

Revisiting the Exchange Rate Pass Through: A General Equilibrium Perspective*

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Abstract

A large literature estimates the exchange rate pass-through to prices (ERPT) using reduced-form approaches, whose results are an important input at Central Banks. We study the usefulness of these empirical measures for actual monetary policy analysis and decision making, emphasizing two main problems that arise naturally from a general equilibrium perspective. First, while the literature describes a single ERPT measure, in a general equilibrium model the evolution of the exchange rate and prices will differ depending on the shock hitting the economy. Accordingly, we distinguish between *conditional* and *unconditional* ERPT measures, showing that they can lead to very different interpretations. Second, in a general equilibrium model the ERPT crucially depends on the *expected* behavior of monetary policy, but the empirical approaches in the literature cannot account for this and thus provide a misleading guide for policy makers. We first use a simple model of small and open economy to qualitatively show the intuition behind these two critiques. We also highlight the quantitative relevance of these distinctions by means of a DSGE model of a small and open economy with sectoral distinctions, real and nominal rigidities, and a variety of driving forces; estimated using Chilean data.

JEL Classification: E5, F3, F4.

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1 Introduction

The exchange-rate pass-through (ERPT) is a measure of the change in the price of a good (or basket of goods) after a change in the nominal exchange rate (NER), computed at different horizons after the initial movement in the NER. Its estimates are not only an important part of the international macroeconomics literature, but also for actual monetary policy as well. For instance, when the economy is price taker in the world markets, a change in the nominal exchange rate translates in a movement of the local currency price of goods bought internationally. This affects importable inflation directly and may even affect other sectors of the economy, and for a prolonged period of time if there are propagation mechanisms at play. Recently this topic has received a renewed interest, since many countries experienced large depreciations after the Tapering announcements by the Fed in 2013.

That ERPT estimates are relevant for actual monetary policy can be argued from three different perspectives. First, in the vast majority of Central Banks one can find studies estimating the ERPT for the particular country. Second, international institutions such as IMF, BIS, and IADB, among others, also actively participate in this discussion. For instance, some of the flagship reports of these institutions (such as the World Economic Outlook by the IMF or the Macroeconomic Report by the IADB) include estimates of the ERPT and use them to draw policy recommendations. Moreover, a significant number of papers in this literature comes from economist working at these institutions. Finally, it is easy to find references to the ERPT in many Monetary Policy Reports, proceedings from policy meetings, and speeches by board members at many Central Banks.

The estimates of the ERPT are used at Central Banks and other policy-related institutions for two purposes. The first happens short time after a given depreciation in the NER, when the ERPT measures are used to predict the effect that the depreciation will have on inflation. The second use is for ex-post analysis, after some time has passed since a given depreciation, and its objective is to understand what happened and explain differences, if any, with what was expected to happen. In light to this widespread use, in this paper we question the usefulness of the empirical ERPT measures used for the listed purposes using a general equilibrium framework.

The literature that estimates ERPTs, and that inform policy makers, mostly uses reduced-form empirical approaches, such as vector auto-regressions (VAR) or single equation models.¹ In this paper, we highlight two shortcomings in using the results from these empirical approaches for monetary policy analysis. The first is related to the endogeneity of the NER and the sources behind its fluctuations. The second emphasizes the effect that monetary policy itself can have on ERPT measures, which is completely dismissed by the related literature.

The NER, as any price, is an endogenous variable and its reaction depends on the shock hitting the economy. Particularly, different shocks may affect the NER, prices, and their correlation differently. The empirical literature tries to overcome this endogeneity by isolating “exogenous” movements in the NER. In contrast, in general equilibrium models, it is straightforward to differentiate among shocks, which lead us to distinguish between *conditional* and *unconditional* or *aggregate* ERPT measures. The former refers to the ratio of the percentage change in a price index, relative to that in the NER, that occurs conditional on a given shock. The latter is the analogous ratio obtained from the reduced-form methodologies.

Our first contribution is to study the relationship between conditional and unconditional ERPT. We

¹Some examples are [Devereux and Engel \(2002\)](#), [Campa and Goldberg \(2005\)](#), [Campa and Minguez \(2006\)](#), [Choudhri and Hakura \(2006\)](#), [Ca' Zorzi et al. \(2007\)](#), [Gopinath et al. \(2010\)](#), among many others. [Burstein and Gopinath \(2014\)](#) and [Aron et al. \(2014\)](#) provide extensive surveys of this literature. In the rest of the paper, we use the terms “reduced-form” and “empirical” interchangeably to refer to this literature.

first show analytically that, under certain assumptions in the context of linear, dynamic and stochastic models, the unconditional ERPT obtained using a VAR is a weighted average of the conditional ERPTs in the model. Thus, to the extent that the conditional ERPTs are significantly different depending on the shock, the empirical measures will provide a biased assessment of the expected relationship between the NER and prices. In general, using the unconditional ERPT will systematically miss the expected evolution of the NER and prices.

In the general models, unfortunately, the mapping between unconditional and conditional ERPT cannot be obtained algebraically. Nonetheless, we propose two alternative measures of aggregate ERPT that can be computed for any model to mimic what an econometrician from the empirical literature would obtain if the general equilibrium model was the true data generating process.

We then discuss that, as the reaction of any endogenous variable, the ERPT conditional on a given shock depends on how monetary policy reacts and is expected to react. How this fundamental fact is captured in the empirical ERPT estimates is not clear. It might be argued that in these estimates it is implicitly assumed that monetary policy follows a policy rule that captures the “average” behavior followed by the central bank, during the sample analyzed. However, as there is no explicit description of this rule, it is hard to know what the central bank is assumed to be doing (and expected to do) in the estimated ERPT coefficient. Thus, the use of reduced-form estimates as a way to forecast the likely dynamics of inflation after a movement in the NER (the usual practice in policy related discussion) neglects the fact that monetary policy (both actual and expected) will influence the final outcome. If anything, what would be desirable is to have several ERPT measures, one for each alternative expected path for monetary policy that the Central Bank might consider. However, these cannot be computed using the methodologies applied in the empirical literature.

We show the relevance of distinguishing between conditional and unconditional ERPT, as well as the importance of expected policy behavior, by means of two dynamic and stochastic general equilibrium (DSGE) models. The first is a simple small-open-economy model, with traded and non-traded goods and price rigidities. While the simplicity of the model allows to grasp the intuition behind the two shortcomings of the empirically literature that we highlight, the issue of the quantitative relevance of making these distinctions requires a model that can properly match the dynamics observed in the data. To that end, we then set up a fully-fledge DSGE model with sectoral distinctions, nominal and real rigidities, driven by a wide variety of structural shocks. We estimate it using a Bayesian approach with quarterly Chilean data from 2001 to 2016.²

Our results show that the ERPT conditional on the two main drivers of the NER (a common trend in international prices and shocks affecting the interest parity condition) are quantitatively different, both in the short and in the long run, and for different prices. At the same time, the unconditional ERPTs lie between these two, and are comparable with empirical estimates available in the literature for Chile. Overall, this evidence points to the importance of identifying the source of the shock that originates the NER change in discussing the likely effect on prices.

We also explore how the ERPTs (both conditional and unconditional) vary with different expected paths for monetary policy. In particular, after a nominal depreciation, we compare the benchmark

²Chile is an interesting case of study for several reasons. First, is a large commodity exporter with a high degree of financial capital mobility; which makes relatively easy to identify the sources of foreign shocks. Second, since 2001 the Central Bank has followed a flexible inflation targeting strategy, that has been stable during the sample and it is consider as one of the success cases of inflation targeting, particularly in Latin America. This greatly facilitates the estimation of a DSGE model, without having to deal with possible shifts in the monetary policy framework. Finally, the exchange rate has moved freely most of the time during this sample, which is quite useful to show how diverse shocks may affect the NER. Nonetheless, the main points made in the paper are conceptually quite general, going beyond the particular country chosen for the estimation.

ERPT, where policy behaves according to an estimated Taylor-type rule, with more dovish alternatives.³ In principle, it is not clear how the ERPT will differ in these alternative situations since a more dovish policy will produce a higher inflation and further nominal depreciation. We show that there are some cases in which the conditional ERPT are altered (e.g. under shock to external prices), but others that are not (e.g. shock to the external interest rate), while the unconditional ERPT is always altered. In sum, using the estimated ERPT provides an incomplete, and in general misleading, assessment of alternative policy options, and the expected dynamics under each of them.

Two previous papers in the literature, [Shambaugh \(2008\)](#) and [Forbes et al. \(2015\)](#), also recognize different ERPTs depending on the shock, using VAR models. They use alternative identification assumptions to estimate how several shocks might generate different ERPTs; in the same spirit as our definition of conditional pass-through. We see our work as complementary to theirs from two perspectives. First, these studies do not show how these conditional ERPT measures compares with unconditional ones; a comparison that we explicitly perform to understand the bias that using the unconditional ERPT could generate. Second, they use structural VAR model whose identified shocks can be seen as too general relative to the shocks in a DSGE model.⁴ Our approach can then provide a relatively more precise description of the relevant conditional ERPTs.

The work by [Bouakez and Rebei \(2008\)](#) is, to the best of our knowledge, the only one that uses an estimated DSGE to compute conditional ERPTs (estimating the model with Canadian data) and that also provides a measure that would qualify as unconditional ERPT. Our paper complements these results by providing an unconditional ERPT measure that is directly comparable to the methodology implemented in the empirical literature, and by analyzing the specific relationship between the measures obtained in the reduced-form approaches with the dynamics implied by a DSGE model. Moreover, our estimated DGSE model has a richer sectoral structure, allowing to characterize not only the ERPT for total inflation, but also that for different prices such as tradables and non-tradables. [Corsetti et al. \(2008\)](#) also explore structural determinants of the ERPT from a DSGE perspective and assess possible biases in single-equation empirical methodologies. While our paper shares many common points with this study, we additionally provides a quantitative evaluation of these biases by using an estimated DSGE model. Still, none of these studies explore the second shortcoming we highlight regarding expected monetary policy.

