represents Italy, and the foreign country represents Germany. Here, $\mathbb{E}[\cdot]$, $\sigma(\cdot)$, and $\rho(\cdot)$ denote the mean, the volatility, and the correlation, respectively. Equity market returns for Italy and Germany are computed from Morgan Stanley Capital International (MSCI) Total Return Indexes (TRI). Short-term interest rates retrieved from the OECD are used as countries' risk-free rate proxies. Nominal returns are converted to real using the Consumer Price Index (All Items), which is obtained from the OECD. All macroeconomic aggregates for Italy and Germany are obtained from the OECD. Data are annual and run from 1971 (or later) to 2015. Additional details on the used data are given in Appendix A.

	DATA	[1]	[2]	[3]	[4]
		STR	STR	ATR	ATR
		$\phi_{B,H} = \phi_{B,F} = 0$	$\phi_{B,H} = \phi_{B,F} = 0$	$\phi_{B,H} = 0$, $\phi_{B,F} = 0.005$	$\phi_{B,H} = 0$, $\phi_{B,F} = 0.005$
		$\mu_H = 0.20$, $\mu_F = 0.20$	$\mu_H = 0.35$, $\mu_F = 0.20$	$\mu_H = 0.20$, $\mu_F = 0.20$	$\mu_H = 0.35$, $\mu_F = 0.20$
Asset Prices					**Benchmark**
$\mathbb{E}[R_H - R^f_H]$	6.87	2.07	2.20	2.13	**2.22**
$\mathbb{E}[R_F - R^f_F]$	6.45	2.07	2.11	2.08	**2.09**
$\sigma(R_H - R^f_H)$	28.54	5.72	5.96	5.72	**5.97**
$\sigma(R_F - R^f_F)$	19.90	5.72	5.69	5.60	**5.62**
$\mathbb{E}[R^f_H]$	2.51	2.13	2.03	2.16	**2.06**
$\mathbb{E}[R^f_F]$	2.29	2.13	2.07	2.21	**2.11**
$\sigma(R^f_H)$	3.20	0.28	0.32	0.29	**0.33**
$\sigma(R^f_F)$	1.86	0.28	0.29	0.32	**0.33**
$\rho(R_H - R^f_H, R_F - R^f_F)$	0.64	0.80	0.80	0.81	**0.80**
$\rho(R^f_H, R^f_F)$	0.62	0.71	0.66	0.70	**0.63**
Macro Quantities					**Benchmark**
$E[\Delta y_H]$	1.99	1.91	1.91	1.91	**1.91**
$E[\Delta y_F]$	1.78	1.91	1.91	1.91	**1.91**
$E[G_H/Y_H]$	20.74	20.00	20.00	20.00	**20.00**
$E[G_F/Y_F]$	19.36	20.00	20.00	20.00	**20.00**
$\sigma(G_H/Y_H)$	1.07	1.08	1.08	1.08	**1.08**
$\sigma(G_F/Y_F)$	1.10	1.08	1.08	1.08	**1.08**
$\sigma(\Delta c_H)$	2.26	1.21	1.22	1.21	**1.22**
$\sigma(\Delta c_F)$	1.64	1.21	1.21	1.20	**1.20**
$\sigma(\Delta y_H)$	2.41	2.81	2.91	2.83	**2.92**
$\sigma(\Delta y_F)$	2.01	2.81	2.81	2.78	**2.79**
$\sigma(\Delta s_H)$	5.20	3.40	3.52	3.42	**3.52**
$\sigma(\Delta s_F)$	3.91	3.40	3.39	3.36	**3.35**
$\sigma(\Delta i_H)$	4.55	4.32	4.49	4.34	**4.49**
$\sigma(\Delta i_F)$	4.21	4.32	4.32	4.26	**4.26**
$\sigma(\Delta l_H)$	0.74	1.03	1.21	1.03	**1.21**
$\sigma(\Delta l_F)$	0.85	1.03	1.03	0.97	**0.98**
$\rho(\Delta c_H, \Delta c_F)$	0.51	0.66	0.66	0.67	**0.66**
$\rho(\Delta y_H, \Delta y_F)$	0.73	0.73	0.73	0.73	**0.73**
$\rho(\Delta s_H, \Delta s_F)$	0.51	0.70	0.70	0.70	**0.70**
$\rho(\Delta i_H, \Delta i_F)$	0.43	0.71	0.71	0.72	**0.71**
$\rho(\Delta l_H, \Delta l_F)$	0.44	0.52	0.55	0.51	**0.53**

