Real exchange rate and international spillover effects of US technology shocks

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Abstract: The paper presents new empirical evidence on the international effects of surprise and anticipated technology shocks in the US. We employ the proxy-instrumental variable approach to identify structural vector autoregressions in a panel setting and empirically study the transmission of US technology innovations to the G7 countries. Both unanticipated and anticipated exogenous technology improvements lead to a strong and persistent real appreciation (from the point of view of the US), along with an expansionary effect on US macroeconomic aggregates, except for hours worked which initially decline. Internationally, there is a strong and precisely estimated positive spillover on foreign output, consumption, and hours worked in the case of surprise shocks, and a weaker but still mostly non-negative effect in the case of technology news shocks. We show that the empirical evidence is qualitatively compatible with the predictions of a New Keynesian international business cycle model with imperfect financial markets, traded and non-traded goods and imported intermediate inputs in production.

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1 Introduction

What are the effects of technology shocks in open economies with strong cross-border linkages? In this paper, we estimate structural vector autoregressions (VAR) using macroeconomic data on a panel of countries to uncover the dynamic effects of US technology shocks on the G7 countries (other than the US, henceforth called G6). We make two key contributions. First, we use recently developed proxy-instrumental variable methods to identify both unanticipated, or surprise shocks on US productivity, as well as anticipated shocks representing news of future technology improvement. We assess the effects of both shocks on a wide range of variables that are important for an understanding of the international transmission process of exogenous changes in productivity. Most importantly, we present evidence on the responses of real exchange rates and on the international transmission of shocks in the US on the other countries. Second, we show that most of the evidence is qualitatively consistent with a version of a New Keynesian international business cycle model, and show the influence of some key parameters on the ability of the model to generate empirically plausible results.

A growing recent literature analyzes open economy aspects of technology shocks with VAR models relying on different identification assumptions. However, so far there is substantial disagreement concerning the international transmission of technology shocks and their impact on real exchange rates. While some studies find that an exogenous unanticipated increase in productivity leads to a real appreciation (e.g., Enders et al., 2011, Corsetti et al., 2014), others provide evidence in favor of a real depreciation (e.g., Miyamoto and Lan Nguyen, 2017). Moreover, some studies find that surprise and anticipated technology shocks are associated with a different exchange rate behavior: appreciation following anticipated and depreciation following surprise technology shocks (e.g., Nam and Wang 2015, Levchenko and Pandalai-Nayar 2018).

We contribute to this debate using the proxy-instrumental variables (proxy-VAR for short) methodology (Stock and Watson, 2012, Mertens and Ravn, 2013) that identifies structural shocks through instrumental variables that are arguably correlated with a particular economic shock. In contrast to existing empirical identification approaches, this method has the advantage that neither controversial parameter restrictions, nor assumptions on the contribution of a shock to the forecast error variance of particular variables, nor a priori knowledge of the signs of impulse responses are required. Specifically, we use Fernald's (2014) series of utilization and markup adjusted total factor productivity (TFP) as an instrument that is arguably correlated with a surprise technology shock in the US. This variable is widely used to proxy technology shocks by other studies in closed economy contexts (e.g. Daly et al., 2017, Ramey, 2016, Garin et al., 2019), since it has the advantage that it eliminates endogenous movements in TFP due to non-technological shocks in the presence of variable factor utilization or markup changes. For the identification of anticipated or news shocks, we follow Miranda-Agrippino (2020) and Cascaldi-Garcia and

Vukotic (2020) and use the non-forecastable part of patent applications as an instrument. A key strength of the proxy-VAR method is that it bases identification on an observable instrument correlated with a particular shock, but does not require the instrument to be identical to the shocks themselves, giving robustness to some kinds of measurement error (Mertens and Ravn, 2013).

Our central novel finding is that both surprise and anticipated domestic technology shocks (we take the US to be the domestic economy, henceforth) lead to a strong and persistent real exchange rate appreciation. We argue that this common real exchange rate response to both types of technology shocks is in line with economic theory, as this is precisely what is predicted by standard New Keynesian two country models with imperfect financial markets, tradable and non-tradable goods and a price elasticity of tradable goods of the size of recent empirical estimates. Thus, the empirical effects of properly identified surprise and anticipated US technology shocks are not puzzling from a theoretical point of view.

The real appreciation result turns out to be highly robust to specification changes and is statistically precisely estimated. Furthermore, we find that both shocks lead to a real output increase both domestically and abroad. However, the positive output effect in the foreign economies is weaker than in the US, such that we observe generally positive but quantitatively limited international business cycle spillovers. Similar observations pertain to private consumption and investment. In the US, a surprise technology shock initially lowers hours worked, as predicted by sticky-price models. In the case of anticipated shocks, the productivity increase is delayed for several periods, while domestic consumption increases already on impact and domestic investment decreases in the short-run. It is noteworthy that the delayed productivity effect of the anticipated shock is not imposed a priori as an identification restriction, as in some of the previous papers discussed below, but is estimated in an unconstrained way, which lends credibility to the identification of the news shock by the instrument used. The foreign effects of anticipated US productivity shocks are generally weaker and less precisely estimated, though. Further, with a view on the transmission mechanism, we present evidence that US technology shocks tend to lower real (consumption based) domestic export prices, and at the same time increase the real prices of services that are likely to contain a large non-tradable component. We interpret this as evidence that technology shocks mainly originate from the traded sector of the US economy.

On the theoretical side, we demonstrate that a two-country New Keynesian business cycle model with capital accumulation, traded and non-traded goods and a productive role for imported intermediate inputs is capable of explaining most of the empirical results if technology shocks take place in the sector producing tradable goods. It is well known that the relation between relative consumption and the real exchange rate appears puzzling from the point of view of many simple models. In particular, if there are perfect international markets and assuming that utility is logarithmic in consumption, then efficient international risk sharing implies that relative (domestic to foreign) consumption and the real exchange rate should be proportional. If a productivity shock raises consumption at home, under efficient financial markets this would be accompanied by a home real depreciation such that foreigners are compensated through a positive wealth effect (see Corsetti et al., 2008, for a more detailed discussion). Empirically, our results in line with several previous studies suggest that domestic productivity improvements increase home consumption both absolutely and relatively to the rest of the world, but also tend to lead to a home real appreciation, contrary to the prediction of efficient risk sharing models.

However, under imperfect financial markets it is well known to be possible that a home relative consumption increase and a domestic real appreciation are equilibrium responses to a productivity shock. We show that this outcome is indeed compatible with our model if some key parameter restrictions are fulfilled, in particular a relatively high but empirically realistic price elasticity of tradable goods and complementarity between non-traded and traded goods. Given these, the model's prediction that domestic productivity increases coincide with consumption increases and a real appreciation is well in line with the empirical findings. Moreover the model implies that the productivity improvement leads to an initial employment decline at home together with productivity and employment increases abroad, and a positive response of foreign output, consumption, and investment, and a decline in domestic tradable prices associated with an increase in non-tradable prices, much as we find empirically.

Related literature. The paper is related to various strands of literature. A number of papers have empirically analyzed the effect of unanticipated technology shocks on the real exchange rate, with conflicting results. The result of a real appreciation following a favorable domestic technology innovation that we find using proxy-instrumental variables is also found by Enders et al. (2011) and Corsetti et al. (2014) using sign-restricted VARs. In contrast, Nam and Wang (2015) find a real depreciation of the US currency relative to an aggregate of other countries, and both Levchenko and Pandalai-Nayar (2018) and Miyamoto and Lan Nguyen (2017) report a real exchange rate or terms-of-trade depreciation of the US vis-a-vis Canada. The former two papers assume that a surprise technology shock can be identified as the contemporaneous residual of TFP in a reduced form VAR, and the latter uses the long-run restriction that only US technology affects domestic labor productivity in the long run and the short-run restriction that the US is recursively exogenous with respect to Canadian shocks. Compared to these papers, ours is complementary in that it uses the proxy-instrumental variables method as an alternative identification scheme, and in considering a broad set of empirical macro variables for the panel of G7 countries that comprise several of the largest trading partners of the US.[3] News shocks have originally been discussed in closed-economy contexts (Beaudry and Portier, 2006, Barsky and Sims, 2011, Schmitt-Grohe and Uribe, 2012). The open economy dimension of anticipated shocks

[3]In a related paper, Rüth (2020) also uses external instruments to investigate the Dornbusch exchange rate overshooting hypothesis.

has recently been explored by Kamber et al. (2017), Nam and Wang (2015), and Levchenko and Pandalai-Nayar (2018). The first of these uses a combination of a short-run zero restriction on TFP and sign restrictions to identify anticipated shocks, but does not look at real exchange rates. The latter two papers identify an anticipated technological shock as the one that maximizes the forecast error variance of TFP over a fixed horizon, as in Barsky and Sims (2011), and find a domestic real appreciation after positive technology news. In contrast to these studies, the patent based indicator of anticipated technological change that we use in the present paper as an instrumental variable allows us to identify news shocks without restricting the short-run or long-run response of productivity a priori.

Concerning the international spillovers of technological shocks, Miyamoto and Lan Nguyen (2017) and Levchenko and Pandalai-Nayar (2018) find positive effects of US shocks on Canadian output, and Kamber et al. (2017) find similar results with respect to three further countries. Corsetti et al. (2014) and Nam and Wang (2015) estimate an increase in relative output in the US relative to an aggregate of other countries following a positive US technology shock, but do not report how the relative response is distributed between the actual output levels of both countries or aggregates. In the present paper, in contrast, we report the responses of domestic and foreign output levels, as well as those of other macroeconomic aggregates and international relative price measures, for both the US and the G6 panel of foreign economies.

The rest of the paper is organized as follows. Section 2 contains the empirical results. We explain the empirical method in Section 2.1, discuss the data used in Section 2.2, and present results in Section 2.3. Section 3 introduces the theoretical model, Section 4 shows the model impulse responses and compares them to the empirical evidence, whereupon Section 5 concludes.

2 Empirical effects of US technology shocks

In this section, we describe the method used to identify surprise and anticipated technology shocks, outline the estimation of the transmission process, and discuss the data definitions and the econometric specification used to produce the empirical results.

2.1 Econometric method

We aim at identifying the structural impulse responses of US and foreign macro variables to US technology shocks. To this end, we estimate a series of two-country VAR models, where one country is always the US and the other country is one out of the G7 countries other than the US (i.e. Canada, France, Germany, Italy, Japan, and the UK), and constrain the parameters governing impulse responses to be the same across the different VAR models. This amounts to assuming that the transmission of US technology shocks is the same for all of the non-US G7 countries (labelled the G6), which allows to use the panel dimension of the data to enlarge the degrees of freedom in the estimation. As a robustness check, we also compare the results to those obtained by estimating separate unconstrained two-country VARs or by dropping any one country from the panel to rule out that a single country dominates the results.

Let $x_{i,t}$ be a $K \times 1$ vectors of variables to be analyzed in the VAR, with data available for periods $t = 1, ..., T$ with T the sample size. The number $k_1 < K$ variables in $x_{i,t}$ pertain to the US, whereas $k_2 = K - k_1$ variables pertain to the i-th of the other countries, $i = 1, \ldots, N$ (where $N = 6$ for the G7 countries other than the US). Denoting the $k_1 \times 1$ vector of US variables by $y_t^{(US)}$ and the $k_2 \times 1$ vector of the i-th other country's variables by $y_t^{(i)}$, we have

$$x_{i,t} = \left(\left(y_t^{(US)} \right)', \left(y_t^{(i)} \right)' \right)'.$$

Note that the US component of the variable vector $x_{i,t}$ is the same for all i. We first estimate reduced form VAR models

$$x_{i,t} = c_i + \sum_{j=1}^{p} A_j x_{i,t-j} + u_{i,t},$$

where the A_j are $K \times K$ parameter matrices on lagged variables that are constrained to be the same across countries i, the c_i are $K \times 1$ vectors of constant parameters that are allowed to differ across countries to account for country heterogeneity arising from institutional settings and policy frameworks, and the $u_{i,t}$ are $K \times 1$ vectors containing the reduced form shocks.

More precisely, let $z_{i,t-1}$ be the $pK \times 1$ vector that collects p lags of the variables in $x_{i,t}$, defined as $z_{i,t-1} = (x'_{i,t-1}, \ldots, x'_{i,t-p})'$. The reduced form VAR model is

$$x_{i,t} = c_i + A z_{i,t-1} + u_{i,t}, \qquad i = 1, \ldots, N,$$

where $A = (A_1, ..., A_p)$ is the $K \times pK$ matrix of lag parameters. Define

$$\underset{(K \times T-p)}{X_i} = (x_{i,p+1}, \ldots, x_{i,T}), \qquad \underset{(K \times N(T-p))}{X} = (X_i, \ldots, X_N),$$
$$\underset{(pK \times T-p)}{Z_i} = (z_{i,0}, \ldots, z_{i,T-1}), \qquad \underset{(pK \times N(T-p))}{Z} = (Z_i, \ldots, Z_N),$$

and to allow for cross-sectionally different constants, define $D = I_N \otimes \mathbf{1}'_{T-p}$ where I_N is the N-dimensional identity matrix and $\mathbf{1}_{T-p}$ is a column vector of ones of length $T - p$. Denoting $\widetilde{Z} = (D', Z')'$, the least squares estimate is

$$(\widehat{c}_1, \ldots, \widehat{c}_{N,} \widehat{A}) = X \widetilde{Z}' \left(\widetilde{Z} \widetilde{Z}' \right)^{-1},$$

and the reduced form residual matrix is $\widehat{U} = (X - \widehat{A}\widetilde{Z})'$, where each column contains the time series of residuals for one of the K equations, with the N country specific residual time series vertically stacked.

The corresponding structural model is

$$B^{-1} x_{i,t} = B^{-1} c_i + \sum_{j=1}^{p} B^{-1} A_j x_{i,t-j} + e_{i,t},$$

where B is a parameter matrix and $e_{i,t} = B^{-1} u_{i,t}$ is the vector of structural, economically interpretable *i.i.d.* shocks assumed to be mutually uncorrelated having a diagonal covariance matrix $E(e_{i,t}e'_{i,t}) = \Omega$. Knowledge of B would allow to identify the structural impulse responses that are given by the coefficients of the structural vector moving average

$$x_{i,t} = \sum_{h=0}^{\infty} R_h B e_{i,t-h},$$

where R_h contains the reduced form vector moving average matrices that can be estimated by inverting the reduced form autoregressive lag polynomial $(I_K - A_1L - ... - A_pL^p)$ using the estimates of A_j, $j = 1, ..., p$, with L being the lag operator and I_K the K-dimensional identity matrix; note that $R_0 = I_K$ by construction, such that each column of B contains the contemporaneous or impact effect of a particular structural shock.

Since

$$Be_{i,t} = u_{i,t}, \tag{1}$$

the identification problem consists of the well-known problem that while the reduced form residuals $u_{i,t}$ and their covariance matrix can easily be estimated as above, this does not suffice to pin down the structural mutually uncorrelated shocks $e_{i,t}$ and their impact matrix B. Here, we follow Stock and Watson (2012, 2018) and Mertens and Ravn (2013) and use external instruments to identify columns of B of particular interest, which is the so-called proxy-VAR approach.

In particular, we are interested in identifying the impulse responses to a surprise US technology shock and an anticipated US technology (or news) shock. Suppose (for expositional ease and without loss of generality) that the surprise shock is the first element in $e_{i,t}$. Further, suppose there is a proxy-instrument z_t^S available (where the superscript S is for surprise) that is correlated with a surprise US technology shock but not with other shocks, such that

$$E\left(z_t^S e_{i,t}^{(1)}\right) = a \neq 0 \;\text{ and } E\left(z_t^S e_{i,t}^{(k)}\right) = 0 \quad \text{for } k = 2, ..., K,\; i = 1, ..., N, \tag{2}$$

where $e_{i,t}^{(k)}$ denotes the k-th element in $e_{i,t}$. From (1), it follows that $E(z_t^S u_{i,t}) = BE(z_t^S e_{i,t}) = B_1 a$, where B_1 denotes the first column of B, the k-th element of which will be denoted $B_1^{(k)}$. Consequently,

$$\frac{B_1^{(k)}}{B_1^{(1)}} = \frac{E\left(z_t^S u_{i,t}^{(k)}\right)}{E\left(z_t^S u_{i,t}^{(1)}\right)},$$

where $u_{i,t}^{(k)}$ is the k-th element in $u_{i,t}$. Hence, instrumental variable (IV) regressions of the estimate of $u_{i,t}^{(k)}$ on the one of $u_{i,t}^{(1)}$ using $\mathbf{1}_N \otimes z_t^S$ as the instrument (where $\mathbf{1}_N$ is an $N \times 1$ vector of ones) identifies the elements of B_1 *relatively* to the first element $B_1^{(1)}$.

For an anticipated US technology shock, if there is a proxy-instrument z_t^A (where the superscript A is for anticipated) that is correlated only with the US technology news shock, the procedure described above can be used to identify the relative coefficients in another column of the impact matrix, say B_2. Empirically (as described further below) the instrument

z_t^A is available only for a shorter sample period (1982q2 to 2014q4) than the other variables (which range from 1973q1 to 2019q1). Thus, in estimating the relative B_2 coefficients, we use only the part of the reduced form residuals pertaining to this shortened sample period. It is a general feature of proxy-VAR methods that the estimation sample for the reduced form VAR and the B_2 parameters can differ, and Stock and Watson (2018) show that when the instrument is available only for a shorter time period using the longer sample for the VAR estimation improves estimation efficiency. For both shocks, we check the strength of the instruments through first stage F tests.

Since the IV regression only identifies the relative elements of B_1 or B_2, this so far only identifies the structural impulse responses (which depend on the actual values of the respective column of B) up to scale and sign. Stock and Watson (2012, 2018) solve this by normalizing e.g. $B_1^{(1)} = 1$, meaning that the identified shock has a unit impact effect on the first variable. However, other normalizations are possible as well, as pointed out by Paul (2020), such as a particular size of the impact effect on any other variable, or a normalization of the size of a peak effect over the estimated impulse response. We will use different normalizations below. Importantly, while normalizations just shift the impulse responses in scale and sign leaving their properties unchanged (both over time and cross-sectionally), one has to take care to incorporate the particular normalization chosen when computing standard errors. Following the advice of Stock and Watson (2018), we do this by applying the same normalization inside of each repetition of the bootstrap procedure used to construct confidence bands.

Specifically, we use the moving blocks bootstrap that has recently been recommended by Jentsch and Lunsford (2018) for proxy-VARs in order to appropriately take into account the uncertainty about the relation between the structural shocks and the instruments and thus to obtain consistent confidence bands. We follow Jentsch and Lunsford (2018) and use as block length $\kappa T^{1/4}$ rounded to the next integer, where $\kappa = 5.03$ and T is the sample size, which for our baseline specification results in a block length of 19. The confidence bands reported below are based on 10,000 bootstrap repetitions.

2.2 Data and specification

We use quarterly macroeconomic data on the G7 countries for the flexible exchange rate era from 1973q1 to 2019q1, the last period available for all series. Series which are originally at a higher frequency (like prices and exchange rates) are converted to quarterly averages. Most data series are from the St. Louis Fed database (FRED) or the OECD quarterly national accounts; Appendix A1.1 gives full details on data sources and definitions. Throughout, we keep a core set of variables that allows to study the central aspects of the domestic and international repercussions of US technology shocks, and then augment the VAR models with different sets of additional variables to address specific questions.

The core variable set includes as US variables $y_t^{(US)}$ the log of labor productivity measured as real GDP per hours worked in the nonfarm business sector, the logs of real GDP, real private consumption and real domestic investment, and the level of stock prices measured by the NASDAQ composite index. The choice of variables is motivated by including the main macroeconomic aggregates and variables that are expected to most directly respond to technology shocks. In particular, labor productivity should be strongly affected by a current (surprise) technology change, whereas anticipated technology shocks that have no immediate but only a delayed effect on productivity should be foreshadowed in stock price movements, in particular of those firms that develop or use advanced technologies, many of which are listed in the NASDAQ index.[4] Related studies explicitly refer to the idea that stock price movements reflect the market's expectation of future developments in the economy and are thus useful for identifying news shocks. For example, Beaudry and Portier (2006) use the strong correlation between stock returns and future productivity growth rates to identify anticipated changes in productivity. Note that by including labor productivity and GDP, hours worked are of course implicitly represented in the VAR and their shock response can be read off as the difference between the impulse responses of GDP and labor productivity (for clarity, we explicitly show the hours response in one of the specifications below).

For the foreign variables $y_t^{(i)}$, we include for each of the G6 countries the logarithm of the bilateral real exchange rate relatively to the US, and G6 output measured as each country's level of real GDP in logs. The real exchange rate is measured as the log of the ratio of the bilateral nominal exchange rate (the price of a G6 currency unit in US dollars) times the foreign country's consumer price index (CPI) over the US CPI, such that a decrease in the series is a real appreciation of the US dollar with respect to the foreign country. We use the term appreciation or depreciation consistently from the perspective of the US henceforth. The core set of variables is thus $CORE = \{$US productivity, US output, US consumption, US investment, US stock prices, G6 real exchange rates, G6 output$\}$.

The reduced form VAR is estimated with four lags of each variable and country specific constant terms. To identify US technology shocks, we use the proxy-instrumental variable technique described above. For the surprise shock, we use as z_t^S Fernald's (2014) series on the growth rate of utilization and markup adjusted total factor productivity in the US, which is widely used as a proxy for technology shocks in the literature, e.g. Stock and Watson (2012), Daly et al. (2017), Ramey (2016) or Garin et al. (2019). While less sophisticated measures of TFP (like simple Solow residuals) would endogenously respond to the business cycle due to possibly time-varying capacity utilization or cyclical price-cost markups, Fernald (2014) carefully eliminates these sources of endogenous movements such that his resulting purified TFP series can be understood as solely reflecting exogenous technology variations. Indeed, Garin et al. (2019) shows that the adjusted TFP series

[4] Because our patent based news instrument is more directly linked to the industrial sector, we prefer to work with the NASDAQ index compared to the S&P 500. In fact, the latter also includes companies operating in the financial sector which might act as confounding entities, especially during times of severe financial disruptions like the financial crisis of 2007-2008. Nevertheless, our main results are robust to including the S&P 500 index instead of the NASDAQ index in the VARs.

cannot be predicted by other macroeconomic shock measures, like monetary, fiscal, and oil price innovations.