The relationship between monetary policy and the ERPT has been the topic of several studies, but none has analyzed explicitly how alternative expected paths of the monetary rate affects the ERPT, which is a crucial input for policy makers. For instance, [Taylor \(2000\)](#), [Gagnon and Ihrig \(2004\)](#) and [Devereux et al. \(2004\)](#) use dynamic general equilibrium models to see how monetary policy can alter the ERPT, proposing that a greater focus on inflation stabilization can provide an explanation to why the empirical measures of ERPT seems to have declined over time in many countries. Others have analyzed how monetary policy should be different depending on structural characteristics associated with the ERPT, such as the currency in which international prices are set, the degree of nominal rigidities, among others. Some examples are [Devereux et al. \(2006\)](#), [Engel \(2009\)](#), [Devereux and](#)

³Specifically we assume that, for a given number of periods, the Central Bank announces that it will maintain the policy rate in the level that existed before the shock, returning to the estimated rule afterwards. This exercise tries to mimic what would happen if a policy maker is presented with an estimated ERPT coefficient that is relatively low and convinces itself that the likely effect on inflation will be small, deciding not to change the policy stance.

⁴[Shambaugh \(2008\)](#) uses long-run restrictions and identifies shocks such as relative demand, relative supply, nominal, among others. In contrast, with our DSGE model, we can identify a variety of shocks that fall into each of these categories, each of them generating different conditional ERPTs. In the case of [Forbes et al. \(2015\)](#), shocks are identified by sign restrictions, which does not take into account that shocks that imply very different dynamics can have the same sign responses. In fact, in our estimated model the two main drivers of NER movements generate the same sign for impulse responses, but they imply significantly different ERPTs.

Yetman (2010), and Corsetti et al. (2010). The point we want to stress, although related to these previous papers, is however different: the choice of the expected policy path can have an important influence in the realized ERPT; an issue that is generally omitted in policy discussions.

The rest of the paper is organized as follows. Section 2 describes the empirical strategies used in the literature and their relationship with DSGE models. The analysis based on a simple model is presented in Section 3. The quantitative DSGE model and the ERPT analysis based on it are included in Section 4. Conclusions are discussed in Section 5.

2 The Empirical Approach to ERPT and DSGE Models

In this section we first describe two methodologies generally used in the reduced-form literature to estimate the ERPT: single-equation and VAR models. We then use a general linearized DSGE model to introduce the concept of conditional ERPT. Finally, we discuss the relationship between the conditional ERPT from the DSGE model and the measured obtained using a VAR approach.

2.1 The Empirical Approach

The empirical literature mostly features two alternative approaches to compute the ERPT: single-equation, distributed-lag models and vector auto-regressions. In the first the estimated model takes the form,

$$\pi_t^j = \alpha + \sum_{j=0}^K \beta_j \pi_{t-j}^S + \gamma c_t + v_t, \quad (1)$$

where π_t^j denotes the log-difference in the price of a good (or basket of goods) j , π_t^S is the log-difference of the NER, c_t is a vector of controls (either external to the economy or domestic) and v_t is an error term. The parameters α , β_j , and γ are generally estimated by OLS, and the ERPT h periods after the movement in the NER is computed as $\sum_{j=0}^h \beta_j$, representing the percentage change in the price of good j generated by a 1% permanent change in the NER.

The VAR strategy specifies a model for the vector of stationary variables x_t that includes π_t^S , π_t^j , as well as other control variables (both of domestic and foreign origin). The reduced-form VAR(p) model is,

$$x_t = \Phi_1 x_{t-1} + \dots + \Phi_p x_{t-p} + u_t, \quad (2)$$

where Φ_j for $j = 1, \dots, p$ are matrices to be estimated, and u_t is a vector of i.i.d. reduced-form shocks, with zero mean and variance-covariance matrix Ω . Associated with u_t , the “structural” disturbances w_t are defined as,

$$u_t = P w_t, \quad (3)$$

where P satisfies $\Omega = P P'$, assuming the variance of w_t equals the identity matrix. In the empirical ERPT literature P is assumed to be lower triangular, obtained from the Cholesky decomposition of Ω , and the ERPT h periods ahead is defined as.

$$ERPT_{\pi^j}^V(h) \equiv \frac{CIRF_{\pi^j, \pi^S}^V(h)}{CIRF_{\pi^S, \pi^S}^V(h)}, \quad (4)$$

where $CIRF_{k,i}^V(h)$ is the cumulative impulse-response of variable k , after a shock in the position associated with variable i , h periods after the shock. In other words, the ERPT is the ratio of

the cumulative percentage change in the price relative to that in the NER, originated by the shock associated with the NER in the Cholesky order.⁵

While both approaches can be found in the literature, here we use the VAR as a benchmark for several reasons. First, in the most recent papers the VAR approach is generally preferred. Second, the ERPT obtained from (1) assumes that after the NER moves, it stays in that value forever. In contrast, the measure (4) allows for richer dynamics in the NER after the initial change. Third, the OLS estimates from (1) will likely be biased, as most of the variables generally included in the right-hand side are endogenous. The VAR attempts to solve this strategy by including lags of all variables, and by means of the identification strategy, as long as the Cholesky decomposition is correct.⁶ Finally, the VAR model might, in principle, be an appropriate representation of the true multivariate model (as we will discuss momentarily), but the same is not generally true for single-equation models.

2.2 DSGE models and Conditional ERPT.

The linearized solution of a DSGE model takes the form,

$$y_t = Fy_{t-1} + Qe_t, \quad (5)$$

where y_t is a vector of variables in the model (exogenous and endogenous, predetermined or not), e_t is a vector of i.i.d. structural shocks, with mean zero and variance equal to the identity matrix, and the matrices F and Q are non-algebraic functions of the deep parameters in the model.⁷

Using the solution, the ERPT conditional to the shock e_t^i for the price of good j is defined as,

$$CERPT_{\pi^j, i}^M(h) \equiv \frac{CIRF_{\pi^j, e^i}^M(h)}{CIRF_{\pi^S, e^i}^M(h)}, \quad (6)$$

This is analogous to the definition of $ERPT^V(h)$ in (4), with the difference that the response is computed after the shock e_t^i , and we can compute one for each shock in the vector e_t .

2.3 The Relationship Between VAR- and DSGE-based ERPT

We want to explore the relationship between $ERPT_{\pi^j}^V(h)$ and $CERPT_{\pi^j, i}^M(h)$, in order to construct a measure of unconditional ERPT from the DSGE model that is comparable to $ERPT_{\pi^j}^V(h)$. Relevant for this discussion is the work of [Ravenna \(2007\)](#), who explores conditions under which the dynamics of a subset of variables in the DSGE model can be represented with a finite-order VAR model. The general message is that it is not obvious that a DSGE model will meet these requirements, implying that the relationship we wish to find can only be obtained analytically for specific cases.⁸

⁵In general, it is assumed that π_t^S is ordered before π_t^j in the vector x_t . In addition, if the vector x_t contains foreign variables and the country is assumed to be small relative to the rest of the world, these variables are ordered first in x_t and the matrices Φ_j are assumed to have a block of zeros to prevent feedback from domestic variables to foreign ones at any lag.

⁶We will describe in the next subsection how that assumption will generally not hold if a DSGE model is the true data generating process. But at least the VAR methodology attempts to deal with the endogeneity issue, while the single-equation, OLS based approach does not.

⁷This solution can be obtained by several methods after linearizing the non-linear equilibrium conditions of the model, and can be implemented in different packages, such as Dynare.

⁸A related issue is analyzed by [Fernández-Villaverde et al. \(2007\)](#), showing conditions under which the shocks identified in a VAR for a subset of the variables in a DSGE can capture the same shocks as those in the DSGE model. However, as the empirical VAR literature of ERPT does not claim that it is identifying any particular shock that can be interpreted from a DSGE model, this aspect is not as relevant for our discussion.

In Appendix A.1 we show that, if the assumptions for the existence of a finite VAR representation of the DSGE model hold, and if π_t^S is order first in the VAR, the following relationship holds

$$ERPT_{\pi^j}^V(h) = \sum_{s=1}^{n_e} CERPT_{\pi^j,s}^M(h)\omega_s(h), \quad (7)$$

where n_e is the number of shock in the vector e_t . In other words, the ERPT obtained from the VAR is a weighted sum of the conditional ERPTs in the DSGE model. For $h = 0$ the weight $\omega_s(0)$ corresponds to the fraction of the forecast-error variance of the NER, at horizon $h = 0$, explained by the shock s . For $h > 0$ the weight $\omega_s(h)$ is equal to $\omega_i(0)$ adjusted by how different the response of the NER in horizon h is, relative to the moment the shock i hits the economy ($h = 0$).⁹ In simpler terms, the weights depend on the relative importance that each shock has in explaining the fluctuations in the NER.

The relationship (7) is an important result because it implies that, to the extent that the conditional ERPTs are different, the estimates based on the VAR will generally give an incorrect interpretation. If only one shock can hit the economy at a given period, the VAR will always miss the resulting ERPT. In the most realistic case in which all shocks are active every period, only if the combination of shock hitting the economy is equal to the weights implicit in the VAR-based ERPT, the VAR will give an appropriate assessment of the likely dynamics of inflation. But in the context of shocks with a continuous support, this event has zero probability. Of course, this distinction only matters to the extent that the conditional ERPTs are quantitatively different, which justifies our analysis in the following sections.

The conditions behind (7) may not hold in general DSGE models. Thus, we propose two alternatives to compute the unconditional ERPT. The first one assumes that the relationship in (7) holds in general. We label this as $UERPT_{\pi^j}^M(h) \equiv \sum_{s=1}^{n_e} CERPT_{\pi^j,i}^M(h)\omega_s(h)$, where $CERPT_{k,i}^M(h)$ is computed as in (6), and $\omega_s(h)$ is analogous to the one in (7).