assumed that countries differ in both their fiscal policies and labor market rigidities. The introduction of an additional source of heterogeneity exacerbate the differences between cross-country moments. In particular, we observe a larger difference between home and foreign volatilities of macro aggregates and stock returns. Consistent with the empirical evidence, the country featuring higher wage rigidities and the zero-deficit policy also has higher stock market volatility and higher expected returns. Almost 31% of the observed equity excess return spread can now be explained by the model. However, the absolute amount of the excess return volatility is still about 3 to more than 4 times lower than what is empirical observed in Germany and Italy, respectively.[10]

Qualitatively, the signs of the differences between the home and foreign volatilities of macro aggregates in the model are consistent with the empirical evidence except for labor growth volatilities. In particular, consumption, output, R&D investment, and capital investment growth are all more volatile in the rigid economy (i.e. the home country or Italy in this example) than in the more flexible economy (i.e. the foreign country or Germany in this example). However, labor growth is more volatile in Italy than in Germany, contrary to the empirical data. This equilibrium effect is rooted in the different degrees of wage rigidities and heterogeneous fiscal policies affecting labor income taxes in the model that imply more volatile labor growth for the rigid economy, i.e. the home economy. In addition, the model does not match the observed spread between the interest rates of the two countries. This result is due to market incompleteness. In our model, the home country is riskier than the foreign country because of higher labor market rigidities and because of the zero-deficit policy. Therefore, households in the home country have higher precautionary saving needs than households in the foreign country. Given that markets are incomplete, the only possibility for households of the home country to save more is to invest more in the local bond, thus decreasing the local interest rate as compared to the foreign interest rates.

The cross-country correlation of the equity risk premia is relatively high in all the calibrations but different from unity, consistent with empirical data. This moment does not change significantly when heterogeneity between countries is introduced. The correlation of the risk-free rates across countries is also in line with empirical data and depends on the heterogeneity across countries. In our model, the correlations among macroeconomic quantities is explained by the trade channel. Wage rigidities make the home economy more exposed to macroeconomic shocks, while the tax-smoothing policy makes the foreign country less exposed to macroeconomic shocks. The combined effect of these two forces is a reduction in the correlation between the risk-free rates.[11] Overall, the two sources of heterogeneity considered, namely heterogeneity in fiscal policy and in labor market flexibility, do a good job in replicating the observed differences between the two targeted European countries. Thus, in the following Section 4.3 we study the diffusion of macroeconomic shocks between the two countries.

[10]This is a well-known feature of production economies. Recent solutions to this issue include financial shocks to the tightness of firms' borrowing constraint (Nezafat and Slavík, 2015) or infrequent renegotiation of wages coupled with stochastic leverage (Favilukis and Lin, 2016). However, given the technical complexity of our model these modifications are beyond the scope of this paper.

[11]Note that a recent class of models featuring segmented international capital markets and financial frictions tend to generate perfectly correlated international asset returns, inconsistent with financial data (Devereux and Yetman, 2010; Devereux and Sutherland, 2011).

4.3 Asymmetric tax regimes and international transmission of shocks

Fiscally weak countries, especially in Europe, are generally characterized by restrictive fiscal policies and, at the same time, tend to sustain economic growth by adopting new technologies from abroad. Therefore, the questions we ask ourselves are: what is the effect of a shock to the probability of adoption when a country is constrained to a zero-deficit policy? How is the shock transmitted internationally when the two countries are heterogeneous? In Figure 1, we depict the impulse response functions of domestic and foreign macro quantities in response to a positive domestic adoption probability shock for the benchmark calibration. After the increase in the adoption probability, the home country experiences an economic expansion and aggregate quantities, such as output, labor, and investments, increase. An exception is consumption, which drops initially in the home country following the shock but increases from about 10 quarters onward (Figure 1, Panel A). The adoption probability shock lowers the opportunity cost of investment. This makes consumption less attractive and stimulate investments in both physical capital and R&D which later stimulates consumption as well.