For the anticipated technology shock, we us as z_t^A a series based on forecast-adjusted US patent applications constructed following Miranda-Agrippino et al. (2020); for the identification of anticipated technology shocks based on patent applications see also Cascaldi-Garcia and Vukotic (2020). The underlying idea is that the protection granted to new inventions through the patenting system constitutes a powerful incentive to file appropriate applications before they are diffused and commercialized. Hence, patent applications at any point in time embed a signal about potential future technology changes. To account for potential endogeneity issues, we explicitly control for several factors when constructing the instrument. In particular, we closely follow Miranda-Agrippino et al. (2020) and construct z_t^A as the growth rate of patent applications that is unforecastable from its own lags and forecasts from the Survey of Professional Forecasters (SPF). Specifically, we recover the instrument for identification of anticipated technology shocks using the residuals of the regression

$$pa_t = c + \sum_{j=1}^{4} \gamma_j pa_{t-j} + x_t'\beta + \varepsilon_t, \tag{3}$$

where pa_t is the quarterly growth rate of all utility patent applications in quarter t, c is a constant, ε_t is a stochastic disturbance, γ and β are parameters, and x_t is a vector of control variables containing the one quarter and one year forecasts for real output growth, the unemployment rate, inflation (based on the GDP deflator), real federal government spending, real non-residential investment, and real corporate profits net of taxes from the SPF.[5] By controlling for professional forecasts, the instrument is orthogonal to forecastable future macroeconomic developments that could also influence patent applications. Importantly, the patent data are unavailable to forecasters at the time the forecast is made, such that the residual captures only the new information conveyed by the patent applications.[6] The instrument z_t^A for the anticipated technology shock is thus the OLS residual of (3). Due to the availability of the patent applications series, the regression can be estimated for the period 1982q2 - 2014q4, such that the instrument z_t^A is restricted to this sample range.

It is important to notice that both for surprise and anticipated US technology shocks, the instruments appear to be strong, as judged by the first stage F statistic. As shown in Table 1, in both cases the respective values are well above 10, suggesting that weak instruments are unlikely to be a concern for the analysis.

[5]Miranda-Agrippino et al. (2020) also use narrative tax and monetary policy shocks in x_t, using the measures by Romer and Romer (2004, 2010) and Mertens and Ravn (2012). We do not use these as this would require shortening the available series for the instrument to end in 2006. However, we verified that all of the results reported below are robust to including these additional controls.

[6]Miranda-Aggripino et al. (2020, p. 10) confirm that "because of the release schedule of the SPF, the information set conditional on which forecasts are made is in fact relative to the previous quarter; hence, the collection of forecasts ... captures pre-existing beliefs about the macroeconomic outlook."

	Surprise technology shock	Anticipated technology shock
First stage F statistic	821.48	17.34
Sample	1973q1 - 2019q1	1982q1 - 2014q4

Table 1: Instrument relevance

2.3 Empirical results

2.3.1 Key results

Figure 1 shows impulse responses to a surprise US technology shock for a specification consisting of the core variables plus G6 real private consumption and investment, together with bootstrapped 68 % (dark shaded areas) and 90 % (light shaded areas) confidence intervals obtained from 10,000 bootstrap repetitions. We normalize the scale of the shock such that it increases US labor productivity by one percent in the impact period.

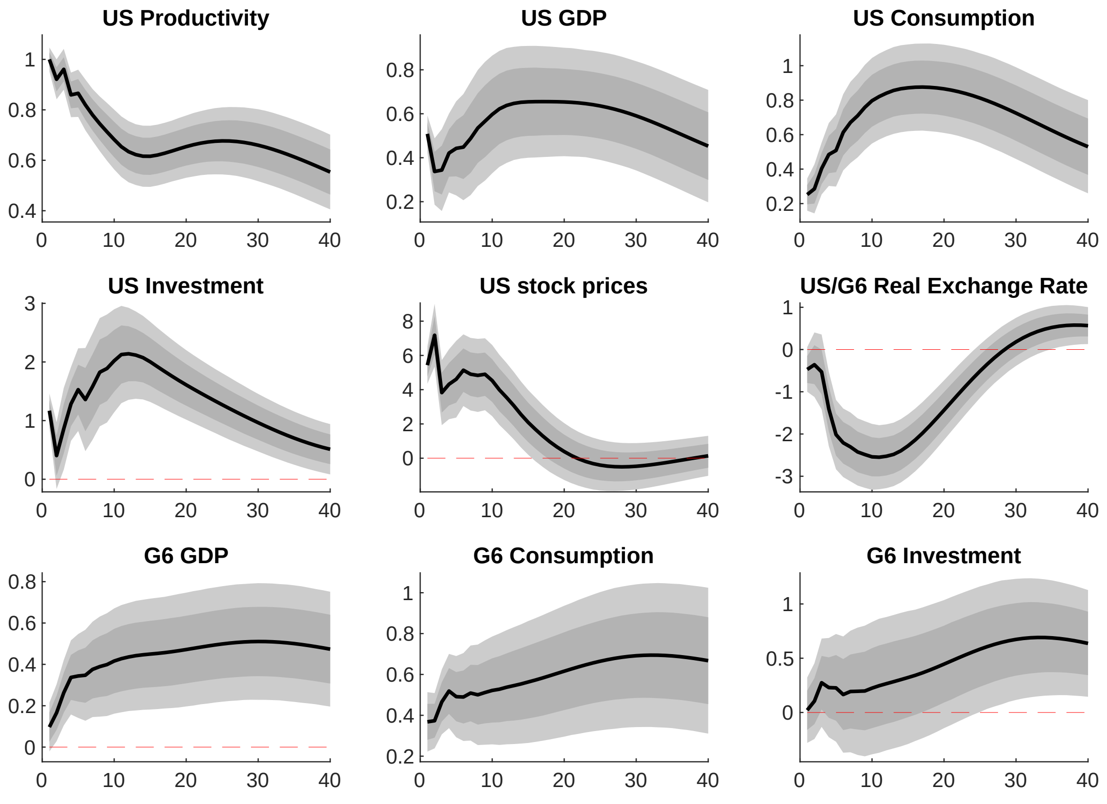


Figure 1: Baseline results. Surprise technology shock.

Notes: Solid lines show point estimates. Shaded areas indicate 68% and 90% bootstrapped confidence intervals. The unit of the horizonal axis is a quarter and the sample is 1973q1-2019q1.

US labor productivity increases significantly and persistently after the surprise technology shock. The strongest effect materializes already in the impact period, after which productivity slowly returns to normal, with the response remaining highly significant for all periods of the impulse response horizon. Moreover, the shock leads to a significant increase in US real and financial variables. In particular, the productivity improvement raises GDP on impact and along the impulse response with a hump-shaped pattern that reaches a maximum after around four years. Private consumption and investment follow the same pattern, with a quantitatively much larger response of investment. Stock prices strongly jump upwards already on impact, and the response remains statistically significantly different from zero for about the first four years after the shock. Note that since GDP rises less than productivity, the implied response of hours worked is negative. Thus, while the positive effect of a technology improvement on consumption and investment is in line with standard models of the real business cycle variety, the negative hours reaction is not. However, the latter is predicted by sticky-price models of the New Keynesian variant, as will be further discussed below in the context of Figure 6.

Of particular interest for our research question is the real exchange rate response. Figure 1 shows that the real exchange rate strongly appreciates, with a statistically insignificant response in the first few quarters but followed by a strong, highly significant hump-shaped negative reaction afterwards. The maximum decline occurs around three years after the shock hits the economy. This real appreciation is actually an extremely robust result, and also holds with little change in all modified VAR models reported in the next subsection.

The strong real appreciation following an exogenous productivity improvement is one of our central results. It runs counter to the intuition of many standard theoretical models, since it implies that the increased home goods supply through a positive technology shock comes with an increase of the relative price of the home consumption basket relatively to the foreign one. A similar empirical finding has been reported in some of the previous literature (e.g. Corsetti et al., 2008, Enders et al. 2011). However, these studies do not differentiate between surprise and anticipated technology shocks, and the identification assumptions are different. These authors also point out that the combination of a real appreciation with a consumption increase in the home economy is often interpreted as evidence against internationally complete financial markets. The reason is that the risk sharing condition implied by financial market completeness would suggest that a real appreciation would have to be accompanied by a larger decline in the home marginal utility of consumption compared to foreign, which with standard preferences should entail a lower consumption increase at home than in the foreign economy.

The latter does not seem to be the case, however, as the responses of the foreign economies shown in Figure 1 display markedly positive but quantitatively limited international spillovers. Foreign GDP, private consumption and investment all rise significantly after an unanticipated US technology improvement (though the foreign investment response is significantly different from zero only later in the adjustment process), but generally less so than their US counterparts. As a consequence, the negative conditional comovement between domestic consumption and the real exchange rate is puzzling, at least at first sight. This finding is also related to the observation by Backus and Smith (1993) that the often observed unconditionally non-positive correlation between consumption and the real exchange rate is not easily compatible with a complete financial markets setting. Moreover, as discussed in Enders and Müller (2009), even with financial market incompleteness the evidence for negative consumption - real exchange rate comovements has been found difficult to reconcile with the predictions by standard business cycle models. Corsetti et al. (2008) point out that, depending on the elasticity of international demand for domestic goods, it is possible to rationalize this finding within models of incomplete financial markets, though for some variants with the implication that the international spillovers from a domestic productivity increase are negative. As the impulse responses in Figure 1 show, however, empirically there is a strong positive spillover effect on the foreign economies, where output, consumption and investment all rise after a US productivity increase. In the theoretical model section below, we take this point up and present a model that simultaneously explains why a home technology improvement can lead to a real appreciation combined with positive international spillovers, specifically a strong home consumption increase and a weaker but positive foreign consumption and output increase.

Figure 2 shows the impulse responses in the same specification for an anticipated US technology shock. Since in this case the impact period pertains to the time when a future technology improvement is first reflected in new patent applications (as opposed to the time when the improvement is actually implemented), the anticipated shock does not necessarily have any non-zero effect on productivity on impact. However, the future change in technology should be foreshadowed in forward looking variables like stock prices. Therefore, to get comparability between the two sets of impulse responses, we choose a different normalization and scale the anticipated shock such that it produces the same impact response on stock prices as the surprise shock.

Figure 2 shows that an anticipated technology shock, in the sense of increased expectations of future US technology improvements, has a delayed positive effect on US productivity which becomes statistically significantly positive about three years after the shock. In other words, the identified news shock implies a slow diffusion of new technologies to the economy which boosts labor productivity only with a substantial lag.[7] The productivity response makes intuitive sense and coincides with the dynamics obtained when simulating an anticipated technology shock in many DSGE models. Importantly, the empirical responses are obtained only by assuming that the instrument is informative about technology news, and not by imposing restrictions on the impact response of productivity, or the pattern of diffusion of technology, or on the share of the variance that is accounted for by the identified shock as in the method by Barsky and Sims (2011) (see section 2.3.4 for further discussion).[8]

[7] Miranda-Agrippino et al. (2020) and Cascaldi-Garcia and Vukotic (2020) find a similar productivity response pattern.

[8] Below, in Section 2.3.3 we show that the fall in labor productivity in the first two years following the anticipated technology shock is due to a relatively strong increase in hours worked that outweighs the positive GDP response. As a robustness check, we estimate the same VAR but replace labor productivity with unadjusted total factor productivity. It turns out that the diffusion to total factor productivity is much faster implying a significant positive response of total factor productivity already one year after the shock

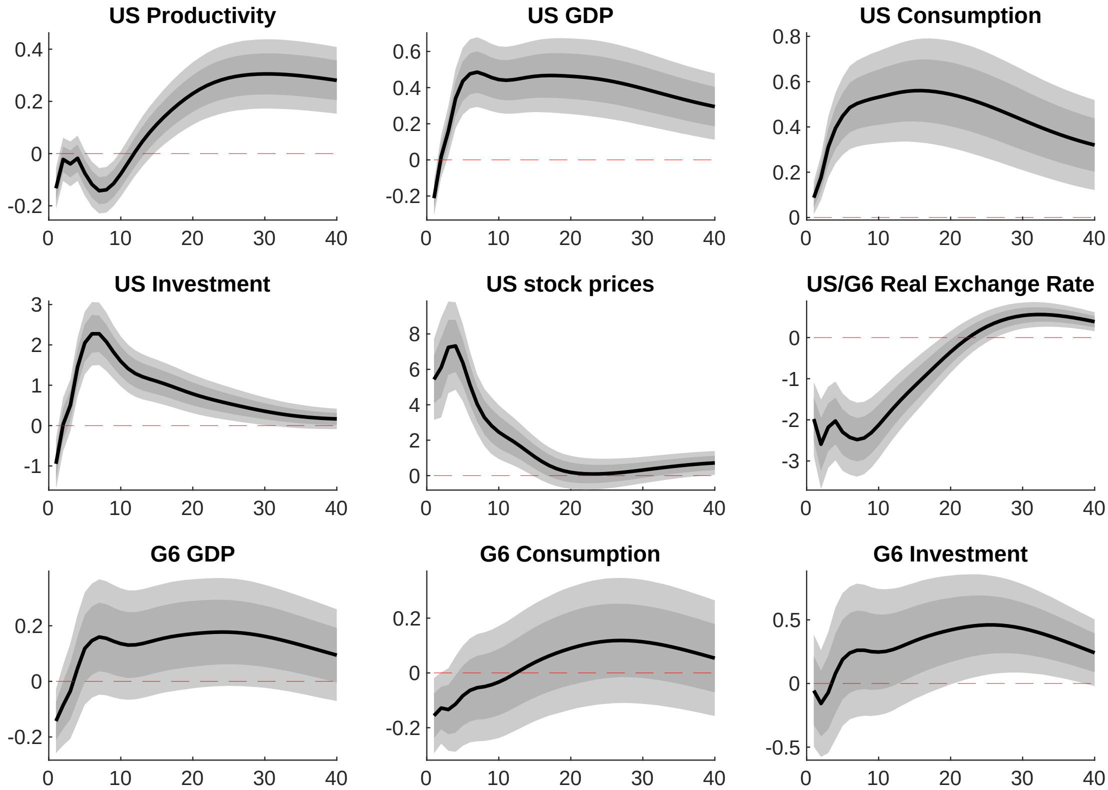


Figure 2: Baseline results. Anticipated technology shock.

Notes: Solid lines show point estimates. Shaded areas indicate 68% and 90% bootstrapped confidence intervals. The unit of the horizonal axis is a quarter and the sample is 1973q1-2019q1.

The technology news shock has strong expansionary effects on the US economy. Similar to the productivity response, GDP and investment increase in a delayed manner, with initial reactions very slightly negative. The initially weak private consumption increase is borderline significant at the 90% confidence level. After a delay of several quarters, all of the aforementioned variables show a persistent positive hump-shaped reaction with peak responses after around two years for investment and after around five years for GDP and consumption, respectively. In contrast, US stock prices increase immediately, and also the real exchange rate strongly and significantly appreciates already on impact, which suggests that financial markets respond more quickly to news about future technology than the real economy. Thus, we find that both technology shocks lead to a strong and persistent real exchange rate appreciation in stark contrast to the recent literature which based on other identification strategies provides evidence for a shock-dependent exchange rate response (see Nam and Wang 2015, Levchenko and Pandalai-Nayar 2018, and the discussion in section 2.3.4).

The response of most of the US variables is well in line with the theoretical intuition from standard models. Since the shock signals future profit opportunities for US firms, households anticipate higher future wealth and start consuming more, whereas output, investment and,

materialized. Importantly, all remaining results are very similar to our baseline specification with labor productivity. In addition, the responses to a surprise technology shock are also comparable to our baseline estimates when replacing labor productivity by unadjusted total factor productivity (see Figure A4).

in particular, actual labor productivity lag behind. The delayed productivity increase is the hallmark of models of news shocks, which underlines the credibility of the empirical identification of this shock. The same is true for stock prices, which surge immediately due to the increased expectations of higher future firm profits.

Similar to the estimates concerning the surprise technology shock, the news shock also induces positive international spillovers. In particular, the point estimate of the response of foreign output qualitatively mirrors the one seen for the US, in that there is a delayed and hump-shaped increase that follows an initially weak and slightly negative reaction. However, the foreign GDP response is mostly insignificant at the 90% level and only the peak response attains significance at the 68% level. The response of foreign private consumption is altogether insignificant, while foreign investment shows a partly significant increase. The relative size of the point estimates of the foreign responses is generally considerably smaller compared to the domestic responses, and the peak increase of foreign GDP is only about half as large as the one of US GDP. Thus, just as was the case for surprise shocks, also anticipated US technology shocks appear to have their strongest effect domestically. International spillovers appear weaker and less precisely estimated for the anticipated shock; however, there is scarcely any evidence for negative foreign responses to US surprise and anticipated technology shocks.

Surprise technology shock

	US Prod.	US GDP	US Cons.	US Inv.	US SP	US/G6 RER	G6 GDP	G6 Cons.	G6 Inv.
$h = 0$	0.95	0.18	0.05	0.05	0.09	*0.00*	*0.00*	0.05	*0.00*
$h = 4$	0.72	0.06	0.07	0.02	0.07	0.02	0.02	0.06	*0.00*
$h = 8$	0.55	0.06	0.09	0.03	0.08	0.04	0.02	0.05	*0.00*
$h = 16$	0.53	0.08	0.13	0.07	0.07	0.08	0.03	0.05	*0.00*
$h = 24$	0.51	0.10	0.15	0.09	0.07	0.08	0.04	0.06	*0.01*
$h = 40$	0.43	0.10	0.15	0.10	0.06	0.08	0.05	0.07	*0.01*

Anticipated technology shock

	US Prod.	US GDP	US Cons.	US Inv.	US SP	US/G6 RER	G6 GDP	G6 Cons.	G6 Inv.
$h = 0$	0.07	0.12	*0.03*	*0.13*	0.37	0.22	*0.03*	*0.03*	*0.00*
$h = 4$	0.02	0.10	0.16	0.11	0.41	0.23	*0.01*	*0.02*	*0.00*
$h = 8$	0.03	0.15	0.20	0.19	0.35	0.29	*0.01*	*0.01*	*0.01*
$h = 16$	0.04	0.18	0.24	0.21	0.28	0.28	*0.01*	*0.00*	*0.01*
$h = 24$	0.10	0.21	0.26	0.22	0.26	0.26	*0.02*	*0.01*	*0.02*
$h = 40$	0.18	0.20	0.23	0.20	0.23	0.26	*0.02*	*0.01*	*0.03*

Table 2: Forecast error variance decomposition.

Notes: Entries in italics are statistically insignificantly different from zero at the 90% level..

While Figures 1 and 2 show the dynamic responses to surprise and anticipated US technology shocks, they do not allow for a quantitative statement about how important both shocks are in driving US and international variables. Therefore, Table 2 reports the forecast error variance (FEV) decomposition of the nine variables in our benchmark VAR model at various horizons. The upper panel presents the share of the FEV attributable to the surprise technology shock and the lower panel the respective share to the anticipated shock. Entries in italics are statistically insignificantly different from zero at the 90% level.[9] In line with theoretical predictions, we find that the surprise technology shock explains a large share of the FEV of US labor productivity in the very short run, whereas for the anticipated shock the share increases along the forecast horizon. In the long run, the anticipated shock explains about 18% of US labor productivity, which is comparable to the results reported in Miranda-Agrippino et al. (2020).[10] It is, however, much less than what is reported by Nam and Wang (2015), who find that almost 60% of movements in US productivity are due to anticipated technology shocks, and that surprise and anticipated shocks together account for almost 90% of fluctuations in US productivity at long horizons. In contrast, our findings imply that both technology shocks combined explain around 60% of long-run changes in US productivity, which suggests that other shocks, such as demand, monetary and fiscal policy, or financial market shocks, can make significant contributions to long-run productivity fluctuations. These differences are due to the different identification method used in Nam and Wang (2015) and other studies which rely on the method by Barsky and Sims (2011) to identify anticipated shocks (see section 2.3.4 for a detailed comparison).

The surprise technology shock explains a large share of the FEV of US GDP at short horizons. In contrast, the share of the FEV of US GDP due to the anticipated technology shock steadily increases with the forecast horizon. The surprise technology shock accounts for 18% of US GDP fluctuations in the very short run, whereas around 20% of movements in US GDP in the long run are due to anticipated shocks. Further, a sizeable share of the variance of stock prices is due to anticipated technology shocks. This finding supports the idea that forward-looking variables, like stock prices, react immediately to news about future economic developments and with a diminishing effect over time. Importantly, at all horizons the anticipated shock explains a larger share in the FEV of the real exchange rate than the surprise shock, very much in line with the findings by Nam and Wang (2015). Moreover, this result lends support to the hypothesis that exchange rate volatility is mainly attributed to changes in expectations about future economic fundamentals rather than changes in current fundamentals (e.g., Engel and West, 2005). In total, the identified surprise and anticipated technology shocks together account for around 35% of the FEV of the US/G6 real exchange rate at the very long horizon. Turning to the G6 economies, we find that both technology shocks explain a relatively small share of the FEV in real

[9] The construction of the FEV decomposition follows Montiel Olea et al. (2020).

[10] Miranda-Agrippino et al. (2020) use the utilization-adjusted Fernald (2014) TFP measure in their baseline VAR and find that anticipated technology shocks, identified through a patent instrument, account for around 10% of productivity fluctuations at the very low frequency.

variables. When aggregating, surprise and anticipated US technology shocks account for 7% of long-run GDP fluctuations in the G6 countries.

2.3.2 Robustness

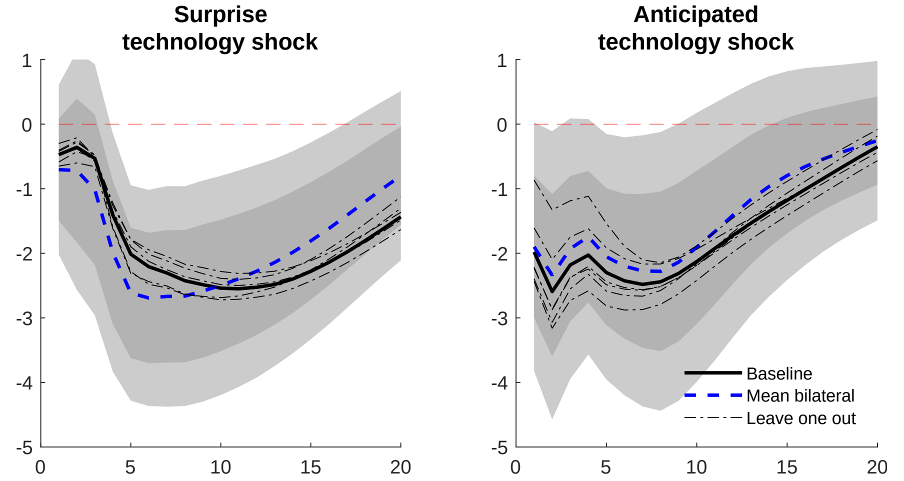
In this section, we demonstrate in how far the central result of real appreciation due to both shocks is robust to several modifications of the baseline model. In particular, we show that the result is not driven by the sample weight of a particular influential single country, and demonstrate that a domestic real exchange rate appreciation is present vis-a-vis each individual G6 country when estimating separate bilateral VARs (thus abstaining from using the panel dimension of the data). Moreover, we check for the possibility of internationally correlated technology shocks, and briefly discuss other robustness checks.