The second measure of unconditional ERPT answers the following question: what would be the ERPT that someone using the empirical VAR approach would estimate if she has an infinite sample of the variables commonly used in that literature, generated by the DSGE model? We call this alternative unconditional ERPT using a Population VAR, labeled as $UERPT_{\pi^j}^{PV}(h)$; which is analogous to (4) but when the matrices Φ_j and Ω are obtained from the population (i.e. unconditional) moments computed from the solution of the DSGE model.¹⁰

In conclusion, for any particular DSGE model, we have two unconditional ERPTs to compare with the conditional ones, in order to assess their differences. In the following sections we apply these measures to both the simple and the quantitative DSGE model.

3 A simple DSGE Model

In this section we develop a simple DSGE model to show the importance of differentiating between conditional and unconditional ERPT as well as taking into account the expected paths of monetary policy. The model is based in Schmitt-Grohé and Uribe (2017, sec. 9.16), extended to include a Taylor rule for the interest rate, indexation and external inflation.

⁹See Appendix A.1 for the precise expression for $\omega_s(h)$.

¹⁰Appendix A.2 shows how this is computed.

3.1 Description of the Model

The model is relatively small and has only necessary ingredients to highlight the differences in ERPT that we want to show. It has only three shocks (world interest rate, external inflation and monetary policy) to show the differences between conditional and unconditional ERPT¹¹. The model also features two sectors (tradable, T , and non-tradable, N) to show differences between ERPT in different prices. Third, it has a monetary policy that sets the interest rate to evaluate the differences in ERPT of alternative expected paths for the interest rate. Finally, it includes Calvo pricing in sector N with indexation to past inflation, for its importance in the transmission of changes in the exchange rate to internal prices. Appendix B presents all the equilibrium conditions and the computation of the steady state.

3.1.1 Households

There is a representative household that consumes, works and saves. Her goal is to maximize,

$$E_0 \sum_{t=0}^{\infty} \beta^t \left\{ \frac{C_t^{1-\sigma}}{1-\sigma} - \xi \frac{h_t^{1+\varphi}}{1+\varphi} \right\}$$

where C_t is consumption and h_t are hours worked, β is the discount factor, σ is the risk aversion parameter, φ is the inverse of the Frish elasticity of labor supply and ξ is a scale parameter. The budget constraint is

$$P_t C_t + S_t B_t^* + B_t = h_t W_t + S_t R_{t-1}^* B_{t-1}^* + R_{t-1} B_{t-1} + \Pi_t.$$

Here P_t the price of the consumption good, S_t the exchange rate, B_t^* the amount of external bonds bought by the household in period t , B_t amount of local bonds bought by the household in t , W_t is the wage, R_t^* is the external interest rate, R_t is the internal interest rate, and Π_t collects all the profits of the firms in the economy, since households are the owners of firms.

The consumption good is a composite of tradable consumption, C_t^T , and non-tradable consumption, C_t^N . Additionally, non-tradable consumption is an aggregate of non-tradable varieties, $C_t^N(i)$. These technologies are described by,

$$C_t = \left[\gamma^{1/\varrho} (C_t^N)^{\frac{\varrho-1}{\varrho}} + (1-\gamma)^{1/\varrho} (C_t^T)^{\frac{\varrho-1}{\varrho}} \right]^{\frac{\varrho}{\varrho-1}}$$

$$C_t^N = \left[\int_0^1 (C_t^N(i))^{\frac{\epsilon-1}{\epsilon}} di \right]^{\frac{\epsilon}{\epsilon-1}}$$

where γ is the share of N in total consumption, ϱ is the elasticity of substitution between C_t^N and C_t^T , and ϵ is the elasticity of substitution between the varieties $i \in [0, 1]$ of non-tradables. From the minimization problem, we obtain the definition of the consumer price level as,

$$P_t = [(1-\gamma)(P_t^T)^{1-\varrho} + \gamma(P_t^N)^{1-\varrho}]^{\frac{1}{1-\varrho}}$$

where P_t^T is the local price of the tradable good and P_t^N is a price index for the non-tradable composite.

¹¹Those shocks were particularly chosen because of their importance in the larger model of the next section.

3.1.2 Firms

There are two sectors, tradables and non-tradables. The former is assumed to have a fixed endowment, Y^T , each period with a local price $P_t^T = S_t P_t^{T,*}$, where $P_t^{T,*}$ is the foreign price of the tradable good. In contrast, in the non-tradable sector, each firm $j \in [0, 1]$ produces using labor,

$$Y_t(j) = h_t(j)^\alpha$$

Where $Y_t(j)$ is the production of firm j , $h_t(j)$ is the hours hired and $\alpha \in (0, 1]$ is a parameter. Firm j faces a downward sloping demand given by:

$$Y_t(j)^N = \left(\frac{P_t^N(j)}{P_t^N} \right)^{-\epsilon_N} Y_t^N$$

They choose prices a la Calvo, where the probability of choosing prices each period is $1 - \theta$. In the periods that firms don't choose prices optimally, they update their prices using with a combination of past inflation, π_{t-1} and the inflation target, $\bar{\pi}$:

$$\pi_{t-1}^\zeta \bar{\pi}^{1-\zeta}$$

where $\zeta \in [0, 1]$. Note here that the final indexation in the model depends of the parameter θ as well as ζ , because at the end, the fraction of prices in the N sector that is indexed to past inflation is $\theta\zeta$, because is among the prices that are not chosen optimally, the fraction that is indexed to past inflation. Also, in the long-run indexation is complete, in the sense that all prices will change at the same rate $\bar{\pi}$. This eliminates the welfare cost of price dispersion in steady state (and in an first-order approximation). Finally, it is important to distinguish between dynamic and static indexation.

3.1.3 Monetary Policy

We assume a simple Taylor rule for the domestic interest rate:

$$\left(\frac{R_t}{R} \right) = \left(\frac{\pi_t}{\bar{\pi}} \right)^{\alpha_\pi} \left(\frac{GDP_t}{GDP} \right)^{\alpha_y} \exp(e_t^m)$$

where the variables without a time subscript are steady state values, GDP_t is gross domestic product (see the appendix for a definition) and e_t^m is the monetary shock, assumed to be i.i.d.

3.1.4 Foreign Sector

The rest of the world provides the external price of the tradable output, $P_t^{T,*}$ and the external interest rate, R_t^* . For the first, we assume $\pi_t^* \equiv P_t^{T,*}/P_{t-1}^{T,*}$ follows an exogenous process. The external interest rate relevant for the country, R_t^* is given by

$$R_t^* = R_t^W + \phi_B \left(\exp(\bar{b} - B_t^*/P_t^{T,*}) - 1 \right)$$

where R_t^W is the risk-free external interest rate, which follows an exogenous process and $\phi_B, \bar{b} > 0$ are parameters. This equations is the closing device of the model.

3.1.5 Exogenous processes and Parametrization

The model includes 3 shocks: the monetary policy shock, ϵ_t^m , foreign inflation, π_t^* , and the risk-free external interest rate, R_t^W . It is assumed that each one of these shocks has a process

$$\log(x_t/x) = \rho_x \log(x_{t-1}/x) + u_t^x,$$

for $x_t = \{\epsilon_t^m, \pi_t^*, R_t^W\}$ and u_t^x is *iid.*. It is assumed initially that $\rho_x = 0.5$ for $x = \{\pi^*, R^W\}$ and $\rho_{\epsilon^m} = 0$. Table 1 shows the parametrization used, which closely follows [Schmitt-Grohé and Uribe \(2017, sec. 9.16\)](#). In the baseline parametrization, we set the indexation parameter $\zeta = 0$, to latter explore the role of different values for ζ .

Table 1: Parametrization Simple Model

| Parameter | Value | Description |
|--------------|---------------|--|
| β | 1.0316^{-1} | Discount factor |
| σ | 2 | Risk aversion |
| φ | 0.5 | Inverse Frisch elasticity |
| ϱ | 0.5 | Elasticity of substitution between C^T and C^N |
| γ | 0.74 | Share of C^N in C |
| α | 0.75 | Labor share in N |
| ϵ | 6 | Elasticity of substitution across varieties N |
| θ | 0.7 | Probability of no price change in N sector |
| ζ | 0 | Indexation to past inflation in N sector |
| α_π | 1.5 | Taylor rule parameter of π |
| α_y | 0.5/4 | Taylor rule parameter of GDP |
| ϕ_B | 0.0000335 | Parameter of debt-elastic interest rate |
| $\bar{\pi}$ | $1.03^{1/4}$ | Inflation target |
| pT | 1 | Relative price tradables in steady state |
| h | 0.5 | Hours worked in steady state |
| s^{tb} | 0.05 | Share of trade balance in GDP in steady state |

Notes: The source of all parameters is [Schmitt-Grohé and Uribe \(2017, sec. 9.16\)](#), except the ones in the Taylor rule and the steady state values. For the ones in the Taylor rule is [Taylor \(1993\)](#) and the steady state values are normalizations. In the case of s^{tb} was put such that the country was a net debtor in steady state.