The beneficial effect of the positive shock in the probability of adoption is transmitted to the foreign country through the channel of trade in intermediate goods especially in the long run (i.e. after around 40 quarters) in the case of output, capital investment, and labor (Figure 1, Panels B, C and D). Differently, the effect for consumption and R&D investment is negative initially and only marginally positive in the long run (Figure 1, Panels A and E). Initially, the negative effect on consumption is also here driven by the substitution effect which implies that the household shifts resources away from consumption to investments. In the long run, the stronger adoption channel leading to higher output and capital investment stimulates the increase in consumption. The positive effect of a positive adoption probability shock is thus less pronounced and only significantly visible in the long run in the foreign country. This result reflects recent empirical evidence suggesting that technology adoption has a stronger effect on countries' long-run economic growth than R&D investments (Choi, González, and Gray, 2013). Moreover, the tax-smoothing policy leads to a slightly higher tax rate over the whole 80 quarters in the foreign country which implies that the foreign country runs a small fiscal surplus (Figure 1, Panels F and H).

The terms of trade do not react much to a positive adoption probability shock (Figure 2, Panel J). On impact of the shock, the terms of trade in the home country $Q_{H,t}$ depreciate, but they appreciate and revert back to the steady state subsequently. The beneficial effect of the increase in the probability of adoption is transmitted to the foreign country but its implications for macroeconomic quantities are different. Overall, the positive effect on macroeconomic prospects of the foreign country is smaller but more long lasting as compared to that observed in the home country. Three factors contribute to this result. First, only a part of the surplus production generated in the home country is sold abroad. Second, the economic expansion in the foreign country activates the counter-cyclical tax adjustment mechanism, i.e. the foreign country raises taxes initially (Figure 2, Panel F), pays back debt (Figure 2, Panel H) and reduces taxes later (Figure 1, Panel F), that partially offsets the stimulus generated by the positive productivity shock of the home country. Finally, the labor market of the home country is rigid and thus tends to react more to macroeconomic shocks.

In our model, economic growth also depends on the internal production of intermediate goods and thus on the productivity of domestic capital. It is, therefore, important to understand the effect

Figure 1: Asymmetric Tax Regimes and Heterogeneous Labor Markets: The Effects of a Home Country Adoption Probability Shock

This figure depicts impulse response functions for 80 quarters of the following home country (solid black line) and foreign country (dashed red line) macroeconomic quantities and asset returns: consumption $C_{j,t}$, output $Y_{j,t}$, capital investment $I_{j,t}$, R&D expenditure $S_{j,t}$, labor hours $L_{j,t}$, total government revenues $T_{j,t}$, patent value $V_{j,t}$, labor tax rate $\tau_{j,t}$, debt to GDP ratio $B_{j,t}/Y_{j,t}$, expected consumption growth $\mathbb{E}_t[\Delta c_{j,t+1}]$, terms of trade $Q_{j,t}$, risk-free rate $r^f_{j,t}$, with respect to a positive one standard deviation adoption probability shock in the home country $\upsilon^A_{H,t}$ (i.e. $\epsilon^\theta_H > 0$). Panels A, B, C, D, E, G, J, and K show log deviations from the steady state in percentage points. Panels F, H, I, and L show absolute deviations from the steady state in percentage points. All parameters are set as in Table 1, benchmark calibration [4].

