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Abstract

This paper analyzes the effect of productivity shocks originating from other countries on economic growth in the home country. Traditionally, productivity shocks have been considered as driving forces of economic growth in their home countries. However, productivity improvements occur both at home and overseas. In liberalized global markets, economic growth is, in theory, also attributable to productivity shocks from other countries. Using data from 18 countries, we show that numerous countries benefit from productivity spillovers. Nevertheless, their impacts on the economy differ according to the origin of the economic shocks. On the one hand, US shocks are rather pervasive and affect many economies and regions, regardless of their development stage. On the other hand, shocks from other country groups exert less influence over foreign economies.

Keywords: productivity, economic growth, international transmission, global vector autoregression
JEL classification: C32, O47

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1 Introduction

Globalization has accelerated especially after World War II due to the initiatives of the Bretton Woods institutions, such as the International Monetary Fund and the World Bank. Economic liberalization has been considered to be particularly successful at regional level. For example, the European Union (EU) and the Association of South-East Asian Nations (ASEAN), among others, have removed virtually all trade barriers in order to promote intra-regional trade. Furthermore, the creation of single currency areas, like the Eurozone, represents the ultimate form of regional liberalization. Such economic liberalization is often related to the free movement of goods, services, capital, and labor and has been advanced on the basis of the standard economic theory, which predicts that countries will benefit from removing cross-border trade barriers.

However, advanced countries have recently shifted towards protectionism. The US president, Donald Trump, expressed strong interest in protecting domestic industries, i.e., the 'America First' policy, to correct prolonged and large US trade deficits. Conservative movements have also occurred in Europe. Following its 2016 referendum, the UK has decided to leave the EU to gain more independent control of its immigration policies. In 2017, Germany imposed a cap on immigration, particularly that from the Middle East. In short, many people nowadays doubt the outcome of economic liberalization. There is a significant gap between the standard economic theory and actual economic policies implemented by many advanced countries.

Against this background, our study attempts to investigate the role of spillover effects of productivity shocks in the context of economic growth. More specifically, we analyze the following spillover effects within the last three decades. First, we quantify the magnitude of US spillover effects on the rest of the world because the US possesses many advanced industries such as information technology. Second, in order to investigate the significance of spillovers originating in the US, we compare them with productivity shocks originating in other parts of the world. In short, we confirm that there are asymmetric effects in external spillovers and that US spillovers exert more influence over global markets.

This paper contributes to the literature in the following ways. First, at least in theory, productivity improvements, along with capital and labor, are known to be an essential factor for economic growth. However, despite efforts to remove cross-country barriers, productivity spillovers in the international context have rarely been studied, in particular by using historic macroeconomic data (see the Literature survey section).[1] We primarily study the extent to which US productivity has affected its own economic growth and that of other country groups. Whereas country-specific outcomes are important, we are interested in a more general outcome that is relevant to formulating future international economic policies in many countries.

Second, we use a Global Vector Auto-Regressive (GVAR) model (Pesaran et al. (2004)) in order to investigate the cross-country spillover effects of productivity shocks. The empirical literature on productivity spillover remains limited largely due to technical challenges involving the handling of multi-country models with many variables. Two broad approaches that have been used recently to handle this problem include GVAR and the factor-augmented VAR (FAVAR) models. To the best of our knowledge, none of these methods have been used before in the context of productivity shocks. Compared to the FAVAR, the GVAR approach can combine different macroeconomic variables of a large number of countries in a much more efficient manner. GVAR models tackle the 'curse of dimensionality' problem by imposing restrictions directly on the parameters of the model. In particular, all foreign economies are typically approximated by one representative economy, constructed as a (trade-) weighted average of foreign economies. Here, individual country models are added by means of a consistent econometric approach to create a global model, where cointegration is allowed for variables within and across countries. On the other hand, FAVAR models capture country-specific dynamics only through idiosyncratic components (i.e., the residuals). Also, in GVAR models, data can be used in levels and, therefore, long-run information in the data is retained.

Third, this paper contributes to the GVAR literature. Instead of generalized impulse response functions (GIRFs) that are commonly used in the GVAR literature, structural generalized impulse response functions (SGIRFs) are used for dynamic analysis, in order to better identify the shocks. This goes beyond most previous studies to identify shocks and at least partially overcomes one of the main criticisms regarding the identification and use of GIRFs in GVAR models. Also, instead of commonly used fixed trade weights,

[1] The inexplicit treatment of spillover effects in empirical studies is attributable to the standard statistical approach, such as panel data estimation methods, that often use common time dummies to capture cross-sectional dependence across countries.

time-varying trade weights are used to construct foreign-specific variables of individual country models. This is more realistic, as it controls for the changing relationship between the participating countries for different parts of the business cycle (e.g., rapid growth in the US economy throughout most of the 1990s, the dot-com bubble in 2001, and the financial crisis of 2008).

All subsequent parts of the paper are organized as follows: Section 2 reviews the literature on productivity spillover. Section 3 explains the GVAR model and Section 4 discusses the data and some important statistical properties of the GVAR model. In Section 5, our results are presented and discussed. Finally, Section 6 presents our conclusions.

2 Literature Survey on economic growth and productivity spillovers

Economic growth has been recognized as an important research and policy topic. Therefore, many researchers have developed economic theories and attempted to discover what factors contribute to economic growth using time-series and/or panel data. The classic economic theory (Solow (1956)) points to labor and capital as essential ingredients for economic growth. Therefore, as summarized in Eq. (1), the standard economic growth model can be expressed in terms of the Cobb-Douglas production function:

$$Y_t = K_t^{\alpha}(A_t L_t)^{1-\alpha} \tag{1}$$

where Y_t is aggregate production at time t ($t = 1, ..., T$), K_t is capital, and L_t is labor. A weight α represents the significance of capital in the production ($\alpha \in [0, 1]$) and a higher value of α shows that the country produces more capital-intensive goods. In the classic economic growth theory, these production factors (K and L) are assumed to be exogenous, whereby increases in these factors contribute to economic growth.

However, previous studies have found that capital and labor alone fail to explain the historical experiences of many countries.[2] In this regard, more recent literature considers productivity, human capital, education, and research and development (R&D) as addi-

[2] See Jones (2016) for a comprehensive survey on empirical results.

tional factors contributing to economic growth.[3] For example, Lucas (1988) discussed the importance of education and diversification in skills. Similarly, Mankiw and David (1992) confirmed human capital proxied by education as an important factor of economic growth using a comprehensive set of countries. The importance of R&D is empirically confirmed in India (Raut (1995)) and in a panel of countries (Coe and Helpman (1995); Coe and Hoffmaister (1997)). These extensions are equivalent to the recognition of investment in humans. Efforts to improve human capital are now widely included as part of economic policies.

In terms of Eq. (1), A may capture these extra elements missing in the classic economic theory and is known as the slow residual or as the total factor productivity (TFP). A can be thought of as factors, such as innovation and R&D, to improve productivity. When A that is generated endogenously by R&D or human capital is included, the model can explain sustainable economic growth. Therefore, economic growth has traditionally been analyzed without considering the explicit role of cross-border spillovers, which is not surprising when the market has only limited access to global markets.

Alternatively, education effects (S) and productivity can be treated separately (Hall and Charles (1999), Frankel and Romer (1999)). Education is expected to improve labor efficiency, closely following Mincers wage equation. (Mincer (1974)).

$$Y_t = K_t^{\alpha}(e^{\vartheta(S_t)}A_t L_t)^{1-\alpha} \tag{2}$$

A theoretical link between international trade and economic growth has been developed over the last two decades. For example, Grossman and Helpman (1991) explained the role of international trade in economic growth, and Ventura (1997) provided theoretical justification for quick economic growth experienced by export-oriented countries. Previous studies looked at spillover effects of productivity improvements in a particular country, such as Spain (Barrios and Eric (2002)), China (Lin and Kwan (2016)), England (Girma (2005)), and India (Raut (1995)). Gorg and Strobl (2001) reviewed earlier literature and found that spillover effects are more clearly observed in microdata analysis. Similarly, they observed large spillover effects in open and developing markets. By identifying trade, financial, and indirect linkages, Arora and Athanasios (2005) showed

[3] These factors may not be mutually exclusive.

that international trade as an engine of economic growth generally holds true for both advanced and developing countries. The indirect linkage is a channel through which business and consumer confidence in advanced countries affects confidence in developing countries. Keller (2002) documented that productivity at home is influenced by R&D originating from both home and foreign countries. The 20% of home productivity improvements are found to be caused by R&D in foreign countries. Keller and Yeaple (2013) pointed out that knowledge transfer may occur through exchanging intermediaries, as well as direct communication. They found evidence that direct communication becomes more difficult as the distance between companies increases. More broadly, productivity spillovers contributed more to economic growth than did the international trade of goods (Weil (2009)).

