Productivity Shock in the US and Its Effects on real exchange rate and net exports: A cross-country perspective

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Abstract

International transmission of productivity shock, specifically the effects on the real exchange rate (RER), is a widely discussed issue, but a large share of the literature consists of theoretical modeling, and the predictions of the models are inconsistent. Empirical studies investigate how the world economy as a whole is affected by productivity growth in large economies. This thesis, however, investigates the effects of US productivity shocks on 48 individual countries and finds that the responses can differ, depending on country characteristics. US productivity shock is identified via sign restrictions in the Vector Autoregressive (VAR) model and the influence of country characteristics on the effects is tested with cross-country Ordinary Least Square (OLS). This study finds novel evidence that aggregate US RER appreciates but bilateral RER can appreciate or depreciate, depending on country characteristics. A country experiences appreciation in US RER if it has high consumption home bias, a strong trade relationship with the US, or its economy is more open to trade. Aggregate US net exports decline because of decreased exports and increased imports. In terms of bilateral trade, US exports to countries where the US RER appreciates more decline, and imports of intermediate goods to the US increases. US net exports increase to countries where the financial markets are more complete.

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1. Introduction

What impact does productivity shock have on the real exchange rate (RER)? Previous literature approaches this issue by using two models: the international real business cycle (IRBC) model and the Harrod–Balassa–Samuelson (HBS) model. A large share of the previous studies centers on theoretical modeling, and the predictions of the two models are not supported with empirical evidence. Generally, the IRBC theory predicts short–run depreciation and the HBS forecasts long–run appreciation. However, predictions for the movement of RER are conflicting even under the same model, and some studies propose that the theories do not hold.[3] All these inconsistent results are as a result of a lack of empirical studies.

Recently, significant empirical works by Berka et al. (2018) and Corsetti et al. (2008, 2014), in both the IRBC and HBS fields, have been published. Traditional HBS theory predicts long–run appreciation in the RER but there was little empirical evidence due to the poor sectoral data regarding productivity. Berka et al. (2018) point out the problems with the data in previous studies and mention that reliable results with insufficient data were long–run cointegration between the RER and productivity. Berka et al. (2018), however, have overcome the previous problem with the data and document appreciation in the RER even in the short–run. The standard IRBC model asserts that productivity shock leads to depreciation in the RER. However, Corsetti et al. (2008, 2014) have found appreciation in the RER for

[3] Gubler and Sax(2019) show that RER depreciates in response to productivity growth since 1980s unlike HBS theory expects. They use annual data of 23 OECD countries and show that HBS effects are not valid for 1984–2008 while they are for 1970–1992.

the first time with the standard IRBC model and document empirical evidence with US data. According to their studies, wealth effect and consumption home bias are key features to explain the RER appreciation. The appreciation mechanism in those studies is as follows. Productivity growth raises the relative wealth of the home country where the shock occurs. If the financial market in the home country is incomplete, household consumption increases along with the increased wealth. In addition, if consumption in that country is biased toward domestically produced goods, consumption demand for domestic products rises excessively. Accordingly, the price of domestic goods increases and the RER appreciates. Follow-up studies, such as by Enders and Muller (2009), Nam and Wang (2018), Hamano (2013), and Kolmann (2016), apply additional assumptions to the basic model or employ a new method to identify productivity shock. They also report appreciation in the RER. Recent empirical studies using both theories suggest that the RER can appreciate in response to productivity growth. However, they analyzed shocks in large economies, namely the US and the EU, and present aggregate impacts on the world economy. Even though aggregate US RER appreciates, bilateral RER of the US to individual neighboring countries can move in the opposite direction or the magnitude of appreciation can vary. However, there is no empirical study that examined the effect on multiple individual countries.

The contribution of this thesis is to investigate the effects of a US productivity shock on 48 individual countries and to discover what factors cause the reaction to vary across countries. The work done by Corsetti et al (2008, 2014) is a benchmark study and this thesis develops it further. The Corsetti et al (2008, 2014) studies have found aggregate impacts of a US productivity shock on the global economy, but this thesis extends the analysis to individual countries.

This analysis consists of two procedures. The first stage is to identify a US technology shock via sign restrictions of the Vector Autoregressive (VAR) model and to establish the movement of the US RER and net exports from both aggregate and bilateral perspectives. The second stage is to run a cross−country regression of estimated responses from the first stage and to establish whether the responses can vary, depending on country characteristics.

The results indicate that a US technology shock leads to an appreciation in aggregate US RER and a decline in US aggregate net exports, which is consistent with the findings of Corsetti et al. (2014). However, the responses of individual countries to US technology shock can be diverse. To determine what country characteristics cause such differences, cross−country OLS was used. The characteristics are 1) consumption home bias, 2) trade intensity with the US, 3) completeness of financial markets, 4) trade openness, and 5) exports of intermediate goods to the US. Some of these factors appear as parameters in theoretical literature, but they have never been tested empirically.[4] In terms of RER responses, the regression results show that the US RER appreciates more in countries with high consumption home bias, strong trade relationship with the U.S, and more openness to trade. In terms of net exports, US exports decrease as the RER appreciates and imports of

[4] Corsetti et al. (2008, 2014) assume that consumption bias for home goods exists and financial market is incomplete. Those parameters are included in the theoretical model and calibrated only for the US. But this paper measures them for 48 individual countries.

intermediate goods increase. Net exports from the US to countries with more complete financial markets increase.

The traditional view of the IRBC model, which states that a productivity growth in a country has positive spillover effects to its neighboring countries, is widely accepted. According to this view, US productivity growth results in a depreciation in the US RER, which indicates lower international price of US goods. Other countries then benefit from cheaper US products. However, recent empirical studies suggest that a US productivity shock induces price increases in US goods, which means that US productivity growth can have a negative impact. These results are also confirmed in this study, which extends the knowledge of recent empirical studies and finds that negative transmission of a US productivity shock can be strong in countries with a high home bias of consumption, a strong trade relationship with the US, and high trade openness.

Chapter 2 describes the VAR model and reports the effects of a US productivity shock on the RER and net exports. Chapter 3 determines the country characteristics that induce different effects across countries. Chapter 4 describes extended experiments to check the robustness of the results, and chapter 5 concludes the study.

2. Productivity Shock and Its Impact

A. Structural VAR Model with Sign Restrictions

I estimated the effects of US productivity shock on the RER and net exports with a structural VAR model. A US productivity shock was identified via sign restrictions proposed by Uhlig (2005). Signs imposed on key variables follow Corsetti et al. (2008).

Technology shock in this study is set as a standard TFP shock for all traded goods produced in the US. Technology shock was introduced as TFP by Kydland and Prescott (1982) and various measurement methods were developed later. Ramey (2016) reviewed the literature for macroeconomic shocks and synthesized the methods for the estimate. According to the study, three methods are mainly used in the VAR model to identify technology shock: (1) the long-run restriction of Gali (1999), (2) the sign restrictions from Uhlig (2005), and (3) the news shock from Barsky and Sims (2011). While news shock refers to an expectation that productivity will improve in the future, long-run and sign restrictions are used to identify already realized shocks. Identification with long-run restrictions assumes that only a technology shock can have a permanent effect on labor productivity. However, later studies suggest that other factors can induce a permanent change on labor productivity and long-run restrictions can cause distortions in the estimates.[5] Considering the shortcomings of long-run restrictions, this study selected sign restrictions to identify technology shock. The sign restrictions imposed on the variables were set similar to Corsetti et al. (2008).

I implemented a structural VAR model with six endogenous and six exogenous variables. The vector representation of the model follows Uhlig (2005). The VAR model assumes that all endogenous variables are dependent on their past values of order p. Thereafter, the model is set as equation (1).

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[5] Uhlig (2004) argues that other shocks affect labor productivity in the long run such as dividend tax shocks and preference shocks. Juvenal (2011) describes that substantial distortions can arise from a small-sample bias (Faust and Leeper, 1997) or a lag-truncation bias (Chari et al., 2007).

Structural−form VAR model : $AY_t = C(L)Y_{t-1} + v_t$

$$E\left[v_t v_t^{'}\right] = I_m \quad \cdots\cdots\cdots (1)$$

where Y_t is a vector of 6x1 of endogenous variables. Y_t consists of 1) labor productivity of manufacturing sector, 2) manufacturing output, 3) consumption, 4) relative price of manufactured goods, 5) relative output of manufacturing sector, 6) RER or net exports. To avoid having too many variables in the model, the first five variables were fixed and the sixth variable set as RER or net exports. A is a square matrix of structural parameters, which represents the contemporaneous relationship among endogenous variables. C(L) is a lag polynomial of order p, where $C(L) = C_0 + C_1L + C_2L^2 + \cdots + C_pL^p$. v_t is a vector of exogenous variables, and the elements of v_t are mutually orthogonal and normalized to be of variance 1, thus, $E\left[v_t v_t^{'}\right] = I_m$. v_t is interpreted as structural shock. For instance, the first element of v_t refers to unexpected shocks to labor productivity, the second element indicates unexpected shocks to manufacturing output, and those two shocks are independent. Equation (1) is a structural model since it is derived from underlying economic theory, and the parameters and shocks can be interpreted with economic meaning.

The structural model cannot be estimated directly. Thus, it was modified by multiplying by A^{-1}, then the reduced−form model was derived. The reduced−form model was estimated by OLS and the parameters of the structural model were restored by implementing certain restrictions.