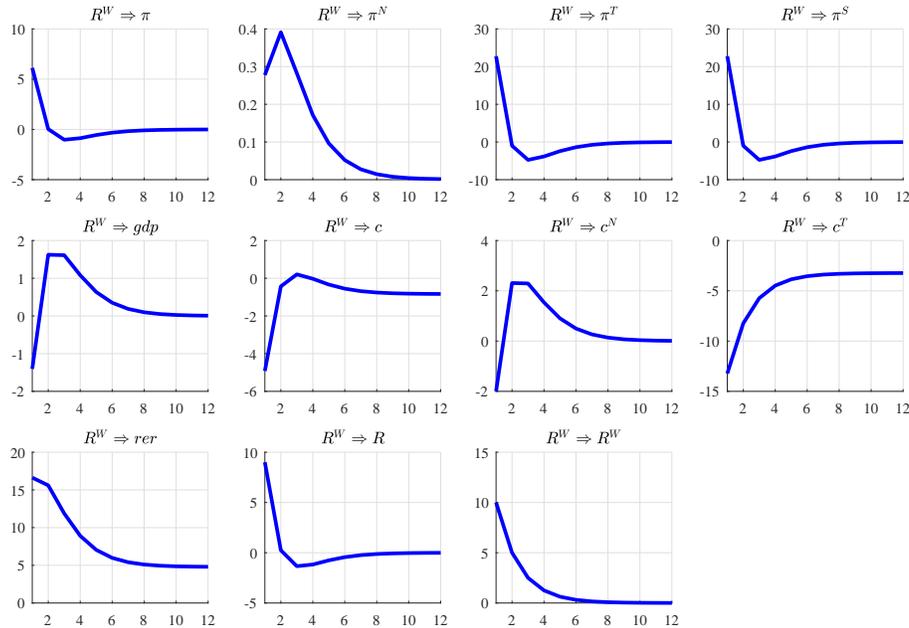
3.2 Conditional vs. Unconditional ERPTs

In this section we show how even in this simple model important differences among the conditional ERPTs arise, depending on the shock that is hitting the economy and also on the prices considered. Note first that, by construction, the reaction of tradable inflation and the nominal exchange rate depreciation is the same for the monetary shock and the shock to the external interest rate, implying a conditional ERPT for these shocks equal to one at all horizons. Also note that since the real exchange rate and all relative prices are stationary in the model, these shocks will also have a conditional ERPT of one in the long run for non-tradable and total prices as well. In contrast, this is not the case for foreign-inflation shock, which does not require a complete ERPT to any domestic price, at any horizon.

To understand the propagation of the different shocks, we first present the impulse-response analysis. A positive change in the external interest rate, showed in figure 1, causes two effects: a negative income effect (because this economy is assumed to be a net debtor), and an intertemporal substitution

effect, increasing the incentives to save today. Both of them decreases current demand of both goods, while at the same time increase labor supply. The drop in the demand for non-tradables, as well as the increase in labor supply, tend to decrease the relative price of these goods, leading to a real depreciation.¹² Due to sticky prices, the nominal exchange rate also increases. Inflation rises for both types of goods and, as a result, the policy rate increases.¹³

Figure 1: IRF to the External Interest Rate



Note: Each graph displays the percentage change, relative to steady state, originated by the shock, in the following variables: total, non-traded and tradable inflation (π , π^N and π^T), nominal depreciation (π^S), output (gdp), total, non-traded and tradable consumption (c , c^N and c^T), the (CPI-based) real exchange rate (rer), the policy rate (R), and the variable hit by the shock.

A negative shock to external inflation, showed in figure 2, affects the economy through several channels.¹⁴ In principle, this shock should affect export-related income, generating a wealth effect. However, as the domestic price of tradables is fully flexible, *ceteris paribus*, the relevant relative price (the price of exports over that of imports) does not change; so this channel is not active in this simple model.¹⁵ Another channel is due to the fact that foreign bonds are denominated in dollars: an unexpected drop in foreign prices will increase, *ceteris paribus*, the burden of interest payments from external debt in domestic currency units, generating a negative wealth effect. These channels tend to contract aggregate demand, which reduces consumption of both goods and increase labor supply. Since the non-traded sector has to clear, its relative prices fall. Both a nominal and a real depreciation

¹²The effect on the equilibrium consumption (and output) of non-tradables depends on which of the two changes (drop in the demand, or increase in supply) dominates. Given the chosen parametrization, in the short run output contracts, and then it increases above the steady state. In contrast, tradable consumption drops after the shock and converges to the steady state from below.

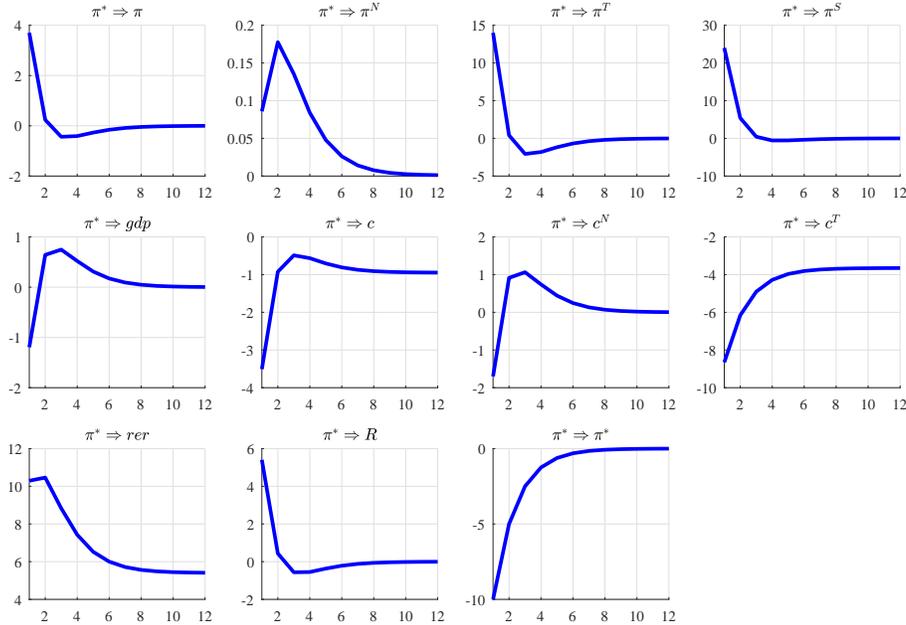
¹³Inflation in non-tradables rises due to the policy rule: as the target is on aggregate inflation, total inflation is less volatile if both traded and non-traded inflation move in the same directions. Under the same calibration, but using a policy rule that targets non-traded inflation only, it can be shown that non-traded inflation will not move after the shock, and all the adjustment comes from traded inflation only.

¹⁴We analyze a negative shock to obtain a nominal depreciation.

¹⁵This will not be the case in the quantitative model, where the domestic price of imports is sticky.

materialize, inflation rises for both types of goods and the policy rate increases. While qualitative these effects are analogous to those originated by a rise in the world interest rate, there is an important difference that will have an impact in the ERPT discussion. For after this shocks the rise in traded inflation due to the depreciation is attenuated by the drop in foreign inflation. As we will see, this leads to a smaller conditional ERPT under this shock.

Figure 2: IRF to External Inflation



Note: See Figure 1.

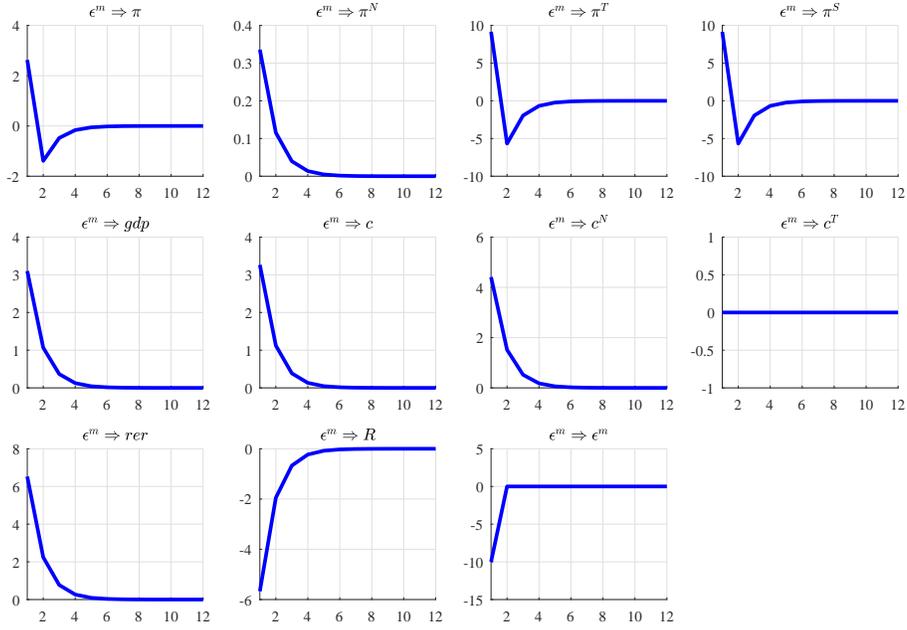
Finally, a negative shock to the policy rule, showed in figure 3 generates an drop in the nominal interest rate for a given value of inflation and output. This causes an intertemporal substitution effect towards current consumption.¹⁶ The higher demand of non-tradables causes an increase in its relative price as well as a rise in its output. This lead to both a real and nominal depreciation.

We now turn to the conditional ERPTs which, as can be seen in figure 4, can significantly differ depending on the shock. First note that, as expected, the ERPTs of tradable prices is in general much higher than of non-tradable, since the former is not subject to price rigidities. For tradable prices, as discussed at the beginning of the section, the conditional ERPT given either a foreign interest rate or a monetary policy shock equals one since the first period. In contrast, the ERPT as a response to foreign inflation is around 0.6 in the first period and it decreases over time. This is in line with the distinction we made when analyzing the responses to a shock in foreign inflation.

For non-tradable prices, it is also true that the conditional ERPT in response to foreign interest rate and monetary shock is higher than after a foreign-inflation shock; but it is not equal to one. As seen in the figure, it is only for the monetary shock that the ERPT becomes close to one around the 8th quarter, being much lower for the foreign interest rate. Note that as a response to foreign inflation, the ERPT is only 0.02 even after 12 quarters.