We investigate spillover effects using macroeconomic data that have not been analyzed as extensively as microdata, but are nonetheless useful in order to draw a general conclusion. Here, an economic growth equation is expressed in terms of per capita, which is the most standard measure for aggregate economic activities when comparing economic development across countries. This measure differs from another popular specification based on GDP per labor. While GDP per labor may be more consistent with the concept of productivity, we study GDP per capita because of its prevalence in economics and its significant implications for economic policies. Furthermore, only a few countries under our investigation release labor statistics. This an important factor in our decision, since this study covers a wide range of countries. When multiple countries become research targets and population (N) replaces labor, Eq. (1) can be re-stated for countries i as:

$$\frac{Y_{it}}{N_{it}} = \left(\frac{K_{it}}{N_{it}}\right)^{\alpha} A_{it}^{1-\alpha} \tag{3}$$

Panel data allow us to utilize cross-sectional information resulting in statistically more reliable outcomes, in addition to being expected to offer a general conclusion relevant to most investigated countries. In natural logarithmic form, we can derive the standard growth equation that has been investigated by many researchers.

$$y_{it} = \alpha k_{it} + (1-\alpha)a_{it} \tag{4}$$

where $y_{it} = ln(Y_{it}/N_{it})$, $k_{it} = ln(K_{it}/N_{it})$, and $a_{it} = lnA_{it}$. Similarly, Eq. (2) can be expressed in terms of per capita as:

$$\frac{Y_{it}}{N_{it}} = \left(\frac{K_{it}}{N_{it}}\right)^{\alpha} (A_{it}e^{\vartheta(S_{it})})^{1-\alpha} \tag{5}$$

or

$$y_{it} = \alpha k_{it} + (1-\alpha)a_{it} + (1-\alpha)\vartheta(S_{it}) \tag{6}$$

Importantly, these questions are the classic specification for panel data analyses, which assume cross-sectional independence and thus cannot capture spillover effects from overseas. In other words, they are designed for closed economies and do not contain foreign variables that directly influence home economic growth. This assumption has become increasingly unrealistic in the modern world. To mitigate it, we use the GVAR model to extend these specifications to include spillover effects. This extension has been widely recognized among researchers and is indeed in line with Lucas (1988), who introduced human capital spillovers in order to explain different patterns in economic growth. Given that people (or labor) and capital are less mobile than knowledge across countries, it is more natural to consider the effect of cross-border technological transfers on per capita income. In connection to this, Comin and Bart (2010), using data from 166 countries, showed that the speed of technology diffusion has been accelerated in modern times. Over 25% of differences in per capita income can be explained by cross-country variation in technological adoption.

Whenever economic growth at home can also be explained by productivity improvements in other countries (a^*_{it}), Eq. (6) will be stated in a more general form by including varieties of external shocks originating from other variables. For example,

$$y_{it} = \alpha k_{it} + (1-\alpha)a_{it} + \beta a^*_{jt} + (1-\alpha)\vartheta(S_{it}) \tag{7}$$

where $i \neq j$, and $\beta > 0$ when there are positive productivity spillovers from overseas. However, β can be negative when productivity improvements in other countries lead to a deterioration in external competitiveness of a home country. Furthermore, we extend this specification using the GVAR model and analyze the heterogeneous effects of productivity shocks on economic growth, rather than the homogeneous effects that are assumed in Eq.

(7).

3 The GVAR model

The GVAR approach introduced by Pesaran et al. (2004) gives a relatively simple, yet effective way to model present global economy, where each country, and different macroeconomic factors within countries, are related to each other. The methodology of GVAR modelling consists of two different stages. First, a separate model known as the VARX is estimated for each country separately, where the letter X indicates the presence of an exogenous component in the VAR. If any of the variables have unit roots and are cointegrated, the model is estimated in their error-correcting form. In these individual VARX (or the vector error correction model with exogenous variables, VECMX, in the presence of cointegration) models, each country has two different types of variables: domestic and foreign. Domestic variables are endogenous in the model, while foreign variables are exogenous and have their corresponding foreign variables. These foreign variables are constructed using a weight matrix, so that the relative importance of different countries is reflected properly in the analysis. They provide a connection between the evolution of the domestic economy and that of the rest of the world. The foreign variables must be weakly exogenous, an assumption that needs to be tested. In the second step, the individual VARX (or VECMX) models are combined together in a consistent manner with the help of a link matrix to build a global model.

•**Individual country model** Let there be $N+1$ countries in the model, indexed by $i = 0, 1, 2, ..., N$, where country 0 is the reference country. Each country i then follows the VARX (p, q) model, which can be defined as:

$$y_{i,t} = a_{i,0} + a_{i,1}t + \sum_{j=1}^{p} \alpha_{i,j} y_{i,t-j} + \sum_{j=1}^{q} \beta_{i,j} y^*_{i,t-j} + u_{i,t} \tag{8}$$

for $t = 1, 2, ..., T$. Here, $k_i \times 1$ matrix $y_{i,t}$ represents the endogenous domestic variables and $k_i^* \times 1$ matrix $y^*_{i,t}$ represents the corresponding (weakly) exogenous foreign variables. k and k^* are the numbers of domestic and foreign variables respectively, $a_{i,0}$ is a $k_i^* \times 1$ vector of fixed intercepts and $a_{i,1}$ is a $k_i^* \times 1$ vector of coefficients on the deterministic time trends. p and q are the lag lengths of domestic and foreign variables respectively. They are selected according to the Schwartz Bayesian (SB) information criterion. Finally, $u_{i,t} \sim iid(0, \Sigma_{u_i})$.

The vector of foreign country-specific variables, $y^*_{i,t}$, is obtained from weighted averages of each variable across all other countries in the sample. More specifically, for any $i, j = 0, 1, ..., N$,

$$y^*_{i,t} = \sum_{j=0}^{N} w_{i,j,t} y_{j,t}, \tag{9}$$

where $w_{i,j,t}$ is a weighting factor that captures the importance of a country j for a country i, with $\sum_{j=0}^{N} w_{i,j,t} = 1$ and $w_{i,i,t} = 0$. Most of the GVAR literature uses fixed trade weights based on bilateral trade volumes. However, these may be subject to temporal changes and, as a result, a fixed weight might confuse the results. In order to account for the changes that took place throughout the sample period, this paper uses time-varying weights to construct foreign variables in country-specific models. These are constructed as three-year moving averages to smooth out short-run business cycle effects in the bilateral trade flows. More compactly, setting $p_i = max(p, q)$, Eq. (8) can be written as:

$$A_{i,0} z_{i,t} = a_{i,0} + a_{i,1} t + \sum_{j=1}^{p_i} A_{i,j} z_{i,t-j} + u_{i,t} \tag{10}$$

where vector $z_{i,t} = ({x_{i,t}}', {x^*_{i,t}}')'$ represents both domestic and foreign variables and coefficient matrices are $A_{i,0} = (I_{k,i}, -\beta_{i,0})$ and $A_{i,j} = (\alpha_{i,j}, \beta_{i,j})$.