Reduced−form VAR model: $Y_t = A^{-1}C(L)Y_{t-1} + A^{-1}v_t$

$$= B(L)Y_{t-1} + u_t$$

$$E\left[u_t u_t^{'}\right] = \Sigma \quad \cdots\cdots\cdots (2)$$

where $B(L) = A^{-1}C(L)$, and $u_t = A^{-1}v_t$. Since $u_t = A^{-1}v_t$, then $E\left[u_t u_t^{'}\right] = A^{-1}E\left[v_t v_t^{'}\right]A^{-1'} = A^{-1}A^{-1'} = \Sigma$. The parameters of the reduced model, B(L) and Σ, were estimated by OLS. The purpose of the VAR model is to derive the responses of endogenous variables to structural shocks. In this study, its purpose is to find the responses of the RER and net exports to positive productivity shock. The responses of $\mathbf{Y}$ to structural shock up to k horizons is denoted as Ψ_k, and it can be computed using estimates of B(L) and A^{-1}.

$$\Psi_k = \sum_{h=0}^{k} B_{k-h}\Psi_h \ , \Psi_0 = A^{-1}v, \quad k > 1, k - h \geq p \quad \cdots\cdots\cdots (3)$$

Proposition 1 in the study by Uhlig (2005) shows that the structural parameter of A^{-1} can be represented as Pq, where P is a Cholesky decomposition of Σ and q belongs to the hypersphere of unitary radius. Since Σ is estimated, the A^{-1} can be computed from the Cholesky decomposition, q can be drawn from the unit sphere, and q can be interpreted as structural shock $\mathbf{v}$. Sign restrictions were imposed at this point to identify productivity shock and the Bayesian approach was adopted since Uhlig (2005) argues that the Bayesian approach is suitable for sign restrictions. Positive productivity shock drives prices up and output down. Numerous candidate vectors of q were drawn from the unit sphere while Σ and B(L) were drawn from a Normal-Wishart posterior. With the derived parameters, the impulse response, Ψ_k, was calculated. If a q vector induced restricted variables to react in accordance with the assumed signs, it was considered to be productivity shock and the results were retained. If the variables did not respond to the assumed signs, the q were discarded.

The endogenous variables of the VAR model and sign restrictions are demonstrated in Table 1. This study investigates the productivity shock in the tradable goods sector of the US, and the data of the manufacturing sector represents the tradable goods sector.

Table 1 Endogenous variables of VAR model and sign restrictions

	Variables		Sign restrictions
1	Log(Labor Productivity of US manufacturing sector)	$\log LP_{US}$	+
2	Log(Manufacturing production in the US)	$\log Y_{mf,US}$	+
3	Log(Private consumption in the US)	$\log C_{US}$	
4	Log(Relative price of manufactured goods in the US)[6]	$\log \frac{PPI_{mf,US}}{CPI_{service,US}}$	−
5	Log(manufacturing output relative to GDP in the US)	$\log \frac{Y_{mf,US}}{GDP_{US}}$	+
6[7]	Log(RER)	$\log RER$	
	Net exports of US to partner/GDP of partner,	$\frac{NE_i}{GDP_i}$[8]	

Positive productivity shock, or supply shock, raises output and lowers prices. Positive demand shock, such as monetary expansion, induces both output and prices to rise. While both positive demand shock and supply shock increase output, prices react in opposite directions in response to each shock. This study identified productivity shock imposing sign restrictions on prices and output variables, where price was set to decrease and output to increase. The effect

[6] This relative price is a proxy for the relative price of US manufactured goods in terms of non-tradable goods. The price was measured as the log of relative US domestic producer price index of manufactured goods over the service consumer price index

[7] The VAR model has 6 endogenous variables to avoid having too many variables, and the 6th variables are set as RER or net exports in turn.

[8] i indicates trade partner of the US, and it can be a country or the rest of the world.

of demand shock was controlled, and the impulse responses were purely as a result of productivity shock. Four variables were employed to represent output and price, namely 1) labor productivity of the US manufacturing sector, 2) manufacturing production of the US, 3) manufacturing output relative to GDP in the US, and 4) the relative price of manufactured goods in the US. Positive signs restrictions were imposed on the output variable and negative signs restriction was imposed on the price variable. The detailed description and movement of variables followed Corsetti et al. (2008, 2014).[9] Productivity shock in the US tradable goods sector was set as an increase in labor productivity in US manufacturing relative to foreign labor productivity in the manufacturing sector in the model. When providing an impulse in productivity growth in the model, prices fall and output increases. This study imposed sign restrictions on four variables to identify productivity shock in the US tradable sector. The variables and corresponding signs are indicated in Table 1. Sign restrictions were placed for 20 quarters from the first quarter. For price, the restriction was imposed from the fifth quarter to consider nominal rigidities. I used the Bayesian approach suggested by Uhlig (2005) for estimation and inference. The reduced-form parameter, B(L) and Σ were drawn 1,000 times from the Normal-Wishart posterior of coefficients. For each draw of the parameters, impulse responses were simulated another 1,000 times, and only the responses that satisfied those sign restrictions were retained.

This study examines the effects of US productivity shock on individual countries and also reports the aggregate effects on the rest of the world to evaluate whether the results of this study are consistent with those in the

[9] Corsetti et al. (2008, 2014) set a standard open-economy DSGE model and derived the responses of price and output variables to productivity shock.

literature. Corsetti et al. (2014) set an aggregate of nine countries, where quarterly labor productivity data in the manufacturing sector is available, as the rest of the world (ROW). This study could obtain labor productivity data in the manufacturing sectors of seven countries from 1989 onwards and for five countries from 1981. Three different measures were used to build aggregate data for the rest of the world: 1) an aggregate of 5 countries (ROW1), 2) an aggregate of 7 countries (ROW2), and 3) an aggregate of all the countries in the world (ROW3). The aggregated variables, $\log LP_{ROW}$, $\log Y_{m\,f,ROW}$, $bg\ C_{ROW}$, logRER, NE_{ROW}, and GDP_{ROW}, were average weighted by GDP shares at PPP values. The counterpart for the impact of US productivity shock is either ROW or individual countries. Table 2 shows how these counterparts are defined.

Table 2 Counterpart of US productivity shock

Counterpart	Sample periods	Countries	Notes
ROW1	1981–2017	Canada, Japan, Korea, Mexico, South Africa	An aggregate of 5 countries
ROW2	1989–2017	Canada, Japan, Korea, Mexico, South Africa, France, Norway	An aggregate of 7 countries
ROW3	1981–2017	All countries in the world	An aggregate of all countries
Individual country (i)	1993–2017	48 countries	48 individual countries

The impact of US productivity shock was examined in terms of individual countries (i) or the rest of the world (ROW). The variables of the VAR model were measured based on either US–i relation or US–ROW relation. The endogenous variables according to each counterpart are presented in Table 3.

Table 3 Endogenous variables of VAR model[10]

VAR variables	Counterpart of US productivity shock		
	ROW1, ROW2	ROW3	i (individual country)
1	$\log LP_{US} - \log LP_{ROW}$	$\log LP_{US}$	$\log LP_{US}$
2	$\log Y_{mf,US} - \log Y_{mf,ROW}$	$\log Y_{mf,US}$	$\log Y_{mf,US}$
3	$\log C_{US} - bg\ C_{ROW}$	$\log C_{US}$	$\log C_{US}$
4	$\log \frac{PPI_{mf,US}}{CPI_{service,US}}$	$\log \frac{PPI_{mf,US}}{CPI_{service,US}}$	$\log \frac{PPI_{mf,US}}{CPI_{service,US}}$
5	$\log \frac{Y_{mf,US}}{GDP_{US}}$	$\log \frac{Y_{mf,US}}{GDP_{US}}$	$\log \frac{Y_{mf,US}}{GDP_{US}}$
6	logRER[11]	logRER[12]	logRER[13]
	$\frac{NE_{ROW}}{GDP_{ROW}}$	$\frac{NE_{ROW}}{GDP_{US}}$	$\frac{NE_i}{GDP_i}$

B. Data

Quarterly data was used for the simulation. Labor productivity is real output per hour for all persons in the manufacturing sector, which was obtained from the Federal Reserve Economic Data (FRED). Manufacturing production is an index of real output with 2012 = 100, from FRED. Private consumption is household expenditure with real value, which was from the International Financial Statistics (IFS). The prices of US manufactured goods are measured by PPI for the total manufacturing sector, and the prices for non-tradable goods are measured by CPI for all urban consumers (services less energy services).

[10] Labor productivity and manufacturing output variables are available for 5 and 7 countries. Those variables were input as the difference between the US and ROW where data was available, otherwise the US values were used.

[11] RER is an average of 5 or 7 countries, weighted by GDP shares at PPP value.

[12] RER is a real effective exchange rate of the US from Federal Reserve Economic Data.

[13] RER is a real exchange rate of US against individual country i.

Both of these were from FRED. Real GDP was obtained from FRED, and is in billions of chained 2012 dollars.

Bilateral US RER against i was calculated with the nominal exchange rate and price level of the two countries as follows:

$$\mathrm{RER} = \mathrm{E}\frac{P^{US}}{P^{i}} \cdots\cdots\cdots (4)$$

where E indicates nominal exchange rate, and P^{US} and P^{i} stand for price index of US and country i, respectively. The price index can be measured in various ways, such as CPI for all goods, CPI for manufactured goods, unit labor cost, PPI, and export deflator. Basically, I measured the RER with CPI for all goods, with the RER based on the CPI obtained from FRED. However, alternative prices indices were used to build the RER and the results are shown in the robustness check in Chapter 2.4, with 1) the US aggregate RER based on manufacturing CPI and 2) the manufacturing unit labor cost employed for the robustness test.

The RER in bilateral relationships was calculated based on CPI. The CPI of the US and of individual countries was obtained from the IFS. Aggregate real exchange rate, which was calculated with five or seven countries, were average weighted by GDP shares at PPP value. Corsetti et al. (2014) used this calculation. The US real effective exchange rate (REER) from FRED was used for aggregate US RER.

Net exports of the US were obtained from the US Census. Net exports were replaced by real exports or imports in the simulation to understand what drives the movement of net exports. Nominal exports and imports were downloaded from the US Census and converted into real value with the CPI of the US.