Country heterogeneity. We first note that our results are not driven by the sample weight of a particularly influential single country. To demonstrate this, the upper part of Figure 3 compares the impulse responses for real exchange rates for several alternative setups. The solid lines repeat the baseline case, i.e. the responses from Figures 1 and 2, where where the left graph shows the response following a surprise technology shock and the right graph presents the respective response after an anticipated technology shock. The dashed lines, in comparison, show the corresponding impulse responses obtained from averaging over six estimated individual bilateral VARs, each using data only for the US and one out of the G6 countries. The shaded areas are the means of the confidence bands from the bilateral models. The results are similar to the baseline panel results. The dash-dotted lines in the upper part of Figure 3 show the impulse responses from six additional VAR estimates where each model drops one of the G6 countries from the sample. As Figure 3 shows, both surprise and news technology shocks in the US in all cases lead to a strong appreciation of the real exchange rate. In particular the size and shape of the real exchange rate response is very similar across the different estimates.

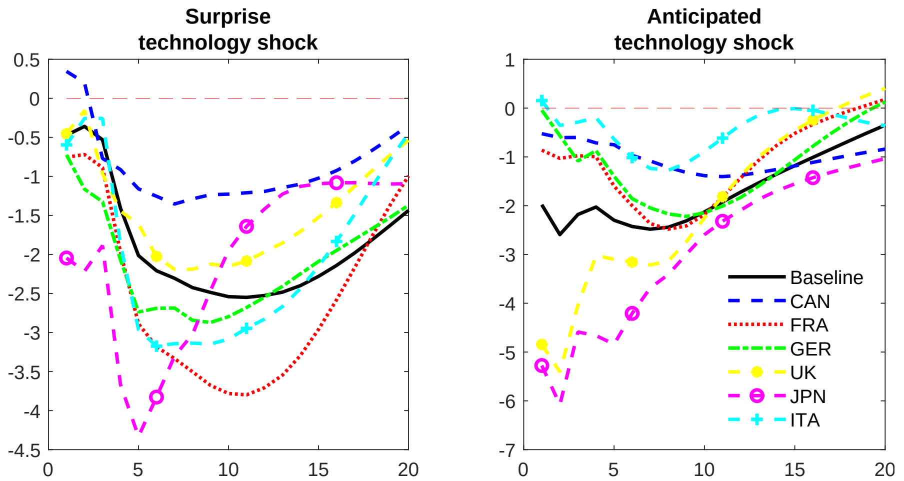
To further investigate the robustness of the exchange rate response following both technology shocks, the middle panel of Figure 3 reports the results of the six estimated bilateral VARs. Here, we do not restrict the responses to be the same for all G6 countries but allow for country-specific exchange rate dynamics. We find that the appreciation of the real exchange rate in response to US surprise and anticipated technology shocks is present for all estimated bilateral VARs. Nevertheless, there is some degree of country heterogeneity. Understanding in greater detail the underlying causes of the country-specific responses is beyond the scope of our paper but might be of particular interest for future research.[11] Most importantly, from a qualitative point of view our finding that surprise and anticipated US technology shocks lead to a real exchange rate appreciation is a common feature across all G6 countries. Consequently, the results reported above seem to describe the general tendencies in the data well and do not appear to be driven by unusual observations in any

[11] Potential candidates for the country-specific responses to US technology shocks might be trade and financial linkages.

(a) Key country.



(b) Bilateral VARs.



(c) Relative variables.

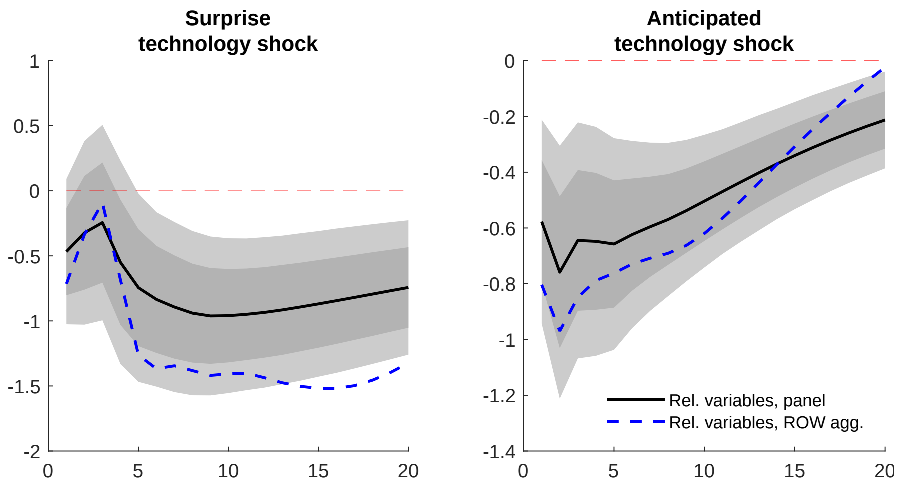


Figure 3: Robustness (real exchange rate response).

Notes: Solid lines show point estimates. Shaded areas indicate 68% and 90% bootstrapped confidence intervals. The unit of the horizonal axis is a quarter and the sample is 1973q1-2019q1 in the first two rows and 1973q1-2017q4 in the last row.

particular country.

Correlated shocks. In our baseline specification, we assume that the respective instruments are correlated with the US technology shocks only and are uncorrelated with exogenous technology improvements in other countries. However, it seems possible that there is a global technology cycle which affects several countries simultaneously. To check for this possibility, we proceed in two ways. First, we use a measure of utilization adjusted TFP in the G6 countries as an additional variable, and test in how far it responds to the identified US technology shocks. A markedly positive response of foreign TFP would be worrisome for our identification strategy, since it is reasonable to assume that TFP and surprise technology shocks in the G6 are correlated, such that by implication US and foreign technology shocks would be correlated. While for the G6 countries there is no quarterly data similar to Fernald's (2014) TFP measure available, annual utilization adjusted TFP growth rates for the G6 is provided for 1974 to 2006 on Andrei Levchenko's website.[12] We interpolate linearly by assuming that within a given year each quarter has the same TFP growth rate, and integrate to get (log-) levels. The results are presented in Figure A1 in Appendix A1.3. The responses of the G6 adjusted TFP series are practically flat and entirely insignificant following both surprise and news technology shocks in the US (while the responses of the other variables do not change much). Of course, this needs to be interpreted cautiously because the result depends on interpolated series. However, there is no indication of a noteworthy relation between US technology shocks and foreign utilization adjusted TFP.

A second way to safeguard against the possibility of international shock correlation (that does not rely on interpolated data) is to follow Corsetti et al. (2014) or Enders et al. (2011) and estimate VARs with relative variables, i.e. entering each of the core US variables as a (log) ratio over its counterpart in each of the G6 countries.[13] The restriction required for identification then changes to assuming that our instruments are correlated only with the shocks that alter the relative productivity in the US over the G6. Compared to our baseline approach, this is a weaker restriction in that it allows that the instruments include information about changes in foreign productivity, but are only correlated with technology movements that affect the US more strongly. The solid lines in the lower panel of Figure 3 show the results using the relative variables in a panel setup, whereas the dashed lines come from a model where US variables enter relatively to a weighted aggregate of the G6 countries (the construction of the G6 aggregate is described in Appendix A1.1). In both variants, there is a pronounced appreciation. The quantitative scale of the response is smaller for the surprise shock than in the baseline case shown in Figure 1, but for both shocks the real exchange rate reacts negatively throughout and the appreciation is statistically significant from a few quarters after the shock onwards. In sum, we interpret these results as evidence that our empirical strategy identifies valid US technology shocks that are not strongly correlated with foreign technology and that robustly lead to a domestic real appreciation.

[12]See https://www.dropbox.com/s/nieeqb2cftde014/Utilization_adjusted_tfp.xlsx?dl=0

[13]Due to shorter data availability for G6 hours worked, the sample for this model only goes to 2017q4.

Possible anticipation in Fernald's measure. Another possible caveat may be that Fernald's (2014) TFP measure might in fact also capture news about future productivity to some extent, which would render it inappropriate for use as an instrument to identify a surprise shock. However, we find that this seems unlikely to be the case. The TFP instrument and the patent news series that we use as the instrument for anticipations are virtually uncorrelated in the sample. Further, we ran a robustness check by first regressing Fernald's TFP measure on the patent instrument and four of its lags, and using the residuals of this regression as an alternative instrument for the surprise shock. In this way, the TFP series is purged from forecastable information available through current and past patent applications, and is thus orthogonal to anticipated technology changes. Figure A2 in Appendix A1.3 shows that the results change only little, and in particular the real exchange rate response is very similar to the baseline model. Hence, we conclude that the surprise instrument seems to be valid in that it captures only unanticipated technology movements.

Further checks. Additionally, in Figure A3 in Appendix A1.3 we present the results of further robustness analyses, which show that the main findings also hold up when varying the lag length, additionally controlling for narrative monetary and tax policy shocks in the construction of the news instrument, including other financial market variables like the S&P 500 index, or leaving out the turbulent Great Recession period by shortening the sample. Moreover, and as previously mentioned, we show that the impulse responses to the anticipated technology shock are very similar when replacing labor productivity by total factor productivity.

To sum up, the empirical results show a clear and mostly precisely estimated response pattern. A US technology improvement has expansionary domestic output and consumption effects. The positive output effect sets in with a delay in the case of news shocks on the expectation of future US productivity improvements. There is a strong and precisely estimated positive spillover on G6 output and consumption in the case of surprise shocks, and a weaker and often insignificant but still mostly non-negative international spillover effect in the case of anticipated shocks. Importantly, both technology shocks lead to a significant and persistent appreciation of the real exchange rate. As we argue below, this finding is key to bring the empirical results to align with theoretical predictions, since a common real exchange rate response is implied by standard two-country business cycle models.

2.3.3 Additional results

In this section, we report the results for other variables of interest. In particular, we look more closely at the response of hours and productivity, investigate nominal variables like prices, nominal interest rates and nominal exchange rates, and report how relative prices of exportable goods and non-tradable goods respond to US surprise and anticipated technology shocks. The aim of these analyses is to recover key empirical results that will inform our theoretical discussion of the international transmission mechanism of technology shocks below.

As a first step, we investigate in more detail the international transmission of US technology shocks on hours worked and labor productivity. This requires re-estimating the VAR with a shorter sample period, since the G6 hours data are only available through 2017q4 (see Appendix A1.1 for a description of the data). Figure 4 shows the result of adding the logarithm of G6 labor productivity (real GDP over hours worked) to the core variables.[14] The responses of home and foreign GDP and the real exchange rate are very similar to the ones reported in Figures 1 and 2 above and are therefore not repeated here. Figure 4 shows that a surprise US technology shock has a positive but rather small effect on labor productivity in the foreign countries. The effect of an anticipated US shock on foreign productivity is largely insignificant. In the case of a surprise US technology shock, hours worked in the US decline significantly on impact and recover only after several quarters, a result that as already noted above is well in line with the prediction of sticky-price models. As pointed out by Gali (1999), the exogenously increased goods supply due to a technology improvement makes firms temporarily lower employment when slowly moving prices cannot immediately jump downwards to generate a commensurately large increase in goods demand. Abroad, in contrast, the hours response is muted on impact but increases in a hump-shaped manner, such that the response becomes significant after some quarters. In the case of an anticipated US technology shock, hours at home increase with a delay after a small and short-lived initial decline, while they generally rise in the foreign countries. In the first two years the gradual increase in hours worked in the US economy outweighs the positive GDP response which explains the observed fall in labor productivity before the technology diffusion ultimately sets in leading to a significant increase in a labor productivity.

Next, we look at the behavior of nominal variables. Figure 5 shows impulse responses for both shocks for a specification where we add to the core variable list US and G6 consumer price indices (CPI) in logarithms and the levels of short-run nominal interest rates related to the stance of monetary policy. For the US, the interest rate is the Federal Funds Rate, for the G6 we use the measures of central bank or call money overnight rates from the FRED database, depending on data availability; see Appendix A1.1 for a detailed description. Also, we replace the real exchange rate variable by the nominal exchange rate, since the model variant estimated here already contains the CPIs such that in conjunction with the inclusion of the nominal exchange rate the response of the real exchange rate is implicit. Figure 5 only shows the responses of the variables added to the core set (or in the case of the exchange rate replaced in it), since the results for the other variables change little relatively to the baseline specification, such that none of the conclusions drawn from the findings discussed above changes.

The nominal exchange rate appreciates strongly from the point of view of the US for both shocks, and the response is similar to the real appreciation found above: hump-shaped in

[14] The bottom rows of Figure 4 result from replacing GDP by hours and keeping labor productivity, which is equivalent to using productivity and GDP and backing out the implied hours response.

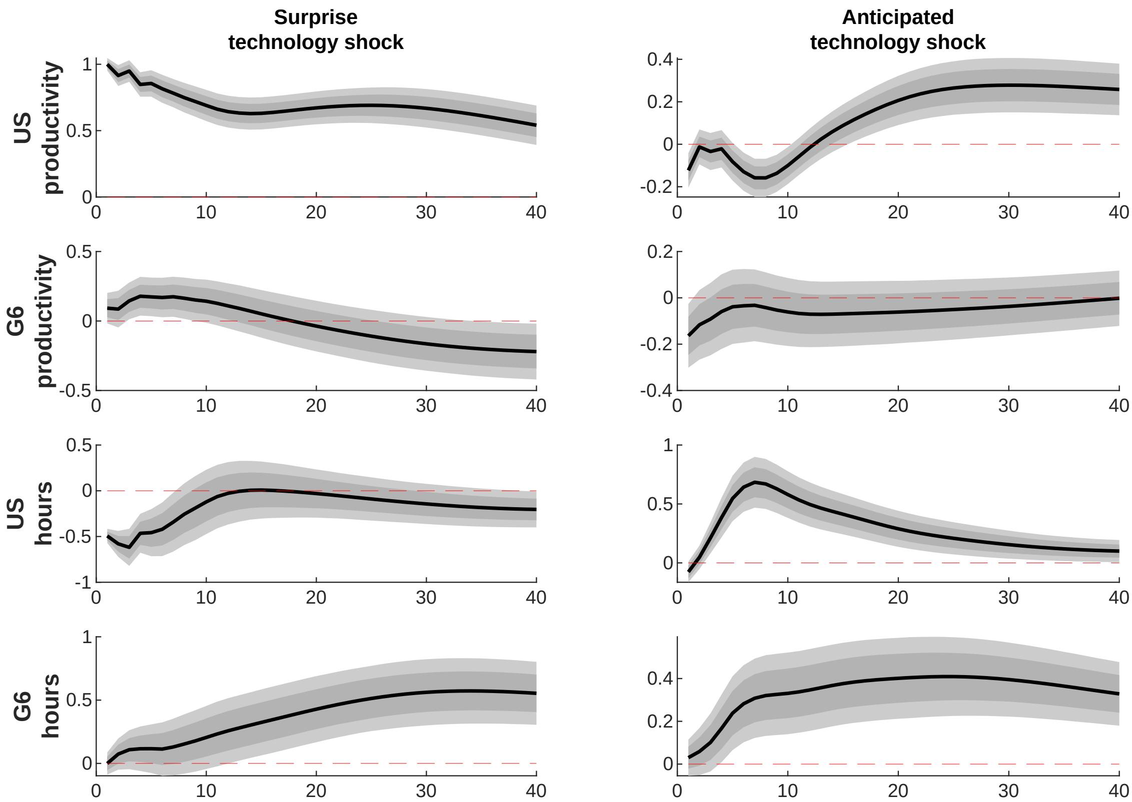


Figure 4: Productivity and hours.

Notes: Solid lines show point estimates. Shaded areas indicate 68% and 90% bootstrapped confidence intervals. The unit of the horizonal axis is a quarter and the sample is 1973q1-2017q4.

the case of surprise technology shocks, and strongest in the first few quarters for anticipated technology shocks. Both shocks tend to lower the consumer price levels in the US but also abroad. The CPI response is negative and statistically significant for the US, and less significant but still generally negative for the G6. The finding for the US is well in line with the standard intuition for technology improvements, since the increased goods supply from higher productivity should exert downward pressure on prices. The reason for a negative price level response abroad is less clear, but could, at least for the surprise technology shock, be due to some positive productivity spillover as shown in Figure 4 above. The short-run interest rates in the US and (with a short lag) in the foreign countries decrease, too, in the case of surprise shocks, and as a tendency (though less significantly) also in the case of anticipated shocks. This behavior of nominal interest rates would fit a setting where monetary policy sets interest rates in the way typically assumed in New Keynesian models, since increased goods supply associated with decreasing prices would call for lower rates to accomodate higher goods demand.

The quantitatively limited response of the price level variables along with the strong nominal US dollar appreciation seen in Figure 5 implies that the real exchange rate appreciation reported above in Figures 1 and 2 is mostly due to the reaction of nominal exchange rates. The finding that real exchange rate movements are dominated by fluctuations in the nominal rate, and not in price levels, is of course common in empirical open econ-

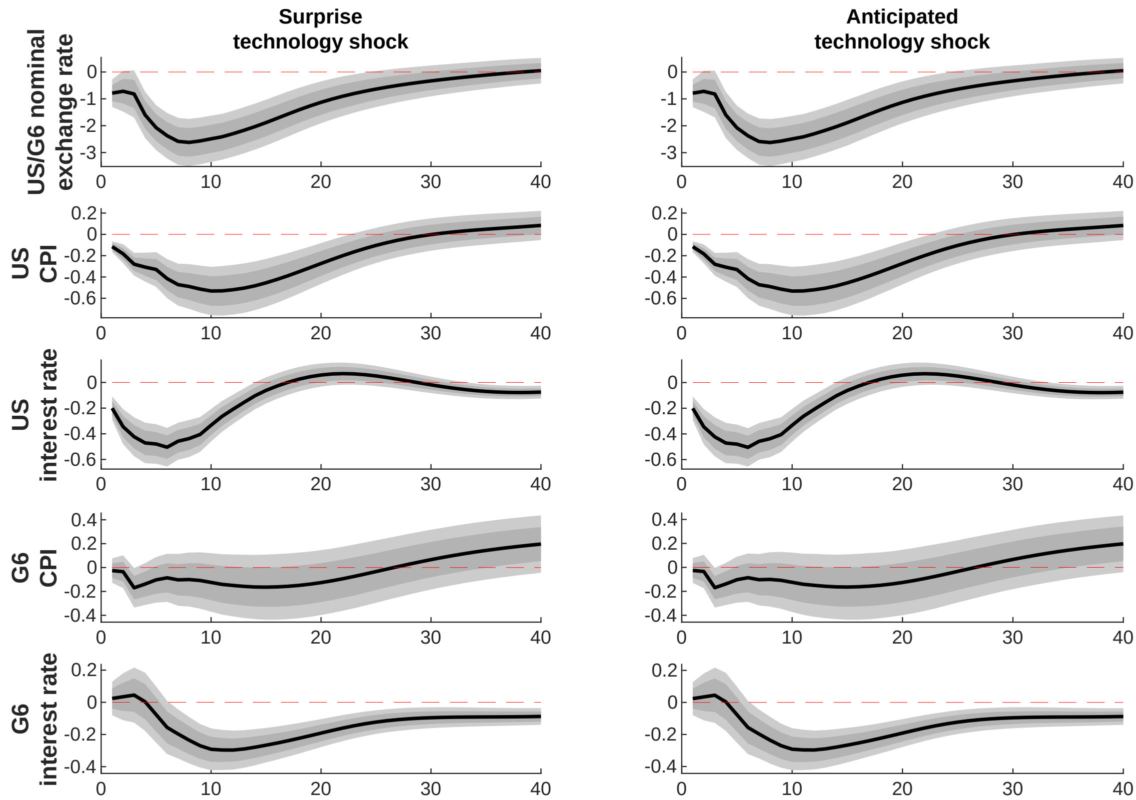


Figure 5: Nominal exchange rate, prices, and interest rates.

Notes: Solid lines show point estimates. Shaded areas indicate 68% and 90% bootstrapped confidence intervals. The unit of the horizonal axis is a quarter and the sample is 1973q1-2019q1.

omy macroeconomics, and can be interpreted as reflecting short-run price stickiness which imparts a strong positive correlation between real and nominal exchange rates.

Finally, Figure 6 shows the results for various measures of relative sectoral prices for the US economy. This investigation is intended to better understand in which sector the technology improvement occurs. In particular, we seek to find out whether the shocks primarily originate from the traded or non-traded goods sector. The first two rows of Figure 6 display the responses from a specification which adds to the core variable set the real price of domestic exports and the real price of services (both relative to the CPI). The real prices of US export goods decline strongly and significantly after a surprise technology shock, and do so with a lag of a few quarters after an anticipated shock. In contrast, a surprise shock significantly increases the relative price of services, while an anticipated shock shows an initial decline followed by a later (though less significant) increase.

We interpret this as evidence for markedly different dynamics in the prices of tradable and non-tradable goods, since the prices of services arguably contain large components which are non-tradable, such as local retailing services. Under this interpretation, technology shocks strongly lower traded prices and increase non-traded prices, most strongly and significantly so for the unanticipated shock.

The third row of Figure 6 shows the results from a specification where we replace the individual export and service price series by their logarithmic ratio, to be able to judge the

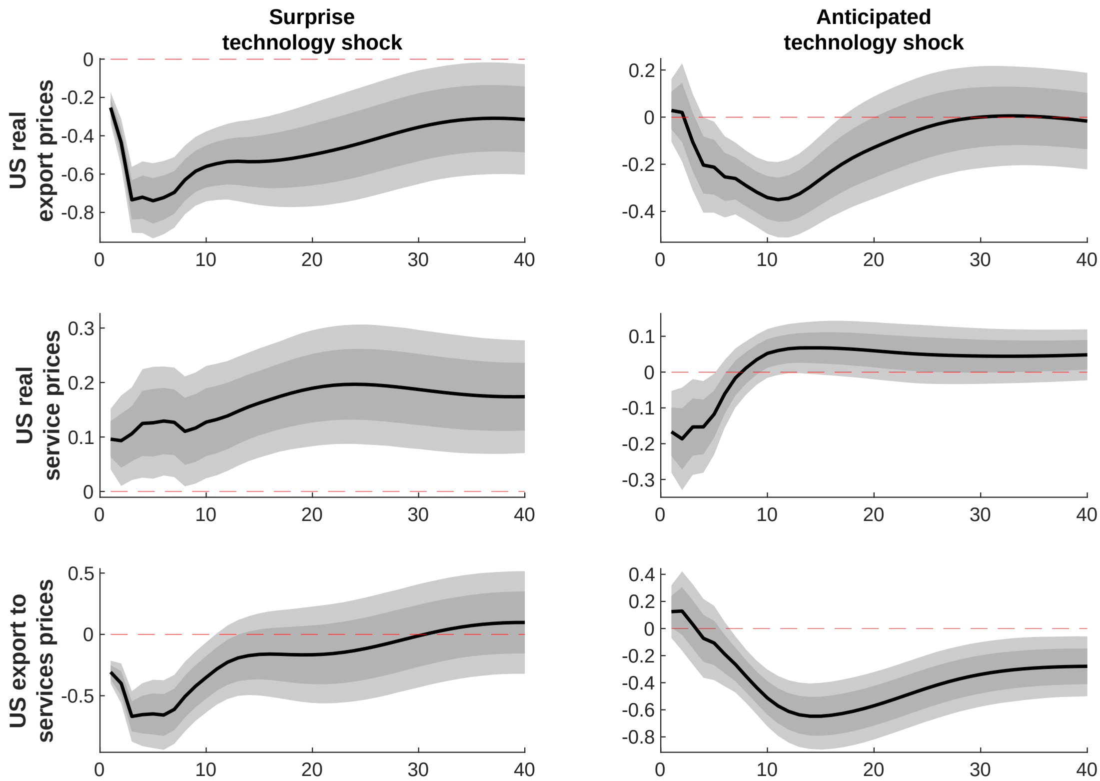


Figure 6: US relative prices.