Because of the characteristics of the macroeconomic variables and to allow for the cointegrating relationship within and between countries, the country-specific VARX models are estimated in the following error-correction form (VECMX):

$$\Delta y_{i,t} = c_{i,0} - \alpha_i {\beta_i}'(z_{i,t-1} - a_{1,t}(t-1)) + \beta_{i,0} \Delta y^*_{i,t} + \sum_{j=1}^{p_i-1} \phi_{i,j} \Delta z_{i,t-j} + u_{i,t} \tag{11}$$

Here, α_i is a $k_i \times r_i$ matrix of rank r_i and β_i is a $(k_i + k^*_i) \times r_i$ matrix of rank r_i. Country-specific VECMX models are estimated using reduced rank regressions conditional on weakly-exogenous foreign variables. This takes into account the possibility of cointegration within domestic variables and across domestic and foreign variables. This way, estimates for r_i, β_i, and α_i are obtained. Other parameters are estimated by OLS from this equation:

$$\Delta y_{i,t} = c_{i,0} + \delta ECM_{i,t-1} + \beta_{i,0}\Delta y^*_{i,t} + \phi_i \Delta z_{i,t-1} + u_{i,t} \tag{12}$$

where $ECM_{i,t-1}$ are the error-correction terms referring to the r_i cointegrating relations of the ith country model.

•**Global model** The next step is to combine individual country-specific parameter estimates into a single global model. All country-specific variables are considered as a single $k \times 1$ global vector $y_t = (y'_{0t}, y'_{01}, ..., y'_{Nt})'$ where $k = \sum_{i=0}^{N} k_i$, so that all the variables are endogenous in the system as a whole. For each country, the corresponding VARX model is obtained from the VECMX model that was estimated. The link matrix W_i, which is the $(k_i + k_i^*) \times k$ matrix collecting the trade weights w_{ij}, $\forall i, j = 0, 1, 2, ..., N$, is used to obtain the identity $z_{i,t} = W_i y_t$. From Eq. (10), it follows that:

$$A_{i,0} W_i y_t = a_{i,0} + a_{i,1} t + \sum_{j=1}^{p_i} A_{i,j} W_i y_{t-j} + u_{i,t} \tag{13}$$

for $i = 0, 1, ..., N$. Then, the $N+1$ systems in Eq. (13) are combined to obtain the global model in levels:

$$G_0 y_t = a_0 + a_1 t + \sum_{i=1}^{p} G_i y_{t-i} + u_t \tag{14}$$

Here, $G_0 = (A_{00}W_0, A_{10}W_1, ..., A_{N0}W_N)'$ is a known nonsingular $k \times k$ matrix that depends on the trade weights and parameter estimates $G_i = (A_{0i}W_0, A_{1i}W_0, ..., A_{Ni}W_N)'$ for $i = 1, 2, .., p$, $a_0 = (a_{00}, a_{10}, ..., a_{N0})'$, $a_1 = (a_{01}, a_{11}, ..., a_{N1})'$, $u_t = (u_{0t}, u_{1t}, ..., u_{Nt})$ and $p = max(p_i)$ across all i. Pre-multiplying Eq. (14) by G_0^{-1}, the GVAR (p) model is obtained as

$$y_t = b_0 + b_1 t + \sum_{i=1}^{p} F_i y_{t-i} + \varepsilon_t \tag{15}$$

where, $b_0 = G_0^{-1} a_0$, $b_1 = G_0^{-1} a_1$, $F_i = G_0^{-1} G_i$ for $i = 1, 2, ..., p$ and $\varepsilon_t = G_0^{-1} u_t$.

The dynamic properties of the GVAR model in Eq. (15) can then be examined using Structural Generalized Impulse Response Functions (SGIRFs).

4 Data and relevant tests

Prior to the formal analysis, this section describes the data, the model specification, and the results of the weak exogeneity test.

4.1 Data and model specification

We use quarterly data from 1991 to 2016 for advanced and developing countries. There are 18 countries in the sample, divided into four groups. 1) The EU group consists of seven countries including Belgium, France, Germany, Italy, Netherlands, Switzerland and the UK.[4] 2) The non-OECD group consists of all the countries in the sample that are not part of OECD. It includes Brazil, China, Hong Kong, India, Mexico, Russia, and Taiwan. 3) Countries in the sample that do not fall into the above two categories are included in the 'Others' group. These are Canada, Japan, and Korea. 4) The USA is considered separately, as we are primarily interested in investigating spillover effects from the US to other countries.

Regional variables for the groups 'EU', 'Non-OECD' and 'Others' were constructed by aggregating country-specific variables over N countries.

$$y_t = \sum_{i=1}^{N} \omega_i y_{i,t}$$

where y_t denotes a regional variable, $y_{i,t}$ is the value of that variable for country i, and ω_i represents the relative importance of a country i within the region. Following Dees et al. (2007), ω_i is computed by dividing the PPP-GDP figure of each country by the total sum across the N countries of the region, such that their weights add up to unity.

Spillover effects may be related to the level of trade with the rest of the world. Therefore, a country's openness to other countries is calculated as (Import+Export)/GDP. Table 1 shows the openness of each country vis-a-vis the USA. This table shows the ratio being often greater than one. It follows that the majority of countries are indeed more open than the US. Only two countries exhibit evidence of lesser openness than the US, but even in these cases the ratios are close to the US level.

[4] Though Switzerland is not part of the EU and the UK will soon exit from the EU, they are included in this group for geographical proximity and historical links with the EU.

[Table 1]

The model will be estimated with data on real GDP growth, expenditure on R&D, capital stock and the TFP. The TFP is used as a proxy for productivity. The source of real GDP and population data is *Oxford Economics*. Production data are expressed in US dollars to make international comparisons later in our analysis. The TFP and capital stock data are collected from *Penn World Table Ver.9*. R&D data are collected from the OECD and are only available for the countries in the sample that are part of the OECD. For non-OECD countries, we assume no significant R&D activities. Annual data are converted to quarterly data, using a quadratic function of the Eviews.

[Fig. 1]

The TFP of selected countries is shown in Fig. (1). Since this statistic indicates TFP of a country relative to the US, it shows a marked difference in TFP among countries. Germany exhibits steady improvements in TFP and convergence with that of the US. Brazil and Japan fail to improve TFP after 1990 and show divergence from the US. Chinese TFP shows rather different trajectories compared to other countries. It is highly volatile and has shown steady increases since 2000, which is consistent with its rapid economic growth. However, TFP of all four countries is less than one and thus is below the level of the US, thereby confirming the significant size of the US TFP compared to all other countries.

[Fig. 2]

Fig. (2) shows the ratio of R&D to GDP for selected countries and regions. The OECD data suggest that most countries spend about 1 to 3 percent of GDP on R&D. However, there is a variation in the trend of this variable among countries. While this ratio is stable over time for most countries and regions, China has increased R&D expenditure remarkably in recent times. Nonetheless, this ratio remains relatively high in the US over this century, while remaining low in Russia.

The correlation among key variables is summarized for each country group in Table 2. Generally, the variables are positively correlated with each other. Notably, the TFP is positively correlated with GDP growth. On the other hand, contrary to expectations, capital has a negative relationship with other economic variables.

[Table 2]

Next, we check the stationarity and cointegration of data. First, the stationarity of data is examined for all the country-specific domestic variables and their corresponding foreign variables. In addition to the commonly used Augmented Dickey Fuller (ADF) test, the Weighted-Symmetric Dickey Fuller (WS) test suggested by Park and Fuller (1995) is also used for this purpose.[5] The lag length was selected according to the SB criterion. The unit root tests are conducted with variables in levels with an intercept and time trend. The results for the level data for domestic variables are shown in Table 3. The t-values are shown with the 5% critical values. As expected, there is a mix of stationary and non-stationary data across country groups. However, the majority of data seem to follow a non-stationary process, as we often fail to reject the null hypothesis of the unit root process.