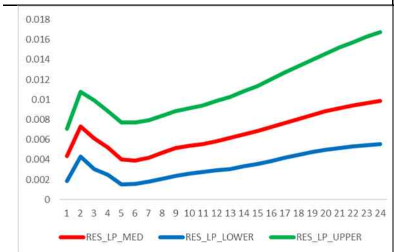
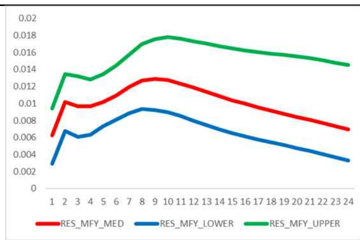
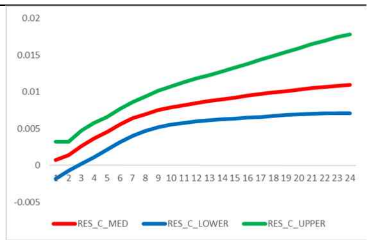
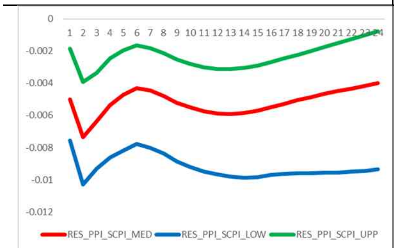
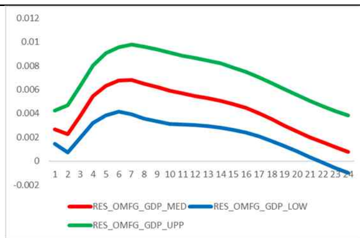
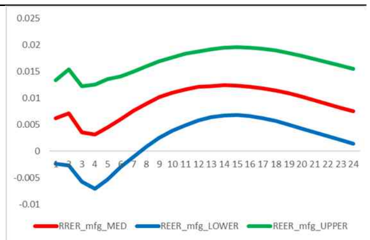
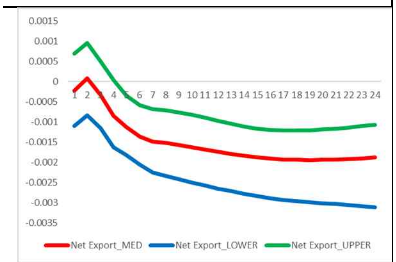
C. Responses of Real Exchange Rate and Net Exports to Productivity Shock

Figure 1 displays the impulse responses of US variables to a positive productivity shock in the US manufacturing sector vis-a-vis the rest of the world. Each figure presents the Bayesian credible intervals, which are the 16^{th} and 84^{th} percentiles of the posterior distribution of the responses. The median is presented in the middle. The four variables were restricted by signs, and they are labor productivity, manufacturing output, relative price of manufactured goods, and manufacturing output over GDP. Three other variables, private consumption, RER, and net exports, were not restricted. Labor productivity, manufacturing output, and relative manufacturing output to GDP increased for over 20 quarters, with the 16^{th} percentiles of responses remaining above zero. The relative price of manufactured goods decreased after productivity shock occurred, with the 84^{th} percentile response below zero beyond 20 quarters. The relative labor productivity of the US rose by 0.7% in median in response to productivity shock. The median manufacturing output and the median consumption increased by 1.1% and 0.16%, respectively. The relative price of manufactured goods decreased by a median of 0.7%. The 84^{th} percentile of the RER rose above zero after 7 quarters. This indicates that the RER appreciates. The median RER appreciated by 0.7% initially and peaked at 1.2% appreciation after 12 quarters. The ratio of net exports to GDP decreased gradually, and the median trade deficit reached 0.1% of GDP after 4 quarters. The decrease in net exports can be derived from a decline in exports or an increase in imports. Real exports and real imports were entered in the model to check which one caused the decrease in net exports. Figure 3 demonstrates that it is not clear whether the change in exports is positive or negative, but documents a statistically significant increase in imports. Positive productivity shock causes US imports to increase and leads to a decline in net exports.

Variables of interest are the RER and net exports. Figure 2 depicts aggregate US RER and net exports, which were measured based on the US–ROW relationship. The US aggregate RER appreciates and aggregate net exports decrease after productivity improves. These results are consistent with the initial findings of Corsetti et al. (2014) and those in their follow–up studies, but are in contrast to the predictions of the traditional IRBC model. The interpretation of these results is that the US RER appreciates in relation to the rest of the world and US exports to the world decline after productivity growth in the US. However, the RER and net exports of the US in bilateral relationships with individual countries do not correspond to the movements of the aggregate ones. Figure 4 and Figure 5 show the US RER and net exports in bilateral relationships. While aggregate US RER appreciates in relation to the rest of the world, the US RER can appreciate or depreciate against individual countries (i). Similarly, while US net exports to the world decrease, net exports of US to individual country i can increase or decrease. This finding implies that the impact of US productivity shock on individual countries can be diverse and country characteristics do play a role to cause such differences. Corsetti et al.'s (2014) studies investigate the impact of US productivity shock on the global economy. However, this study examines the impacts on individual countries and identifies the country characteristics that causes the impacts to vary across countries. The test to identify the role of country characteristics is described in the following section.

Figure 1 Responses of US variables to a positive productivity shock[14]

(US vs ROW)

Labor Productivity (US–ROW)	Manufacturing Output (US–ROW)	Consumption (US–ROW)
		
Relative price of manufactured goods (US)	Manufacturing output/GDP, (US)	US RER (+ indicates appreciation)
		
US net exports		
		

[14] The data for the rest of the world(ROW) is an aggregate of 5 countries from 1981 to 2017 to compare the results of this paper with Corsetti et al.(2014) which measured ROW by similar way.

Figure 2 Responses of aggregate US RER and net exports[15]

(US vs ROW)

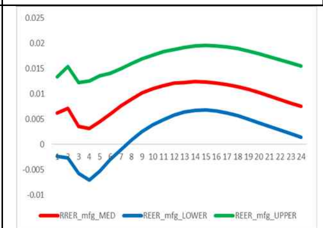
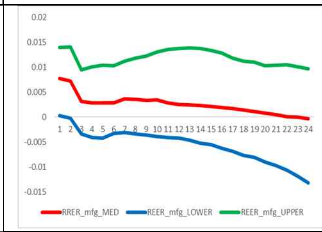
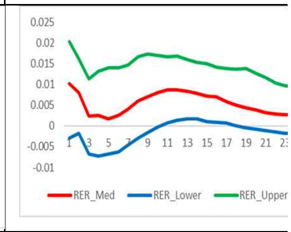
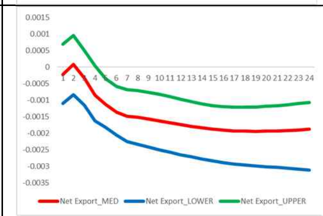
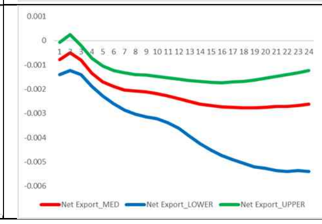
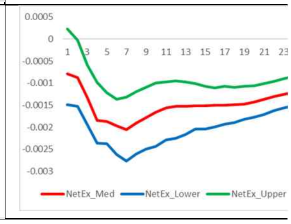
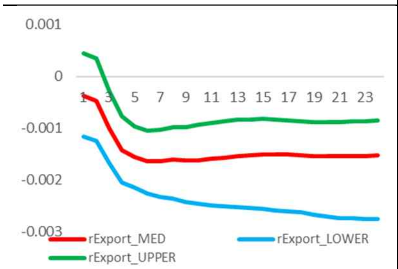
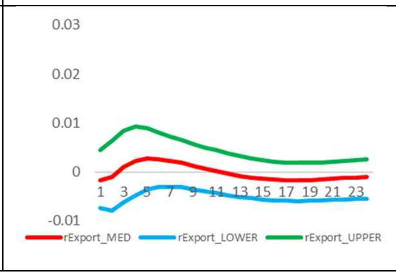
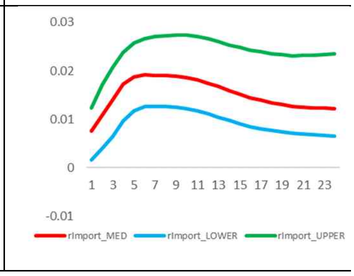
	US vs ROW1 (1981–2017)	US vs ROW2 (1989–2017)	US vs ROW3 (1981–2017)
RER (+ indicates appreciation)			
Net exports (− indicates decrease)			

Figure 3 Responses of aggregate US net exports, exports and imports[16]

(US vs ROW3)

Net Exports	Exports	Imports
		

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[15] The data for the rest of the world(ROW) is an aggregate of 5 countries from 1981 to 2017 or an aggregate of 7 countries to compare the results of this paper with Corsetti et al.(2014), where ROW was measured by similar way.

[16] Net exports in the VAR model is the ratio of $\frac{Net\ exports}{GDP}$. Exports and imports in the VAR model are real values of billions of chained 2012 US dollars.