Notes: Solid lines show point estimates. Shaded areas indicate 68% and 90% bootstrapped confidence intervals. The unit of the horizonal axis is a quarter and the sample is 1973q1-2018q3.

significance of the difference in their responses. The responses show that tradable export prices indeed decline strongly and significantly relative to the service prices that we interpret as non-traded prices, immediately in the case of the surprise shock and with a brief lag in the case of the anticipated shock. These findings suggest that technology shocks mostly affect the tradable sector, where productivity improvements lead to lower prices, whereas non-tradable prices mostly show the opposite behavior. The distinction between the price responses of tradable and non-tradable goods will play a key role in our theoretical account of the transmission mechanism of tradable sector technology shocks below. Corsetti et al. (2014) apply a sign restriction approach to estimate the effects of a technology shock that occurs in the traded sector. One of their restrictions is assigned to the ratio between traded and non-traded (services) prices in that the technology shock in the traded sector leads to a fall in the price ratio. Our proxy-VAR approach is more agnostic about the relative price response, as it does not assign any restriction on their dynamic behavior. Nevertheless, our qualitative finding of a fall in the relative price of traded goods is in line with Corsetti et al. (2014) and as shown below also with the predictions of open economy DSGE models with a traded and non-traded sector, which supports the interpretation that our identified technology shocks mainly originate from the traded sector of the US economy.

2.3.4 Comparison to the literature

The result that both surprise and news technology shocks produce a real appreciation in the US is in partial contrast with recent results in related literature. In particular, both Nam and Wang (2015, henceforth NW) using US variables relative to the G6 and Levchenko and Pandalai-Nayar (2020, henceforth LP) using US and Canadian variables report a US real depreciation after a surprise shock, and a real appreciation after a news shock. Apart from differences in the variables selected, the main distinction between both of these papers and our own is the identification approach. We show that it is the latter that is responsible for the partial divergence in outcomes, and argue that the proxy-instrumental variable approach has a number of advantages.

NW and LP use the technology shock identification introduced by Barsky and Sims (2011). This amounts to using a VAR where technology is taken be directly observable as a utilization adjusted TFP measure, and assuming that it is contemporaneously exogenous with respect to all shocks except for a surprise technology shock. Effectively, the surprise shock is thus identified recursively with TFP ordered as the first variable. The news shock is then identified as the shock that has a zero impact effect on TFP and at the same time maximizes the forecast error variance of TFP over a long but finite horizon.

To see the implications, Figure A5 in the Appendix shows the impulse responses of the real exchange rate using this approach with the longest available sample (through 2017q4) and the original samples in NW and LP (ending in 2010q4 and 2010q3, respectively). The first row in Figure A5 applies NW's method to our data and uses, apart from Fernald's (2014) TFP measure, real GDP, consumption, investment, hours and stock prices of the US relatively to the G6. Using the Barsky and Sims (2011) identification, the result to a news shock is a US real appreciation, while the response to the surprise shock is less clear but shows a tendency of real depreciation. Note that we are not quite able to replicate the persistently hump-shaped real depreciation to a surprise shock that NW report. Nevertheless, it is clear that while the news shock response is qualitatively similar to the one that we find, there is an obvious difference in the response to a surprise shock that does not show the real appreciation result that we found using the proxy-VAR identification.

The second row in Figure A5 shows the real exchange rate response in a two-country VAR that, following LP, uses Fernald's (2014) TFP, US real GDP, consumption, hours, a forecast of US real GDP, as well as the US-Canadian real exchange rate, and where again identification follows the Barsky and Sims (2011) method. Similarly to LP, the result is a real depreciation in response to a surprise US technology shock, and a real appreciation following the news shock.

The difference in the responses of a surprise shock is indeed due to the identification technique, as using our proxy-VAR identification approach with the specifications chosen either by NW or LP results in a real US appreciation. While with just-identification it is impossible to statistically test which model should be preferred, there are nevertheless several reasons why we think that our identification through an instrumental variable is advantageous. First, the Barsky and Sims (2011) method attributes as much explanatory power for longer-run TFP movements as possible to the news shock. The underlying idea is that only technology moves observable TFP in the long run. This view is, however, challenged in the recent literature, where several authors find that demand side disturbances like monetary policy shocks can have a long-lasting effect on TFP due to endogenous growth (see Moran and Queralto, 2018 or Jorda et al., 2020). The Barsky and Sims (2011) method would thus attribute the demand-induced part of TFP movements erroneously to anticipated technology. On the other hand, our approach of using patent innovations as an instrument is free from this complication, since the identification is based on an observable proxy-instrument for news. Interestingly, we find that only a relatively small part of the forecast error variance of productivity is attributable to news shocks, which is in line with Miranda-Agrippino et al. (2020), suggesting that the NW and LP news shock in fact picks up some demand shock effects. Second, with respect to the surprise shock both NW and LP assume that contemporaneous technology shocks are directly observable through Fernald's (2014) TFP measure. Instead, we only use this measure as a proxy-instrument that is arguably correlated with technology shocks, but not necessarily identical to it. Thus, as pointed out in Mertens and Ravn (2013), the proxy-VAR technique is robust to measurement error that is very likely to inflict constructed variables like TFP. Conversely, if TFP indeed were a perfect measure of contemporaneous technology shocks free from measurement error, then its use as an instrument as in our approach or its use as a directly observable shock as in NW and LP should produce a very similar result, since the instrument is very strong. If, on the other hand, measurement error is a problem, the instrumental variable approach remains viable, whereas the direct use of TFP as a regressor would tend to produce bias.

Summing up, we argue that the finding of a real appreciation following both types of shocks is due to the more robust identification that the proxy-VAR method provides. In addition, in the next section we show that this result is straightforward to theoretically explain in a two-country business cycle model, whereas we know of no theory that would explain responses of the opposite sign dependent on the type of shock.

3 The model

In this section, we ask in how far the empirical results can be rationalized through the lens of a theoretical model. Specifically, we set up a two-country New Keynesian business cycle model with capital accumulation, traded and non-traded goods, and imperfect financial markets. Since many parts of the model are well known from earlier studies, we only present a brief outline of the model in the main text, while a complete formal description of the model is relegated to Appendix A1.2. The key point is to show that the model is qualitatively in line, for a choice of central parameters based on recent empirical evidence, with a domestic real exchange rate appreciation in response to both surprise and anticipated home technology shocks that arise in the tradable goods sector.

Firms are monopolistic competitors producing individual varieties of goods, and set prices in the producer country's currency facing quadratic price adjustment costs. As in Corsetti et al. (2010), the measure $m \in (0,1)$ of households live in the home country, and $1-m$ in foreign. Likewise, there are m (resp. $1-m$) firms in the home (foreign) traded and non-traded goods sectors each. For simplicity, only firms in the domestic and foreign tradable sectors use capital for production, whereas non-tradable goods in both countries are produced with labor only, and only domestic tradable firms are subject to technology shocks. As in Miyamoto and Lan Nguyen (2017), Lombardo and Ravenna (2014), or Johnson (2014), firms in the tradable sectors also use imported foreign goods as intermediate inputs in production. Financial markets are incomplete, in that only a domestically issued non-contingent bond is traded internationally, and central banks in both countries follow simple Taylor rules to steer nominal interest rates in response to domestic consumer price inflation.

Domestic households maximize

$$E_0 \sum_{t=0}^{\infty} \beta^t \frac{\left(c_t^{\chi} l_t^{1-\chi}\right)^{1-\sigma}}{1-\sigma}, \quad \chi, \beta \in (0,1), \sigma > 0,$$

where c is consumption, l is leisure, and E_0 is conditional expectation as of time 0, and all variables are understood as per capita values unless otherwise stated. This non-additively separable specification of the utility function is widely used in theoretical models since it is well know to be compatible with balanced growth (see King et al. 1988). For our purposes, the implied complementarity between consumption and employment is useful, since it helps bringing about a positive correlation between these variables even in the face of wealth effects entailed by real exchange rate changes. Households receive income from labor supply in the tradable and non-tradable goods sectors as well as from capital rented to the tradable sector. They can also invest in internationally traded home bonds b_t^H with gross nominal interest rate R_t. There is also a bond adjustment cost $(\phi/2)(b_t^H - b^H)^2$ (where b^H is a constant steady state value) with $\phi > 0$ a small parameter that induces stationarity of the allocation (see Schmitt-Grohe and Uribe, 2003). Capital in the tradable sector accumulates subject to adjustment costs according to

$$k_{t+1} = (1-\delta)k_t + \left(1 - \frac{\kappa}{2}\left(\frac{i_t}{i_{t-1}} - 1\right)^2\right) i_t, \tag{4}$$

where k_t is capital, i_t is investment, $\delta \in (0,1)$ is the depreciation rate and $\kappa > 0$ is a parameter governing the size of investment adjustment costs. Since working in the traded and non-traded sectors is perfectly substitutable for households, the real wage in both sectors must be equal, and with a unit time budget $l_t = 1 - n_{Ht} - n_{Nt}$ holds where n_H (n_N) is labor supplied to the home tradable (non-tradable) sector.

Foreign households are similar. They can also invest in the domestic bond, but for simplicity we assume they are not subject to bond adjustment costs, and in a local foreign currency bond that is not internationally traded and is in zero net supply and only serves to define the foreign gross nominal interest rate R_t^*. Here and henceforth, variables and parameters with a '$*$' pertain to the foreign economy.

Goods produced in either economy can be used for consumption or investment (adding to the capital stock in the traded production sector) in both countries, or as an intermediate input in the other country's tradable goods sector. Total per capita consumption c consists of consumption of traded goods c_T and non-traded goods c_N, with the aggregator

$$c_t = \left[(1-\mu)^{1/\psi} c_{Tt}^{\frac{\psi-1}{\psi}} + \mu^{1/\psi} c_{Nt}^{\frac{\psi-1}{\psi}}\right]^{\frac{\psi}{\psi-1}},$$

where $\mu \in (0,1)$ is a share parameter denoting the relative size of non-traded consumption, and $\psi > 0$ is the substitution elasticity between both types of goods. The associated CPI price level is

$$P_t = \left[(1-\mu)P_{Tt}^{1-\psi} + \mu P_{Nt}^{1-\psi}\right]^{\frac{1}{1-\psi}},$$

where P_T (P_N) denotes the price level of traded (non-traded) goods. Optimal demands are

$$c_{Tt} = (1-\mu)\left(\frac{P_{Tt}}{P_t}\right)^{-\psi} c_t, \qquad c_{Nt} = \mu \left(\frac{P_{Nt}}{P_t}\right)^{-\psi} c_t.$$

Foreign consumption has a similar structure, but the non-tradable consumption component has a share parameter μ^* that may differ from the domestic one μ. The real exchange rate is defined as $q_t = X_t P_t^*/P_t$, where X_t is the nominal exchange rate (the home currency price of a foreign currency unit) and P_t^* is the foreign consumption price level.

Tradable consumption consists of home and foreign produced consumption goods, c_H and c_F,

$$c_{Tt} = \left[(1-\gamma)^{1/\eta} c_{Ht}^{\frac{\eta-1}{\eta}} + \gamma^{1/\eta} c_{Ft}^{\frac{\eta-1}{\eta}}\right]^{\frac{\eta}{\eta-1}}, \tag{5}$$

with share parameter $\gamma \in (0,1)$ and substitution elasticity $\eta > 0$. The parameter η is commonly referred to as the trade elasticity, as it doubles as the absolute value of the price elasticity of demand for domestic tradable goods. The associated tradable price level is

$$P_{Tt} = \left[(1-\gamma)P_{Ht}^{1-\eta} + \gamma P_{Ft}^{1-\eta}\right]^{\frac{1}{1-\eta}},$$

where P_H (P_F) denotes the price level of home (foreign) produced goods in domestic currency, and the optimal demands are

$$c_{Ht} = (1-\gamma)\left(\frac{P_{Ht}}{P_{Tt}}\right)^{-\eta} c_{Tt}, \qquad c_{Ft} = \gamma \left(\frac{P_{Ft}}{P_{Tt}}\right)^{-\eta} c_{Tt}.$$

A similar demand structure holds in the foreign country, where however the share parameter γ^* may differ from the domestic one γ.

There is a measure $m \in (0,1)$ of home based firms each producing a tradable variety that can be used as a consumption or investment good or as an intermediate input in the other economy, and a measure $1-m$ of foreign firms / varieties. Denoting the individual home (foreign) produced variety by c_{Hi} (c_{Fi}), the aggregators are

$$c_{Ht} = \left(\int_0^m \left(\frac{1}{m} \right)^{\frac{1}{\theta}} c_{Hit}^{\frac{\theta-1}{\theta}} di \right)^{\frac{\theta}{\theta-1}}, \quad c_{Ft} = \left(\int_m^1 \left(\frac{1}{1-m} \right)^{\frac{1}{\theta}} c_{Fit}^{\frac{\theta-1}{\theta}} di \right)^{\frac{\theta}{\theta-1}},$$

where $\theta > 1$ is the substitution elasticity between individual varieties, hence demands are

$$c_{Hit} = \frac{1}{m} \left(\frac{P_{Hit}}{P_{Ht}} \right)^{-\theta} c_{Ht}, \quad c_{Fit} = \frac{1}{1-m} \left(\frac{P_{Fit}}{P_{Ft}} \right)^{-\theta} c_{Ft}, \tag{6}$$

where P_{Hi} (P_{Fi}) is the i-th individual home (foreign) produced variety's price in domestic currency, and $P_{Ht} = \left(\int_0^m \left(\frac{1}{m} \right) P_{Hit}^{1-\theta} di \right)^{\frac{1}{1-\theta}}$ and $P_{Ft} = \left(\int_m^1 \left(\frac{1}{1-m} \right) P_{Fit}^{1-\theta} di \right)^{\frac{1}{1-\theta}}$. Again, foreigners are similar.

There are also a measure m of producers in the home non-traded sector. Individual non-traded consumption goods c_{Ni} aggregate in the same way as traded goods, such that demand is

$$c_{Nit} = \frac{1}{m} \left(\frac{P_{Nit}}{P_{Nt}} \right)^{-\theta} c_{Nt}, \tag{7}$$

with P_{Ni} the price of the individual non-traded variety, and $P_{Nt} = \left(\int_0^m \left(\frac{1}{m} \right) P_{Nit}^{1-\theta} \right)^{\frac{1}{1-\theta}} di$, and similarly for the foreign non-traded sector.

Investment is also composed of tradable (i_T) and non-tradable (i_N) investment goods aggregating through

$$i_t = \left[(1-\omega)^{1/\psi} i_{Tt}^{\frac{\psi-1}{\psi}} + \omega^{1/\psi} i_{Nt}^{\frac{\psi-1}{\psi}} \right]^{\frac{\psi}{\psi-1}},$$

with $\omega \in (0,1)$, giving rise to the demand functions

$$i_{Tt} = (1-\omega) \left(\frac{P_{Tt}}{P_{It}} \right)^{-\psi} i_t, \quad i_{Nt} = \omega \left(\frac{P_{Nt}}{P_{It}} \right)^{-\psi} i_t$$

where the associated investment price level is

$$P_{It} = \left[(1-\omega) P_{Tt}^{1-\psi} + \omega P_{Nt}^{1-\psi} \right]^{\frac{1}{1-\psi}}.$$

Here, the investment price level P_I can differ from the consumption price level P if the non-tradable share in investment ω differs from the one for consumption μ, as is empirically the case (see below). The composition of the tradable component of investment is the same as for tradable consumption (see 5), such that demand functions are

$$i_{Ht} = (1-\gamma) \left(\frac{P_{Ht}}{P_{Tt}} \right)^{-\eta} i_{Tt}, \quad i_{Ft} = \gamma \left(\frac{P_{Ft}}{P_{Tt}} \right)^{-\eta} i_{Tt}$$

where i_H (i_F) is the domestic (foreign) component of tradable investment. The composition of investment with respect to individual varieties is the same as for consumption goods, such that individual investment goods demands have the same structure as individual consumption goods demands, see (6) and (7). Foreign investment demands have a similar structure, but the non-tradable investment component has a share parameter ω^* that may differ from the domestic one ω .

Firms in the home (foreign) tradable goods sector use intermediate goods imported from the foreign (home) country as inputs in the production process. In the home (foreign) economy, there is a measure m $(1-m)$ of perfectly competitive firms that bundle foreign (home) produced goods into intermediate inputs for use in the home (foreign) tradable production sector. Each domestic bundler buys foreign intermediate goods v_{Fi} at individual prices P_{Fi} and assembles the intermediate input v from them that is then sold at the price P_F to domestic tradable goods firms. The intermediate input production function is

$$v_t = \left(\int_m^1 \left(\frac{1}{1-m} \right)^{\frac{1}{\theta}} v_{Fit}^{\frac{\theta-1}{\theta}} di \right)^{\frac{\theta}{\theta-1}},$$

and the bundler chooses v_{Fi} to maximize profits giving rise to the demand function

$$v_{Fit} = \frac{1}{1-m} \left(\frac{P_{Fit}}{P_{Ft}} \right)^{-\theta} v_t.$$

Likewise, a foreign bundler buys home produced intermediate goods varieties v_{Hi}^* at price P_{Hi}^* and sells them to foreign traded goods firms at price P_H^*, such that the demand function is

$$v_{Hit}^* = \frac{1}{m} \left(\frac{P_{Hit}^*}{P_{Ht}^*} \right)^{-\theta} v_t^*.$$

Since intermediate goods are the same goods as those used for consumption and investment purposes, the aggregate price indices of intermediates P_F and P_H^* are the same as given above.

The law of one price holds on the level of traded varieties, $P_{Hit} = X_t P_{Hit}^*$, $P_{Fit} = X_t P_{Fit}^*$, and consequently also on the level of price indices,

$$P_{Ht} = X_t P_{Ht}^*, \quad P_{Ft} = X_t P_{Ft}^*.$$

Consequently, with a measure m of home and $1-m$ of foreign consumers, and the same measure of firms in each sector in each country, total demand for a home tradable variety can be written as

$$y_{Hit} = \left(\frac{P_{Hit}}{P_{Ht}} \right)^{-\theta} (c_{Ht} + i_{Ht}) + \frac{1-m}{m} \left(\frac{P_{Hit}^*}{P_{Ht}^*} \right)^{-\theta} (c_{Ht}^* + i_{Ht}^* + v_t^*), \tag{8}$$

and total demand for a foreign traded variety is

$$y_{Fit} = \frac{m}{1-m} \left(\frac{P_{Fit}}{P_{Ft}} \right)^{-\theta} (c_{Ft} + i_{Ft} + v_t) + \left(\frac{P_{Fit}^*}{P_{Ft}^*} \right)^{-\theta} (c_{Ft}^* + i_{Ft}^*), \tag{9}$$

whereas demand for a non-traded home variety is

$$y_{Nit} = m \left(c_{Nit} + i_{Nit} \right) = \left(\frac{P_{Nit}}{P_{Nt}} \right)^{-\theta} (c_{Nt} + i_{Nt}), \tag{10}$$

and for a non-traded foreign variety is

$$y_{Nit}^{*} = (1-m)\left(c_{Nit}^{*} + i_{Nit}^{*}\right) = \left(\frac{P_{Nit}^{*}}{P_{Nt}^{*}}\right)^{-\theta}\left(c_{Nt}^{*} + i_{Nt}^{*}\right). \tag{11}$$

Firms in each sector are monopolistic competitors each producing a particular variety of the output good subject to Rotemberg (1982) - style quadratic price adjustment costs. The size of these price adjustment costs is assumed to be the same in all sectors. Firms in the domestic and foreign tradable sectors produce using labor, capital and imported intermediate goods inputs, whereas the non-traded sectors use only labor for simplicity. Additionally, domestic tradable firms are subject to technology shocks.

Specifically, an individual firm in the domestic tradable goods sector maximizes the present discounted value of real profits on behalf of its household-owners subject to quadratic price adjustment costs,

$$\sum_{t=0}^{\infty} E_0 \beta^t \frac{\lambda_{t+1}}{\lambda_t}\left[\frac{P_{Hit}}{P_{Ht}} y_{Hit} - w_t \frac{P_t}{P_{Ht}} n_{Hit} - r_t \frac{P_t}{P_{Ht}} k_{it} - \frac{\zeta}{2}\left(\frac{P_{Hit}}{P_{Hit-1}} - 1\right)^2 - \frac{P_{Ft}}{P_{Ht}} v_{it}\right],$$

where n_{Hi}, k_i and v_i are labor, capital and intermediate inputs rented by the i-th home traded sector firm, and $\zeta > 0$ measures the size of price adjustment costs. Maximization is subject to the demand constraint (8) and the production constraint

$$y_{Hit} = z_{Ht}\left(n_{Hit}^{a} k_{it}^{1-a}\right)^{\vartheta} v_{it}^{1-\vartheta}, \quad a, \vartheta \in (0,1),$$

where the technology level z_H follows an exogenous AR(1) with

$$z_{Ht} = (1-\rho) + \rho z_{Ht-1} + \varepsilon_t + \epsilon_{t-2},$$

where ε_t is a serially uncorrelated random surprise shock innovation, ϵ_{t-2} is a serially uncorrelated random anticipated technology innovation, and $\rho \in (0,1)$. In a symmetric equilibrium where $P_{Hi} = P_H$, each firm hires the same amount of factor inputs and produces the same quantity of output. Since the measure of firms, households and intermediate input bundlers is m, each firm's factor inputs are equal to aggregate per capita values n_H, k and v. An analogous tradable production structure exists in the foreign country, with the only differences that there is no technology shock in the foreign economy and the foreign intermediate input share ϑ^* may differ from its domestic counterpart ϑ.

Firms in the domestic non-tradable sector solve a similar problem, with the difference that for simplicity their production process uses only labor n_N such that $y_{Nit} = n_{Nit}$, and and non-tradable firms also operate subject to the same Rotemberg pricing problem as described for tradable firms above. Foreign non-tradable firms are similar.