[Table 3]

The next step is to define the country-specific VARX models. The GVAR model has the flexibility of handling different specifications for different countries (i.e., the number of domestic and foreign variables that goes into each country-specific model). However, since the countries in the sample have trading relations and are expected to affect each other, all the country models initially include all four variables as domestic and foreign variables (constructed using the weight matrix mentioned in the previous section).[6] Next, the order of the country-specific VARX (p_i, q_i) model is selected using the SB criterion. While selecting the lag order, p_i and q_i were not allowed to go over 2, because of the small sample size compared to the large number of parameters to be estimated. The selected order of the VARX model is shown in Table 4.

[Table 4]

For all country groups, the VARX (2,1) model is selected. Given that some of the variables are non-stationary, Johansen's cointegration test is conducted in order to determine the number of cointegrating relations for each country group. Here, the specifications consider Case IV according to Pesaran et al. (2000), where a linear deterministic trend is implicitly allowed for the cointegration space, but can be eliminated in the dynamic part

[5]The WS test exploits the time reversibility of a stationary autoregressive process in order to increase their power performance. Many authors like Leybourne et al. (2005) and Pantula et al. (1994) show evidence of superior performance of the WS test as compared to the ADF test.

[6]Several robustness checks were also conducted by leaving out some variables as foreign variables for countries that are less integrated with other countries in terms of trade. However, the main findings of the paper are not affected.

of VEC models. The number of cointegration relations for each country group based on the trace statistics is also shown in Table 4. All country groups seem to have either three or four cointegrating relations. Next, individual country-specific VECMX models were estimated, subject to the reduced rank restrictions. Corresponding error-correcting terms were then derived. These ECMs were subsequently used to conduct the weak exogeneity test.

4.2 Weak exogeneity test

As mentioned earlier, one of the main assumptions of the GVAR model is the weak exogeneity of the country-specific foreign variables $y^*_{i,t}$. In general, a variable in a VARX model is considered weakly exogenous if it is not dependent on contemporaneous values of endogenous variables, but is likely to depend on the lagged values of these endogenous variables. More formally, $y^*_{i,t}$ is considered weakly exogenous if $y_{i,t}$ does not affect $y^*_{i,t}$ in the long-run, but $y^*_{i,t}$ is said to be 'long-run forcing' for $y_{i,t}$. As shown in Johansen (1992), this assumption allows proper identification of the cointegration relations. In the formal test, the joint significance of the estimated error-correction terms in auxiliary equations for the country-specific foreign variables $y^*_{i,t}$ is tested. Specifically, for each lth element of $y^*_{i,t}$ a regression of the following form in conducted:

$$\Delta y^*_{i,t,l} = a_{i,l} + \sum_{j=1}^{r_i} \delta_{i,j,l} \widehat{ECM}_{i,j,t-1} + \sum_{s=1}^{p_i^*} \phi'_{i,s,l} \Delta y_{i,t-s} + \sum_{s=1}^{q_i^*} \Psi_{i,s,l} \Delta \widetilde{y}^*_{i,t-s} + \eta_{i,t,l} \tag{16}$$

where $\widehat{ECM}_{i,j,t-1}$, for $j = 1, 2, ..., r_i$ are the estimated error-correction terms corresponding to the r_i cointegrating relations found for the i th country, and p_i^* and q_i^* are the orders of the lagged changes for the domestic and foreign variables respectively. The test for the weak exogeneity is an F-test of the joint hypothesis that $\delta_{i,j,l} = 0$ for $j = 1, 2, ..., r_i$ in the above equation. It is not necessary that lag orders of p_i^* and q_i^* are the same for the underlying country-specific model. They are selected using the SB criterion.

[Table 5]

The results are shown in Table 5. As can be seen, all the variables pass the weak exogeneity test, as the assumption of exogeneity cannot be rejected at the 5% level. This is a very desirable result, as it confirms the suitability of the GVAR model for this region. Based on the eigenvalues, the model was also found to be stable.

5 Results

By means of the SGIRF analysis, this section investigates the effects of US TFP shocks on the home economy (i.e., real GDP, R&D spending, and capital stock). Similarly, we study the effects of TFP shocks of the major trading partners of the US (grouped into the EU, non-OECD and other groups).

5.1 Structural generalized impulse response function (SGIRF) analysis of US productivity shocks

The identification of shocks has been a major issue in GVAR models. In order to conduct dynamic analysis, the vast majority of research papers using GVAR models rely on the GIRF proposed by Koop et al. (1996) and further developed by Pesaran and Shin (1998). The identification of shocks in a GVAR model is complicated due to the cross-country interactions and high dimensionality of the model.

The identification in a traditional VAR analysis is usually achieved by using the orthogonalized impulse-response functions (OIRFs) that require a certain ordering of variables. This approach is often not suitable for GVAR models, as it requires ordering not only of the variables, but also countries. As a result, when a large number of variables and countries are included in the model, it becomes difficult to justify such ordering based on economic theory and empirical findings. The advantage of GIRFs is that they are invariant to the ordering of countries and variables. This is very convenient for models like GVAR that involve many countries and variables. However, it comes at a cost. Critics often argue that in GIRFs, the error terms are not orthogonal and it allows correlation among them. This, in turn, makes economic interpretation of shocks difficult.

We take this into account by using SGIRFs instead of GIRFs. The SGIRF allows the most dominant economy in the model to be ordered first and also its variables to have certain ordering. Since the main aim of this paper is to investigate spillover effects of productivity shocks arising in the US, the largest economy in the model, the US and its variables are ordered first. This means that the identifying scheme for the model of the US is based on a lower-triangular Cholesky decomposition and has the following ordering: [R&D, TFP, capital, GDP]'. Thus, for the US, R&D is ordered first, followed by TFP because greater expenditure on R&D could increase TFP. This assumes that R&D spending affects TFP contemporaneously, but not vice versa. TFP is then followed by capital and GDP. This ordering system assumes that GDP is the most endogenous variable, which is a realistic assumption to make. Other countries and their variables are kept unrestricted. More about the GIRF and SGIRF is discussed in the Appendix.

The main aim of this paper is to evaluate the effects of US productivity shocks on the US itself as well as the spillover effects on other countries. This result is depicted in Fig. (3). It shows the SGIRF for the US, the EU, non-OECD and the rest of the countries (i.e., Others) to one standard deviation (SD) positive TFP shock to the US. For each country, reactions of GDP, R&D, capital, and TFP are depicted for up to 40 quarters. The associated 90% bootstrap confidence bands, computed on the basis of 1000 replications, are also displayed by dotted lines.

[Fig. (3)]

The results show that a TFP shock in the US not only has a positive effect on real GDP of the US, but also has positive spillover effects on the real GDP of its main trading partner countries. This effect is statistically significant for the US, the EU and non-OECD country groups, but not highly significant for others. For all countries, the effect is much smaller on impact. It increases over time and stays significant for up to 16 quarters (i.e., four years) for most country groups. This implies quick cross-country transmission of innovation.

After a US TFP shock, R&D spending shows a statistically significant positive reaction in the US and some negative reaction in the EU and non-OECD countries (though significant only for the first few quarters). This result indicates that US productivity shocks are positively associated with its own R&D spending, but it is not strongly correlated with other countries' R&D spending. In fact, the initial reactions of the EU and the non-OECD countries' R&D are negatively associated with US productivity shocks.[7] Similarly, the reaction of capital after a US TFP shock is mostly insignificant for all country

[7]R&D shocks to the EU and non-OECD countries (results not showed here, but available on request) actually also have no significant effect on the GDP of their own countries

groups. The TFP instead shows some positive reaction to shocks in the US, but does not show any significant results for other countries.

5.2 Productivity shocks in the EU, Non-OECD and Others

Fig. (4), (5) and (6) show the response of the same variables to one standard deviation (SD) positive shock in 'the EU,' 'non-OECD,' and 'Others' country groups respectively. The first row of each figure shows the response of GDP to a TFP shock. The EU's TFP shock does have some positive and significant effects on GDP of the EU and the other country groups. Compared to the US TFP shock, these reactions are smaller in magnitude. EU's TFP shock also increases US R&D and has a further positive effect on its own TFP. Such reactions are, however, significant for a very short period of time. A shock to the non-OECD group's TFP has some positive significant effect on its own GDP, but spillover effects are not highly significant. A shock to the final group 'Others' has no significant effect on the GDP of any country groups either. In terms of the effect on other variables, results are not very significant.