Figure 4 Responses of bilateral US RER

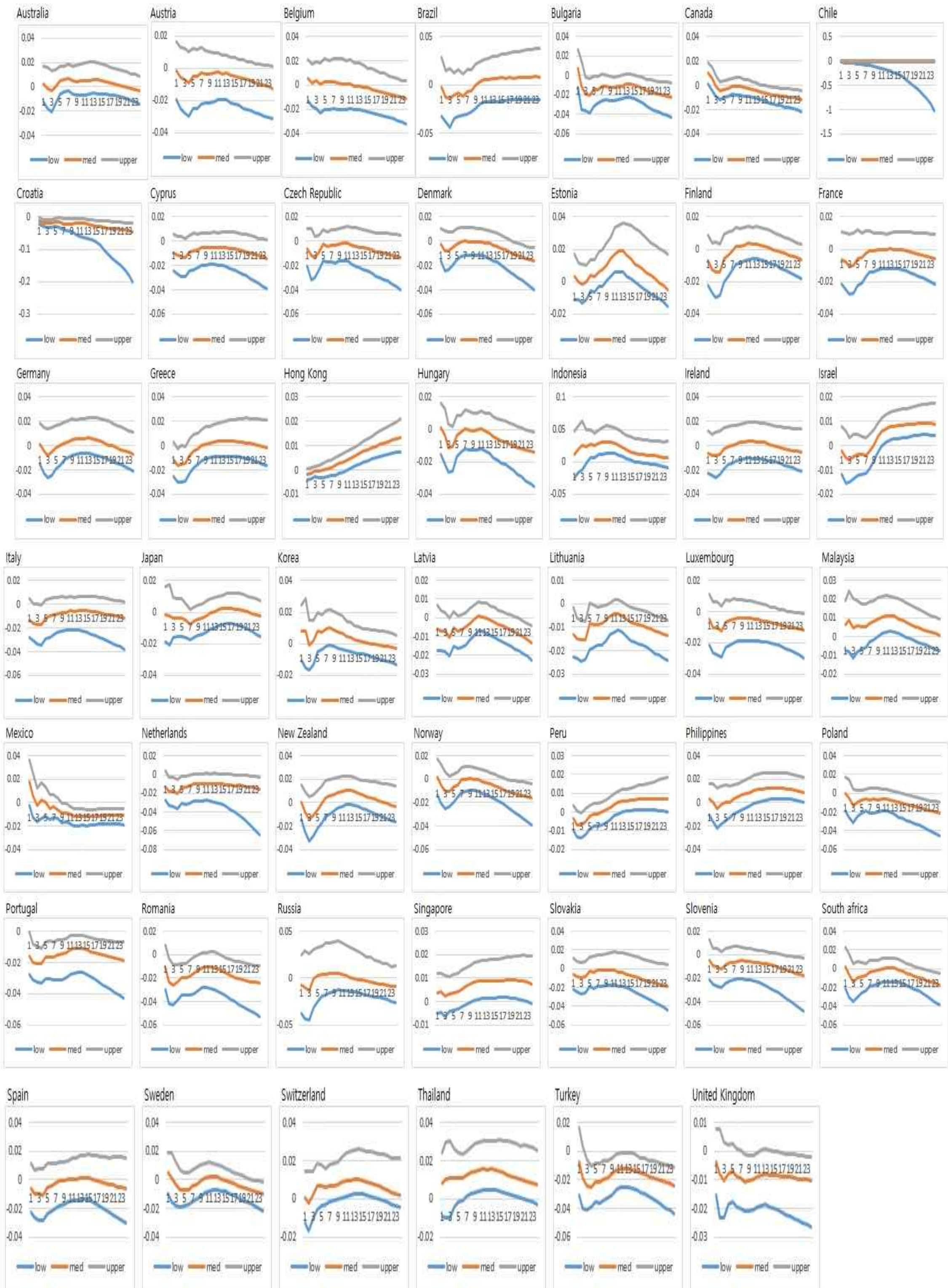
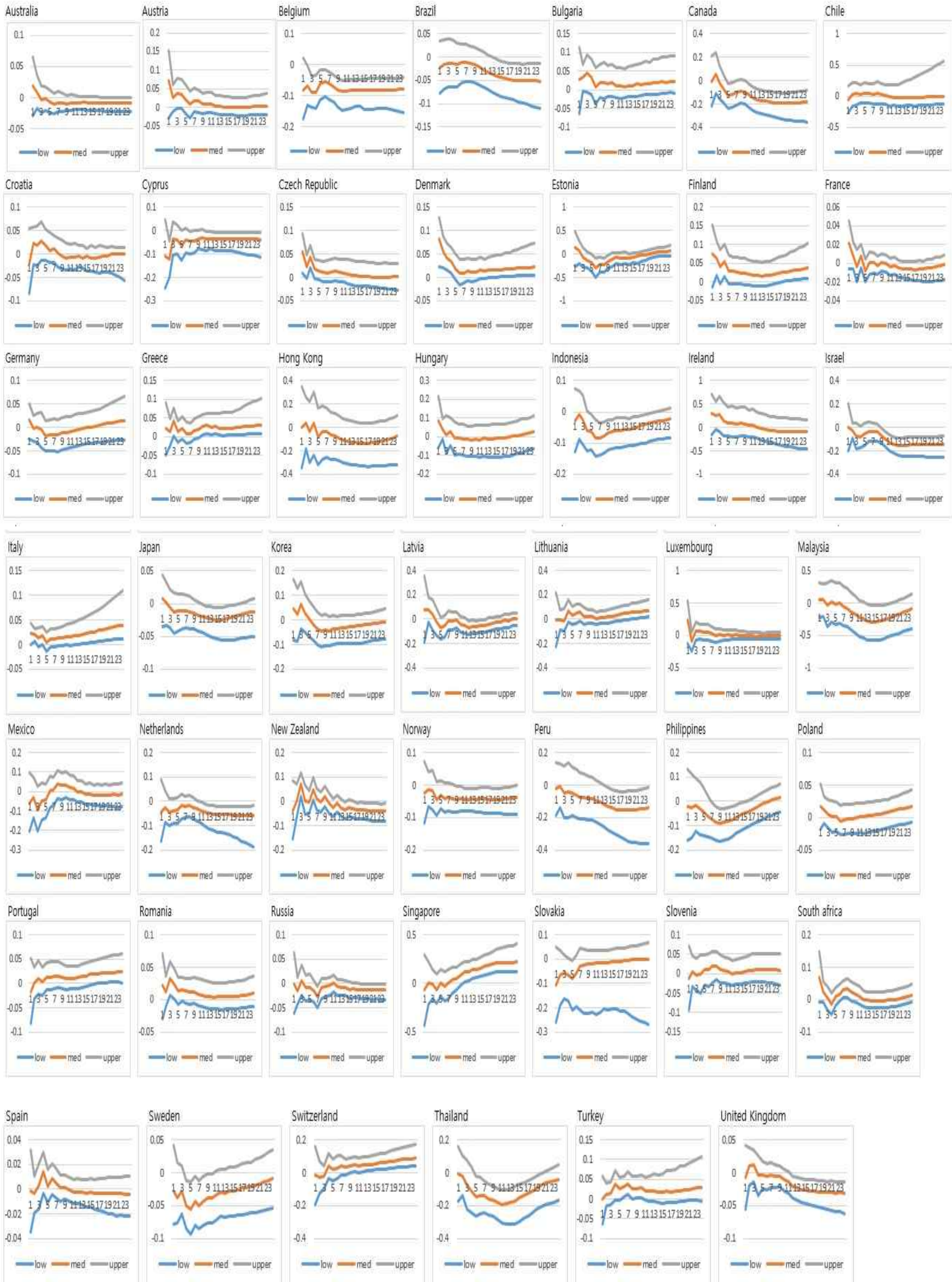


Figure 5 Responses of bilateral US net export[17]



[17] Net exports in the VAR model was measured as the ratio of $\frac{Net\ exports}{GDP}x100$.

3. Different Impact Across Countries and the Role of Country Characteristics

A. Factors that Cause Varied Responses to Productivity Shock

The results in the previous chapter indicate that US productivity shock leads to the appreciation in US aggregate RER relative to the rest of the world and a decline in US net exports to the world. However, the responses of the RER and net exports in bilateral relationships between the US and individual countries are not uniform. The varied responses of bilateral RER and net exports can result from country characteristics. This chapter investigates the role of country characteristics on the varied responses with the OLS estimate.

There are several studies that investigate the impacts that US productivity shock causes in the global economy. Occasionally, some studies examine the effect of US productivity shock on individual countries, such as Canada (Miyamoto & Nguyen, 2017; Choudri & Schembri, 2014). However, there are few empirical studies that examine the impacts of US productivity shock on multiple individual countries or show that the impacts can vary across countries.

This study differs from previous research on some points. First, this study investigates the impact of US productivity shock on 48 individual countries while previous studies investigate the aggregate effects on the world or the effects on a few neighboring countries. Second, this study finds that US productivity shock can have different impacts on neighboring countries, depending on the countries' characteristics. There are cross-country empirical studies, but they examine the characteristics of the countries where productivity shocks happened while this study analyzes the characteristics of shock−recipient countries.[18] Third, productivity shock is identified and measured in a more accurate way in this study, while many of the cross−sectional studies use GDP per capita as a proxy for productivity of the tradable sector.

This study uses the country characteristics described in previous studies as independent variables for the OLS model. The majority of cross−sectional empirical studies that examine the appreciation in aggregate RER in response to productivity shock use simple models with one explanatory variable and regress the relative productivity of tradable goods on the RER. However, some studies employ additional independent variables. According to Tica and Druzic (2006), additional explanatory variables frequently used in the literature are openness of economy and government spending. Government spending is added since it can affect the demand for non−tradable goods. Government spending is used to control the effect of government demand shock on the RER. The dependent variable in this study is the RER responses of the VAR model described in the previous section. In the VAR model, sign restrictions were imposed on price and productivity variables to identify productivity shock. The sign restrictions rule out the impacts of government demand shocks and identify productivity shock only. Since the demand shock was already controlled in the VAR model, there is no need to include government spending as independent variable in this study. Instead, other independent variables found in previous empirical studies, such as openness of economy and exchange rate regime, are used.

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[18] Tica and Druzic(2006) surveyed cross−country empirical studies to test HBS theory. Country characteristics were used as explanatory variables of OLS but they were characteristics of shock−occurrence countries. Yet this study analyzed that the impact of US shock can differ across countries depending on the characteristics of shock−recipient countries.

Furthermore, this study includes other country characteristics that have not yet been investigated in the literature. Newly added explanatory variables that represent country characteristics are 1) consumption home bias, 2) trade with the US, 3) completeness of financial market, and 4) exports of intermediate goods to the US.

1) Consumption home bias

The US RER in relation to a country i is the real price of a US consumption basket relative to that of country i. The RER (Q) can be calculated with the nominal exchange rate (E), price level in the US (P^{US}), and price level in i (P^i).

$$Q = \frac{EP^{US}}{P^i} \quad \cdots\cdots\cdots\cdots \text{(5)}$$

The RER can be decomposed to tradable-based and non-tradable-based RER.

$$Q = Q_T Q_N \quad \cdots\cdots\cdots\cdots \text{(6)}$$

where Q_T and Q_N indicate tradable-based and non-tradable-based RER, respectively. Q_T and Q_N can be expressed with the price of tradables (P_T) and non-tradables (P_N), as done by Lee and Tang (2007).

$$Q_N = \frac{\left(\frac{P_N^{US}}{P_T^{US}}\right)^{1-\alpha^{US}}}{\left(\frac{P_N^i}{P_T^i}\right)^{1-\alpha^i}} \quad \cdots\cdots\cdots\cdots \text{(7)}$$

$$Q_T = \frac{EP_T^{US}}{P_T^i} = \left(\frac{EP_T^{US*}}{P_T^{US}}\right)^{1-\beta_i} \left(\frac{EP_T^{i*}}{P_T^i}\right)^{\beta_i} \left(\frac{P_T^{i*}}{P_T^{US*}}\right)^{\beta_{US}-\beta_i} \quad \cdots\cdots\cdots\cdots \text{(8)}$$

where P_T^{US} is the price of tradable goods produced in the US and P_T^i is the price of tradable goods produced in country i, β_i and β_{US} are weights of home-produced tradables in total consumption, namely consumption home bias. The asterisk (*) indicates the price in the US, and no asterisk denotes the price in country i.