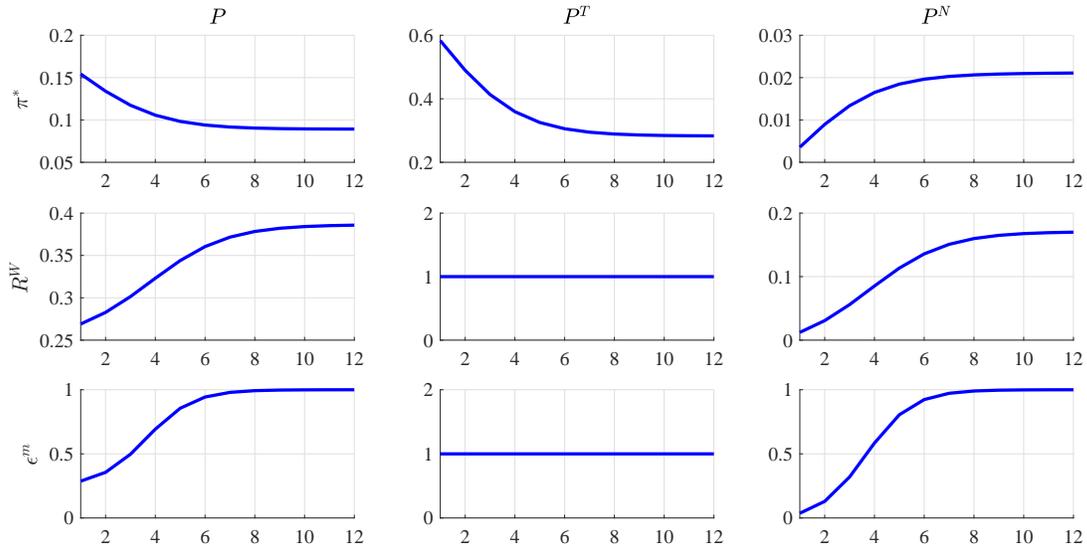
¹⁶Under the chosen parametrization, the consumption of tradables is not affected by a domestic shock due to the assumption that the inter-temporal elasticity of substitution total consumption is the inverse of the intra-temporal elasticity between traded and non-traded goods. It can be shown that under this assumption the consumption of tradables can only be affected by foreign shocks in this model.

Figure 3: IRF to a Monetary Shock



Note: See Figure 1.

Figure 4: Conditional ERPT



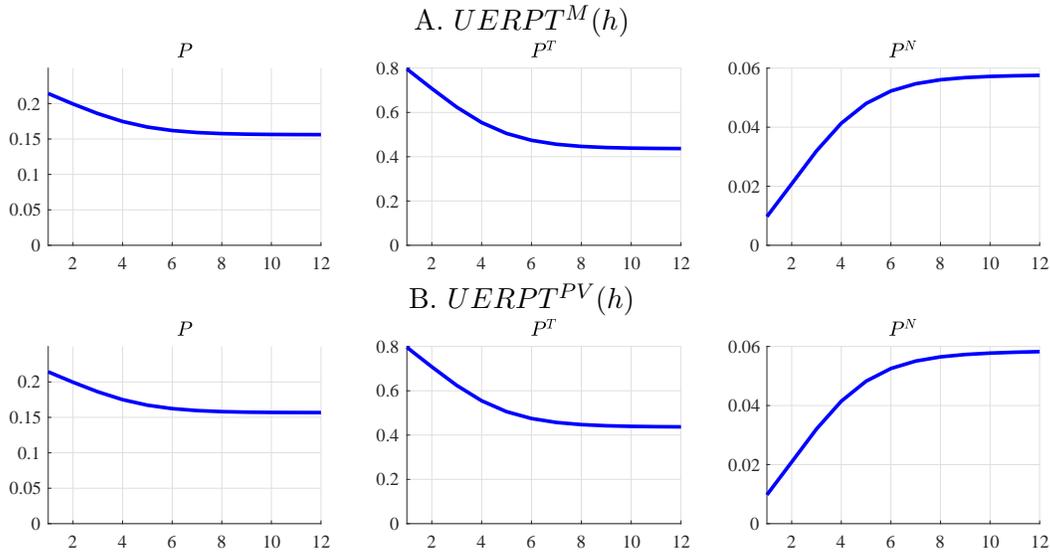
Note: Each graph show the conditional ERPT for the price in each particular column (respectively, CPI, P , tradables, P^T , and non-tradables, P^N), conditional on the shock in each particular row (respectively, foreign inflation, π^* , world interest rate, R^W , and monetary policy, e^M).

Since the CPI is an average of tradable and non-tradable price indices, its conditional ERPT lies between the conditional ERPTs of these two prices. So, for consumer prices, we can see that the highest ERPTs are in response to the monetary shock, then to foreign interest rate and then to foreign

inflation. Also note that it is increasing in the case of the monetary shock and foreign interest rate, but decreasing in the case of foreign inflation.

In figure 5 we can see the unconditional ERPTs calculated using the two measures explained in the previous section.¹⁷ As can be inferred from comparing the unconditional ERPTs, in figure 5, with the conditional ones, in figure 4, the shock to foreign inflation is seems to be relatively important in explaining the nominal depreciation rate, and so it weights more in the unconditional ERPT measures. This can be seen by noticing that, first, the unconditional ERPTs of each price are closer to the ones of that shock than to those of the the other shocks and, second, that the unconditional ERPT of total CPI and tradables are decreasing while the one of non-tradable prices is increasing.

Figure 5: Unconditional ERPT



As discussed in the introduction of the paper, we can see how much information is lost if the averaging imposed by the unconditional ERPT measures to predict the effect in prices after a given shock. Only in the case that “the given shock” is a specific combination of the three shocks of the model, the predicted movement in prices using the unconditional ERPTs will be correct. In all other cases, it will be incorrect. How important is this bias will depend on which price is being predicted and which shock or shocks hit the economy. In this simple model, it seems that the mistakes using the unconditional measures are less of a problem for tradables in the first quarters, since all the conditional ERPTs are relatively high. But this is in part due to the assumption a complete pass-through to domestic tradable prices.

In contrast it is more misleading for non-tradables and consumer prices, particularly after a policy shock and long horizons. In that specific example one would use an ERPT of around 0.05 and 0.16 for non-tradables and consumer prices respectively and the actual values are around 0.9 and 0.95. Overall, even in this simple model, the differences between conditional and unconditional ERPT measures cannot be taken from granted.

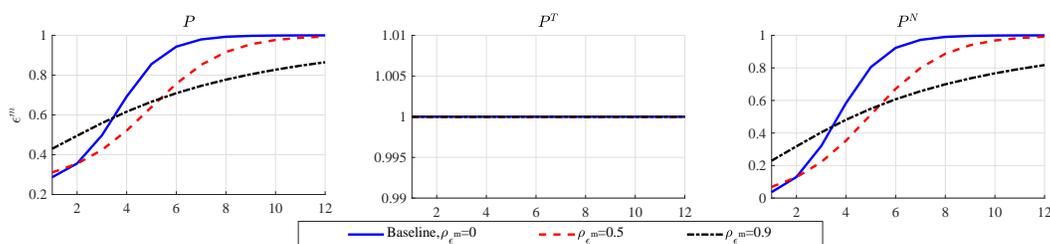
¹⁷For the population-VAR measure ($UERPT^{PV}$) the variables included are $\{\pi_t^S, \pi_t, \pi_t^T, \pi_t^N\}$ and the VAR included 15 lags. This number was chosen so that both unconditional measures were similar.

3.3 Importance of Expected Monetary Policy for ERPTs

This subsection shows the importance of taking into account expected monetary policy when discussing about ERPT. A first exercise to analyze this is to simply change the autocorrelation of the policy shock, implying a different policy path relative to the baseline. The second exercise is closer to a real world alternative: it compares the conditional ERPTs to the foreign shocks and the unconditional ERPTs in the baseline model with cases when the policy rate, instead of following the rule, is held fixed for a number of periods, starting at the same time the shock hits the economy.

Figure 6 presents the conditional ERPT to the monetary policy shock in the baseline calibration, as well as the alternatives in which the policy shock displays an autocorrelation of either 0.5 or 0.9.¹⁸ One can see that the ERPT for non-tradables and total CPI changes significantly with more persistent shocks, and not in an homogeneous matter¹⁹. When the autocorrelation increases from 0 to 0.5, the ERPTs of P^N and P are not much affected in the very short run, but they increase systematically starting from around the second quarter. This implies that it converges to 1 faster than in the baseline case. In contrast, when the autocorrelation is further increased, the short run ERPT increases, but displaying a slower convergence to 1, making the ERPT smaller than the baseline starting around the 3rd quarter.

Figure 6: Conditional ERPT under more persistent policy shocks



Notes: Each graph shows the Conditional ERPT to the monetary shock calculated for models with different values of the autocorrelation of the monetary shock. The blue solid line shows the baseline model with *iid* monetary shocks, the dashed red line shows the model with an autoregressive coefficient of 0.5 and the dash-dotted black line shows the case with an autoregressive coefficient of 0.9.

The second exercise, shown in Figure 6, compares alternative policy paths. In the baseline, after each shock the policy rate follows the rule, as shown in the impulse responses in the previous section. Alternatively, we assume that at the time the shock hits the economy, the policy maker credibly announces that the policy rate will be maintained fixed (at its steady-state value) for a given number of periods, returning to the Taylor rule afterwards.²⁰ In the figure, the baseline is contrasted with the cases in which the interest rate is fixed for 2 and 4 periods. A priori, the effect on the ERPT is not obvious. On one hand, as fixing the rate following a nominal depreciation is more dovish, inflation will likely be higher. But on the other, a more dovish policy path induces a higher NER. Therefore, the effect on the ratio computed in the ERPT is not obvious.