[Fig. (4), (5), (6)]

Interestingly, a positive TFP shock is associated with increases in R&D spending for the US and other country groups. This might be due to the size of the US R&D and the fact that US multinational firms are much more global in terms of investing in other country groups. An increase in productivity in the rest of the world creates greater incentives for them to expand their business by spending more on R&D. On the contrary, R&D spending in the EU decreases when there is a positive TFP shock in 'Non-OECD' and 'Others' country groups. These results might explain why the EU is still lagging behind the US in terms of research and innovation and are in line with findings of Miller and Atkinson (2014). While the US is able to make best use of productivity improvements in other countries, the rest of the world fails to do so.

5.3 The asymmetric effect of productivity shocks

In order to compare the magnitude of US shocks with that of other country groups, we calculate the ratio of impulse responses (Table 6). For country groups X and Y, the ratio of (X→X)/(Y→Y) indicates the relative importance of shocks in the home economy. Therefore, (EU→EU)/(USA→USA) compares the impact of EU shocks on the EU economy with that of US shocks on the US economy. If this ratio equals unity, it follows that their impact on their own economy is identical. Similarly, (X→Y)/(Y→X) gives us information about which direction of productivity shocks are relatively more important between X and Y. When this ratio is higher than unity, it means that economic shocks from X are greater than that from Y.

Table 6 shows the average of this ratio over 40 time horizons. Since this ratio is less than unity, we can interpret that the US shocks are more influential than shocks from other country groups over its own economy as well as that of other country groups. At times, we find a negative ratio, implying that productivity shocks have had negative impacts on the economy in one of country group pairs. In short, there is asymmetry in the effect of productivity improvements across country groups. Given that the US is not the most open economy in the world, the relatively more significant effect of US shocks is attributable to the amount of expenditure on productivity improvements and the presence of multinational firms that utilize advanced technology. Thus, we confirm heterogeneous responses of productivity shocks on the economy. Our results provide the reasons why previous macroeconomic analyses often fail to detect the role of productivity spillovers in economic growth; that is, productivity spillovers are not long-lived and are insignificant for some countries.

[Table 6]

6 Concluding remarks

This paper empirically investigates the impact of productivity spillovers in global markets, where productivity shocks affect not only home economies, but other countries too. In order to capture such spillover effects, we have used the GVAR to model global economies, which allows us to estimate heterogeneous reactions to spillovers across country groups. By doing so, we have arrived at noteworthy results.

Generally, we find that while productivity shocks are asymmetric in global markets, productivity improvements have generally contributed to economic growth, leading us to conclude that liberalizing international markets is beneficial to many (but not all) countries. Productivity shocks originating from the US are more influential over the rest of the world than those from other countries. Our country group analyses suggest that US shocks are positively correlated with economic growth of other countries and thus global markets benefit from the spillover of productivity improvements. In contrast, such a clear positive relationship can hardly be observed in the analysis of productivity shocks originating from other country groups.

Because our analysis is based on macroeconomic data, we cannot provide a detailed and insightful explanation regarding the asymmetric effect. However, our results are consistent with the extent of the US innovation. The US spends more on innovation than any other country. In this regard, the finding that global markets benefit from US productivity shocks will be valuably supplemented by multi-country analyses using firm- or industry-level data in future studies.

Appendix

GIRF and SGIRF

The generalized impulse-response functions (GIRFs) was introduced by Koop et al. (1996) and further developed by Pesaran and Shin (1998). Let us consider the model obtained during the solution of the GVAR, expressed in terms of the country-specic errors given by Eq. (14). The GIRFs are based on the definition:

$$GIRF(y_t; u_{i,l,t}; h) = E(y_{t+h}|u_{i,l,t} = \sqrt{\sigma_{ii,ll}}, I_{t-1}) - E(y_{t+h}|I_{t-1}) \tag{17}$$

where I_{t-1} is the information set at time $t-1$, $\sigma_{ii,ll}$ is the diagonal element of the variance covariance matrix Σ_u corresponding to the l^{th} equation in the i^{th} country, and h is the horizon. GIRFs are invariant to the ordering of variables and they allow for correlation of the error terms (the error terms are not orthogonal).

The structural generalized impulse-response functions (SGIRFs) used in this paper allows ordering of variables to one country. As the US is the largest and the most dominant economy in this model, it is ordered first and its variables are ordered in the way mentioned in Section 4.1. The SGIRFs are invariant to the ordering of other countries and their variables. Let us consider the $VARX^*(p_1, q_1)$ model for the US.

$$y_{1,t} = a_{1,0} + a_{1,1}t + \sum_{j=1}^{p} \alpha_{1,j} y_{1,t-j} + \sum_{j=1}^{q} \beta_{1,j} y^*_{1,t-j} + u_{1,t} \tag{18}$$

Let $V_{1,t}$ be structural shocks given by $V_{1,t} = P_1 u_{1,t}$, where P_1 is the $k_1 \times k_1$ matrix of coefcients to be identied. The identication conditions using the triangular approach of Sims (1980) require $\Sigma_{v,1} = Cov(v_{1,t})$ to be diagonal and P_1 to be lower triangular. Let Q_1 be the upper Cholesky factor of $Cov(u_{1,t}) = \Sigma_{u,1} = Q_1^{'} Q_1$ so that $\Sigma_{v,1} = P_1 \Sigma_{u,1} P_1^{'}$ with $P_1 = (Q_1^{'})^{-1}$ Under this orthogonalization scheme $Cov(v_{i,t}) = I_{k_0}$

Pre-multiplying the GVAR model in Eq. (14) by

$$P_{G_1}^1 = \begin{bmatrix} P_0 & 0 & 0 & 0 \\ 0 & I_{k_1} & 0 & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & I_{k_n} \end{bmatrix}$$

It follows that

$$P_{G_1}^1 G_1 y_t = P_{G_1}^1 G_1 y_{t-1} + ... + P_{G_1}^1 G_p y_{t-p} + v_t \tag{19}$$

where $v_t = (v_{1t}', u_{1t}', ..., u_{Nt}')$ and

$$\Sigma_v = Cov(v_t) = \begin{bmatrix} V(v_{1t}) & Cov(v_{1t}, u_{1t}) & . \ . \ . & Cov(v_{1t}, u_{Nt}) \\ Cov(u_{1t}, v_{1t}) & V(u_{1t}) & . \ . \ . & Cov(u_{1t}, u_{Nt}) \\ \vdots & \vdots & & \vdots \\ Cov(u_{Nt}, v_{1t}) & Cov(u_{Nt}, u_{1t}) & . \ . \ . & V(u_{Nt}) \end{bmatrix}$$

with

$V(v_{1t}) = \Sigma_{v,11} = P_1 \Sigma_{u,11} P_1^1$ and $Cov(v_{1t}, u_{jt}) = Cov(P_1 u_{1t}, u_{jt}) = P_0 \Sigma_{u_{1j}}$

By using the definition of the generalized impulse responses with respect to structural shocks given by

$$SGIRF(y_t; v_{l,t}; h) = E(y_{t+h} | I_{t-1} \varrho_l' v_t = \sqrt{\varrho_l' \Sigma_v \varrho_l,}) - E(y_{t+h} | I_{t-1}) \tag{20}$$

it follows that for a structurally identified shock, v_{lt} such as a US trade shock the SGIRF is given by

$$SGIRF(y_t; v_{l,t}; h) = \frac{\varrho_j A_n (P_{G_1} G_1)^{-1} \Sigma_v \varrho_l}{\sqrt{\varrho_l \Sigma_v \varrho_l}}, \ h = 0, 1, 2, ; j = 1, 2, ..., k$$

where $\varrho_l = (0, 0, ..., 0, 1, 0, ..0)'$ is a selection vector with unity as the l^{th} element in the case of a country-specific shock, Σ_v is the covariance matrix of structural shocks, and $P_{G_1}' G_1$ is defined by the identification scheme used to identify the shocks.