Home bias (β_i) is a component of tradable-based RER (Q_T). The equation (8) was modified to see the role of β_i more clearly.

$$Q_T = \left(\frac{P_T^{US}}{P_T^i}\right)^{\beta_i} \left(\frac{P_T^{i*}}{P_T^{US*}}\right)^{\beta_{US}} \frac{EP_T^{US*}}{P_T^{US}} = \left(\frac{P_T^{US}}{P_T^i}\right)^{\beta_i} Q_{T,Rest} \quad \cdots\cdots\cdots\cdots \ (9)$$

$$\text{where } Q_{T,Rest} = \left(\frac{P_T^{i*}}{P_T^{US*}}\right)^{\beta_{US}} \frac{EP_T^{US*}}{P_T^{US}}$$

$$Q = Q_T Q_N = \left(\frac{P_T^{US}}{P_T^i}\right)^{\beta_i} Q_{T,Rest}\, Q_N \quad \cdots\cdots\cdots\cdots \ (10)$$

According to Corsetti et al. (2008), the price of US goods is expected to rise after productivity shock, if consumption home bias exists in the US and the US financial market is incomplete. Then $\frac{P_T^{US}}{P_T^i}$ can be assumed to be greater than 1 after productivity growth in the US. Since $\frac{P_T^{US}}{P_T^i}$ is greater than 1, $\left(\frac{P_T^{US}}{P_T^i}\right)^{\beta_i}$ increases as the consumption home bias of country i (β_i) rises. A higher Q indicates an appreciation in the US RER against country i, according to the setting in equation (5). Assuming all else remains the same, the US bilateral RER against country i appreciates if country i has a higher consumption home bias.

Home bias is measured as the ratio of consumption of domestically produced tradable goods to the consumption of total tradable goods. The Inter-

Country Input–Output Table of OECD provides relevant consumption data for each country. Home bias was calculated as an average for the period from 1995 to 2015, where the data is available.

$$HomeBias = \frac{Consumption\ of\ domestically\ produced\ tradable\ goods}{Consumption\ of\ total\ tradable\ goods} \cdots\cdots\cdots (11)$$

2) Trade with the US

Miyamoto and Nguyen (2017) investigated the US permanent technology shock and its impacts on Canada and Mexico. The results show that the US technology shock raises output in both countries and the output increases sharply after they joined NAFTA. This suggests that strong trade ties with the US can be an important transmission channel for US shock. The simulation of the VAR model previously described indicates that the US aggregate RER appreciates after productivity growth. Therefore, it can be expected that the US bilateral RER will appreciate more in a country with strong trade ties with the US.

This study measured the trade relations between the US and individual countries with both conventional trade data and value–added trade data. Due to the growing global supply chain, various countries join in the process of production. However, conventional trade statistics do not reflect the complex international production process. Production inputs are sourced globally, but the traditional trade data do not account for the contribution of all countries involved in the production. Thus, this study used OECD TiVA statistics, which measures the value added by all countries involved in the production process. Trade relations between the US and a country i was measured as the trade between two countries over the total trade of country i. The trade was measured by either traditional gross trade flow or by the value−added trade between two countries. Value−added trade between the US and a country captures their trade relation in the global supply chain.

$$\mathbf{Trade\_with\_US} = \frac{\textit{Gross Exports and Imports with the US}}{\textit{Gross Exports and Imports with the World}} \times \mathbf{100} \quad \cdots\cdots\cdots(12)$$

$$\mathbf{VA\_Trade\_with\_US} =$$

$$\frac{\textit{Value added imports from US} + \textit{Domestic Value added exports to the US}}{\textit{Foreign Value added imports} + \textit{Domestic value added exports}} \mathbf{x100}$$

$$\cdots\cdots\cdots(13)$$

Value−added export and import data are available for the period between 2005 to 2015 on the OECD TiVA database. Gross trade data were obtained from UN Comtrade. Since the value−added data is available for the period 2005–2015, both indices were calculated as the average for those years.

3) Completeness of financial market

An economy is exposed to various shocks that cause fluctuation in income. The level of consumption in an economy is driven by income. If an economy experiences a negative shock, consumption shrinks as income decreases. According to the theory of international consumption risk sharing, such consumption risk can be insured through the financial market. If the financial market is complete (developed), agents of an economy can hold productive assets of other countries and cover the risk of income fluctuation from country−specific shocks. Optimal consumption levels can then be achieved and consumption does not react to income fluctuations. Full consumption risk sharing is possible with complete financial markets. If a financial market is incomplete, consumption risk is not fully covered. In other words, consumption changes along with income. If the financial market is complete, consumption risk is fully hedged and consumption is optimal with consumers' utility maximized, and consumption level changes only by price, not by wealth. However, agents in incomplete financial markets are exposed to country−specific consumption risk, where consumption changes with changes in wealth. Consumption rises as wealth increases or the other way around. Therefore, consumption is sensitive to wealth change in countries with incomplete financial markets while it does not respond to wealth in countries with complete financial markets. When the US aggregate RER appreciates after productivity growth, the RERs of other countries depreciate relatively, and their relative wealth decreases. If a country has a more complete financial market, its consumption is not sensitive to a decline in wealth. In trade between the US and country i, i may not decrease imports from the US even if its wealth decreases since consumption is not affected by wealth. Therefore, it follows that US exports to countries with more complete financial markets may not decrease even when US aggregate net exports to the world decrease after productivity growth.

The completeness of financial markets was measured as a level of the development of the stock market. I measured it dividing the sum of asset and liability of portfolio investment by the GDP of a country. Portfolio investment data is available from the International Financial Statistics of the IMF and the GDP was obtained from the World Economic Outlook database of the World Bank. Since the data is available since 1993, the index is an average of the period from 1993 to 2017.

$$\textbf{FinancialComplete} = \frac{\textbf{Portfolio Investment}}{\textbf{GDP}} \times \mathbf{100} \quad \cdots\cdots\cdots (14)$$

4) Exports of intermedia goods to the US

This study makes the same two assumptions as Corsetti et al. (2008, 2014), namely that the financial market is incomplete and consumption home bias exists. Since the financial market is incomplete, consumption risk is not fully covered and US consumption increases due to positive productivity shock. Since consumption is biased for domestic goods, demand for domestic goods rises strongly. Since supply rises gradually, demand exceeds supply in the short-run. Excess demand for domestic goods drives prices up, and the US RER appreciates. If US consumption rises in response to a positive productivity shock, it leads to a decrease in net exports, as the VAR results indicate. The decrease in net exports is as a result of either a decline in exports or an increase in imports. Imports can be divided into the imports of final goods and imports of intermediate goods. Since home bias causes the demand for domestic goods to strongly rise, it can undermine demand for imported foreign final goods. Simultaneously, US imports of intermediate goods can increase due to increased domestic production. Accordingly, I deduce that the decline in net exports is partly induced by an increase in intermediate imports. Thus, the US will increase imports of intermediate goods.

I measured the share of intermediate goods exports to the US in the total exports of a country to the US. Exports to the US from a country with a higher index are expected to rise. In other words, US imports from a country with a higher index are expected to rise. The export of intermediate goods to the US from individual countries can be calculated from OECD TiVA data. Since the data is available for the period between 2005-2015, the index was calculated as an average of this period.

$$\mathbf{Exportshinterm\_to\_US} = \frac{\text{exports of intermediate goods to the US}}{\text{total exports to the US}} \times \mathbf{100} \quad \cdots\cdots\cdots (15)$$

5) Imports of intermediate goods from the US

Lian et al. (2020) showed that information technology has advanced significantly since the 1990s, and this caused a decrease in the price of investment goods. The exports of input[19] accounts for approximately 62% of the total exports of goods from the US as of the second quarter of 2020. Since US exports include a large share of intermediate goods, the price of which has declined due to productivity shock, the US is expected to increase the export of intermediate goods. This means that US exports to countries that have been importing intermediate goods from the US is expected to rise.

I measured the share of intermediate goods imports from the US in the total imports of a country. If a country has a higher index, it imports more intermediate goods from the US, and an increase in imports from the US can be experienced after productivity growth in the US. The index was computed from OECD TiVA data and is an average for the period 2005-2015.

$$\mathbf{Importsinterm\_from\_US} = \frac{\mathbf{imports\ of\ intermediate\ goods\ from\ the\ US}}{\mathbf{total\ imports\ from\ the\ US}} \times \mathbf{100} \quad \cdots\cdots\cdots(16)$$

6) Openness

De Broeck and Sloke (2006) measured the openness of an economy as trade openness, exports plus imports divided by the GDP. They suggest that the response of the RER is expected to be more pronounced in more closed economies. This study measured openness as financial openness or trade

[19] It includes industrial supplies and materials, and capital goods except automotive.

openness. Chinn and Ito (2006) measured the openness of the capital account of a country and provided the annual index for the period 1996–2017. This study employed the Chinn–Ito index to represent financial openness. Trade openness is a measure of the ratio of trade over GDP of a country. While there is trade data available for most countries from 1993, the data is available from 2000 for a few countries, such as South Africa. Thus, trade openness was calculated as an average for the period 2000–2017 for all countries.

$$\mathbf{Financial\ Openness} = \mathbf{Chinn\ \&\ Ito\ index} \quad \cdots\cdots\cdots(17)$$

$$\mathbf{TradeOpenness} = \frac{\mathbf{Exports + Imports}}{\mathbf{GDP}} \times \mathbf{100} \quad \cdots\cdots\cdots(18)$$

7) Other variables

The aggregate US RER appreciates as US productivity grows, as shown in the VAR estimates in the previous chapter. The appreciation is expected to be clear when the exchange rate is not controlled. Ilzetzki et al. (2018) formulated an index to represent the exchange rate system of each country. A higher index reflects a floating exchange rate system. This study used an average of the index for the period 1993–2016 ($ExchangeRegime$) to capture the exchange rate system of each country. Certain countries displayed drastic changes in the exchange rate systems, mostly when joining the Eurozone. In those cases, entire periods were divided into before and after the drastic change in the system and the average was calculated for the longer period.