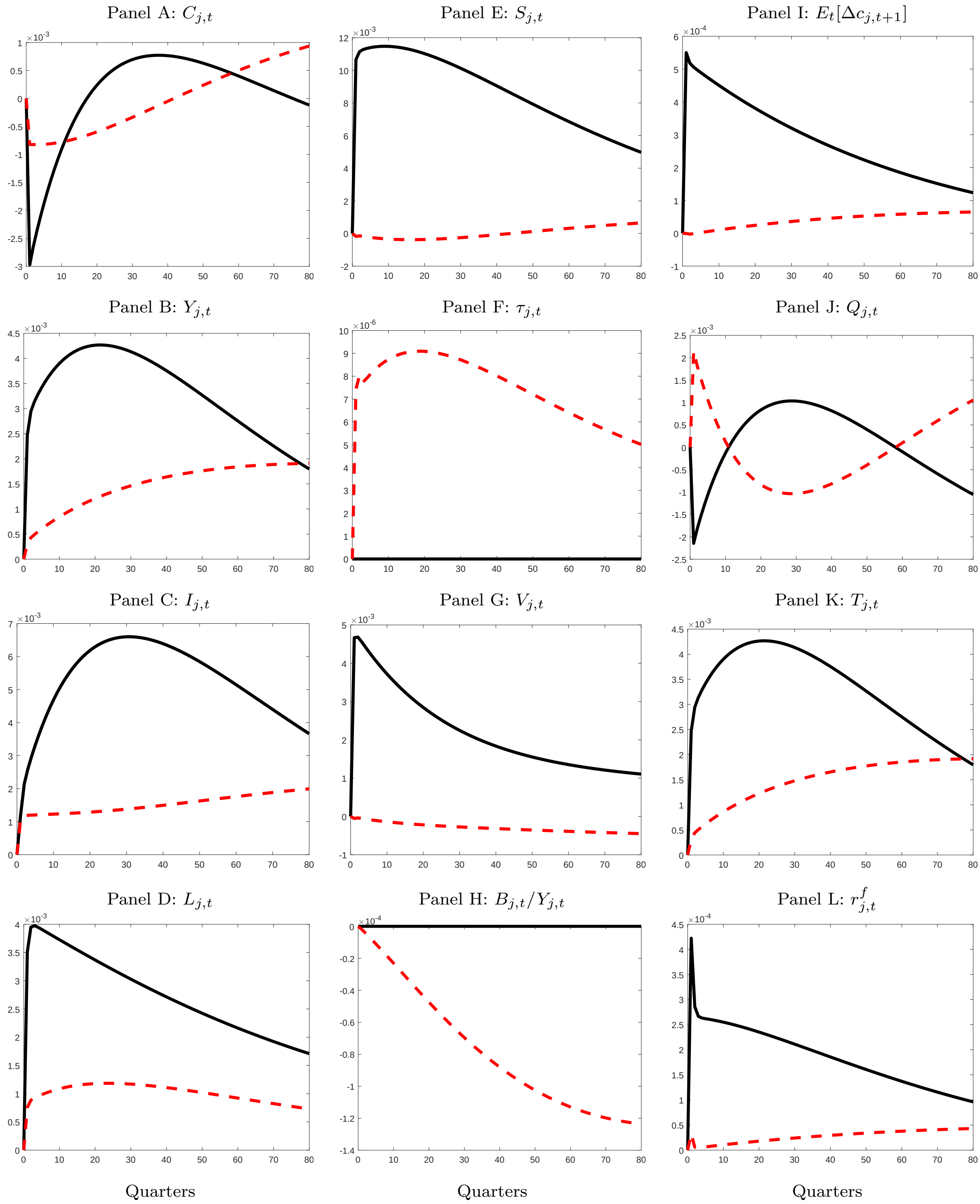