As can be seen, the effects alternative policy path are not monotone. When the interest rate is fixed for 2 periods, the conditional ERPTs are generally higher than when the interest rate follows

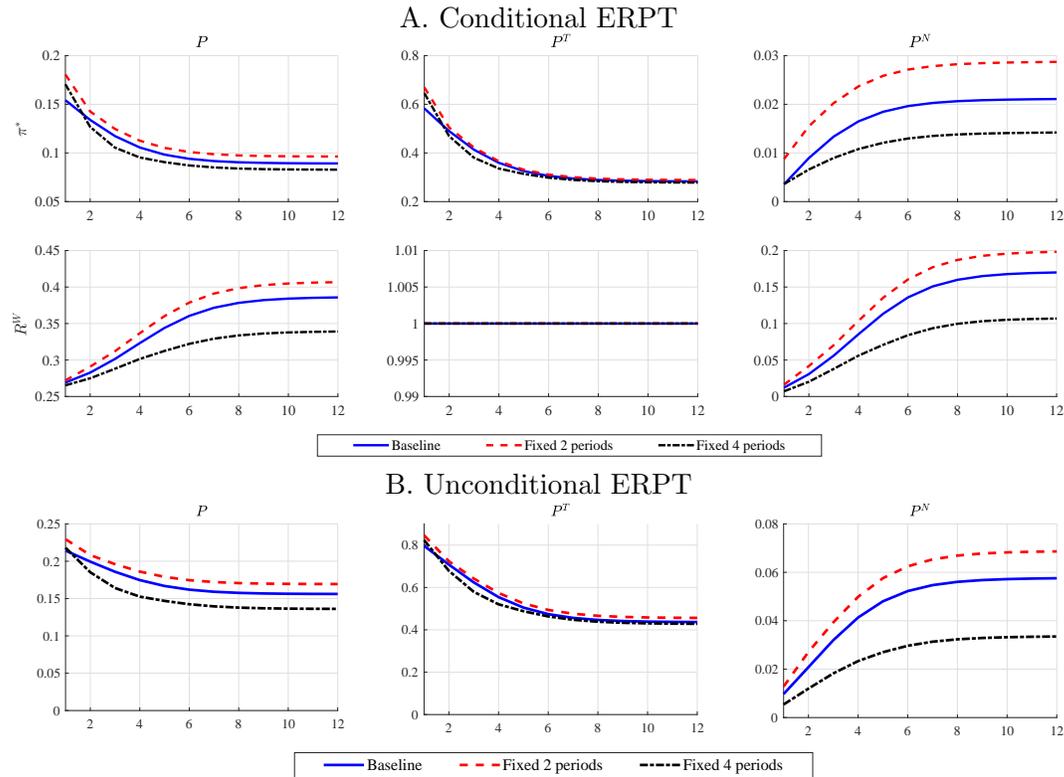
¹⁸For the models that change the autocorrelation of the monetary shock, the only conditional ERPT that is affected is after a monetary shock.

¹⁹There is no change in the ERPT of the tradable good, since by construction for this shock it is one.

²⁰Computationally, this is implemented by a backward-looking solution as in [Kulish and Pagan \(2016\)](#) or the appendix in [Garcia-Cicco \(2011\)](#).

the Taylor rule. In contrast, when the interest rate is fixed for 4 periods, conditional ERPTs are not only lower than when the interest rate is fixed for 2 periods, but also they are lower than when it is allowed to move following the policy rule. Moreover, the influence of alternative policy paths seems to be more important for the conditional ERPTs after a foreign interest rate shock than after foreign inflation movement. As expected, the changes in the unconditional ERPT go in the same direction and the conditional ERPTs.

Figure 7: Conditional and Unconditional ERPT fixing the policy rate for T periods



Notes: the graphs show the conditional ERPT to foreign inflation and the foreign interest rate, as well as the unconditional measure $UERPT^M(h)$, for alternative paths of the policy rate. The solid blue line is the baseline model, the dashed red line is the case when the rate is held fixed for two periods, and the dash-dotted black line is the case that is fixed for 4 periods.

Overall, we have shown that alternative policy paths can greatly influence the ERPT, both conditional and unconditionally. Thus, it would be much more informative for policy makers if they are presented with alternative ERPTs measures, for different choices of future policy paths. The methodologies from the empirical literature cannot produce such an exercise. And while a DSGE model can be used to this end, as we mentioned in the introduction there is no such analysis available in the model-based literature.

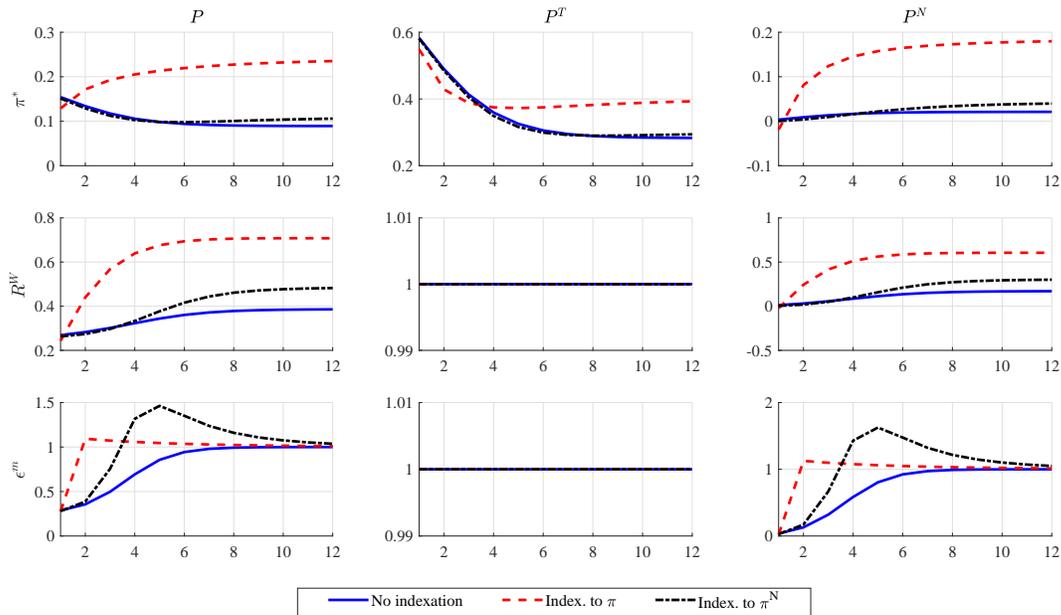
3.4 Sensibility of ERPTs to different parameters

The ERPTs, as any other statistic that depends on the dynamics of the model, can crucially change with alternative parameter values. One of the parameters relevant for inflation dynamics in general and for ERPT in particular is indexation to past inflation. The baseline version of the model assumes that the N sector, which is the only sector where prices are locally set, is indexed to the inflation

target when prices are not chosen optimally. Instead, we here show the results when that sector uses indexation to their own inflation, π_{t-1}^N or to total inflation, π_{t-1} .

When indexation is only to the target, the connection between non-tradable prices and the nominal exchange rate is only through a general equilibrium channel. For a given shock, the N market has to clear, and so prices move. If we add indexation to the own inflation when prices are not set optimally, there will be an amplification mechanism at work for the same general equilibrium effect. This is because, as long as after a given shock there is a change in non-tradable inflation and the nominal exchange rate, for the same change in the nominal exchange rate, the change in non-tradable inflation will be amplified due to indexation. This can be seen in the conditional and unconditional ERPTs in figures 8 and 9. Compared to the baseline case, this model shows higher ERPTs in general, with the same general evolution for foreign shocks and an overreaction for the monetary shock.

Figure 8: Conditional ERPT for Alternative Parameters Concerning Indexation

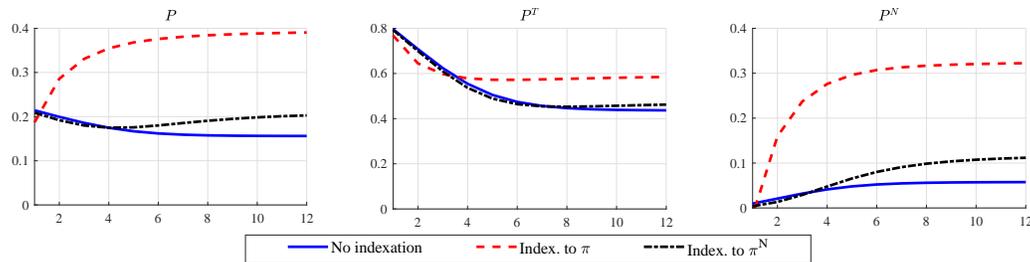


Notes: This figure shows Conditional ERPTs calculated for models with different indexation dynamics. The blue solid line shows the baseline model, which has indexation to the inflation target, the dashed red line shows the model with indexation to total inflation and the dash-dotted black line shows the case with indexation to sectoral N inflation.

When the indexation is to total inflation there is an important change in price dynamics. This is because now, in addition to the general equilibrium effect, changes in the exchange rate will have a direct impact on non-tradable inflation, since exchange rate movements are directly transmitted to tradable inflation and this way to total inflation. As the ERPTs of tradable prices is in general very high, this change in the model brings an important increase in the ERPTs of non-tradable prices as well as total prices. This is true for both conditional and unconditional ERPTs, and particularly important for ERPTs conditional in foreign shocks.

There are other model features that can have a direct impact on ERPTs. Some of these are introduced in the quantitative model of the next section, such as the case of using imported inputs in the production of local goods, introducing price rigidities in the imported sector, using importable goods in investment, nominal rigidities and indexation in wages, among others.

Figure 9: Unconditional ERPT for Alternative Parameters Concerning Indexation



Notes: Only $UERPT^M$ is reported. This figure shows Unconditional ERPTs calculated for models with different indexation dynamics. The blue solid line shows the baseline model, which has indexation to the inflation target, the dashed red line shows the model with indexation to total inflation and the dash-dotted black line shows the case with indexation to sectoral N inflation.

4 The Quantitative DSGE Model

As we have argued, the shortcoming we highlight with the empirical approach to ERPT are of a quantitative nature, and therefore a model that is able to satisfactorily match the dynamics observed in the data is required. To that end, in this section we reproduce the analysis presented with the simple model using a DSGE model estimated using Chilean data. Given that the model is relatively large, here we present an overview of the model, leaving to the Appendix D the full description, as well as the equilibrium conditions, parametrization strategy and goodness-of-fit analysis. We then proceed by analyzing what are the main driving forces behind exchange rate fluctuations in the model, and provide intuition on how these shocks propagate to the economy. Then we perform the comparison between conditional and unconditional ERPT, and we finish by analyzing how alternative policy paths influence the ERPT.