In each country, a central bank follows a simple Taylor - type rule to choose the nominal interest rate R (R^*) in response inflation, with

$$R_t = \frac{1}{\beta} R_{t-1}^{\rho_R} \pi_t^{\varphi(1-\rho_R)}, \quad R_t^* = \frac{1}{\beta} R_{t-1}^{*\rho_R} \pi_t^{*\varphi(1-\rho_R)}$$

where $\pi_t = P_t/P_{t-1}$ ($\pi_t^* = P_t^*/P_{t-1}^*$) is domestic (foreign) CPI inflation, the parameter $\rho_R \in (0,1)$ allows for interest rate smoothing, φ is the long-run inflation reaction coefficient satisfying the Taylor principle $\varphi > 1$, and in a steady state with price stability the interest rates in both countries are $1/\beta$.

In equilibrium, all markets clear, and profits of all domestic firms are paid out in lump-sum way to domestic households. Aggregating the per-capita budget constraint over m domestic households and using the definition of firm profits yields the aggregate home budget constraint

$$\left(c_t + \frac{P_{It}}{P_t} i_t + b_t^H\right) m = m\frac{R_{t-1} b_{t-1}^H}{\pi_t} + \frac{P_{Ht}}{P_t} y_{Ht} + \frac{P_{Nt}}{P_t} y_{Nt} - m\frac{P_{Ft}}{P_t} v_t.$$

The corresponding foreign budget constraint is redundant by Walras' law. For later use, we define domestic and foreign GDP as

$$GDP_t = \frac{P_{Ht}}{P_t} y_{Ht} + \frac{P_{Nt}}{P_t} y_{Nt} - m\frac{P_{Ft}}{P_t} v_t, \quad GDP_{Ft} = \frac{P_{Ft}^*}{P_t^*} y_{Ft} + \frac{P_{Nt}^*}{P_t^*} y_{Nt}^* - (1-m)\frac{P_{Ht}^*}{P_t^*} v_t^*.$$

The full set of equilibrium conditions is given in Appendix A1.2.

4 Model results

4.1 Parameter choice

We divide the parameters into three sets. The parameters in the first set take on conventional values common in the literature. These include the discount factor $\beta = 0.99$, the depreciation rate $\delta = 0.025$, the interest rate persistence in the Taylor rule $\rho_R = 0.8$ and the inflation reaction coefficient $\varphi = 1.5$. The price elasticity of individual goods varieties is $\theta = 10$ to imply a steady state markup of slightly above 10 per cent. The technology shock persistence is set to the value $\rho = 0.95$, and the choice for the utility parameter $\chi = 0.336$ ensures that total steady state labor input (allocated to working in the tradable and non-tradable sectors) is 0.3. The inverse of the intertemporal consumption substitution elasticity is chosen at $\sigma = 2$. The bond adjustment cost parameter is set to $\phi = 0.01$ to ensure steady state uniqueness without materially affecting the dynamics. The steady state home asset level b^H is set such that it implies that the domestic economy runs a steady state trade deficit of two per cent of GDP, resulting in $b^H = 0.7506$.[15] The production elasticity of labor is $a = 2/3$. Home and foreign are assumed to be of the same size, $m = 0.5$. We assume zero inflation in the steady state and choose the price adjustment cost parameter ζ by analogy with a corresponding Calvo type model where firms adjust prices on average every four quarters, as commonly assumed in the literature, resulting in $\zeta = 11.65$. The investment adjustment cost parameter is set to $\kappa = 2.5$ since this ensures that the peak response of domestic investment is roughly three times as large as the one of GDP, as is approximately true empirically.

[15] In a steady state (denoted by dropping time indices) with zero inflation and $R = 1/\beta$, the domestic budget constraint is $b^H = -\frac{\beta}{1-\beta}(gdp/m - c - i)$, which we use to calibrate b^H such that the per capita trade balance (in brackets) is -0.02 times per capita GDP.

The second set of parameters pertains to international trade linkeages. Here, we choose realistic values based on empirical observations. Specifically, we use the values reported in Lombardo and Ravenna (2014) who use input-output tables to provide the average shares of imports and non-tradables of demand components for several countries. Thus, based on table 1 in Lombardo and Ravenna (2014) the share of imports in US tradable consumption is chosen as $\gamma = 0.19$, the share of non-tradables in US consumption is $\mu = 0.701$ and in investment is $\omega = 0.577$, whereas the share of imported intermediates in US GDP is set at $1 - \vartheta = 0.076$. For the foreign counterparts, we average the values for the G6 countries given in Lombardo and Ravenna (2014) to find $1 - \gamma^* = 0.175$, $\mu^* = 0.405$ $\omega^* = 0.404$ and $1 - \vartheta^* = 0.174$.

For the third set of parameters, we conduct a sensitivity analysis. These are the parameters that are key for the results concerning the real exchange rate and international shock transmission, namely the substitution elasticity η between home and foreign tradables, i.e. the price elasticity of the demand for tradable goods (or trade elasticity for short), and the substitution elasticity ψ between traded and non-traded goods. For the trade elasticity, we choose a baseline value of $\eta = 1.5$, which is in the range of empirical estimates provided by Boehm et al. (2020). However, as there is considerable uncertainty around this parameter, with several authors using larger or smaller values, we explore the sensitivity of the results with respect to this parameter below. Concerning the substitution elasticity ψ between traded and non-traded goods, there is little empirical guidance. We choose $\psi = 0.5$ as the baseline value, which is close to the one in Benigno and Thoenissen (2008). A low substitutability between traded and non-traded goods can also be seen as a shorthand way to capture the idea in Corsetti et al. (2008) that non-traded goods need to be demanded alongside traded goods, which in their case is due to local distribution services and in our case is modeled more directly as complementarity between both types of goods in consumption.

4.2 Results

Figure 7 shows the impulse responses of the model to an autocorrelated surprise technology shock in the domestic tradable goods sector that raises domestic labor productivity by one percent on impact.

Looking at domestic responses first, the positive technology shock raises production in the home country such that GDP rises in a hump-shaped fashion, while the real exchange rate appreciates. Domestic employment declines on impact, such that domestic productivity increases (we show the response of total labor input n, which as the sum of labor in the tradable and non-tradable sectors, $n = n_H + n_N$, is the counterpart to the empirical hours worked variable used in the VAR models). Domestic consumption and investment also increase in a hump-shaped fashion. The relative price of home tradable goods in terms of the price of non-tradable goods, P_H/P_N, declines strongly.

The domestic responses to the productivity improvement are well in line with the empirical results. The increase in domestic GDP, consumption and investment is a standard

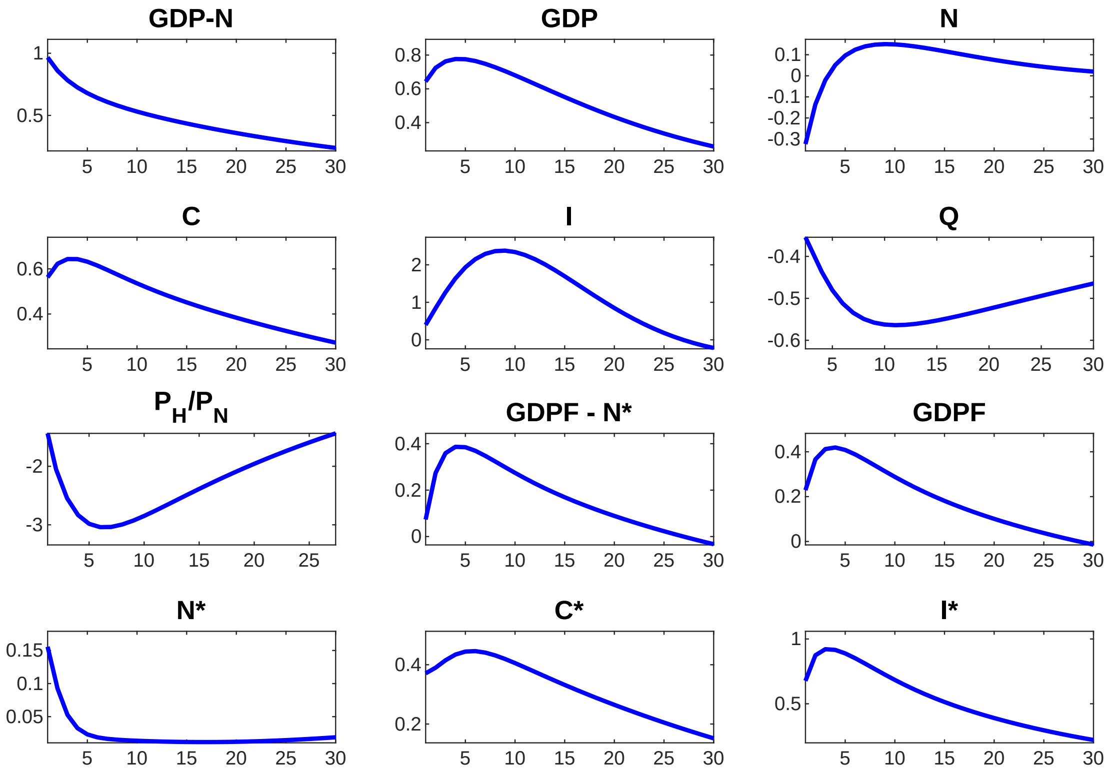


Figure 7: Model results. Surprise technology shock.

result that would hold in many RBC and New Keynesian models. The initially negative employment response is however entirely due to price stickiness, since with higher goods supply and limited short-term movements of their prices, the demand increase is not large enough to maintain the pre-shock employment level during the adjustment process. The real appreciation and the relative price decline of tradable goods are also in line with the empirical results.

Concerning the foreign responses to the domestic productivity shock, foreign GDP, total (tradable plus non-tradable sector) employment, consumption and investment all rise, but less so than their domestic counterparts. Since foreign employment increases slightly less than foreign GDP, foreign productivity increases somewhat. Thus, while the international transmission of the shock is generally positive, its quantitative effect is lower abroad than domestically. The model results accord well with the empirical evidence in that the foreign GDP response is about half as large, at its peak, as the domestic one. Qualitatively, all the aforementioned aspects, the positive but limited transmission on foreign GDP and its components, the slight increase in foreign hours that contrasts the strong initial decline in home hours, and the relatively small foreign productivity increase correspond to the empirical results shown above. However, the very persistent and hump-shaped increase in foreign employment that we found empirically cannot be explained by the model.

In the following, we discuss in more detail the transmission mechanism in the model that leads to an increase in home and foreign economic activity coupled with a real exchange rate appreciation. The surprise technology shock raises the supply of domestic tradable goods.

This lowers their prices, which in turn increases the demand for them, in particular for the relatively high demand elasticity η that we consider. As a partial effect, the decline in domestic tradable prices would lead to a real depreciation of the home currency. However, there is another partial effect that in general equilibrium generates a real appreciation. In particular, as the demand for home tradable goods rises due to their lower relative price, the demand for home non-tradable consumption and investment goods also increases, in particular since we assumed complementarity between both types of goods. Therefore, the production of domestic non-tradable goods expands, too. Since there is no productivity increase in the non-traded sector, this is associated with a relative price increase of domestic non-tradables. This second partial effect from a non-traded price increase is compatible with a domestic real appreciation, and for the chosen parameters it dominates the effect from a traded price decline, such that a real appreciation occurs in equilibrium.

Foreigners also increase their demand for home produced tradables that have become cheaper due to the technology improvement. Therefore, foreign output as well as consumption and investment rise, though the expenditure switching away from foreign goods is mitigated by the domestic real appreciation. Rising foreign consumption and investment must be matched by an increase in foreign non-traded production with an associated foreign non-tradable price increase (which takes place for the same reasons as in home). A home real appreciation, since it limits the foreign consumption and investment increase, thus also limits the non-tradable foreign demand increase, and thus leads to a relatively weak increase in foreign non-tradable prices, making the home real appreciation an equilibrium outcome.

Foreign productivity nevertheless rises, since home produced goods are used as intermediate goods in foreign production, such that the domestic technology improvement lowers foreign factor costs and makes foreign tradable production increase. This positive effect on foreign productivity is, however, relatively small (with a share of 0.175 for imported intermediates in foreign production), such that the additional foreign production can be absorbed without a decline in foreign employment, unlike the case in the domestic economy where the direct effect of the technology shock triggers a short-run decrease in domestic hours. In sum, the model is qualitatively compatible with the empirical evidence on a supply-induced domestic boom coinciding with a real appreciation of the home currency and a positive international transmission effect.

Figure 8 shows the theoretical impulse responses for the domestic anticipated technology shock. We assume that the shock is anticipated two periods before it materializes. The real exchange rate appreciation is actually very similar to the one under a surprise shock. Domestic productivity initially does not rise, even declines slightly, reflecting the delay between the anticipation and the realization of the technology improvement. The expected higher future productivity increases domestic wealth, such that home consumption demand rises. The same positive wealth effect would tend to reduce home labor supply, which is, however, overturned by the consumption-employment complementarity embedded in the

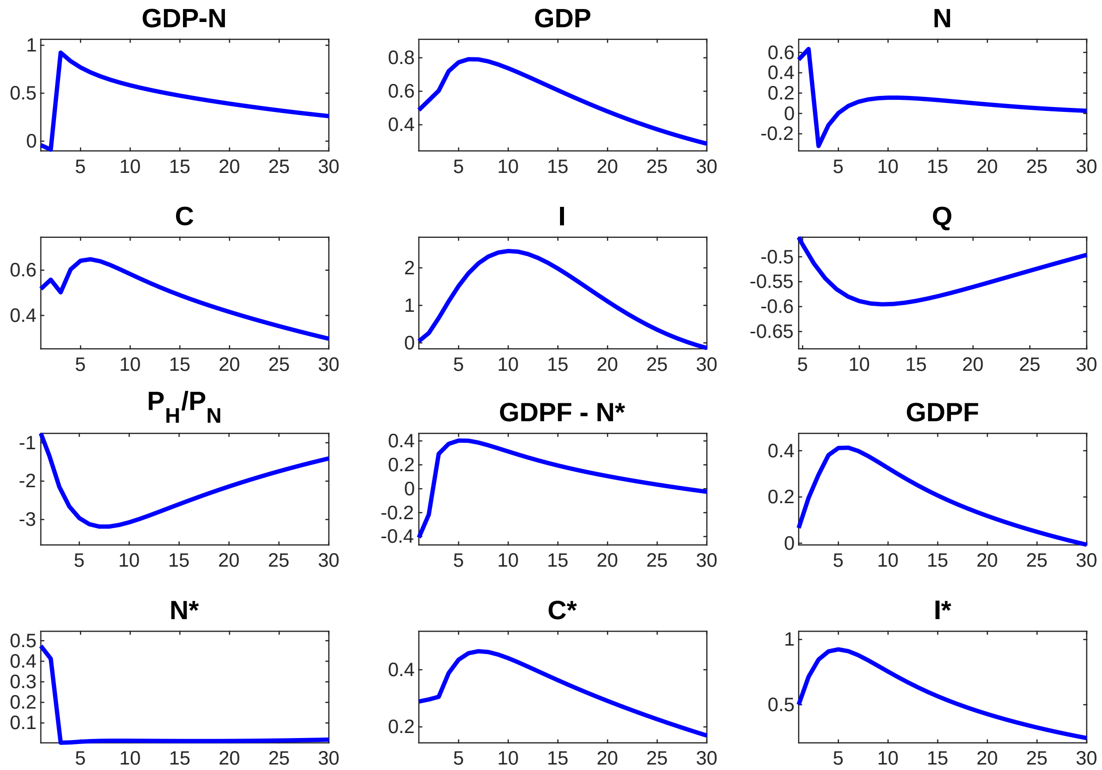


Figure 8: Model results. Anticipated technology shock.

nonseparable specification of household utility. Employment thus increases initially, while the negative employment effect of the realized productivity improvement that is due to price stickiness occurs only later to overturn the initial effect. The effect on relative prices is similar to one under the surprise shock such that the price of home tradable goods relative to non-tradable goods falls.

As for international transmission, the increased home production again lowers domestic tradable prices, since the future productivity improvement is frontloaded into declining prices due to the presence of price adjustment costs. As a consequence, foreign factor costs for imported intermediate inputs are lowered, such that foreign production increases. Foreign labor demand thus also rises, and the higher present value of foreign income increases foreign consumption, though quantitatively mitigated through the negative wealth effect of the real depreciation of the foreign currency. Investment reacts positively with a lag in both countries.

Compared to the empirical results, the model succeeds in capturing the delayed domestic and foreign productivity and investment increase, as well as the immediate domestic consumption increase. Contrary to the empirical evidence, however, GDP in the model rises also on impact, instead of with a delay. In the same vein, the lagged response of foreign consumption and GDP that we reported in the empirical section is not reproduced by the model, though in these cases the empirical results were rather imprecisely estimated such that there is considerable uncertainty concerning the effects in the data. The hump-shaped positive empirical response of foreign employment is also not captured by the model, and the weakly negative foreign productivity response only holds in the initial periods in the model. However, from a qualitative perspective, the model is able to reproduce our empirical finding of a boom in the domestic and foreign economy together with an appreciation of the real exchange rate in response to an anticipated technology shock in the home economy.[16]

4.3 Sensitivity

To assess the sensitivity of the model results with respect to a number of key parameters, Figure 9 shows several impulse responses to a surprise technology shock for different parameter constellations. The legend in Figure 9 describes which parameter is changed, whereas all other parameters are kept at their baseline values. We only show the sensitivity analysis for the surprise shock, since the conclusions for a news shock would be similar (the corresponding figure for the news shock is available upon request).

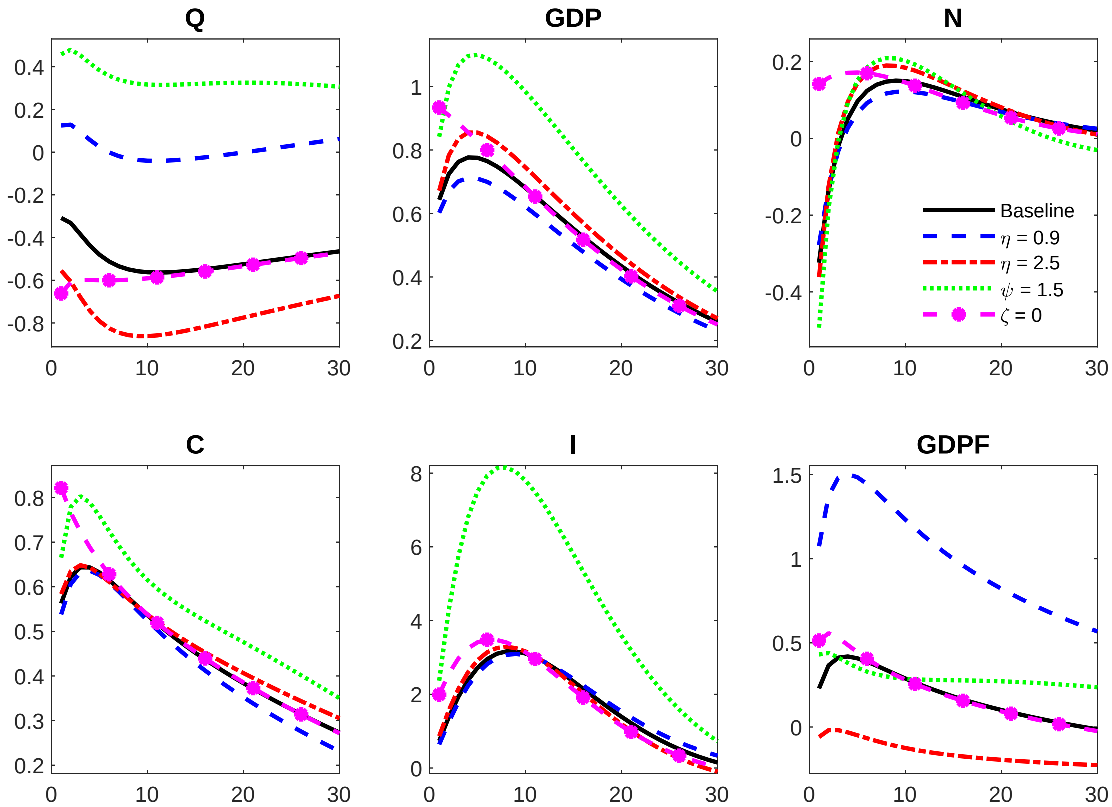


Figure 9: Sensitivity. Surprise technology shock.

The dashed and the dashed-dotted lines in Figure 9 show the crucial importance of the trade elasticity η. With a low trade elasticity ($\eta = 0.9$, dashed lines), the real exchange rate depreciates, and the effect on foreign output is stronger than the domestic one. The same would be true (only more strongly) for even lower trade elasticities. The reason for these counterfactual outcomes is that with relatively inelastic demand for home tradables,

[16]Figure A6 in the Appendix also shows the responses of the nominal exchange rate, home and foreign inflation, and home and foreign interest rates to both technology shocks. Very much in line with the empirical evidence on the surprise technology shocks, the model produces an appreciation of the nominal exchange rate, a fall in home and foreign prices, together with a reduction in both policy rates. The anticipated technology shock leads to a similar fall in the exchange rate whereas the reduction in both inflation and interest rates is more delayed.

the increased supply leads to a larger price decline which lowers the price of the domestic consumption basket strongly enough such that a real depreciation results. In this case, there is a very strong positive effect on foreign real variables, since the demand switch to home tradables is limited. Conversely, the dashed-dotted lines show the effect of a larger trade elasticity $\eta = 2.5$. The domestic real appreciation turns out considerably stronger, but the spillover to foreign GDP is non-positive and thus much weaker than in the baseline case. The reason is that with a more price elastic demand for domestic tradables, a technology improvement in this sector entails a larger demand shift away from foreign tradables. While non-tradable foreign production still increases, for a very high trade elasticity this does not suffice to overcompensate the decline in foreign tradable production by much. Likewise, the positive effect on foreign productivity through cheaper intermediate inputs imported from the home country is too weak to ensure a strong positive spillover to foreign GDP in the high trade elasticity case. As a consequence, there is a trade-off between the model's ability to engender a quantitatively strong real appreciation in response to a home tradable technology shock and its ability to predict a sizeable positive effect on foreign GDP, since the first aspect is achieved by a high and the second by a low trade elasticity.

A reverse consideration is true with respect to the substitution elasticity between tradable and non-tradable goods, ψ. The dotted lines in Figure 9 show the case of $\psi = 1.5$, i.e. a much higher elasticity than the baseline case $\psi = 0.5$. If non-tradables and tradables are more easily substituted, a real depreciation obtains, since the technology shock in tradables leads to a weaker accompanying increase in non-tradables, and thus to a weaker non-tradable price increase. Conversely, with higher substitutability the switch towards more productive tradables, both in their roles as final demand and intermediate inputs, is stronger since tradable demand is tied less closely to relatively unproductive non-tradable production. As a consequence, domestic output, consumption and particularly investment rise strongly. Thus, high substitutability between traded and non-traded goods yields the combined result of very strong domestic responses coupled with a real depreciation, which is in contrast to the empirical evidence.