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Table 1: Country's openness

Country group	Country	Country's openness relative to the USA
EU	Belgium	5.508
	France	2.047
	Germany	2.188
	Italy	1.923
	Netherlands	4.945
	Switzerland	3.960
	UK	2.188
Non-OECD	Brazil	0.917
	China	1.910
	HK	13.551
	India	1.417
	Mexico	2.132
	Russia	2.306
	Taiwan	4.331
Others	Canada	2.712
	Japan	0.986
	Korea	2.929

Notes: The openness is calculated as (Export+Import)/GDP. The statistics show the ratio of country's openness vis-a-vis that of the USA.

Table 2: The correlation of variables within country groups

	TFP	R&D	GDP	Capital
USA				
TFP	1			
R&D	0.366	1		
GDP	0.816	0.374	1	
Capital	-0.589	-0.692	-0.446	1
EU				
TFP	1			
R&D	0.542	1		
GDP	0.329	0.686	1	
Capital	-0.686	-0.925	-0.643	1
Non-OECD				
TFP	1			
R&D	0.361	1		
GDP	0.436	0.936	1	
Capital	-0.685	-0.822	-0.820	1
Others				
TFP	1			
R&D	0.338	1		
GDP	0.388	0.990	1	
Capital	-0.572	-0.896	-0.916	1

Notes: Full sample.

Table 3: Unit root tests for the domestic variables

Domestic variable	Statistic	Critical value	EU	Non-OECD	Others	USA
TFP	ADF	-3.45	-2.51	-1.80	-4.19	-1.88
	WS	-3.24	-2.70	-1.01	-4.09	-2.20
R&D	ADF	-3.45	-2.67	-1.63	-0.49	-5.12
	WS	-3.24	-2.18	-1.15	-0.73	-4.88
GDP	ADF	-3.45	-1.35	-2.29	-2.32	-1.50
	WS	-3.24	-1.16	-1.87	-2.30	-1.27
Capital	WS	-3.24	-0.93	-2.03	-3.13	-1.54
	ADF	-2.89	1.06	0.20	0.22	-0.71

Notes: Unit root tests examine the null hypothesis of the unit root. The 5% critical values are reported.

Table 4: Order of the VARX model and the number of cointegrating relations

	p_i	q_i	# Cointegrating relations
EU	2	1	3
Non-OECD	2	1	4
Others	2	1	4
USA	2	1	3

Notes: The lag length is determined by the Schwartz Bayesian information criterion. The number of cointegrating relationships is based on trace statistics of Johansen tests.

Table 5: Weak exogeneity test

Country	F-test	Critical value	TFP	R&D	GDP	Capital
EU	F(2,71)	3.12	1.27	2.48	2.29	0.28
Non-OECD	F(5,68)	2.34	1.89	0.86	2.24	1.09
Others	F(3,70)	2.73	0.08	1.27	1.73	1.62
USA	F(3,70)	2.73	1.95	1.78	0.23	1.17

Notes: The 5% critical values are reported.

Table 6: The impact of productivity shocks

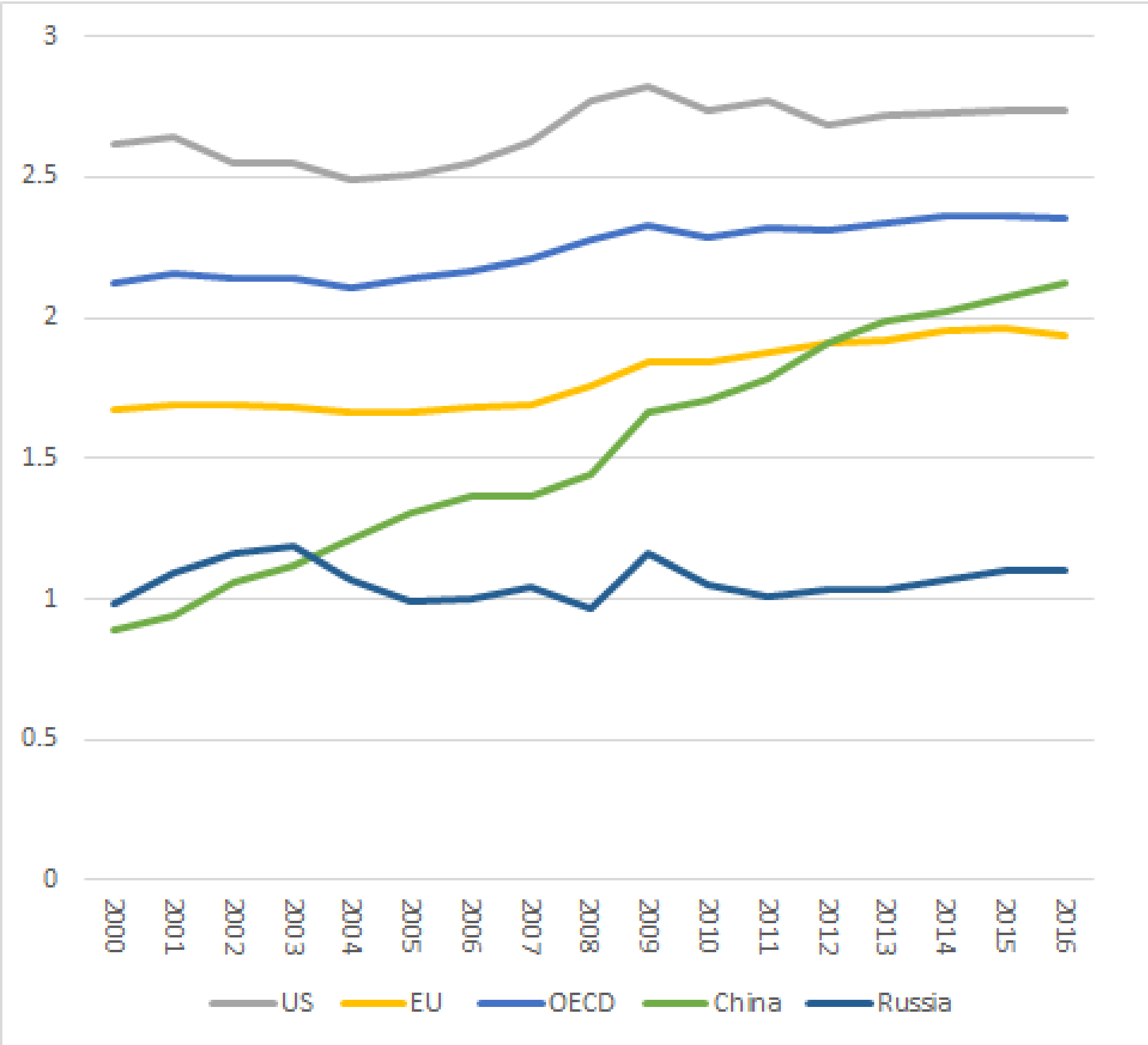
	(EU→EU)/ (USA→USA)	(EU→USA)/ (USA→EU)	(NonOECD→NonOECD)/ (USA→USA)	(NonOECD→USA)/ (USA→NonOECD)	(Others→Others)/ (USA→USA)	(Others→USA)/ (USA→Others)
Average	0.244	0.060	-0.423	-0.255	-0.192	-0.099
Std Error	0.111	0.080	0.258	0.109	0.181	0.105
Medium	0.290	0.061	-0.385	-0.302	-0.231	-0.248
Mini	-1.172	-0.834	-5.168	-1.276	-2.335	-0.944
Max	1.594	1.324	2.384	1.866	1.717	1.571

Notes: The ratio of the magnitude of productivity shocks is reported.