4.1 Model Overview

Our setup is one of a small open economy with both nominal and real rigidities, and incomplete international financial markets. There are three goods produced domestically: Commodities (C), Non-tradables (N), and an exportable good (X). The first is assumed to be an exogenous endowment that is fully exported, while the other two are produced by combining labor, capital, imported goods (M , which are sold domestically through import agents) and Energy (E). Consumption (both private and public) and investment goods are a combination of N , X and M goods.²¹ The model features exogenous long run-growth under a balanced growth path assumption, although we allow for sector-specific trends in the short-run.

Households derive utility from consumption and leisure, borrow in both domestic- and foreign-currency-denominated bonds, and have monopoly power in supplying labor. Moreover, we assume imperfect labor mobility across sectors. Household's utility exhibits habits in consumption, and investment is subject to convex adjustment costs.

Firms in the X , N and M sectors are assumed to have price setting power, through a monopolistic-competition setup. The problem of choosing prices, as well as that of setting wages, is subject to Calvo-style frictions, with indexation to past inflation. As discussed above, the possibility of indexation to

²¹Final consumption also requires Energy and Food, which are the items that are considered in the non-core part of inflation in Chile. These are assumed to be produced by combining X and M goods; although having a different price dynamic in the short run.

aggregate inflation is relevant to determine the ERPT to different goods, particularly non-tradables. Accordingly, we allow indexation to both past CPI and own-sector inflation, as well as the target, estimating the parameters that govern the relative importance of each of these indexations.

Monetary policy sets the interest rate on domestic bonds, following a Taylor-type rule that responds to past policy rate (smoothing), deviations of inflation from the target, and the growth rate of GDP relative to its long-run trend. Fiscal policy is assumed to finance an exogenous stream of consumption using lump-sum taxes and proceedings from the ownership of part of the commodity production. The final relevant agent is the rest of the world, where international prices and interest rates are set exogenously, following the small-open economy assumption.

The model features 24 shocks, both of domestic and foreign origin. These are:

- Domestic (15): Consumption preferences, Labor supply (X and N), Stationary productivity (X y N), long run trend, Desired markups (M , X and N), Endowment of commodities, Relative prices of Food and Energy, Efficiency of investment, Government consumption, and Monetary policy.
- Foreign (9): World Interest Rate (risk free), Foreign premium (described later), International prices of commodities, imported goods and CPI for trade partners, demand for exports of X , GDP trade partners.

All these variables are assumed to be AR(1) process, with the exception of international prices which we describe below.

The parameter values are chosen by a combination of calibration and Bayesian estimation. The data used is from Chile, at a quarterly frequency from 2001.Q3 to 2016.Q3. The data uses includes aggregate variables for activity, inflation, interest rates and the exchange rate, as well as sectoral series for activity, prices and wages. The dataset also includes international variables such as interest rates, prices and GDP from trading partners. In the appendix we include a complete description of the model and the parametrization strategy. Moreover, we also show that the estimated model can satisfactorily match second moments for the relevant observables in the data.²²

4.2 Main Drivers of the NER and Implied Dynamics

As we discussed before, the analysis of the ERPT requires to first identify the main shocks driving the movements in the NER. While the model features a large number of shocks, the estimation indicates that five shocks can explain almost 95% of the variance of the nominal depreciation. Of these five, four are related with the uncovered interest rate parity in the model (which we later describe): the world interest rate (R^W), two types of risk premia (country premium, $C.P.$, and deviations from UIP), and monetary policy ($M.P.$). The other is a common trend in international prices denominated in dollars (ΔF^*), which we describe in more detail below. In what follows, we first show the relative importance of each of these by means of a variance-decomposition exercise, and then provide intuition for their propagation mechanism.

Table 2 shows the contribution of these five shocks to account for the unconditional variance of the NER depreciation (π^S). In addition, we show the contribution of these shocks in the variance decomposition for alternative inflation measures, the policy rate and the real exchange rate.

As can be seen, the most important shock to account for NER fluctuations is the trend in international prices (ΔF^*), explaining almost 70% of its variance. The risk shock that emerges as deviations

²²All the results presented in the following subsections used the posterior mode as the parameter values.

Table 2: Variance Decomposition

| Var. | <i>M.P.</i> | R^W | <i>C.P.</i> | <i>UIP</i> | ΔF^* | Sum. |
|------------|-------------|-------|-------------|------------|--------------|------|
| π^S | 3 | 8 | 2 | 13 | 67 | 94 |
| π | 3 | 12 | 3 | 5 | 8 | 31 |
| π^T | 4 | 19 | 5 | 9 | 14 | 50 |
| π^M | 3 | 17 | 5 | 8 | 13 | 46 |
| π^N | 2 | 13 | 3 | 2 | 6 | 27 |
| R | 18 | 18 | 5 | 5 | 10 | 56 |
| <i>rer</i> | 3 | 15 | 4 | 11 | 15 | 48 |

Note: Each entry shows the % of the unconditional variance of the variable in each row, explained by the shock in each column, computed at the posterior mode. The shocks correspond to monetary policy (*M.P.*), world interest rate (R^W), country premium (*C.P.*), deviations from UIP (*UIP*) and the trend in international prices (ΔF^*). The variables are: nominal depreciation (π^S), total, tradable, imported and non-traded inflation (respectively, π , π^T , π^M and π^N), the policy rate (R) and the real exchange rate (*rer*).

from the interest parity (*UIP*), as well as the world interest rate (R^W), also explain a non trivial part of the volatility of π^S . Together the three account for almost 90% of the variance of the NER. These five shocks also play a non trivial role in accounting for inflation variability, explaining around 50% of tradable inflation, almost 30% of non-tradable, and 30% of total CPI, as well as and a non-trivial fraction of the variance of R and *rer*. Thus, while clearly not the only relevant factors, the determinants of the NER are important to determine inflation fluctuations as well.

A relevant distinction is that, while the shock to the trend in international prices is the most relevant for the NER, its relative contribution for inflation is smaller. As this is a nominal external shock, the flexible exchange rate framework acts as a shock absorber, isolating to a large extend domestic variables from its influence. This distinction will be crucial for the conditional vs. unconditional ERPT analysis below, for the shock that is most important in explaining the NER is much less relevant for inflation, which can lead to significant biases in the inference of ERPT using VAR models.

Next, we discuss how these shock enter in the model, and the dynamics they generate. The model features three international prices denominated in dollars: Commodities (P_t^{Co*}), Imported goods (P_t^{M*}), and CPI of commercial partners (P_t^*).²³ As relative prices are stationary in the model, these need to cointegrate. Specifically, we assume the following model for these prices:²⁴

$$\hat{P}_t^j = \Gamma_j \hat{P}_{t-1}^j + (1 - \Gamma_j) \hat{F}_t^* + u_t^j, \quad (8)$$

$$\Delta \hat{F}_t^* = \rho_{F^*} \Delta \hat{F}_{t-1}^* + \epsilon_t^{F^*}, \quad u_t^j = \rho_j u_{t-1}^j + \epsilon_t^j,$$

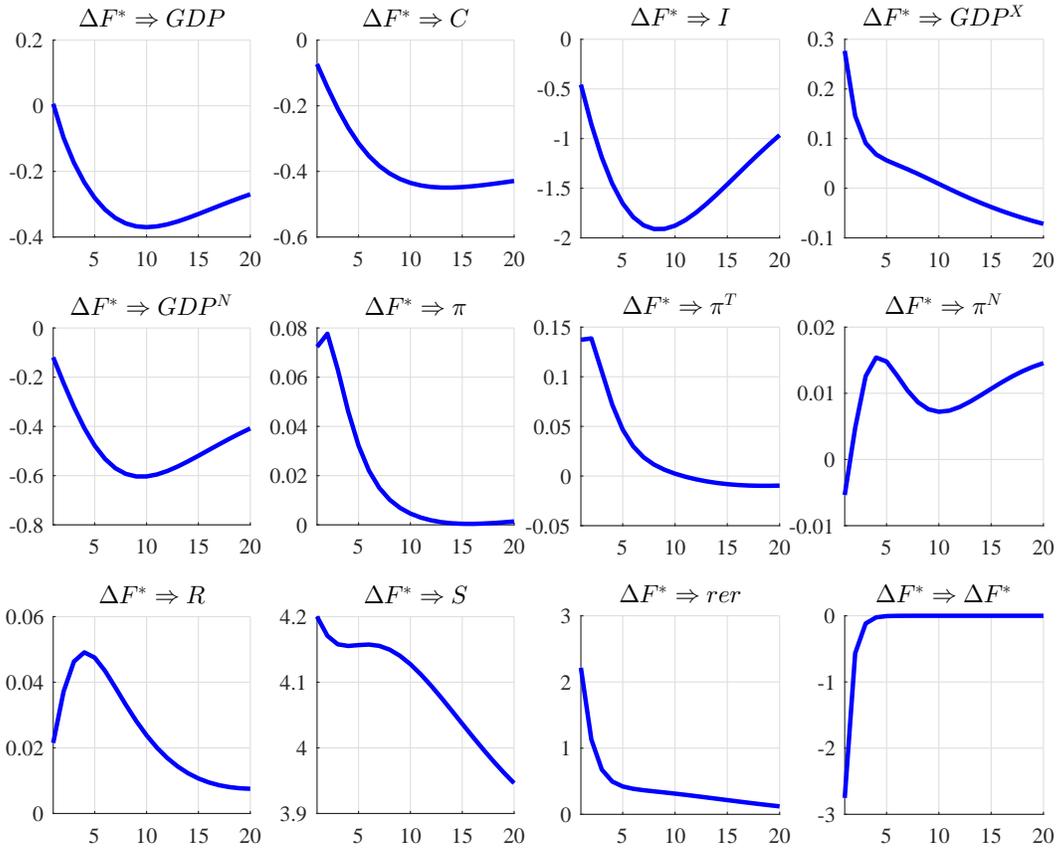
for $j = \{Co*, M*, *\}$. Under this specification, each price is driven by two factors: a common trend (F_t^*) and a price-specific shock (u_t^j). The parameter Γ_j determines how slowly changes in the trend affect each price. The presence of a common trend generates co-integration among prices (as long as $\Gamma_j < 1$), and the fact that the coefficients (8) add-up to one forces relative prices to remain constant in the long run. While in principle both the trend and the price-specific shocks can affect all variables in the model, according to the estimation only the trend is quantitatively relevant to explain fluctuation in the NER.