The RER changes in response to US productivity growth, and then net exports between the US and other countries can be affected by the changes. Consequently, changes in the RER (R_RER) after productivity growth was included as an independent variable where net exports were used as a dependent variable.

A. Cross-country OLS

Cross-country OLS was used to examine the effects of country characteristics on the US RER in relation to country i and US net exports to i. The basic models are as follows;

$$R\_RER_i = \beta_0 + \beta_1 Trade\_with\_US_i + \beta_2 HomeBias_i + \beta_3 FinancialComplete_i + \beta_4 Openness_i + \beta_5 ExchangeRegime_i + \varepsilon_{1i}$$

$$\cdots\cdots\cdots\cdots (19)$$

$$R\_NetExp_i = \beta_0 + \beta_1 Trade\_with\_US_i + \beta_2 HomeBias_i + \beta_3 FinancialComplete_i + \beta_4 Openness_i + \beta_5 ExchangeRegime_i + \beta_6 R\_RER_i + \beta_7 Exportintherm\_to\_US_i + \beta_8 Importintherm\_from\_US_i + \varepsilon_{2i}$$

$$\cdots\cdots\cdots\cdots (20)$$

The dependent variables are US RER in relation to country i (R_RER) or US net exports to i (R_NetExp). These were measured from the VAR results in Section 2.2.

$$\text{R\_RER} \equiv \frac{\sum_{k=1}^{K} RER_k}{\sum_{k=1}^{K} LP_k} \cdots\cdots\cdots\cdots (21)$$

$$\text{R\_NetExp} \equiv \frac{\sum_{k=1}^{K} NE_k}{\sum_{k=1}^{K} LP_k} \cdots\cdots\cdots\cdots (22)$$

where RER_k, LP_k and NE_k are the responses of RER, labor productivity, and net exports, respectively, in the k-th quarter after a productivity shock. R_RER and R_NetExp are cumulative responses of bilateral US RER and net exports in relation to the country i. The periods of accumulation (K) are 4, 8, 12, and 16 quarters. Responses of the RER and net exports were divided by the responses of labor productivity to account for the different size of productivity shocks in each country.

The VAR model with variable RER discussed in the previous section was simulated 630 times and the model with net exports 650 times, which are the number of cases that satisfy sign restrictions. Thus, the OLS was simulated 630 and 650 times for R_RER and R_NetExp, respectively. The results of the regression are presented with the 5^{th}, 16^{th}, 84^{th}, and 95^{th} percentiles of empirical distribution of the regression coefficients. A similar method was used by Kim (2015) and Berka et al. (2018).

Seven independent variables were included to consider country characteristics: 1) trade with the US, measured by gross trade ($Trade\_wth\_US_i$) or value-added trade ($VA\ Trade\_wth\_US_i$), 2) consumption home bias ($HomeBias_i$), 3) financial market completeness ($FinancialComplete_i$), 4) openness of an economy ($Openness_i$), measured by financial openness ($Financial\ Openness_i$) or trade openness ($Trade\ Openness_i$), 5) exchange rate regime ($ExchangeRegime_i$), 6) responses of RER for k quarters (R_RER_i), 7) the exports of intermediate goods from country i to the US ($ExportInterm\_to\_US_i$), and 8) the imports of intermediate goods to country i from the US ($ImportsInterm\_from\_US_i$)

The dependent variables RER and net exports were obtained from the VAR model discussed in the previous section. The sample period for the VAR model is 1993–2017, and the country characteristics of the seven variables should be an average for the same periods. However, some data is not available for 1990s and those variables were averaged for the periods where data is available.

B. Results

The regressions were conducted with 48 individual countries. Dependent variables are the US RER against country i; net exports from the US to country i; real exports from the US to country i; and real imports to the US from country i.[20] The median estimates are described with 68% probability bands in parentheses, and *, **, and *** indicate that the estimates deviate from zero with a greater than 84%, 90%, and 95% probability, respectively.

Table 4 displays the results of the regression with the dependent variable RER at one-year, two-year, three-year, and four-year horizons. When a country has a high consumption home bias, the US RER relative to that country is expected to appreciate, as noted in the previous section. The estimates of home bias present expected positive signs and deviate from zero with a probability greater than 84% for a four-year horizon. The estimates of trade with the US show expected positive signs. Trade with the US was measured by gross trade or value-added trade. Both deviate from zero with a probability greater than 84% in one-year and two-year horizons. Trade openness presents significant positive value for all horizons and deviate from zero with a probability greater than 84% or 90%. This suggests that the RER tends to appreciate when an economy is more open to trade.[21] When trade relations with the US are strong, the RER also appreciates. These two results suggest that trade is an important channel to transmit US productivity shock. The regression results for RER reveal that the US bilateral RER appreciates in

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[20] Net exports is the results of the VAR model, and it was measured as the ratio of $\frac{Net\ exports}{GDP}x100$. Real exports and real imports are not ratios but level.

[21] Financial openness does not produce significant results, and it is not presented in the table.

a country where home bias is high, trade relations with the US are strong, and the economy is more open to trade.

Table 5 documents the regression results for net exports from the US to individual countries. Aggregate US net exports to the world appeared to decrease after productivity increases. However, net exports to individual countries can be diverse. This difference is likely caused by two country characteristics. If a country has a more complete financial market, US net exports to that country may not decrease since the consumption demand of that country is less sensitive to US productivity shock. The estimates of "financial completeness" present significant positive values, and a higher index means a more complete financial market. The results are consistent with the expectation. Net exports from the US will be affected by the RER, thus, "RER responses" after productivity shock were included as independent variables. The results show that US net exports decrease to countries where the US bilateral RER appreciates more.

Net exports are composed of exports and imports. To better understand the movement of net exports, this dependent variable was replaced by real exports or real imports. If aggregate US net exports decrease, it can be as a result of either a decrease in exports or an increase in imports. If the real exports are used as a dependent variable, the estimates of "RER responses" are negative and statistically significant. This indicates that real US exports decrease as the RER appreciates. With the real imports as the dependent variable, an increase in imports can be seen in the countries that export intermediate goods to the US. This means that the US increases imports of intermediate goods after productivity growth. To summarize, US exports decrease due to RER appreciation and imports of intermediate goods increase due to increased production, which results in a decrease in net exports. US exports of intermediate goods is expected to increase, but the coefficients is not significant. US productivity growth lowers the price of US intermediate goods, but the lower price does not boost exports.

In summary, US productivity shock causes US goods to become expensive as aggregate US RER appreciates. Moreover, US aggregate net exports decrease as demand in domestic consumption increases. However, the impacts on the RER and net exports are not uniform across countries. In terms of the RER, US RER appreciates more in a country with a high consumption home bias, strong trade ties with the US, and more openness to trade. In terms of trade, US net exports decreases. When net exports are decomposed into exports and imports, it becomes clear that US exports decrease due to RER appreciation and imports increase due to high demand for intermediate goods.

Table 4 Regression results for US RER in relation to country i

	Dependent variable: RER of one−year horizon			Dependent variable: RER of two−year horizon		
Constant	−3.8 (−7.5, 0.8)	−3.8 (−7.5,0.7)	−3.3 (−7.3.0.9)	**−3.5*** **(−6.7,−0.3)**	−3.8 (−7.5, 0.7)	−3.2 (−6.3, 0.1)
Trade with US	**0.04*** **(0.01, 0.1)**			0.03 (−0.004, 0.1)		
VA Trade with US		**0.05*** **(0.005, 0.1)**	0.04 (−0.001,0.1)		**0.1*** **(0.05, 0.1)**	0.02 (−0.01, 0.1)
Home Bias	2.1 (−3.9, 8.1)	2.1 (−4.1, 8.0)	0.8 (−5.0, 7.1)	2.5 (−2.2, 7.0)	2.1 (−4.1, 8.0)	1.2 (−3.7, 5.7)
Financial Completeness	0.01 (−0.02, 0.04)	0.002 (−0.03, 0.03)	0.01 (−0.02, 0.04)	0.01 (−0.02, 0.04)	0.002 (−0.03, 0.03)	0.01 (−0.02, 0.04)
Trade openness	**0.01*** **(0.001, 0.01)**	**0.01*** **(0.001, 0.01)**	**0.01*** **(0.001, 0.01)**	0.01* (0.001, 0.01)	**0.01*** **(0.001, 0.01)**	**0.01*** **(0.001, 0.01)**
Exchange Regime			0.1 (−0.1, 0.2)			0.1 (−0.04, 0.2)

	Dependent variable: RER of three−year horizon			Dependent variable: RER of four−year horizon		
Constant	**−3.7*** (−6.4, −0.8)	**−3.7**** (−6.4, −0.8)	**−3.3*** (−6.1, −0.6)	**−3.7***** (−5.8, −1.4)	**−3.7***** (−5.8, −1.4)	**−3.4**** (−5.5, −1.1)
Trade with US	0.01 (−0.01, 0.04)			0.005 (−0.02, 0.03)		
VA Trade with US		0.02 (−0.02, 0.04)	0.01 (−0.02, 0.04)		0.01 (−0.02, 0.03)	−0.001 (−0.03, 0.02)
Home Bias	3.5 (−0.7, 7.5)	3.5 (−0.8, 7.4)	2.1 (−2.1, 6.2)	**3.9*** (0.5, 7.1)	**3.9*** (0.4, 7.1)	2.5 (−0.8, 5.9)
Financial Completeness	0.01 (−0.01, 0.04)	0.01 (−0.02, 0.04)	0.01 (−0.01, 0.04)	0.01 (−0.01, 0.03)	0.01 (−0.01, 0.03)	0.01 (−0.01, 0.03)
Trade openness	**0.01*** (0.001, 0.01)	**0.01*** (0.001, 0.01)	**0.01*** (0.001, 0.01)	**0.01**** (0.001, 0.01)	**0.01**** (0.001, 0.01)	**0.01**** (0.001, 0.01)
Exchange Regime			0.1 (−0.02, 0.2)			0.1 (−0.01, 0.2)

The median estimates are reported, and 68% probability bands are reported in parentheses.