Finally, the dashed-circled lines in Figure 9 depict the case of zero price adjustment costs, $\zeta = 0$. Price flexibility eliminates the hump-shaped pattern in the response of the real exchange rate, GDP, and consumption. More importantly, under price flexibility domestic hours worked increases already in the short run in response to a technology shock, in stark contrast to the empirical result reported above. Consequently, while most qualitative model results would go through with price flexibility, stickiness is essential to explain the short-run domestic employment response.

To sum up, the ability of the model to replicate the empirical results reported above rests on a moderately high trade elasticity, combined with complementarity between tradable and non-tradable goods and short-run price stickiness.

5 Conclusion

This paper has presented empirical evidence for the international effects of US technology shocks using a novel identification approach. We have used the proxy-instrumental variable method to identify both surprise and anticipated technological shocks in structural vector autoregressions, applied to a panel setting to empirically study the international transmission of US technology innovations to the rest of the G7 countries.

The empirical results show that a US technology improvement, be it surprising or anticipated, leads to a strong and persistent real appreciation (from the point of view of the US). This effect is precisely estimated and highly robust to changes in the empirical specification, and is associated with a decrease in tradable and an increase in non-tradable goods prices domestically. Positive US technology shocks have an expansionary effect on domestic output, consumption, and investment, but a short-run contractionary effect on domestic hours worked. Internationally, there is a strong and precisely estimated positive spillover on foreign output, consumption, labor productivity and hours worked in the case of surprise shocks, and a less significant but still mostly non-negative international spillover effect in the case of anticipated shocks.

A large literature literature in open economy macroeconomics has noted that a negative correlation between real exchange rates and private consumption appears puzzling from the point of view of basic models where perfect financial markets ensure efficient international risk-sharing. Our empirical results suggest that this negative real exchange rate - consumption link is also present conditional on surprise and anticipated technological shocks. However, we show that this finding is qualitatively compatible with a New Keynesian international business cycle model with imperfect financial markets, provided the elasticity of tradable goods demand is relatively large.

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Appendix

A1.1 Data description and sources

United States

Labor productivity: Real gross domestic product (FRED Database, GDPC1) divided by total hours worked in the non-financial business sector (downloaded from Valerie Rameys' homepage,
https://econweb.ucsd.edu/∼vramey/research.html#data).

Real GDP: Real gross domestic product (FRED Databbse, GDPC1).

Real consumption: Real Personal Consumption Expenditures (FRED Database, PCECC96).

Real investment: Real Gross Private Domestic Investment (FRED Database, GPDIC1).

Stock prices: NASDAQ composite index (FRED Database, NASDAQCOM).

CPI-based real exchange rate: US dollar to G6 national currency nominal exchange rate (inverse of national currency to US dollar exchange rate from FRED Database, see below) times G6 consumer price index (FRED Database) over US consumer price index (FRED Database, CPIAUCSL).

Hours worked: Total hours worked in the non-financial business sector (downloaded from Valerie Rameys' homepage, https://econweb.ucsd.edu/∼vramey/research.html#data).

Consumer price index: Consumer price index for all urban consumers (FRED Database, CPIAUCSL).

Interest rate: Effective federal funds rate (FRED Database, FEDFUNDS).

Export prices: Deflator of exports of goods and services (OECD Economic Outlook Database).

Service prices: Consumer price index for all urban consumers, services less energy services (FRED Database, CUSR0000SASLE).

G6 countries

Nominal exchange rate: Canada: National currency to US dollar exchange rate (FRED Database, CCUSMA02CAQ618N), France: National currency to US dollar exchange rate (FRED Database, CCUSMA02FRQ618N), Germany: National currency to US dollar exchange rate (FRED Database, CCUSMA02DEQ618N), United Kingdom: National currency to US dollar exchange rate (FRED Database, CCUSMA02GBQ618N), Japan: National currency to US dollar exchange rate (FRED Database, CCUSMA02JPQ618N), Italy: National currency to US dollar exchange rate (FRED Database, CCUSMA02ITQ618N).

Consumer price index: Canada: Consumer price index, total, all items (FRED Database, CPALCY01CAM661N), France: Consumer price index, total, all items (FRED Database, FRACPIALLMINMEI), Germany: Consumer price index, total, all items (FRED Database, DEUCPIALLMINMEI), United Kingdom: Consumer price index, total, all items (FRED Database, GBRCPIALLMINMEI), Japan: Consumer price index, total, all items (FRED Database, JPNCPIALLQINMEI), Italy: Consumer price index, total, all items (FRED Database, ITACPIALLQINMEI).

Real GDP: Canada: Gross domestic product by expenditure in constant prices (FRED Database, NAEXKP01CAQ661S), France: Gross domestic product, national currency, volume estimates, OECD reference year (OECD Economic Outlook Database), Germany: Real gross domestic product (Bundesbank, BBNZ1.Q.DE.Y.H.0000.L), United Kingdom: Gross domestic product, national currency, volume estimates, OECD reference year (OECD Economic Outlook Database), Japan: Real gross domestic product (FRED Database, JPNRGDPEXP, and Cabinet Office), Italy: Gross domestic product, national currency, volume estimates, OECD reference year (OECD Economic Outlook Database).

Real consumption: Canada: Gross domestic product by expenditure in constant prices: Private final consumption expenditure (FRED Database, NAEXKP02CAQ661S), France: Private final consumption expenditure, national currency, volume estimates, OECD reference year (OECD Economic Outlook Database), Germany: Real private final consumption expenditure (Bundesbank, BBNZ1.Q.DE.Y.H.0103.L), United Kingdom: Private final consumption expenditure, national currency, volume estimates, OECD reference year (OECD Economic Outlook Database), Japan: Real private consumption expenditure (FRED Database, JPNRGDPPC, and Cabinet Office), Italy: Private final consumption expenditure, national currency, volume estimates (OECD Economic Outlook Database).

Real investment: Canada: Gross fixed capital formation, national currency, volume estimates, OECD reference year (OECD Economic Outlook Database), France: Gross fixed capital formation, national currency, volume estimates, OECD reference year (OECD Economic Outlook Database), Germany: Gross fixed capital formation, national currency, volume estimates, OECD reference year (OECD Economic Outlook Database), United Kingdom: Gross fixed capital formation, national currency, volume estimates, OECD reference year (OECD Economic Outlook Database), Japan: Gross fixed capital formation, national currency, volume estimates, OECD reference year (OECD Economic Outlook Database), Italy: Gross fixed capital formation, national currency, volume estimates, OECD reference year (OECD Economic Outlook Database).

Hours worked: Canada: Hours worked per worker times total employment, total economy (OECD Economic Outlook Database), France: Hours worked per worker times total employment, total economy (OECD Economic Outlook Database), Germany: Hours worked per worker times total employment, total economy (OECD Economic Outlook Database), United Kingdom: Hours worked per worker times total employment, total economy (OECD Economic Outlook Database), Japan: Hours worked per worker times total employment, total economy (OECD Economic Outlook Database), Italy: Hours worked per worker times total employment, total economy (OECD Economic Outlook Database).

Labor productivity: Real GDP divided by hours worked.

Interest rate: Canada: Central bank rate (FRED Database: IRSTCB01CAM156N), France: Central bank rate (FRED Database, IRSTCI01FRM156N), Germany: Central bank rate (FRED Database, IRSTCI01DEM156N), United Kingdom: Bank of England policy rate (1973q1-1977q4, FRED Database, BOERUKM) and call money rate (1978q1-2019q, FRED Database, IRSTCI01GBM156N), Japan: Central bank rate (FRED Database, IRSTCB01JPM156N), Italy: Discount rate (1973q1-1998q4, FRED Database, INTDSRITM193N) and Euro area call money rate (1999q1-2019q2, FRED Database, IRSTCI01EZM156N).

G6 aggregate variables: We construct G6 aggregates by first calculating quarterly growth rates, then aggregating the growth rates weighted by each country's GDP share in the group's total GDP, and finally integrating to get levels. The GDP shares after 1980 are calculated from the PPP-based GDP shares of the world total that we obtain from the International Monetary Fund. For the years before 1980, we fix each countries share to the respective value in 1980.

A1.2 The model

A1.2.1 Households

All variables are understood as per capita values unless otherwise stated. Domestic households maximize

$$E_0 \sum_{t=0}^{\infty} \beta^t \frac{\left(c_t^{\chi} l_t^{1-\chi}\right)^{1-\sigma}}{1-\sigma}, \quad \chi, \beta \in (0,1), \sigma > 0,$$

where c is consumption, l is leisure, and E_0 is conditional expectation as of time 0. Maximization takes place subject to the budget constraint

$$\frac{P_{It}}{P_t} i_t + c_t + b_t^H \leq w_{Ht} n_{Ht} + w_{Nt} n_{Nt} + r_t k_t + \frac{R_{t-1} b_{t-1}^H}{\pi_t} + d_t - \frac{\phi}{2}(b_t^H - b^H)^2, \tag{A.2}$$

with $\phi > 0$. Here, i is investment in the capital stock k (used in the traded goods sector), b^H is the real value of holdings of domestically issued non-contingent internationally traded bonds paying a nominal one period gross return R, $\pi_t = P_t/P_{t-1}$ is the gross consumer price inflation rate with P being the CPI, P_{It} is the price of investment goods (which may differ from the price of consumption goods since investment and consumption may have different shares of non-tradable components), r is the real rental rate obtained from lending capital to the traded goods sector firms, and n_N (n_H) is labor supplied to the non-traded (traded) goods sector, earning a consumption based real wage w_N (w_H). The term $\frac{\phi}{2}(b_t^H - b^H)^2$ captures bond adjustment costs (b^H is the steady state value of b_t^H) introduced to avoid nonstationarity (see Schmitt-Grohe and Uribe, 2003) where the parameter ϕ is chosen small enough such that these adjustment costs do not materially affect equilibrium dynamics. The variable d collects lump-sum payments to the household sector, consisting of firms' profits and the lump-sum rebate of the bond adjustment costs (such that these do not show up in the resource constraint). With a time budget of one, labor supply and leisure are related through $l_t = 1 - n_{Ht} - n_{Nt}$, and capital accumulates according to

$$k_{t+1} = (1-\delta)k_t + \left(1 - \frac{\kappa}{2}\left(\frac{i_t}{i_{t-1}} - 1\right)^2\right) i_t, \tag{A.3}$$

where $\delta \in (0,1)$ is the depreciation rate and $\kappa > 0$ is a parameter governing the size of investment adjustment costs.

Denoting the multiplier on the budget constraint by λ and the one on the accumulation constraint by $\xi\lambda$, the optimality conditions are

$$\lambda_t = \chi c_t^{\chi(1-\sigma)-1} \left(1 - n_{Ht} - n_{Nt}\right)^{(1-\sigma)(1-\chi)}, \tag{A.4}$$

$$\frac{1-\chi}{\chi} \frac{c_t}{1 - n_{Ht} - n_{Nt}} = w_t, \tag{A.5}$$

$$\xi_t \lambda_t = \beta E_t \lambda_{t+1} \left[r_{t+1} + \xi_{t+1}(1-\delta)\right], \tag{A.6}$$

$$\begin{aligned} \lambda_t \frac{P_{It}}{P_t} = \xi_t \lambda_t & \left[\left(1 - \frac{\kappa}{2}\left(\frac{i_t}{i_{t-1}} - 1\right)^2\right) - \kappa\left(\frac{i_t}{i_{t-1}} - 1\right)\frac{i_t}{i_{t-1}}\right] \\ & + \beta\kappa E_t \xi_{t+1}\lambda_{t+1}\left(\frac{i_{t+1}}{i_t} - 1\right)\left(\frac{i_{t+1}}{i_t}\right)^2, \end{aligned} \tag{A.7}$$

$$\lambda_t \left[1 + \phi\left(b_t^H - b^H\right)\right] = \beta E_t \lambda_{t+1} \frac{R_t}{\pi_{t+1}}, \tag{A.8}$$

together with a transversality condition and the budget at equality. Since working in the traded and non-traded sectors is perfectly substitutable for households, the real wage in both sectors must be equal, $w_{Ht} = w_{Nt}$ and is simply denoted by w_t in (A.5) and henceforth.

Foreign households are similar. They can also invest in the domestic bond, but for simplicity we assume they are not subject to bond adjustment costs, and in a local foreign currency bond with gross nominal interest R_t^* that is not internationally traded and is in zero net supply (and only serves to define the foreign gross nominal interest rate R^*). Therefore, their optimality conditions are

$$\lambda_t^* = \beta E_t \lambda_{t+1}^* \frac{R_t^*}{\pi_{t+1}^*},$$

$$\lambda_t^* = \beta E_t \lambda_{t+1}^* \frac{q_t}{q_{t+1}} \frac{R_t}{\pi_{t+1}},$$

where an asterisk denotes a foreign variable, together with the foreign equivalents of (A.3) to (A.7). Here, q is the consumption based real exchange rate defined as $q_t = X_t P_t^*/P_t$, where X is the nominal price of a unit of foreign currency in terms of domestic currency, and P (P^*) is the home (foreign) CPI price level.

A1.2.2 Consumption

Goods produced in either economy can be used for consumption or investment (adding to the capital stock in the traded production sector) in both countries, or as an intermediate input in the other country's tradable goods sector.

Total per capita consumption c consists of consumption of traded goods c_T and non-traded goods c_N, with the aggregator

$$c_t = \left[(1-\mu)^{1/\psi} c_{Tt}^{\frac{\psi-1}{\psi}} + \mu^{1/\psi} c_{Nt}^{\frac{\psi-1}{\psi}}\right]^{\frac{\psi}{\psi-1}},$$

where $\mu \in (0,1)$ is a share parameter denoting the relative size of non-traded consumption, and $\psi > 0$ is the substitution elasticity between both types of goods. The associated CPI price level is

$$P_t = \left[(1-\mu)P_{Tt}^{1-\psi} + \mu P_{Nt}^{1-\psi}\right]^{\frac{1}{1-\psi}},$$

where P_T (P_N) denotes the price level of traded (non-traded) goods. Optimal demands are

$$c_{Tt} = (1-\mu)\left(\frac{P_{Tt}}{P_t}\right)^{-\psi} c_t, \quad c_{Nt} = \mu\left(\frac{P_{Nt}}{P_t}\right)^{-\psi} c_t.$$

Tradable consumption consists of home (foreign) produced consumption goods c_H (c_F), with aggregator

$$c_{Tt} = \left[(1-\gamma)^{1/\eta} c_{Ht}^{\frac{\eta-1}{\eta}} + \gamma^{1/\eta} c_{Ft}^{\frac{\eta-1}{\eta}}\right]^{\frac{\eta}{\eta-1}}, \tag{A.9}$$

with share parameter $\gamma \in (0,1)$ and substitution elasticity $\eta > 0$. The associated tradable price level is

$$P_{Tt} = \left[(1-\gamma)P_{Ht}^{1-\eta} + \gamma P_{Ft}^{1-\eta}\right]^{\frac{1}{1-\eta}},$$

where P_H (P_F) denotes the price level of home (foreign) produced goods in domestic currency, and the optimal demands are

$$c_{Ht} = (1-\gamma)\left(\frac{P_{Ht}}{P_{Tt}}\right)^{-\eta} c_{Tt}, \quad c_{Ft} = \gamma\left(\frac{P_{Ft}}{P_{Tt}}\right)^{-\eta} c_{Tt}.$$

A similar demand structure in the foreign country gives rise to foreign demand for home (foreign) produced consumption goods c_H^* (c_F^*),

$$c_{Ht}^* = (1-\gamma^*)\left(\frac{P_{Ht}^*}{P_{Tt}^*}\right)^{-\eta} c_{Tt}^*, \quad c_F^* = \gamma^*\left(\frac{P_F^*}{P_T^*}\right)^{-\eta} c_T^*,$$

where the foreign currency price indices are given as

$$P_t^* = \left[(1-\mu^*)P_{Tt}^{*1-\psi} + \mu^* P_{Nt}^{*1-\psi}\right]^{\frac{1}{1-\psi}}, \ P_{Tt}^* = \left[(1-\gamma^*)P_{Ht}^{*1-\eta} + \gamma^* P_{Ft}^{*1-\eta}\right]^{\frac{1}{1-\eta}}.$$

There is a measure $m \in (0,1)$ of home based firms each producing a tradable variety that can be used as a consumption or investment good or as an intermediate input in the other economy, and a measure $1-m$ of foreign firms / varieties. Denoting the individual home (foreign) produced variety by c_{Hi} (c_{Fi}), the aggregators are

$$c_{Ht} = \left(\int_0^m \left(\frac{1}{m}\right)^{\frac{1}{\theta}} c_{Hit}^{\frac{\theta-1}{\theta}} di\right)^{\frac{\theta}{\theta-1}}, \quad c_{Ft} = \left(\int_m^1 \left(\frac{1}{1-m}\right)^{\frac{1}{\theta}} c_{Fit}^{\frac{\theta-1}{\theta}} di\right)^{\frac{\theta}{\theta-1}},$$

where $\theta > 1$ is the substitution elasticity between individual varieties, hence demands are

$$c_{Hit} = \frac{1}{m}\left(\frac{P_{Hit}}{P_{Ht}}\right)^{-\theta} c_{Ht}, \quad c_{Fit} = \frac{1}{1-m}\left(\frac{P_{Fit}}{P_{Ft}}\right)^{-\theta} c_{Ft}, \tag{A.10}$$

where P_{Hi} (P_{Fi}) is the i-th individual home (foreign) produced variety's price in domestic currency, and $P_{Ht} = \left(\int_0^m \left(\frac{1}{m}\right) P_{Hit}^{1-\theta} di\right)^{\frac{1}{1-\theta}}$ and $P_{Ft} = \left(\int_m^1 \left(\frac{1}{1-m}\right) P_{Fit}^{1-\theta} di\right)^{\frac{1}{1-\theta}}$.

Foreigners are similar and thus have demand functions

$$c_{Hit}^* = \frac{1}{m}\left(\frac{P_{Hit}^*}{P_{Ht}^*}\right)^{-\theta} c_{Ht}^*, \quad c_{Fit}^* = \frac{1}{1-m}\left(\frac{P_{Fit}^*}{P_{Ft}^*}\right)^{-\theta} c_{Ft}^* \tag{A.11}$$

where c_{Hi}^* (c_{Fi}^*) is consumption of the i-the individual home (foreign) produced variety by foreigners, c_H^* and c_F^* are the corresponding aggregates, and P_H^* and P_F^* are the price indices of home (foreign) goods in foreign currency.

There are also m producers in the home non-traded sector. Individual non-traded goods c_{Ni} aggregate in the same way as traded goods, such that demand is

$$c_{Nit} = \frac{1}{m}\left(\frac{P_{Nit}}{P_{Nt}}\right)^{-\theta} c_{Nt}, \tag{A.12}$$

with P_{Ni} the price of the individual non-traded variety, and $P_{Nt} = \left(\int_0^m \left(\frac{1}{m}\right) P_{Nit}^{1-\theta}\right)^{\frac{1}{1-\theta}} di.$ Likewise, the $1-m$ producers in the foreign non-traded sector face demands

$$c_{Nit}^* = \frac{1}{1-m}\left(\frac{P_{Nit}^*}{P_{Nt}^*}\right)^{-\theta} c_{Nt}^* \tag{A.13}$$

with the foreign currency non-traded price index $P_{Nt}^* = \left(\int_0^{1-m}\left(\frac{1}{1-m}\right) P_{Nit}^{*1-\theta} di\right)^{\frac{1}{1-\theta}}$.

A1.2.3 Investment

Investment is also composed of tradable (i_T) and non-tradable (i_N) investment goods aggregating through

$$i_t = \left[(1-\omega)^{1/\psi} i_{Tt}^{\frac{\psi-1}{\psi}} + \omega^{1/\psi} i_{Nt}^{\frac{\psi-1}{\psi}}\right]^{\frac{\psi}{\psi-1}},$$

with $\omega \in (0,1)$, giving rise to the demand functions

$$i_{Tt} = (1-\omega)\left(\frac{P_{Tt}}{P_{It}}\right)^{-\psi} i_t, \quad i_{Nt} = \omega\left(\frac{P_{Nt}}{P_{It}}\right)^{-\psi} i_t,$$

where the associated investment price level is

$$P_{It} = \left[(1-\omega)P_{Tt}^{1-\psi} + \omega P_{Nt}^{1-\psi}\right]^{\frac{1}{1-\psi}}.$$

The composition of the tradable component of investment is the same as for tradable consumption (see A.9), such that demand functions are

$$i_{Ht} = (1-\gamma)\left(\frac{P_{Ht}}{P_{Tt}}\right)^{-\eta} i_{Tt}, \quad i_{Ft} = \gamma\left(\frac{P_{Ft}}{P_{Tt}}\right)^{-\eta} i_{Tt}$$

where i_H (i_F) is the domestic (foreign) component of tradable investment.

In the foreign economy, the investment goods structure is similar, with potentially different share parameters ω^* and γ^*, such that foreign investment demand functions are

$$i_{Tt}^* = (1-\omega^*)\left(\frac{P_{Tt}^*}{P_{It}^*}\right)^{-\psi} i_t^*, \quad i_{Nt}^* = \omega^*\left(\frac{P_{Nt}^*}{P_{It}^*}\right)^{-\psi} i_t^*,$$
$$i_{Ht}^* = (1-\gamma^*)\left(\frac{P_{Ht}^*}{P_{Tt}^*}\right)^{-\eta} i_{Tt}^*, \quad i_{Ft}^* = \gamma^*\left(\frac{P_{Ft}^*}{P_{Tt}^*}\right)^{-\eta} i_{Tt}^*$$

The composition of investment with respect to individual varieties is the same as for consumption goods, such that individual investment goods demands have the same structure as individual consumption goods demands, see (A.10) and (A.12, A.13).

A1.2.4 Intermediate goods

Firms in the home (foreign) tradable goods sector use intermediate goods imported from the foreign (home) country as inputs in the production process. In the home (foreign) economy, there is a measure m $(1-m)$ of perfectly competitive firms that bundle foreign (home) produced goods into intermediate inputs for use in the home (foreign) tradable production sector. Each domestic bundler buys foreign intermediate goods v_{Fi} at individual prices P_{Fi} and assembles the intermediate input v from them that is then sold at the price P_F to domestic tradable goods firms. The intermediate input production function is

$$v_t = \left(\int_m^1 \left(\frac{1}{1-m} \right)^{\frac{1}{\theta}} v_{Fit}^{\frac{\theta-1}{\theta}} di \right)^{\frac{\theta}{\theta-1}},$$

and the bundler chooses v_{Fi} to maximize

$$P_{Ft} \left(\int_m^1 \left(\frac{1}{1-m} \right)^{\frac{1}{\theta}} v_{Fit}^{\frac{\theta-1}{\theta}} di \right)^{\frac{\theta}{\theta-1}} - \int_m^1 P_{Fit} v_{Fit} di$$

giving rise to the demand function

$$v_{Fit} = \frac{1}{1-m} \left(\frac{P_{Fit}}{P_{Ft}} \right)^{-\theta} v_t.$$

Likewise, a foreign bundler buys home produced intermediate goods varieties v^*_{Hi} at price P^*_{Hi} and sells them to foreign traded goods firms at price P^*_H, such that the demand function is

$$v^*_{Hit} = \frac{1}{m} \left(\frac{P^*_{Hit}}{P^*_{Ht}} \right)^{-\theta} v^*_t.$$

Since intermediate goods are the same goods as those used for consumption and investment purposes, the aggregate price indices of intermediates P_F and P^*_H are the same as given above.