Figure 1: Total factor productivity of selected countries

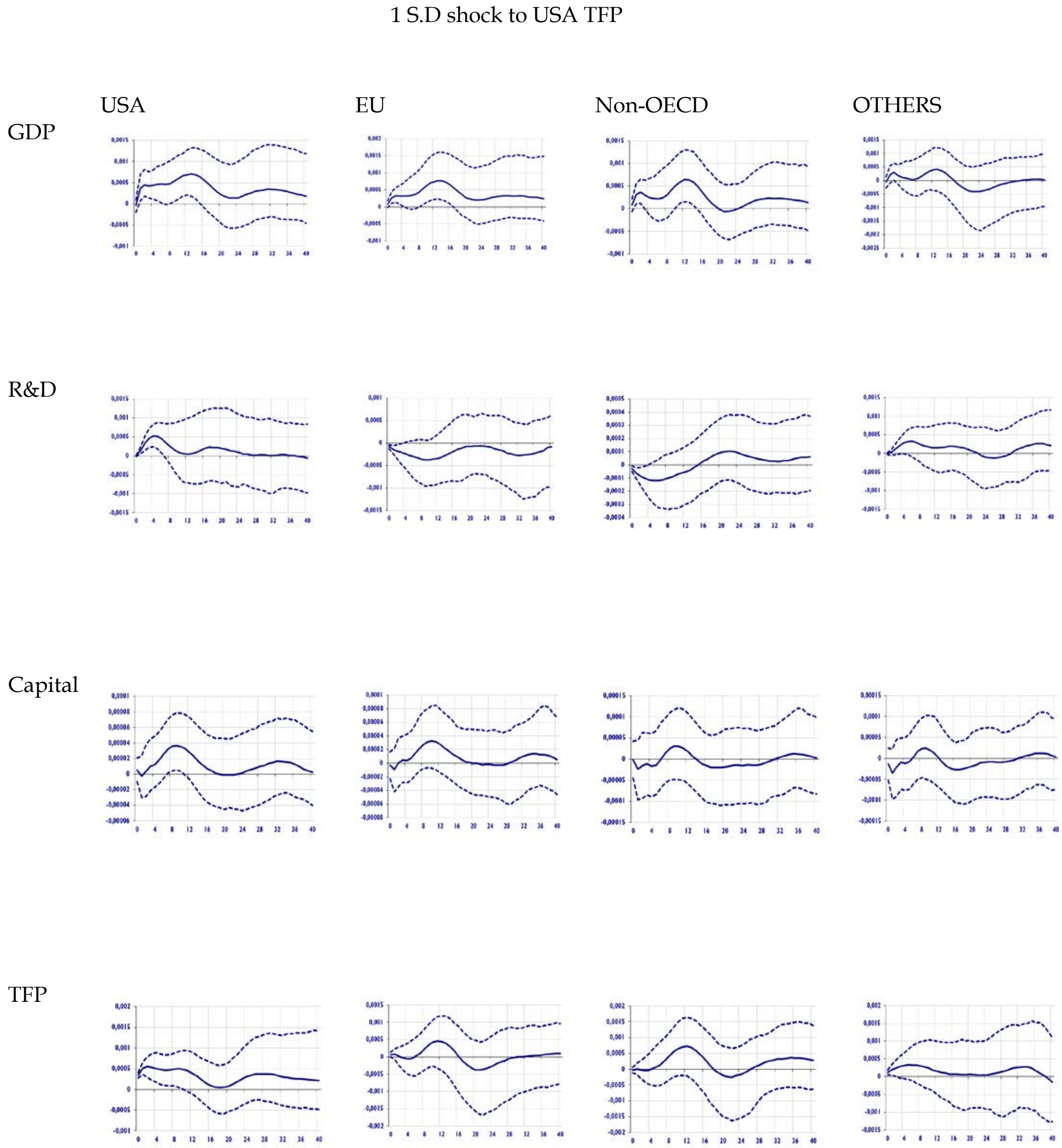
Notes: The data are from the Penn World Table Ver. 9. The US TFP is equal to one.

Figure 2: R&D (% of GDP)



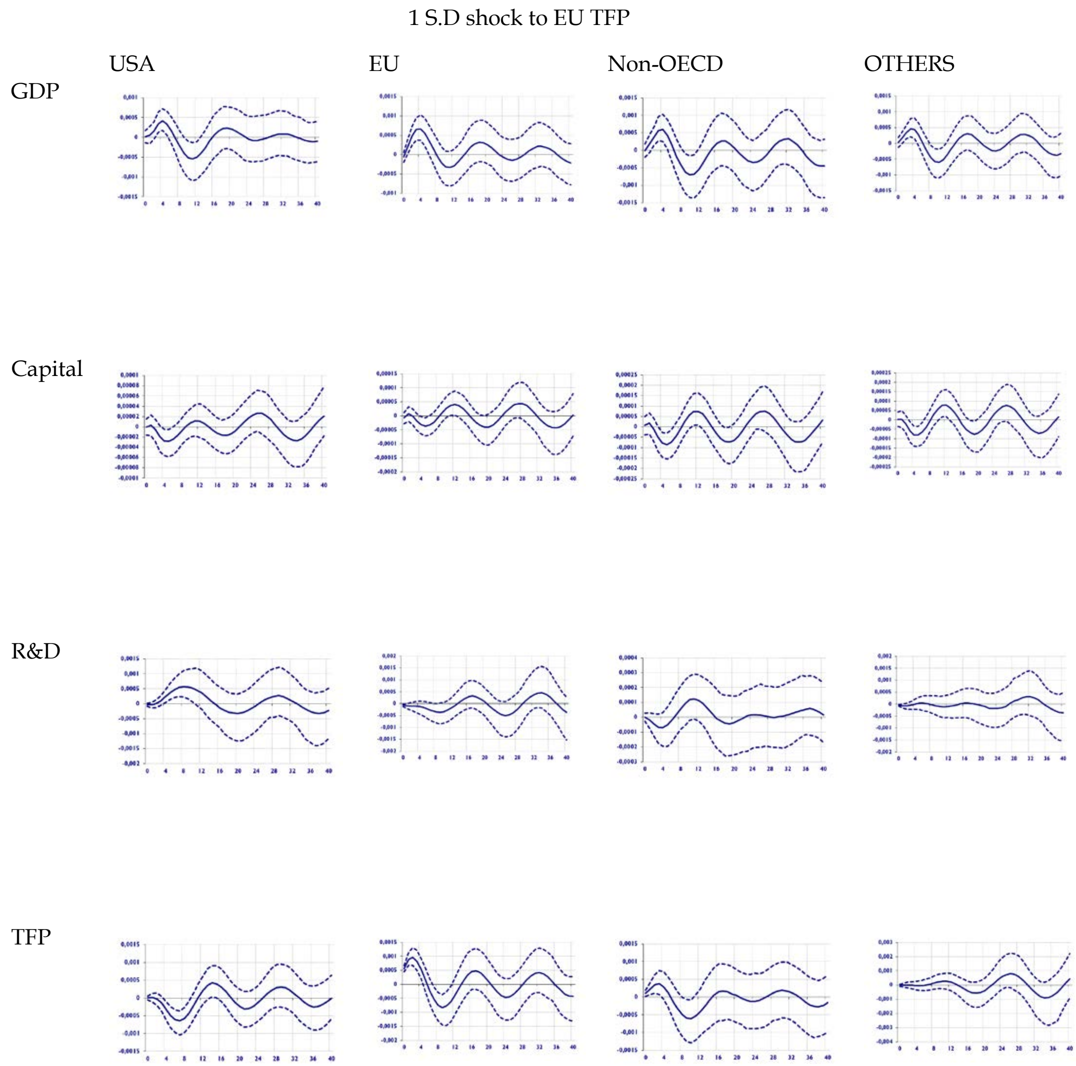
Notes: Data source: `http://stats.oecd.org/Index.aspx?DataSetCode=MSTI_PUB`