*, **, and *** indicate that the estimates deviate from zero with greater than 84%, 90% and 95% probability, respectively.

The increase in the dependent variable US RER means that it appreciates.

Table 5 Regression results for net exports of US

	one−year horizon				two−year horizon			
Dependent / Independent	Net Export		Real Export	Real Import	Net Export		Real Export	Real Import
Constant	−26.3 (−77.0, 29.1)	12.2 (−29.1, 53.3)	−5.0 (−21.5, 11.2)	−6.5 (−16.0, 2.5)	−24.3 (−68.7, 19.7)	5.4 (−24.9, 40.1)	−0.4 (−11.9, 9.3)	−1.3 (−8.3, 6.0)
VA Trade with US	−0.1 (−0.5, 0.4)	−0.1 (−0.5, 0.4)	0.002 (−0.1, 0.1)	−0.03 (−0.1, 0.03)	−0.1 (−0.4, 0.2)	−0.1 (−0.4, 0.3)	0.02 (−0.04, 0.1)	−0.03 (−0.1, 0.01)
Home Bias	3.3 (−36.5, 41.8)	0.7 (−43.0, 39.5)	8,1 (−5.1, 19.9)	−0.6 (−8.9, 8.1)	3.8 (−25.1, 32.0)	1.9 (−28.5, 30.6)	4.4 (−4.4, 11.9)	−3.2 (−9.1, 2.3)
Financial Completeness	0.0 (−0.4, 0.5)	0.2 (−0.0, 0.5)	0.1 (−0.04, 0.2)	−0.01 (−0.1, 0.1)	0.1 (−0.2, 0.4)	**0.2* (0.1, 0.4)**	0.1 (−0.02, 0.1)	−0.01 (−0.05, 0.04)
Trade Openness	−0.0 (−0.2, 0.1)	−0.0 (−0.1, 0.1)	0.002 (−0.02, 0.03)	−0.003 (−0.02, 0.01)	−0.0 (−0.1, 0.1)	−0.0 (−0.1, 0.1)	0.002 (−0.02, 0.02)	−0.002 (−0.01, 001)
Intermediate goods exports to US from i		−0.2 (−0.6, 0.2)		**0.2** (0.1, 0.3)**		−0.1 (−0.5, 0.2)		**0.1** (0.05, 0.2)**
Intermediate goods imports from US to i	0.5 (−0.4, 1.4)		0.005 (−0.2, 0.2)		0.4 (−0.3, 1.2)		−0.01 (−0.2, 0.1)	
RER responses	−67.4 (−198.3, 89.5)	−73.4 (−200, 83.2)	−15.5 (−58, 29.3)	1.7 (−24.3, 30.9)	−43.4 (−89.5, 1.5)	−42.9 (−88.4, 3.1)	**−30.5* (−60, −1.6)**	1.1 (−19.0, 20.3)

Dependent / Independent	three−year horizon				four−year horizon			
	Net Export		Real Export	Real Import	Net Export		Real Export	Real Import
Constant	−15.3 (−51.9, 21.7)	3.4 (−21.5, 33.0	0.5 (−7.8, 8.7)	−1.9 (−7.4, 4.1)	−4.2 (−33.7, 24.3)	3,1 (−17.5, 26.6)	1.5 (−5.4, 8.0)	−2.6 (−6.8, 2.6)
VA Trade with US	−0.1 (−0.4, 0.2)	−0.1 (−0.4, 0.2)	0.03 (−0.01, 0.1)	−0.02 (−0.1, 0.01)	−0.1 (−0.4, 0.1)	−0.1 (−0.4, 0.1)	0.03 (−0.002, 0.1)	−0.02 (−0.05, 0.01)
Home Bias	0.5 (−22.9, 21.7)	−0.9 (−26.0, 21.7)	1.9 (−5.5, 7.3)	−2.9 (−7.6, 1.3)	−1.2 (−19.3, 15.9)	−1.3 (−21.6, 15.9)	0.2 (−5.9, 4.6)	−2.5 (−6.4, 0.9)
Financial Completeness	0.1 (−0.2, 0.3)	**0.2** (0.0, 0.3)**	0.03 (−0.03, 0.1)	−0.01 (−0.05, 0.03)	0.1 (−0.1, 0.3)	**0.1** (0.0, 0.2)**	0.02 (−0.03, 0.1)	−0.02 (−0.04, 0.02)
Trade Openness	−0.0 (−0.1, 0.1)	−0.0 (−0.1, 0.1)	−0.001 (−0.02, 0.01)	−0.003 (−0.01, 0.01)	−0.0 (−0.1, 0.1)	−0.0 (−0.1, 0.1)	−0.001 (−0.01, 0.01)	−0.004 (−0.01, 0.003)
Intermediate goods exports to US from i		−0.1 (−0.4, 0.2)		**0.1** (0.1, 0.2)**		−0.1 (−0.3, 0.2)		**0.1*** (0.1, 0.2)**
Intermediate goods imports from US to i	0.2 (−0.4, 1.0)		−0.01 (−0.1, 0.1)		0.0 (−0.4, 0.6)		−0.03 (−0.1, 0.1)	
RER responses	**−31.0** (−51.5, −10.0)**	**−30.6** (−52, −9.3)**	**−33.9** (−59, −10.7)**	0.7 (−16.5, 17.9)	**−19.3*** (−31.3, −9.0)**	**−19.1** (−31.6, −8.6)**	**−33.7** (−54.1, −14.2)**	−1.4 (−14.0, 14.0)

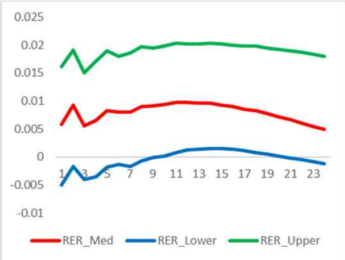
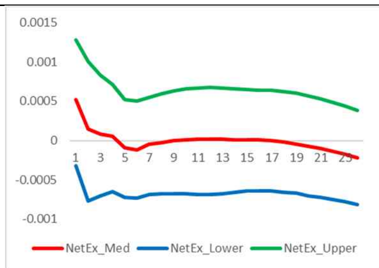
The median estimates are reported, and 68% probability bands are reported in the parentheses.

*, **, and *** indicate that the estimates are different from zero with greater than 84%, 90% and 95% probability, respectively

4. Robustness

The baseline model was extended to check the robustness of the results. First, I changed the sample period of the VAR model in line with the literature. The previous studies, such as Corsetti et al. (2014) and Nam and Wang (2018), selected a sample before 2007 to avoid the effects of the 2008 global financial crisis. Corsetti et al. (2014) used a sample of 1973:1–2004:4 and Nam and Wang (2018) examined the period of 1975:1–2007:4. Since this study set Corsetti et al. (2008, 2014) as a benchmark, the same period, 1973:1–2004:4, was examined. In the baseline model in the previous section, three different measures were used to establish the aggregate US variable. These differed in how many countries were included in the rest of the world, where five countries, seven countries, or all countries were considered, respectively. In this robustness test, I used US data that include all countries as the rest of the world. Figure 6 demonstrates the responses of US aggregate RER and net exports in response to productivity shock for the sample period of 1973:1–2004:4. The results indicate that the RER appreciates and deviates from zero with a probability of 84% for nine quarters after productivity shock. The appreciation in the RER is consistent with the literature and the results of the baseline model of this study. Net exports decrease in the literature and in the baseline model of this study, but the direction of the movement is not clear in the robustness test.

Figure 6 Responses of US aggregate data to productivity shock

Real exchange rate	Net export
	

Second, the RER was calculated with two alternative price indices, which are 1) manufacturing CPI and 2) manufacturing ULC. The baseline model used REER measured with the CPI for all goods. The aggregate RER of the US in the VAR model was represented by the REER. The REER is the real value of a currency against those of its trading partners, which is calculated as a trade-weighted average of RER. The US REER can be measured as follows:

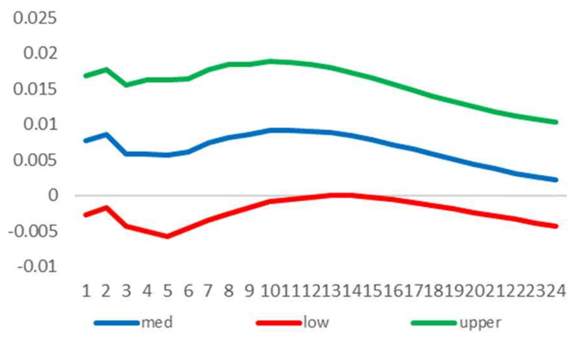
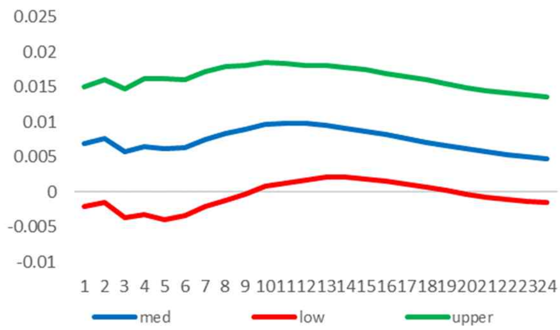
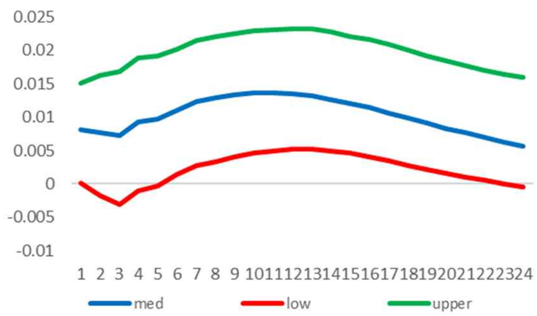
$$\mathrm{REER_{US}} = \sum_{i=1}^{N} \frac{P_{US}}{P_i} \times TradeWeight_i \cdots\cdots\cdots (23)$$

P = CPI, manufacturing CPI, or manufacturing ULC

where P_{US} and P_i are the price indices of the US and country i in dollars, respectively, $TradeWeight_i$ is the trade weight of country i in the total trade of the US, and i is a trade partner of the US. The REER can be measured with various price indices, P_{US} and P_i. This study adopted three different indices, 1) CPI, 2) manufacturing CPI, and 3) manufacturing ULC. The baseline model used the REER based on CPI. This study assumed that goods consist of tradables and non-tradables. The CPI is composed of the price of tradable and non-tradable goods. Manufacturing CPI is close to the price of tradable goods. Manufacturing ULC is the price of non-tradable goods since the ULC is the average cost of labor per unit of output produced.