A1.2.5 Law of one price and market clearing

The law of one price holds on the level of traded varieties, $P_{Hit} = X_t P^*_{Hit}$, $P_{Fit} = X_t P^*_{Fit}$, and consequently also on the level of price indices,

$$P_{Ht} = X_t P^*_{Ht}, \quad P_{Ft} = X_t P^*_{Ft}.$$

Consequently, since there are m home consumers and $1-m$ foreign consumers, and the same number of firms in each sector in each country, total demand for a home tradable variety can be written as

$$y_{Hit} = \left(\frac{P_{Hit}}{P_{Ht}} \right)^{-\theta} (c_{Ht} + i_{Ht}) + \frac{1-m}{m} \left(\frac{P^*_{Hit}}{P^*_{Ht}} \right)^{-\theta} (c^*_{Ht} + i^*_{Ht} + v^*_t), \tag{A.14}$$

and total demand for a foreign traded variety is

$$y_{Fit} = \frac{m}{1-m}\left(\frac{P_{Fit}}{P_{Ft}}\right)^{-\theta}(c_{Ft} + i_{Ft} + v_t) + \left(\frac{P^*_{Fit}}{P^*_{Ft}}\right)^{-\theta}(c^*_{Ft} + i^*_{Ft}), \tag{A.15}$$

whereas demand for a non-traded home variety is

$$y_{Nit} = m\,(c_{Nit} + i_{Nit}) = \left(\frac{P_{Nit}}{P_{Nt}}\right)^{-\theta}(c_{Nt} + i_{Nt}), \tag{A.16}$$

and for a non-traded foreign variety is

$$y^*_{Nit} = (1-m)\,(c^*_{Nit} + i^*_{Nit}) = \left(\frac{P^*_{Nit}}{P^*_{Nt}}\right)^{-\theta}(c^*_{Nt} + i^*_{Nt}). \tag{A.17}$$

A1.2.6 Firms

Firms in each sector are monopolistic competitors each producing a particular variety of the output good subject to Rotemberg (1982) - style quadratic price adjustment costs in setting producer currency prices. The size of these price adjustment costs is assumed to be the same in all sectors. Firms in the domestic and foreign tradable sectors produce using labor, capital and imported intermediate goods inputs, whereas the non-traded sectors use only labor for simplicity. Additionally, domestic tradable firms are subject to technology shocks.

An individual firm in the domestic tradable goods sector maximizes the present discounted value of real profits on behalf of its household-owners,

$$\sum_{t=0}^{\infty} E_0 \beta^t \frac{\lambda_{t+1}}{\lambda_t}\left[\frac{P_{Hit}}{P_{Ht}} y_{Hit} - w_t \frac{P_t}{P_{Ht}} n_{Hit} - r_t \frac{P_t}{P_{Ht}} k_{it} - \frac{\zeta}{2}\left(\frac{P_{Hit}}{P_{Hit-1}} - 1\right)^2 - \frac{P_{Ft}}{P_{Ht}} v_{it}\right],$$

where n_{Hi}, k_i and v_i are labor, capital and intermediate inputs rented by the i-th home traded sector firm, and $\zeta > 0$ measures the size of price adjustment costs. Maximization is subject to the demand constraint (A.14) and the production constraint

$$y_{Hit} = z_{Ht}\left(n^a_{Hit} k^{1-a}_{it}\right)^{\vartheta} v^{1-\vartheta}_{it}, \quad a, \vartheta \in (0,1),$$

where the technology level z_H follows an exogenous AR(1) with

$$z_{Ht} = (1-\rho) + \rho z_{Ht-1} + \varepsilon_t + \epsilon_{t-2},$$

where ε_t is a serially uncorrelated surprise random innovation, ϵ_{t-2} is a serially uncorrelated random anticipated technology innovation, and $\rho \in (0,1)$. In a symmetric equilibrium where $P_{Hi} = P_H$, each firm hires the same amount of factor inputs and produces the same quantity of output. Since the measure of firms, households and intermediate input bundlers is m, each firm's factor inputs are equal to aggregate per capita values n_H, k and v. Letting φ_H

be the multiplier on the demand constraint, symmetric optimality conditions thus are

$$\begin{aligned}
w_t \frac{P_t}{P_{Ht}} &= (1-\varphi_{Ht})\, a\vartheta \frac{y_{Ht}/m}{n_{Ht}}, \\
r_t \frac{P_t}{P_{Ht}} &= (1-\varphi_{Ht})\,(1-a)\vartheta \frac{y_{Ht}/m}{k_t}, \\
\frac{P_{Ft}}{P_{Ht}} &= (1-\varphi_{Ht})\,(1-\vartheta) \frac{y_{Ht}/m}{v_t}, \\
\frac{y_{Ht}}{m}\,(1-\varphi_{Ht}\theta) &= \zeta\,(\pi_{Ht}-1)\,\pi_{Ht} - \beta E_t \frac{\lambda_{t+1}}{\lambda_t}\zeta\,(\pi_{Ht+1}-1)\,\pi_{Ht+1},
\end{aligned}$$

where $\pi_{Ht} = P_{Ht}/P_{Ht-1}$ is domestic producer price inflation, and aggregate traded production is given by

$$y_{Ht} = m z_{Ht} \left(n_{Ht}^{a} k_t^{1-a}\right)^{\vartheta} v_t^{1-\vartheta}.$$

A similar setup in the traded sector of the foreign country, where the measure $1-m$ of firms produces aggregate foreign traded output y_F subject to (A.15) and without technology shocks, yields

$$\begin{aligned}
w_t^* \frac{P_t^*}{P_{Ft}^*} &= (1-\varphi_{Ft}^*)\, a\vartheta^* \frac{y_{Ft}^*/(1-m)}{n_{Ft}^*}, \\
r_t^* \frac{P_t^*}{P_{Ft}^*} &= (1-\varphi_{Ft}^*)\,(1-a)\vartheta^* \frac{y_{Ft}^*/(1-m)}{k_t^*}, \\
\frac{P_{Ht}^*}{P_{Ft}^*} &= (1-\varphi_{Ft}^*)\,(1-\vartheta^*) \frac{y_{Ft}^*/(1-m)}{v_t^*}, \\
\frac{y_{Ft}^*}{1-m}\,(1-\theta\varphi_{Ft}^*) &= \zeta\,(\pi_{Ft}^*-1)\,\pi_{Ft}^* - \beta E_t \frac{\lambda_{t+1}^*}{\lambda_t^*}\zeta\,(\pi_{Ft+1}^*-1)\,\pi_{Ft+1}^*,
\end{aligned}$$

where symbols with an asterisk are the foreign counterparts to the correspondig domestic variables, $\pi_{Ft}^* = P_{Ft}^*/P_{Ft-1}^*$ is foreign producer price inflation in foreign currency, and aggregate foreign traded output is

$$y_{Ft} = (1-m)\left(n_{Ft}^{*a} k_t^{*1-a}\right)^{\vartheta^*} (v_t^*)^{1-\vartheta^*}.$$

Note that the intermediate input share $1-\vartheta^*$ may be different in foreign compared to home.

Firms in the domestic non-tradable sector solve a similar problem, with the difference that for simplicity their production process uses only labor. Aggregating over m firms, the production function for aggregate domestic non-tradable output y_N is

$$y_{Nt} = m n_{Nt},$$

and the symmetric optimality conditions of the same Rotemberg pricing problem as described for tradable firms are

$$\begin{aligned}
w_t \frac{P_t}{P_{Nt}} &= (1-\varphi_{Nt}), \\
\frac{y_{Nt}}{m}\,(1-\varphi_{Nt}\theta) &= \zeta\,(\pi_{Nt}-1)\,\pi_{Nt} - E_t\beta \frac{\lambda_{t+1}}{\lambda_t}\zeta\,(\pi_{Nt+1}-1)\,\pi_{Nt+1},
\end{aligned}$$

where φ_N is the multiplier on (A.16), and $\pi_{Nt} = P_{Nt}/P_{Nt-1}$ is home non-tradable price inflation. A similar setup in the foreign non-tradables sector yields

$$
\begin{aligned}
y_{Nt}^* &= (1-m)n_{Nt}^*, \\
w_t^* \frac{P_t^*}{P_{Nt}^*} &= \left(1-\varphi_{Nt}^*\right), \\
\frac{y_{Nt}^*}{1-m}\left(1-\theta\varphi_{Nt}^*\right) &= \zeta\left(\pi_{Nt}^*-1\right)\pi_{Nt}^* - E_t\beta\frac{\lambda_{t+1}^*}{\lambda_t^*}\zeta\left(\pi_{Nt+1}^*-1\right)\pi_{Nt+1}^*,
\end{aligned}
$$

with foreing non-tradable price inflation in foreign currency denoted $\pi_{Nt}^* = P_{Nt}^*/P_{Nt-1}^*$.

A1.2.7 Monetary policy and budget constraint

In each country, a central bank follows a simple Taylor - type rule to choose the nominal interest rate R (R^*) in response inflation, with

$$
R_t = \frac{1}{\beta}R_{t-1}^{\rho_R}\pi_t^{\varphi(1-\rho_R)}, \quad R_t^* = \frac{1}{\beta}R_{t-1}^{*\rho_R}\pi_t^{*\varphi(1-\rho_R)}
$$

where $\pi_t = P_t/P_{t-1}$ ($\pi_t^* = P_t^*/P_{t-1}^*$) is domestic (foreign) CPI inflation, the parameter $\rho_R \in (0,1)$ allows for interest rate smoothing, φ is the long-run inflation reaction coefficient satisfying the Taylor principle $\varphi > 1$, and in a steady state with price stability the interest rates in both countries are $1/\beta$.

In equilibrium, all markets clear, and profits of all domestic firms are paid out in lump-sum way to domestic households. Aggregating the per-capita budget constraint (A.2) over m domestic households and using the definition of firm profits yields the aggregate home budget constraint

$$
\left(c_t + \frac{P_{It}}{P_t}i_t + b_t^H\right)m = m\frac{R_{t-1}b_{t-1}^H}{\pi_t} + \frac{P_{Ht}}{P_t}y_{Ht} + \frac{P_{Nt}}{P_t}y_{Nt} - m\frac{P_{Ft}}{P_t}v_t.
$$

The corresponding foreign budget constraint is redundant by Walras' law. For later use, we define domestic and foreign GDP as

$$
GDP_t = \frac{P_{Ht}}{P_t}y_{Ht} + \frac{P_{Nt}}{P_t}y_{Nt} - m\frac{P_{Ft}}{P_t}v_t, \quad GDP_{Ft} = \frac{P_{Ft}^*}{P_t^*}y_{Ft} + \frac{P_{Nt}^*}{P_t^*}y_{Nt}^* - (1-m)\frac{P_{Ht}^*}{P_t^*}v_t^*.
$$

A1.2.8 Overview of equilibrium conditions

The following overview gives a list of the model's equilibrium conditions. Relative price ratios are defined with respect to the respective country's consumer price level and denoted by lower case letters, such that

$$
\begin{aligned}
p_{Tt} &= \frac{P_{Tt}}{P_t}, p_{Nt} = \frac{P_{Nt}}{P_t}, p_{Ht} = \frac{P_{Ht}}{P_t}, p_{Ft} = \frac{P_{Ft}}{P_t}, p_{It} = \frac{P_{It}}{P_t}, \\
p_{Tt}^* &= \frac{P_{Tt}^*}{P_t^*}, p_{Nt}^* = \frac{P_{Nt}^*}{P_t^*}, p_{Ht}^* = \frac{P_{Ht}^*}{P_t^*} = \frac{p_{Ht}}{q_t}, p_{Ft}^* = \frac{P_{Ft}^*}{P_t^*} = \frac{p_{Ft}}{q_t}, p_{It}^* = \frac{P_{It}^*}{P_t^*},
\end{aligned}
$$

where the second line uses the law of one price, $P_{Ht} = X_tP_{Ht}^*$ and $P_{Ft} = X_tP_{Ft}^*$, and the definition of the real exchange rate $q_t = X_tP_t^*/P_t$.

Home households:

$$\lambda_t = \chi \left(c_t\right)^{\chi(1-\sigma)-1} \left(1 - n_{Ht} - n_{Nt}\right)^{(1-\sigma)(1-\chi)}$$

$$\frac{1-\chi}{\chi} \frac{c_t}{1 - n_{Ht} - n_{Nt}} = w_t$$

$$\xi_t \lambda_t = \beta E_t \lambda_{t+1} \left[r_{t+1} + \xi_{t+1}(1-\delta)\right]$$

$$\lambda_t p_{It} = \xi_t \lambda_t \left[\left(1 - \frac{\kappa}{2}\left(\frac{i_t}{i_{t-1}} - 1\right)^2\right) - \kappa \left(\frac{i_t}{i_{t-1}} - 1\right) \frac{i_t}{i_{t-1}}\right] + \beta \kappa E_t \xi_{t+1} \lambda_{t+1} \left(\frac{i_{t+1}}{i_t} - 1\right)\left(\frac{i_{t+1}}{i_t}\right)^2$$

$$\lambda_t \left[1 + \phi\left(b_t^H - b^H\right)\right] = \beta E_t \lambda_{t+1} \frac{R_t}{\pi_{t+1}}$$

Foreign households:

$$\lambda_t^* = \chi \left(c_t^*\right)^{\chi(1-\sigma)-1} \left(1 - n_{Ft}^* - n_{Nt}^*\right)^{(1-\sigma)(1-\chi)}$$

$$\frac{1-\chi}{\chi} \frac{c_t^*}{1 - n_{Ft}^* - n_{Nt}^*} = w_t^*$$

$$\xi_t^* \lambda_t^* = \beta E_t \lambda_{t+1}^* \left[r_{t+1}^* + \xi_{t+1}^*(1-\delta)\right]$$

$$\lambda_t^* p_{It}^* = \xi_t^* \lambda_t^* \left[\left(1 - \frac{\kappa}{2}\left(\frac{i_t^*}{i_{t-1}^*} - 1\right)^2\right) - \kappa \left(\frac{i_t^*}{i_{t-1}^*} - 1\right) \frac{i_t^*}{i_{t-1}^*}\right] + \beta \kappa E_t \xi_{t+1}^* \lambda_{t+1}^* \left(\frac{i_{t+1}^*}{i_t^*} - 1\right)\left(\frac{i_{t+1}^*}{i_t^*}\right)^2$$

$$\lambda_t^* = \beta E_t \lambda_{t+1}^* \frac{R_t^*}{\pi_{t+1}^*}$$

$$\lambda_t^* = \beta E_t \lambda_{t+1}^* \frac{q_t}{q_{t+1}} \frac{R_t}{\pi_{t+1}}$$

Capital accumulation:

$$k_{t+1} = (1-\delta) k_t + \left(1 - \frac{\kappa}{2}\left(\frac{i_t}{i_{t-1}} - 1\right)^2\right) i_t$$

$$k_{t+1}^* = (1-\delta) k_t^* + \left(1 - \frac{\kappa}{2}\left(\frac{i_t^*}{i_{t-1}^*} - 1\right)^2\right) i_t^*$$

Consumption demand:

$$c_{Tt} = (1-\mu) p_{Tt}^{-\psi} c_t$$

$$c_{Nt} = \mu p_{Nt}^{-\psi} c_t$$

$$c_{Tt}^* = \left(1 - \mu^*\right) \left(p_{Tt}^*\right)^{-\psi} c_t^*$$

$$c_{Nt}^* = \mu^* \left(p_{Nt}^*\right)^{-\psi} c_t^*$$

$$c_{Ht} = (1-\gamma)\left(\frac{p_{Ht}}{p_{Tt}}\right)^{-\eta} c_{Tt}$$
$$c_{Ft} = \gamma\left(\frac{p_{Ft}}{p_{Tt}}\right)^{-\eta} c_{Tt}$$

$$c^*_{Ht} = (1-\gamma^*)\left(\frac{p_{Ht}/q_t}{p^*_{Tt}}\right)^{-\eta} c^*_{Tt}$$
$$c^*_{Ft} = \gamma^*\left(\frac{p_{Ft}/q_t}{p^*_{Tt}}\right)^{-\eta} c^*_{Tt}$$

Investment demand:

$$i_{Tt} = (1-\omega)\left(\frac{p_{Tt}}{p_{It}}\right)^{-\psi} i_t$$
$$i_{Nt} = \omega\left(\frac{p_{Nt}}{p_{It}}\right)^{-\psi} i_t$$

$$i^*_{Tt} = (1-\omega^*)\left(\frac{p^*_{Tt}}{p^*_{It}}\right)^{-\psi} i^*_t$$
$$i^*_{Nt} = \omega^*\left(\frac{p^*_{Nt}}{p^*_{It}}\right)^{-\psi} i^*_t$$

$$i_{Ht} = (1-\gamma)\left(\frac{p_{Ht}}{p_{Tt}}\right)^{-\eta} i_{Tt}$$
$$i_{Ft} = \gamma\left(\frac{p_{Ft}}{p_{Tt}}\right)^{-\eta} i_{Tt}$$

$$i^*_{Ht} = (1-\gamma^*)\left(\frac{p_{Ht}/q_t}{p^*_{Tt}}\right)^{-\eta} i^*_{Tt}$$
$$i^*_{Ft} = \gamma^*\left(\frac{p_{Ft}/q_t}{p^*_{Tt}}\right)^{-\eta} i^*_{Tt}$$

Market clearing:

$$y_{Ht} = m(c_{Ht} + i_{Ht}) + (1-m)(c^*_{Ht} + i^*_{Ht} + v^*_t)$$

$$y_{Ft} = m\left(c_{Ft} + i_{Ft} + v_t\right) + (1-m)\left(c^*_{Ft} + i^*_{Ft}\right)$$

$$y_{Nt} = m\left(c_{Nt} + i_{Nt}\right)$$
$$y^*_{Nt} = (1-m)\left(c^*_{Nt} + i^*_{Nt}\right)$$

Tradable goods production and pricing:

$$
\begin{aligned}
y_{Ht} &= m z_{Ht} \left(n_{Ht}^{a} k_t^{1-a} \right)^{\vartheta} v_t^{1-\vartheta} \\
w_t/p_{Ht} &= \left(1-\varphi_{Ht}\right) a\vartheta \frac{y_{Ht}/m}{n_{Ht}} \\
r_t/p_{Ht} &= \left(1-\varphi_{Ht}\right)(1-a)\vartheta \frac{y_{Ht}/m}{k_t} \\
p_{Ft}/p_{Ht} &= \left(1-\varphi_{Ht}\right)(1-\vartheta) \frac{y_{Ht}/m}{v_t} \\
\frac{y_{Ht}}{m}\left(1-\varphi_{Ht}\theta\right) &= \zeta\left(\pi_{Ht}-1\right)\pi_{Ht} - \beta E_t \frac{\lambda_{t+1}}{\lambda_t} \zeta \left(\pi_{Ht+1}-1\right)\pi_{Ht+1}
\end{aligned}
$$

$$
\begin{aligned}
y_{Ft} &= (1-m) \left(n_{Ft}^{*a} k_t^{*1-a} \right)^{\vartheta^*} \left(v_t^*\right)^{1-\vartheta^*} \\
w_t^* q_t/p_{Ft} &= \left(1-\varphi_{Ft}^*\right) a\vartheta^* \frac{y_{Ft}^*/(1-m)}{n_{Ft}^*} \\
r_t^* q_t/p_{Ft} &= \left(1-\varphi_{Ft}^*\right)(1-a)\vartheta^* \frac{y_{Ft}^*/(1-m)}{k_t^*} \\
p_{Ht}/p_{Ft} &= \left(1-\varphi_{Ft}^*\right)(1-\vartheta^*) \frac{y_{Ft}^*/(1-m)}{v_t^*} \\
\frac{y_{Ft}^*}{1-m}\left(1-\theta\varphi_{Ft}^*\right) &= \zeta\left(\pi_{Ft}^*-1\right)\pi_{Ft}^* - \beta E_t \frac{\lambda_{t+1}^*}{\lambda_t^*} \zeta \left(\pi_{Ft+1}^*-1\right)\pi_{Ft+1}^*
\end{aligned}
$$

Non-traded goods production and pricing:

$$
\begin{aligned}
y_{Nt} &= m n_{Nt} \\
w_t/p_{Nt} &= \left(1-\varphi_{Nt}\right) \\
\frac{y_{Nt}}{m}\left(1-\varphi_{Nt}\theta\right) &= \zeta\left(\pi_{Nt}-1\right)\pi_{Nt} - \beta E_t \frac{\lambda_{t+1}}{\lambda_t} \zeta \left(\pi_{Nt+1}-1\right)\pi_{Nt+1}
\end{aligned}
$$

$$
\begin{aligned}
y_{Nt}^* &= (1-m) n_{Nt}^* \\
w_t^*/p_{Nt}^* &= \left(1-\varphi_{Nt}^*\right) \\
\frac{y_{Nt}^*}{1-m}\left(1-\theta\varphi_{Nt}^*\right) &= \zeta\left(\pi_{Nt}^*-1\right)\pi_{Nt}^* - \beta E_t \frac{\lambda_{t+1}^*}{\lambda_t^*} \zeta \left(\pi_{Nt+1}^*-1\right)\pi_{Nt+1}^*
\end{aligned}
$$

Price aggregators:

$$
1 = \left[(1-\mu) p_{Tt}^{1-\psi} + \mu p_{Nt}^{1-\psi} \right]^{\frac{1}{1-\psi}}
$$

$$
1 = \left[(1-\mu^*) p_{Tt}^{*1-\psi} + \mu^* p_{Nt}^{*1-\psi} \right]^{\frac{1}{1-\psi}}
$$

$$
\begin{aligned}
p_{Tt} &= \left[(1-\gamma) p_{Ht}^{1-\eta} + \gamma p_{Ft}^{1-\eta} \right]^{\frac{1}{1-\eta}} \\
p_{Tt}^* &= \left[(1-\gamma^*) \left(\frac{p_{Ht}}{q_t} \right)^{1-\eta} + \gamma^* \left(\frac{p_{Ft}}{q_t} \right)^{1-\eta} \right]^{\frac{1}{1-\eta}} \\
p_{It} &= \left[(1-\omega) p_{Tt}^{1-\psi} + \omega p_{Nt}^{1-\psi} \right]^{\frac{1}{1-\psi}}
\end{aligned}
$$

$$p^*_{It} = \left[(1-\omega^*)p^{*1-\psi}_{Tt} + \omega^* p^{*1-\psi}_{Nt}\right]^{\frac{1}{1-\psi}}$$

Definition of inflation rates:

$$\frac{\pi_{Ht}}{\pi_t} = p_{Ht}/p_{Ht-1}$$
$$\frac{\pi_{Nt}}{\pi_t} = p_{Nt}/p_{Nt-1}$$
$$\frac{\pi^*_{Ft}}{\pi^*_t} = \frac{p_{Ft}/q_t}{p_{Ft-1}/q_{t-1}}$$
$$\frac{\pi^*_{Nt}}{\pi^*_t} = p^*_{Nt}/p^*_{Nt-1}$$

Monetary policy:

$$R_t = \frac{1}{\beta} R^{\rho_R}_{t-1} \pi_t^{\varphi(1-\rho_R)}$$
$$R^*_t = \frac{1}{\beta} R^{*\rho_R}_{t-1} \pi_t^{*\varphi(1-\rho_R)}$$

Budget constraint:

$$\left(c_t + p_{It} i_t + b^H_t\right) m = m \frac{R_{t-1} b^H_{t-1}}{\pi_t} + p_{Ht} y_{Ht} + p_{Nt} y_{Nt} - m p_{Ft} v_t$$

A1.3 Additional figures

Figure A1 shows the response of G6 utilization-adjusted TFP to both US technology shocks.