Figure 3: Impulse response functions for an expansionary 1 SD shock to US TFP



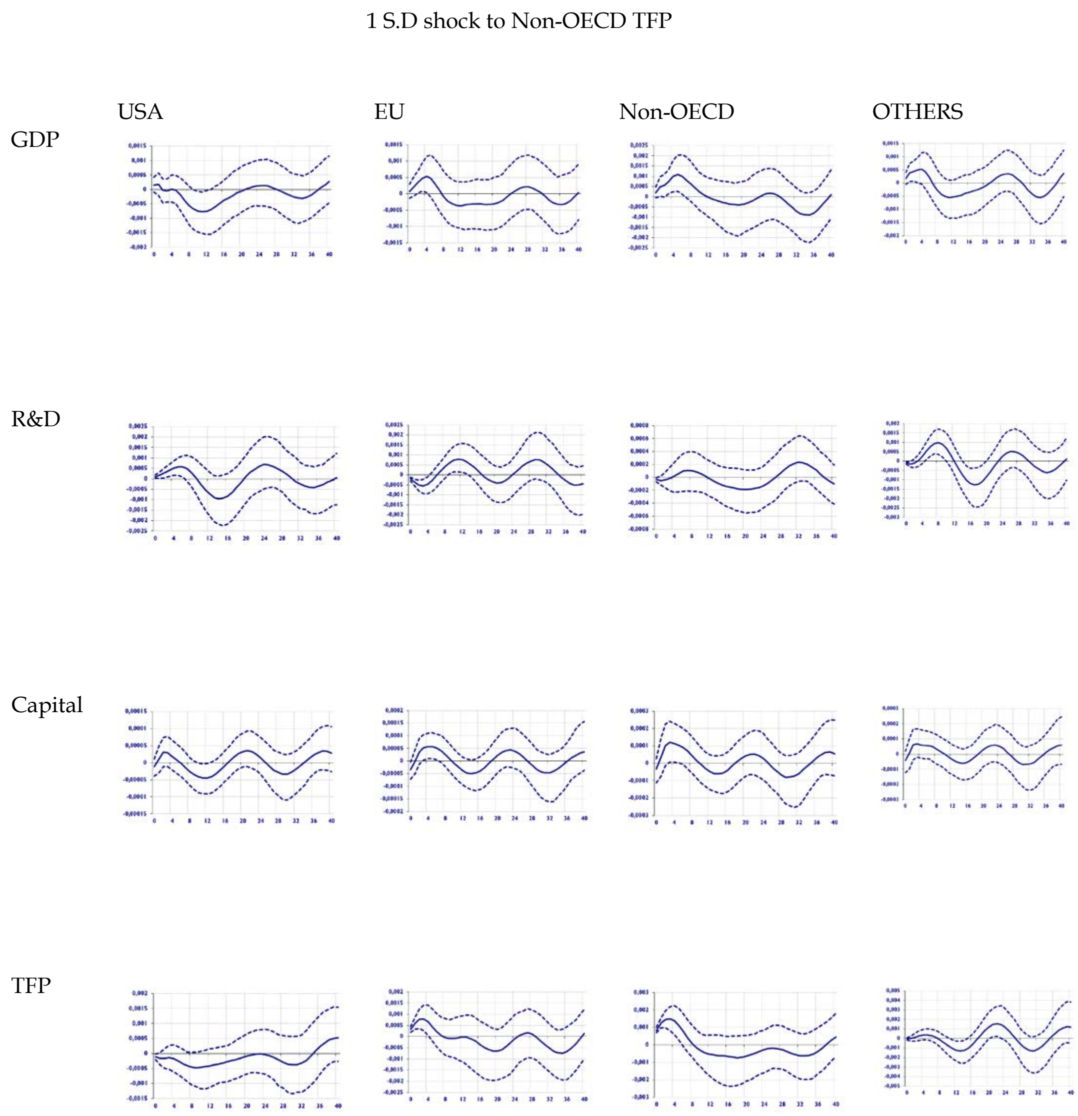
Notes: The figure reports structural generalized impulse response functions (SGIRFs) for the GDP, R&D, capital and TFP. The graphs show bootstrap median estimates with the associated 90% bootstrap confidence bands computed on the basis of 1000 replications of the SGIRFs, where the forecast horizon extends up to 40 quarters and is recorded along the horizontal axis.

Figure 4: Impulse response functions for an expansionary 1 SD shock to EU TFP



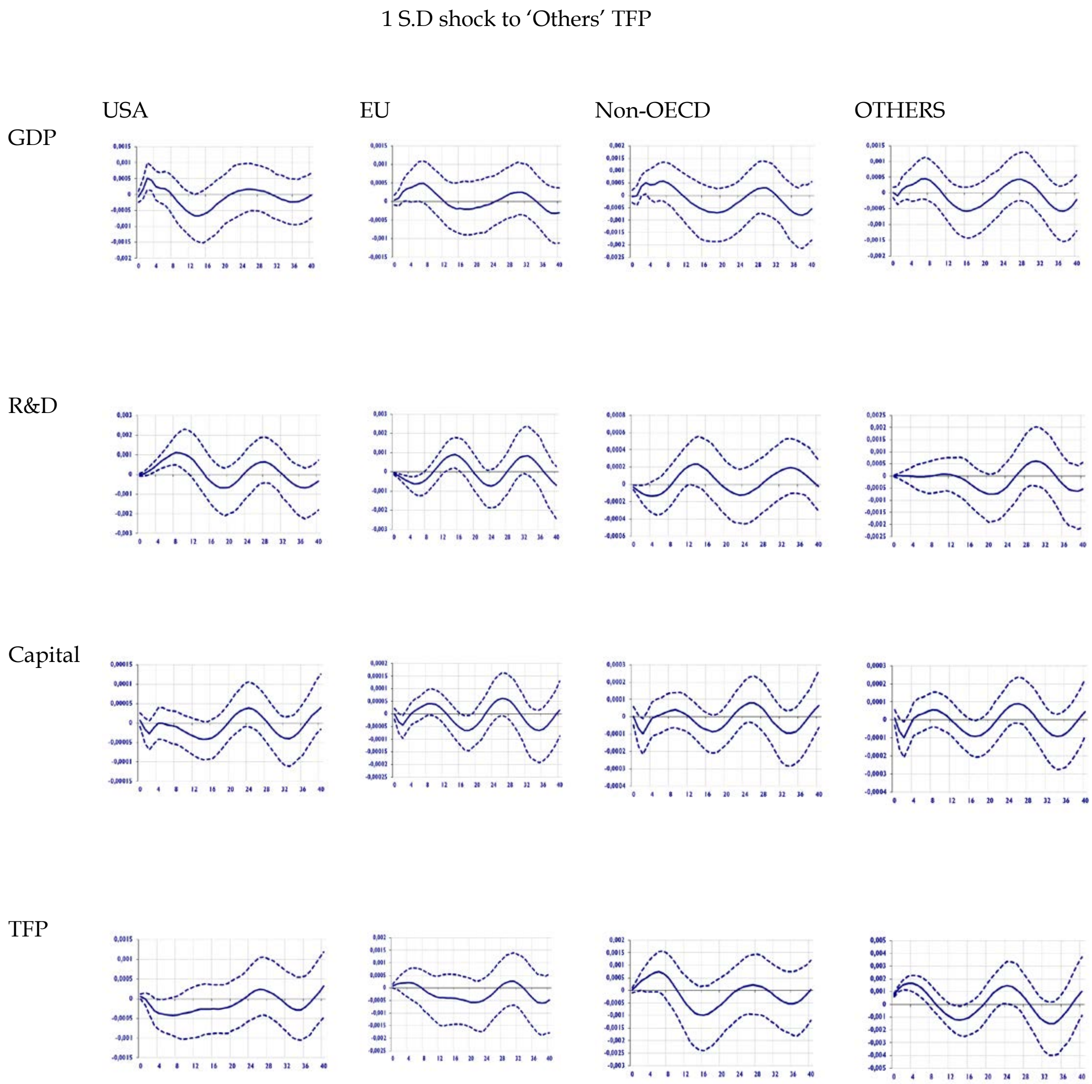
Notes: see Fig.(3)

Figure 5: Impulse response functions for an expansionary 1 SD shock to Non-OECD TFP



Notes: see Fig.(3)

Figure 6: Impulse response functions for an expansionary 1 SD shock to OTHERS TFP



Notes: see Fig.(3)