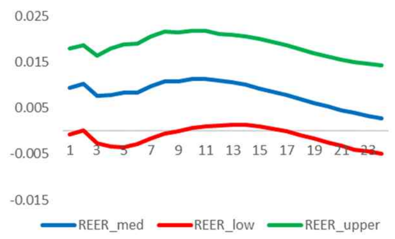
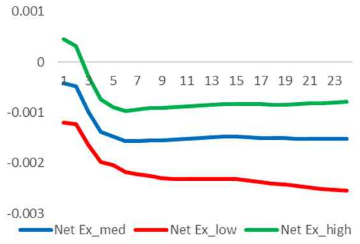
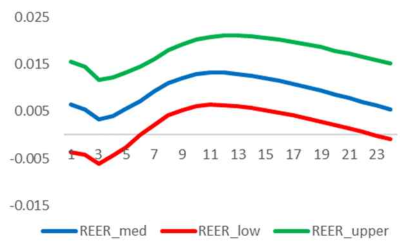
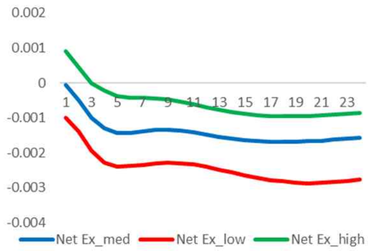
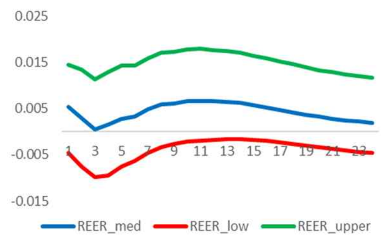
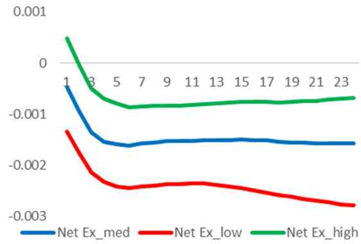
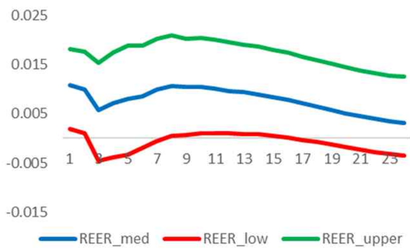
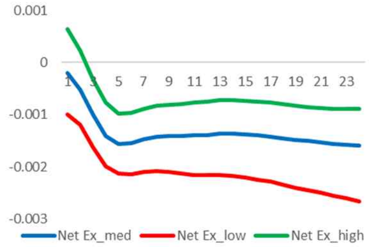
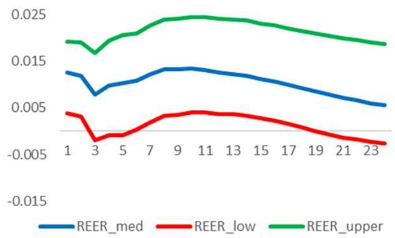
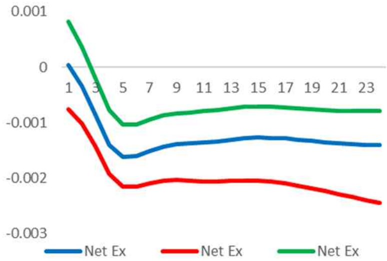
Productivity shock in the tradable goods sector lowers the relative price of tradable goods in relation to non−tradable goods, and then the price index of the US, P_{US}, in the above equation is higher when measured with the price of non−tradable goods. Since manufacturing ULC is the price of non−tradable goods, the US REER is expected to be higher when measured with ULC. Since higher REER means appreciation, the US REER is expected to appreciate strongly when measured with manufacturing ULC. The VAR model was simulated with three different indices, REER based on 1) CPI, 2) manufacturing CPI, and 3) manufacturing ULC. In all cases, the REER appreciate in response to productivity growth in the tradable sector, and the appreciation is strong when the REER is measured with manufacturing ULC, as shown in Figure 7. This is consistent with expectations.

Figure 7 Responses of aggregate US REER to productivity shock

<table>
<tr><td>REER based on CPI
(Baseline model)</td><td>
</td></tr>
<tr><td>REER based on manufacturing CPI</td><td>
</td></tr>
<tr><td>REER based on manufacturing Unit Labor Cost</td><td>
</td></tr>
</table>

Third, the PPI of manufactured goods which was used to measure the relative price of tradable goods in the baseline model, $\log\frac{PPI_{mf}}{CPI_{service}}$, was replaced by the price of investment goods. This study investigated productivity growth in the US manufacturing sector, accordingly, the relative price of manufactured goods is included as a variable. I narrowed down the manufacturing sector into an investment goods sector since there has been significant productivity progress in the US in the production of investment goods. The relative price of manufactured goods can then be replaced by the relative price of investment goods. The advances in information technology has been significant since the 1990s, and it has led to a dramatic decrease in the price of investment goods, according to Lian et al. (2020). The study documents that the relative price of overall investment goods fell by approximately 40% and the relative price of machinery and equipment decreased by approximately 55% relative to 1990. To be precise, the price of computing equipment decreased by 90% and of communication equipment by 60% during the same periods. The study explains that the fall in the prices are mainly due to productivity growth in the relevant sectors. Since the production of investment goods in the manufacturing sector experienced strong productivity growth, I conducted the robustness check in the investment goods sector. The relative price of manufactured goods, $\log\frac{PPI_{mf}}{CPI_{service}}$, was replaced by the relative price of investment goods, and it was represented by four indices 1) the relative price of investment goods, $\log RelP_{invst}$, 2) the PPI of investment goods over service CPI, $\log\frac{PPI_{invt}}{CPI_{service}}$, 3) the PPI of industrial commodities over service CPI, $\log\frac{PPI_{indst}}{CPI_{service}}$, and 4) the PPI of intermediate goods over service CPI, $\log\frac{PPI_{interm}}{CPI_{service}}$. All indices, $RelP_{invst}$, PPI_{invt} , PPI_{indst} , PPI_{interm} , and $CPI_{service}$, were downloaded from FRED. The simulation of the VAR model with the new indices depicts that the RER appreciates and net exports decrease in response to productivity shock. The results are shown in Figure 8.

Figure 8 Responses of US REER and net exports to productivity shock

Relative Price of investment goods	Response of REER	Response of net exports
$\log\frac{PPI_{mf}}{CPI_{service}}$ (baseline model)		
$\log Rel\,P_{invst}$		
$\log\frac{PPI_{invt}}{CPI_{service}}$		
$\log\frac{PPI_{indst}}{CPI_{service}}$		
$\log\frac{PPI_{interm}}{CPI_{service}}$		

The REER appreciates in all cases. The 16^{th} percentiles of responses remain above zero, except the results with $\log\frac{PPI_{invt}}{CPI_{service}}$, which means that the REER appreciates more than 84% of probability. In the case of $\log\frac{PPI_{invt}}{CPI_{service}}$, the 16^{th} percentile remains below zero, and then the appreciation is not statistically significant. Net exports decline in response to productivity shock and the results are statistically significant for all cases.

5. Conclusion

The impact of productivity shock on the RER has been widely studied, but previous literature is centered on theoretical modeling. Two models are mainly used in the literature: IRBC and HBS framework. Generally, traditional IRBC theory predicts short-run depreciation and the conventional HBS model anticipates long-run appreciation. However, the predictions for the movement of the RER are conflicting, even with the same model, and some studies propose that the theories do not hold. Since empirical studies are limited, the predictions of the models are not fully confirmed. Recent empirical studies document that the RER can appreciate in both the short-run and the long-run. However, these studies analyze shocks in large economies, such as US and EU, and examine aggregate impacts on the world economy.

This thesis investigated the effects of US productivity shock on 48 individual countries and found that the effects can differ across countries. This study estimated the responses of the RER and net exports with the VAR model, and found that the responses can vary across countries, depending on country characteristics with cross-country OLS. US productivity shock causes US aggregate RER to appreciate and aggregate net exports to decrease. However, bilateral movement of the RER and net exports are not uniform. In terms of the RER, US RER relative to a country appreciates if the country has high consumption home bias, strong trade ties with the US, or an economy more open to trade. In terms of trade, the decline in net exports results from the decrease in exports and the increase in imports. Exports decrease due to the appreciation in the US RER, and imports of intermediate goods increase. Nevertheless, US net exports increase to countries where the financial markets are more complete.

The widely accepted view of the traditional IRBC model is that productivity growth in a home country will benefit other countries since the relative price of home goods decreases, which results in depreciation in the home RER. Accordingly, net exports of the home country increase due to the depreciation in the home RER. However, this positive transmission was not witnessed in the data. The empirical results of this study show that aggregate US RER appreciates and net exports decrease. The rest of the world faces an increase in the price of US goods after productivity growth, and they have to import US products at higher price. In this respect, US productivity shock can have a negative transmission to the rest of the world. A country is likely to experience more appreciation in the US RER, namely depreciation in the RER of that country, from a US productivity shock if its consumption home bias is high, trade ties with the US is strong, or the economy is more open to trade.

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