Figure A2 presents the results when controlling for potential anticipation effects in the Fernald (2014) TFP measure.

Figure A3 shows the impulse responses of the real exchange rate, domestic and foreign GDP for surprise (first row) and anticipated technology shocks (second row) for various changes in the baseline empirical specification. The black solid lines represent the baseline case and are repeated from Figures 1 and 2 in the main text, along with the corresponding shaded confidence bands. The blue dashed and red dotted lines show the impulse responses for VAR models with 2 or 6 lags respectively. The green dashed-dotted lines show the effect of replacing the stock price index by the log of the S&P 500 index. The yellow dashed-asterisked lines show the results when the empirical sample ends in 2007 to exclude the turbulent Great Recession episode. The magenta dashed-circled lines presents the results when we control for monetary and tax policy shocks in constructing the news shock instrument.

Figure A4 reports the impulse responses to the surprise and anticipated technology shock when replacing labor productivity by total factor productivity.

Figure A5 presents the results when applying the Barsky and Sims (2011) method to our data and to the data using only the original sample ranges in Nam and Wang (2015) (1973q1-2010q4) and Levchenko and Pandalai-Nayar (2018) (1968q4-2010q4). The first row shows the results when using US variables relatively to the G6 series. The second row reports the results for a two-country VAR with US variables and the US-Canadian real exchange rate.

Figure A6 show the theoretical responses of the nominal exchange rate, home and foreign inflation, and home and foreign interest rates in response to both technology shocks.

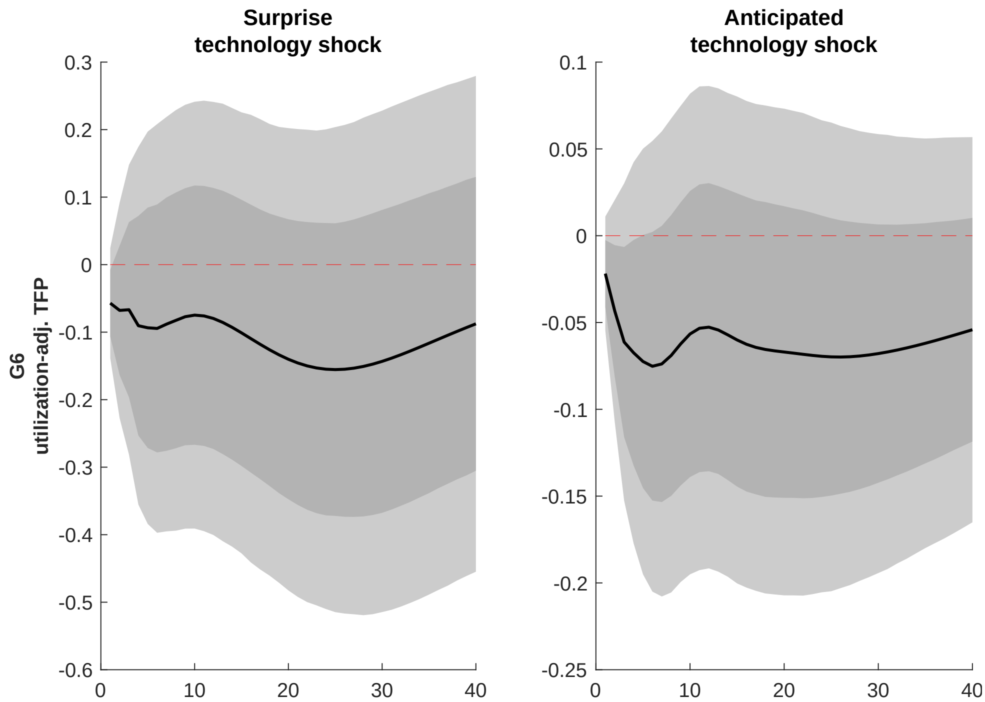


Figure A1: G6 utilization-adjusted TFP.

Notes: Solid lines show point estimates. Shaded areas indicate 68% and 90% bootstrapped confidence intervals. The unit of the horizonal axis is a quarter and the sample is 1974q1-2006q4.

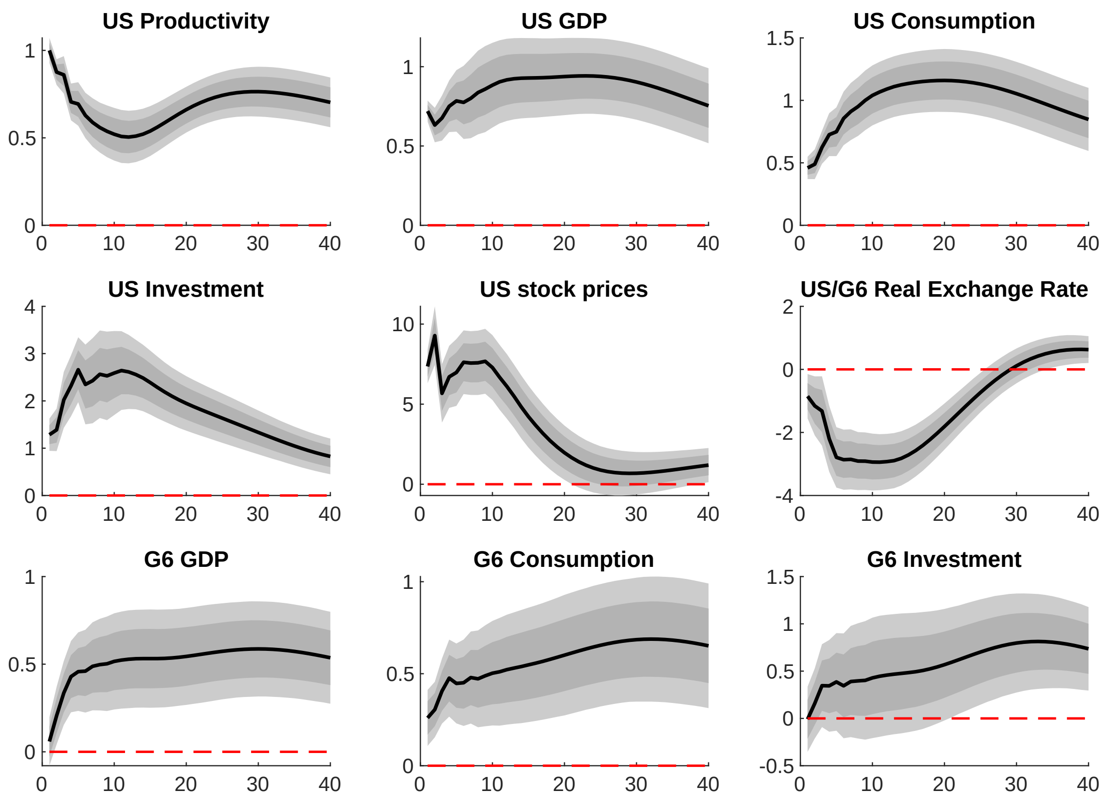


Figure A2: Controlling for anticipation in Fernald (2014) TFP measure.

Notes: Solid lines show point estimates. Shaded areas indicate 68% and 90% bootstrapped confidence intervals. The unit of the horizonal axis is a quarter and the sample is 1973q1-2019q1.

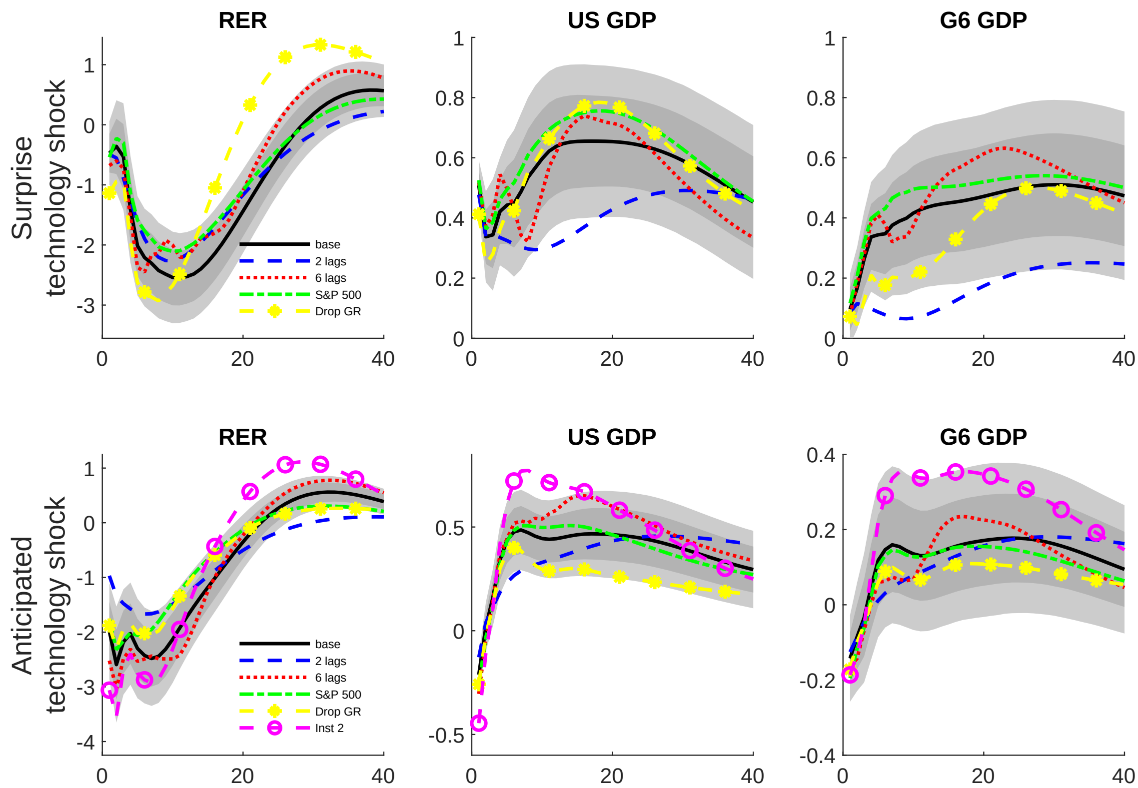
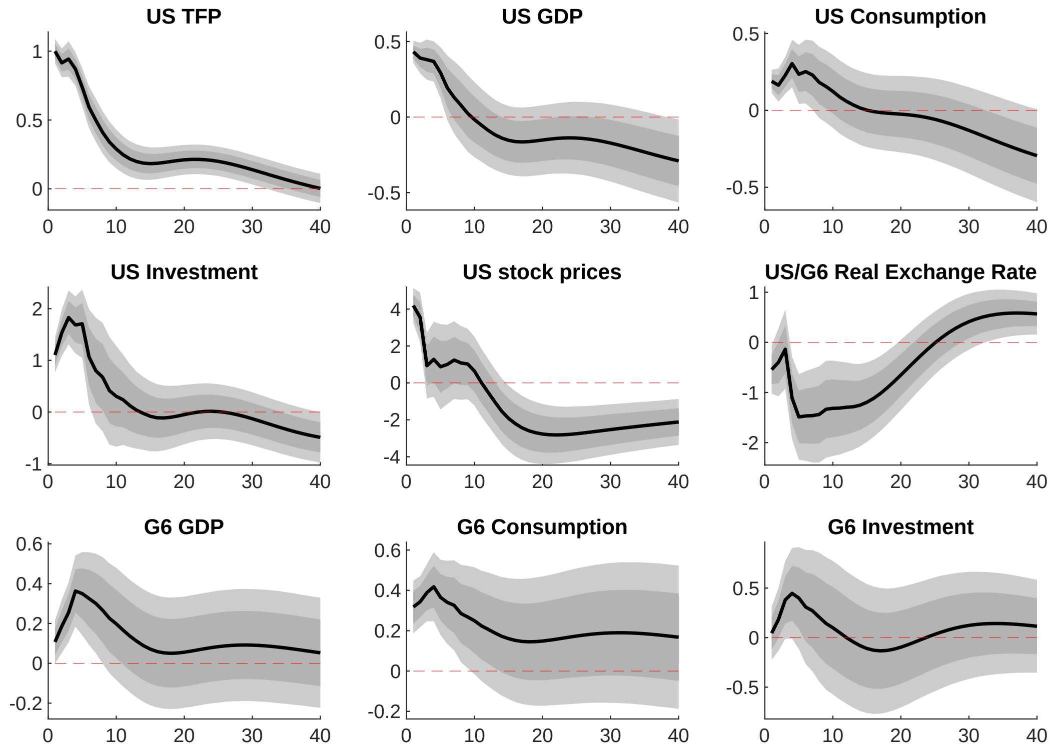


Figure A3: Robustness of empirical results.

Notes: Solid lines show point estimates. Shaded areas indicate 68% and 90% bootstrapped confidence intervals of the baseline models (sample 1973q1-2019q1). The unit of the horizonal axis is a quarter.

(a) Surprise technology shock



(b) Anticipated technology shock.

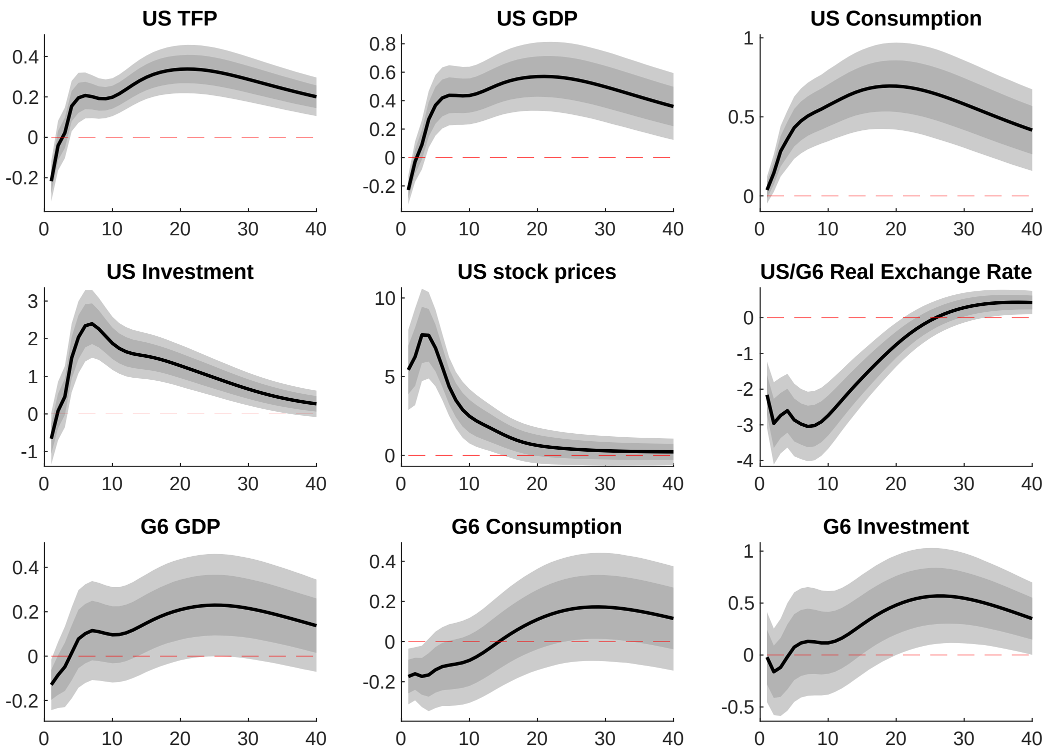


Figure A4: US unadjusted TFP.

Notes: Solid lines show point estimates. Shaded areas indicate 68% and 90% bootstrapped confidence intervals. The unit of the horizonal axis is a quarter and the sample is 1973q1-2019q1.

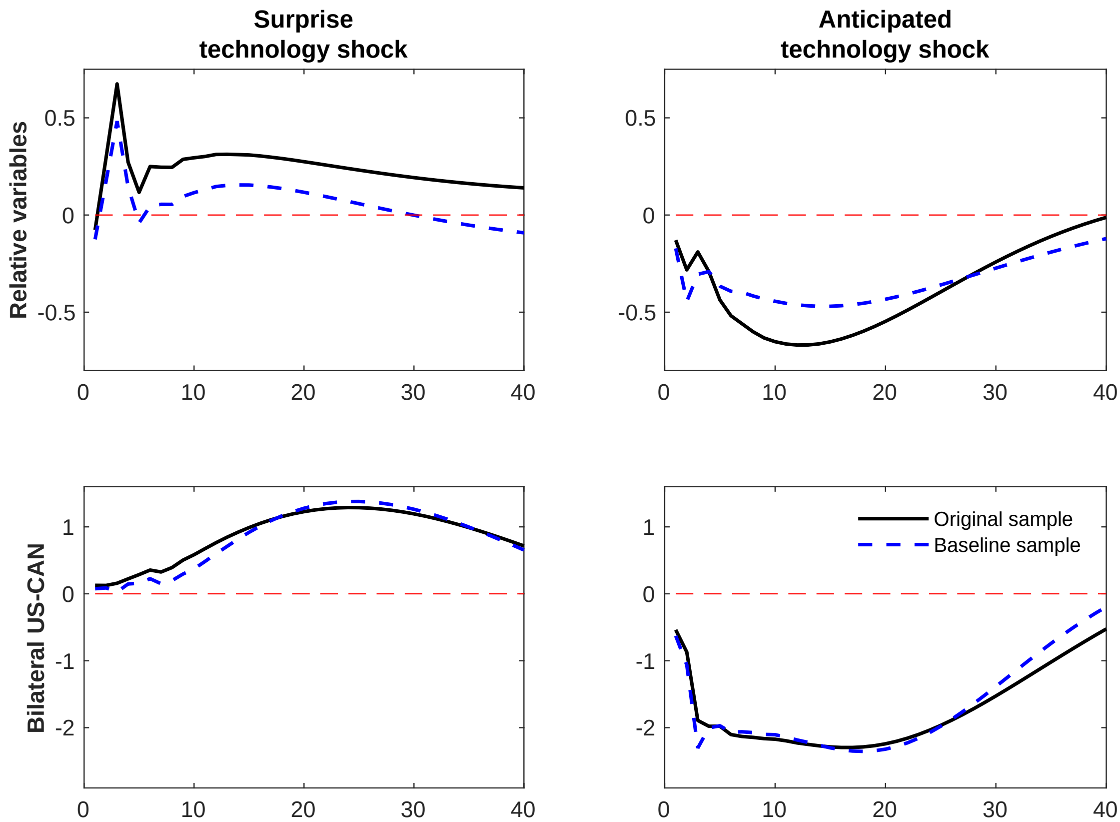


Figure A5: Barsky and Sims (2011) identification (real exchange rate response)

Notes: Baseline sample: 1973q1-2019q1. Original sample relative variables: 1973q1-2010q4. Original sample bilateral US-CAN: 1968q4-2010q4. The unit of the horizonal axis is a quarter.

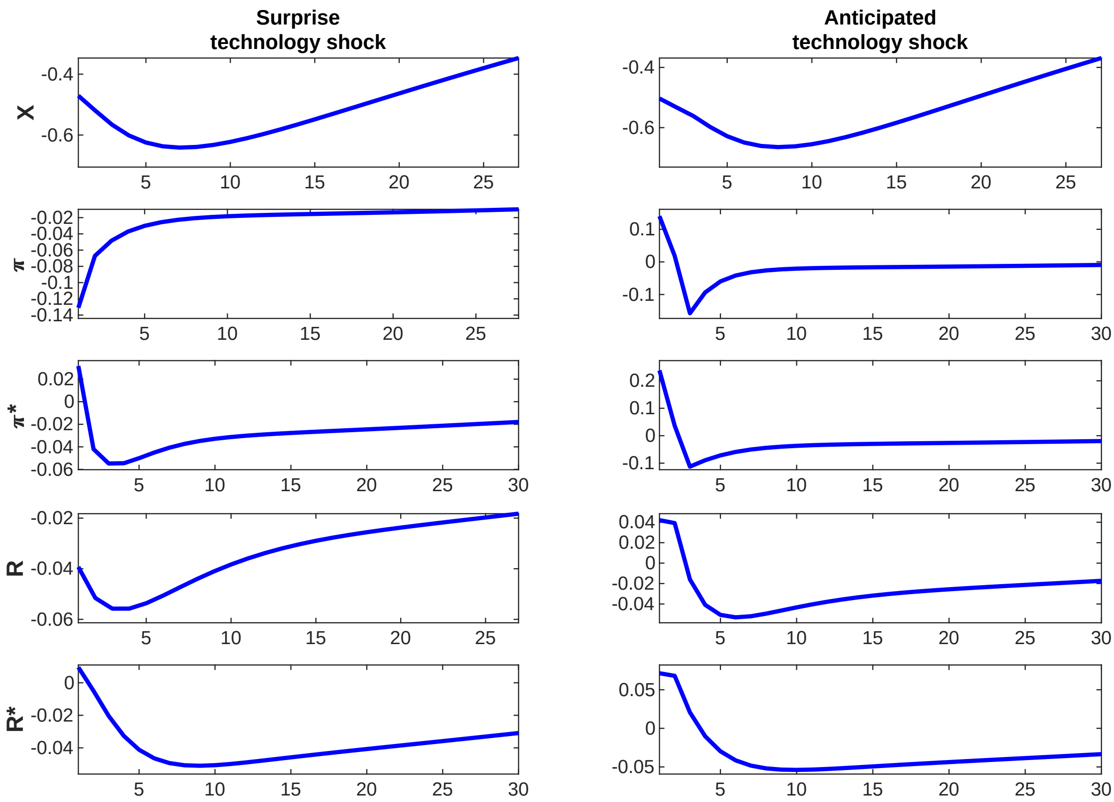


Figure A6: Additional theoretical responses.