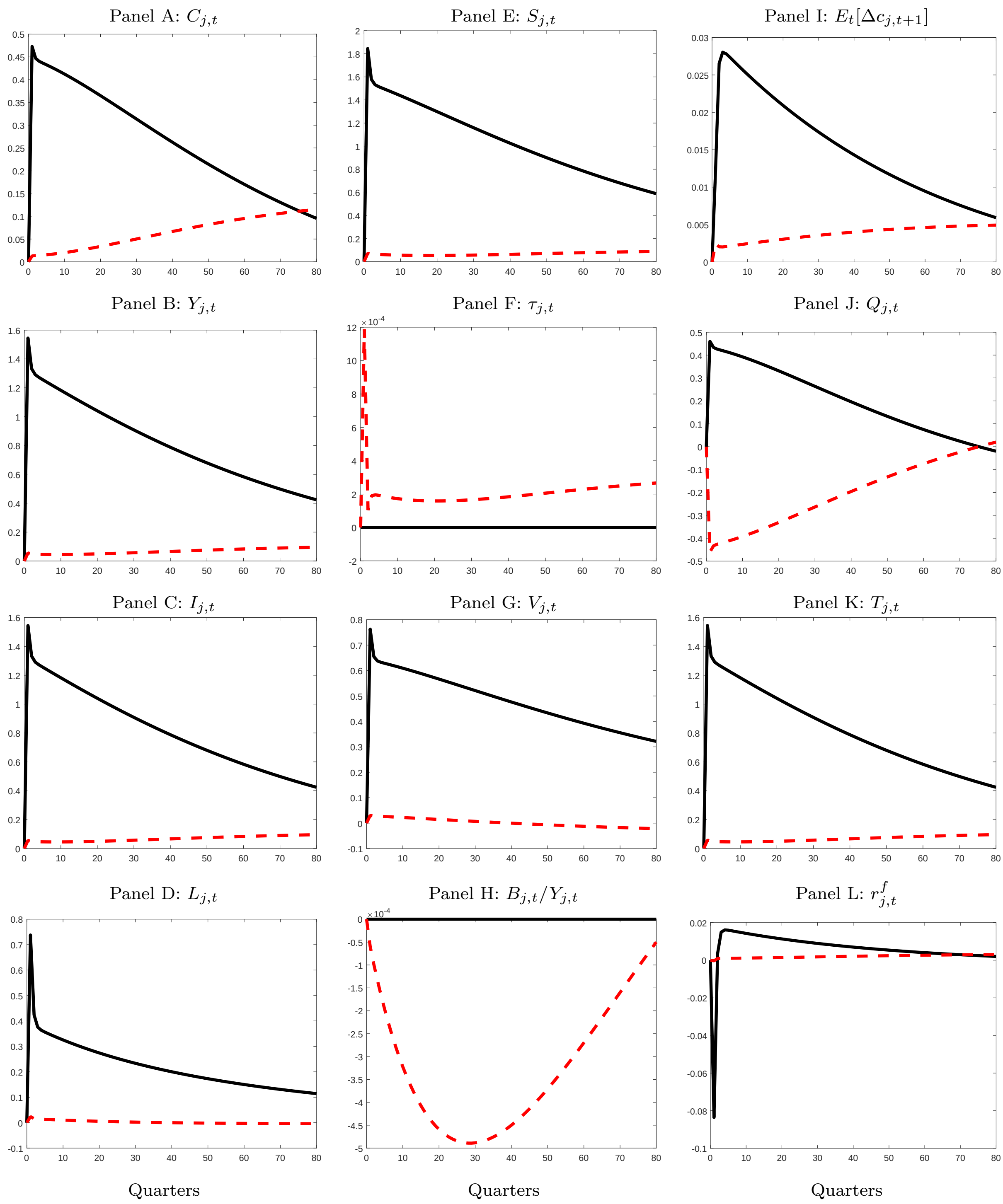


Figure 2: Asymmetric Tax Regimes and Heterogeneous Labor Markets: The Effect of a Home Country productivity Shock

This figure depicts impulse response functions for 80 quarters of the following home country (solid black line) and foreign country (dashed red line) macroeconomic quantities and asset returns: consumption $C_{j,t}$, output $Y_{j,t}$, capital investment $I_{j,t}$, R&D expenditure $S_{j,t}$, labor hours $L_{j,t}$, total government revenues $T_{j,t}$, patent value, $V_{j,t}$, labor tax rate $\tau_{j,t}$, debt to GDP ratio $B_{j,t}/Y_{j,t}$, expected consumption growth $\mathbb{E}_t[\Delta c_{j,t+1}]$, terms of trade $Q_{j,t}$, risk-free rate $r^f_{j,t}$, with respect to a positive one standard deviation productivity shock in the home country $\Omega_{H,t}$ (i.e. $\epsilon^{\Omega}_H > 0$). Panels A, B, C, D, E, G, J, and K show log deviations from the steady state in percentage points. Panels F, H, I, and L show absolute deviations from the steady state in percentage points. All parameters are set as in Table 1, benchmark calibration [4].



of productivity shocks and, in particular, how these shocks are transmitted internationally and their contribution to global risk. In Figure 2, we depict the impulse response functions corresponding to a positive productivity shock of the home country. After the shock, the growth rates of home country's consumption increases significantly. The growth rates of the foreign country increases less on impact but more persistently (Figure 1, Panel I). For instance, after the shock the expected growth rate of consumption of the home country rises immediately by 0.025 percentage points, but it reverts back to the steady state from the third quarter onward. For the foreign country, the positive effect is smaller in magnitude (0.0025 percentage points) but it increases over the whole 80 quarters.

Finally, the positive productivity shock leads to a persistent increase in the terms of trade $Q_{H,t}$ which turn slightly negative at the end of the 80 quarters depicted (Figure 2, Panel J). Due to the higher productivity in the home country, the home country's good yields a higher price in the international goods market.

5 Conclusion

This paper studies the implications of international technology diffusion in a dynamic stochastic general equilibrium model where countries have different fiscal policies and different labor market flexibility. These two sources of heterogeneity help to explain the observed differences in key moments of macroeconomic quantities and asset prices of European countries. Our framework also implies heterogeneity in the transmission mechanism of macroeconomic shocks across countries. Thus, country heterogeneity is not only important to explain macroeconomic quantities and asset prices but also provides a better understanding of the international transmission mechanism of shocks.

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A Data

Table A.1: Data Description

Variable	Period	Source
Macroeconomic Aggregates		
Gross domestic product (expenditure approach)	1971-2015	OECD: National Accounts
Final consumption expenditure of households	1971-2015	OECD: National Accounts
Gross fixed capital formation	1971-2014	OECD: National Accounts
Average Annual Hours Worked by Persons Engaged for Germany/Italy	1971-2011	University of Groningen, University of California, Davis
Final consumption expenditure of general government	1971-2015	OECD: National Accounts
BERD - Compound annual growth rate (constant prices)	1981-2014	OECD: Main Science and Technology Indicators
Consumer price index (all items)	1979-2015	OECD: Consumer Prices
Asset Prices		
MSCI TRI	1979-2015	Datastream
Short-term interest rates, Per cent per annum	1979-2015	OECD: Monthly Monetary and Financial Statistics

B Equilibrium Conditions

For each country $j \in \{H, F\}$ the decentralized equilibrium of our model is defined as

- a sequence of exogenous stochastic processes $\{\Omega_{j,t}, g_{j,t}, \theta_{j,t}\}_{t=0}^{\infty}$;
- an initial vector $\left\{A_{j,0}, A^*_{j,0}, K_{j,0}\right\}$;
- a set of common parameters $\left\{\beta, \gamma, \psi, \kappa, \sigma, \alpha, \xi, \delta, \zeta, \sigma_\Omega, \rho_\Omega, \rho(\varepsilon^\Omega_H, \varepsilon^\Omega_F), \nu, \delta_\upsilon, \chi, \eta, \bar{\theta}, \sigma_\theta, \rho_\theta, \bar{g}, \sigma_G, \rho_G\right\}$;
- a set of country-specific parameters $\{\phi_{B,j}, \rho_{B,j}, \mu_j\}$;
- a sequence of prices, value functions, profits, wages, and adoption probabilities $\Big\{P_{j,t}, P^*_{j,t}, V_{j,t}, W^V_{j,t}, W^{V,*}_{j,t}, J_{j,t}, \Pi_{j,t}, \Pi^*_{j,t}, W_{j,t}, W^u_{j,t}, \upsilon^A_{j,t}\Big\}_{t=0}^{\infty}$;
- a sequence of aggregate macro quantities $\{Y_{j,t}, S_{j,t}, G_{j,t}, I_{j,t}, K_{j,t}, L_{j,t}, \upsilon_{j,t}, Q_{j,t}\}_{t=0}^{\infty}$;
- a sequence of labor tax rates and debt levels $\{\tau_{j,t}, B_{j,t}\}_{t=0}^{\infty}$
- a sequence of pricing kernels and risk-free rates $\left\{\mathbb{M}_{j,t+1}, r^f_{j,t}\right\}_{t=0}^{\infty}$;
- a sequence of quantities and numbers of intermediate goods $\left\{X_{j,t}, X^*_{j,t}, N_{j,t}, A_{j,t}, A^*_{j,t}\right\}_{t=0}^{\infty}$.

such that:

- the state variables $\left\{N_{j,t}, A_{j,t}, A^*_{j,t}, K_{j,t}, \Omega_{j,t}, g_{j,t}, \theta_{j,t}\right\}_{t=0}^{\infty}$ satisfy the laws of motion in Equations (22), (21), (23), (7), (6), (30), and (24);
- the endogenous variables solve the households', producers' and innovators' problems in Equations (1), (2), (3), (16), (17), (18), (19), (20), and (29) and the exchange rate follows (14);
- both the government's budget constraint (31) and the economy's resource constraint (35) are satisfied;
- prices, value functions, returns, tax rates, and debt levels are such that all markets clear: Equations (12), (13), (25), (4), (32), (34), and (33).

The following list gives the equilibrium conditions of this economy:

$$
\begin{aligned}
K_{j,t+1} &= (1-\delta)K_{j,t} + \Lambda\left(\frac{I_{j,t}}{K_{j,t}}\right)K_{j,t} \\
1 &= \mathbb{E}_t\left[\mathbb{M}_{j,t+1}\Lambda'_{j,t}\left\{\frac{\alpha(1-\xi)Y_{j,t+1} - I_{j,t+1}}{K_{j,t+1}} + \left(\frac{1-\delta+\Lambda_{j,t+1}}{\Lambda'_{j,t+1}}\right)\right\}\right], \\
W_{j,t}L_{j,t} &= (1-\alpha)(1-\xi)Y_{j,t}, \\
W_{j,t} &= (e^{\Delta a_{j,t}}W_{j,t-1})^{\mu_j}(W^u_{j,t})^{1-\mu_j}, \\
P_{j,t} &= \nu, \\
P^*_{j,t} &= \nu Q_{j,t}, \\
Q_{j,t} &= C_{j,t}/C_{-j,t}, \\
\Pi_{j,t} &= (\nu-1)\,X_{j,t},
\end{aligned}
$$

$$
\begin{aligned}
\Pi^*_{j,t} &= (\nu-1)\, X^*_{j,t}, \\
X_{j,t} &= \left(\frac{\xi}{\nu}\right)^{\frac{\nu}{\nu-1}} K^{\alpha}_{j,t}\, (\Omega_{j,t} L_{j,t})^{1-\alpha} \left(\left(\frac{\xi}{\nu}\right)^{\frac{1}{\nu-1}} A_{j,t} + \left(\frac{\xi}{\nu Q_{j,t}}\right)^{\frac{1}{\nu-1}} A^*_{j,t}\right)^{-\alpha}, \\
X^*_{j,t} &= \left(\frac{\xi}{\nu Q_{j,t}}\right)^{\frac{\nu}{\nu-1}} K^{\alpha}_{j,t}\, (\Omega_{j,t} L_{j,t})^{1-\alpha} \left(\left(\frac{\xi}{\nu}\right)^{\frac{1}{\nu-1}} A_{j,t} + \left(\frac{\xi}{\nu Q_{j,t}}\right)^{\frac{1}{\nu-1}} A^*_{j,t}\right)^{-\alpha}, \\
\log(\Omega_{j,t}) &= \rho_\Omega \log(\Omega_{j,t-1}) + \epsilon^{\Omega}_{j,t}, \\
u_{j,t} &= \left\{\kappa C_{j,t}^{1-\frac{1}{\sigma}} + (1-\kappa)[N_{j,t}(\bar{L}_j - L_{j,t})]^{1-\frac{1}{\sigma}}\right\}^{\frac{1}{1-\frac{1}{\sigma}}}, \\
(1-\tau_{j,t}) W^u_{j,t} &= \frac{1-\kappa}{\kappa} N_{j,t}^{1-1/\sigma} \left(\frac{C_j, t}{\bar{L}_j - L_{j,t}}\right)^{1/\sigma}, \\
\mathbb{M}_{j,t+1} &= \beta \left(\frac{u_{j,t+1}}{u_{j,t}}\right)^{1/\sigma - 1/\psi} \left(\frac{C_{j,t+1}}{C_{j,t}}\right)^{-1/\sigma} \left(\frac{U^{1-\gamma}_{j,t+1}}{\mathbb{E}_t[U^{1-\gamma}_{j,t+1}]}\right)^{\frac{1/\psi-\gamma}{1-\gamma}}, \\
1 &= \mathbb{E}_t\left[\mathbb{M}_{j,t+1}(1+r^f_{j,t})\right], \\
\upsilon^A_t &= 1/(1+e^{-\theta_{j,t}}), \\
\theta_{j,t} &= (1-\rho_\theta)\overline{\theta} + \rho_\theta \theta_{j,t-1} + \epsilon^{\theta}_{j,t}, \\
A_{j,t+1} &= \upsilon_{j,t} S_{j,t} + (1-\delta_v) A_{j,t}, \\
e^{\Delta a_{j,t+1}} &= A_{j,t+1}/A_{j,t}, \\
\upsilon_{j,t} &= \chi N_{j,t}^{-(\eta-1)} S_{j,t}^{\eta-1}, \\
N_{j,t} &= A_{j,t} + A^*_{j,t}, \\
\frac{1}{\upsilon_{j,t}} &= \mathbb{E}_t[\mathbb{M}_{j,t+1} V_{j,t+1}], \\
A^*_{j,t+1} &= (1-\delta_v) A^*_{j,t} + \upsilon^A_{j,t}(1-\delta_v)(A_{-j,t} - A^*_{j,t}), \\
V_{j,t} &= W^V_{j,t} + J_{j,t}, \\
W^V_{j,t} &= \Pi_{j,t} + (1-\delta_v)\mathbb{E}_t[\mathbb{M}_{j,t+1} W^V_{j,t+1}], \\
W^{V,*}_{j,t} &= \Pi^*_{-j,t} + (1-\delta_v)\mathbb{E}_t[\mathbb{M}_{j,t+1} W^{V,*}_{j,t+1}], \\
J_{j,t} &= (1-\delta_v)\mathbb{E}_t\left[\mathbb{M}_{j,t+1}\left(\upsilon^A_{-j,t} W^{V,*}_{j,t+1} + (1-\upsilon^A_{-j,t}) J_{j,t+1}\right)\right], \\
Y_{j,t} &= C_{j,t} + S_{j,t} + A_{j,t} X_{j,t} + A^*_{j,t} X^*_{j,t} + G_{j,t} + I_{j,t}, \\
Y_{j,t} &= K^{\alpha}_{j,t}\left(\Omega_{j,t} L_{j,t}\left(\left(\frac{\xi}{\nu}\right)^{\frac{1}{\nu-1}} A_{j,t} + \left(\frac{\xi}{\nu Q_{j,t}}\right)^{\frac{1}{\nu-1}} A^*_{j,t}\right)\right)^{1-\alpha}, \\
\frac{G_{j,t}}{Y_{j,t}} &= \frac{1}{1+e^{-g_{j,t}}}, \\
g_{j,t} &= (1-\rho_G)\bar{g} + \rho_g g_{j,t-1} + \epsilon^G_{j,t}, \\
T_{j,t} &= \tau_{j,t} W_{j,t} L_{j,t}, \\
\frac{B_{H,t}}{Y_{H,t}} &= 0, \\
B_{F,t} &= (1+r^f_{F,t-1}) B_{F,t-1} + G_{F,t} - T_{F,t}, \\
\frac{B_{F,t}}{Y_{F,t}} &= \rho_{B,F}\frac{B_{F,t-1}}{Y_{F,t-1}} + \phi_{B,F}(\log L_{F,ss} - \log L_{F,t}).
\end{aligned}
$$

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