²³This lat price is the relevant reference price for exports of X goods, and it also the external price used for the definition of the $rer_t = \frac{S_t P_t^*}{P_t}$.

²⁴A hat denotes log-deviations relative to its long run trend.

While this specification for international prices is more complex than in the simple model in previous section, qualitatively ΔF^* resembles the shock to inflation of traded goods (π^*) in the simple model. Thus, the intuition behind the effect of shocks to ΔF^* is similar to that of π^* in the simple model. Figure 10 shows the impulse response to shock to ΔF^* . After a negative shock to the international trend in prices, aggregate demand falls. As the market for non-traded goods has to clear domestically, the shock generates a fall in the relative price of non-tradables, a real exchange rate depreciation, a drop in production of the N sector, an increase in output in the X sector, and an overall fall in GDP. Moreover, given the real depreciation and the presence of price rigidities, the nominal exchange rate depreciates as well.

Figure 10: IRF to a drop in the trend of international prices



Note: Each graph presents the impulse response function, computed at the posterior mode, expressed as percentage deviations relative to the steady-state. The variables are GDP, Consumption, Investment, GDP in the X and the N sectors, total inflation, tradables and non-tradables inflation (excluding Food and Energy), the monetary policy rate, and the nominal exchange rate, the real exchange rate, and the variable being shocked. The size of the shock is equal to one standard-deviation.

To explain the dynamics of inflation first note that without indexation, the required fall in the relative price of non-tradables would lead to an increase in the price of tradables (due to the nominal depreciation) and a drop in the price of non-tradables, which can actually be observed in the very short run in the figure. But with indexation to aggregate inflation (in both wages and prices), inflation of non-tradables will start to rise after a few periods.²⁵ Therefore, the indexation channel is important to

²⁵The importance of indexation to aggregate inflation in total indexation for the price of non-tradables is estimated

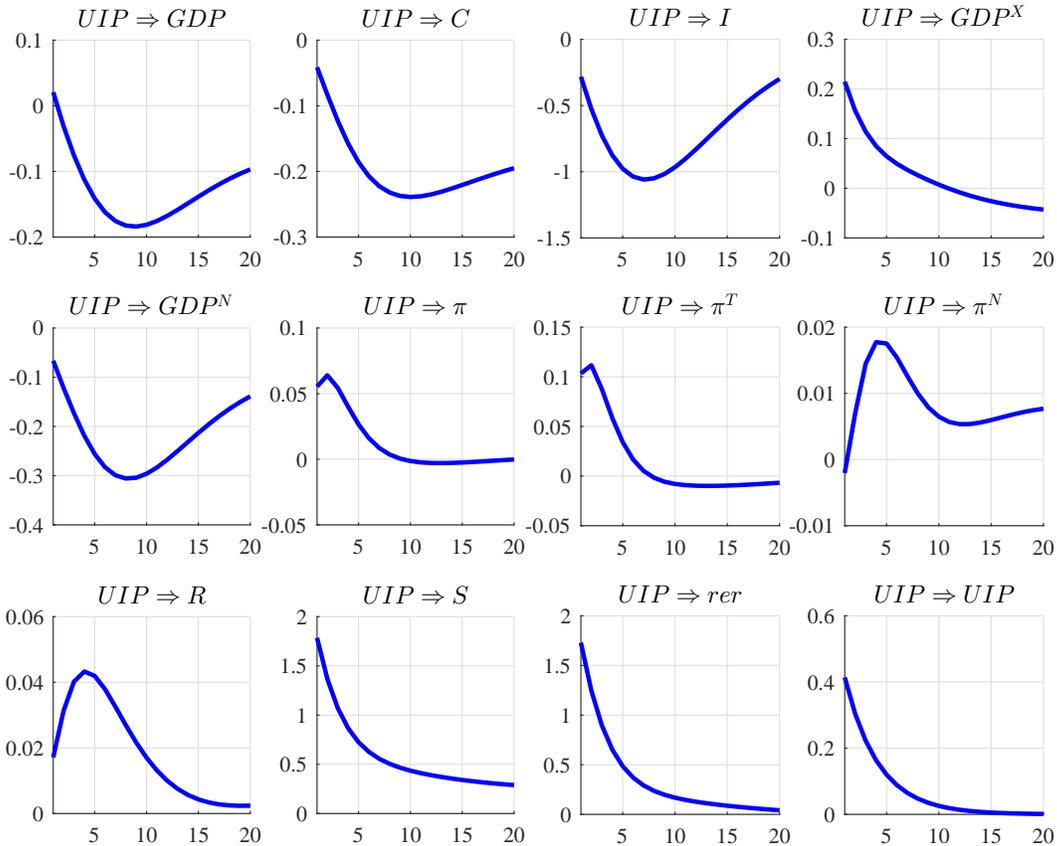
explain the dynamics of inflation (and the ERPT) to non-tradable prices. Finally, given the monetary policy rule, the domestic interest rate increases to smooth the increase in inflation.

The other shocks are associated with the uncovered interest rate parity, which up to first order can be written as,²⁶

$$\hat{R}_t = \hat{R}_t^W + E_t \{ \hat{\pi}_{t+1}^S \} + \phi_b \hat{d}_t^* + \hat{\xi}_t^{R1} + \hat{\xi}_t^{R2}.$$

Here \hat{R}_t is the domestic rate, \hat{R}_t^W is the risk free interest rate, $E_t \{ \hat{\pi}_{t+1}^S \}$ is the expected nominal depreciation, and $\phi_b \hat{d}_t^*$ is a premium elastic to foreign debt, \hat{d}_t^* , which acts as the closing device. Additionally, there are two risk premium shocks $\hat{\xi}_t^{R1}$ and $\hat{\xi}_t^{R2}$. They differ in that the first one is matched with a measure of the country premium in the data (the JP Morgan EMBI Index for Chile),²⁷ while the second is unobservable and accounts for all other sources of risk that explain deviations from the EMBI-adjusted interest rate parity. In the tables and figures $\hat{\xi}_t^{R1}$ is labeled as *C.P.* and $\hat{\xi}_t^{R2}$ is called *UIP*.

Figure 11: IRF to a positive risk shock (deviations from UIP)



Note: See Figure 10.

Figure 11 shows the responses to a positive realization of the *UIP* shock, which qualitatively is to be close to 20%. And for wages in the non-traded sector, only 11% of those that cannot be freely chosen will adjust to aggregate past inflation, and for prices this fraction is close to 20%. Still, one can numerically show that if these were set to zero, the response of π^N is negative for the relevant horizon.

²⁶A hat denotes log-deviations relative to steady state.

²⁷Specifically, the EMBI index is matched with $\phi_b \hat{d}_t^* + \hat{\xi}_t^{R1}$

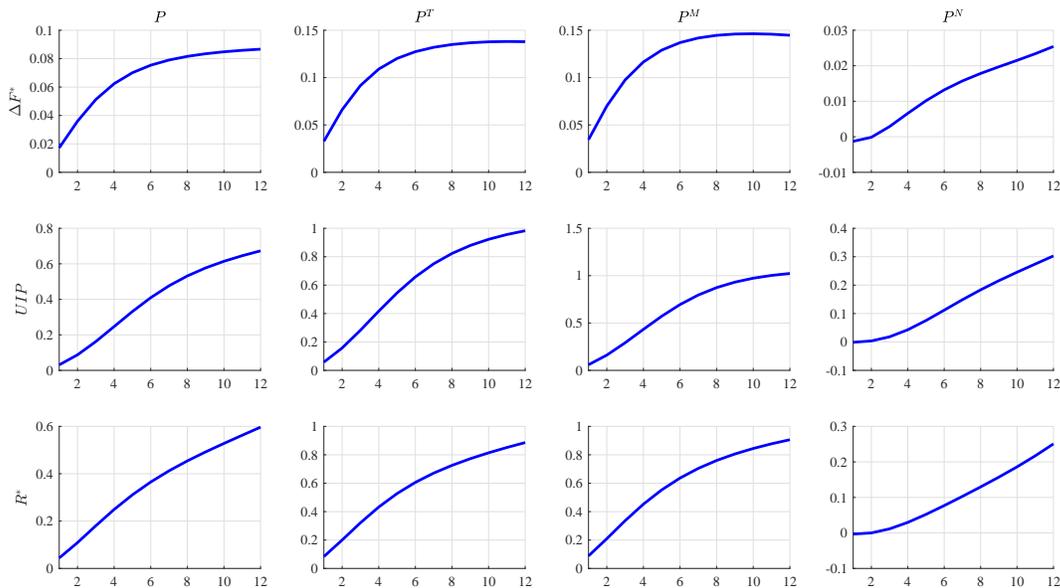
analogous to the influence of world-interest-rate shocks in the simple model.²⁸ This shock increases the cost of foreign borrowing, which triggers both income and substitution effects, leading to a contraction in aggregate demand. This lead to both real and nominal depreciations, and a reduction in all measures of activity; except for production in X that is favored by the relocation from the N sector. All measures of inflation increases, and the role of indexation in explaining π^N is similar to what we describe before. Accordingly, the policy rate rises after this shock.

We conclude by reminding that, as discussed before, even though both shock have an impact through aggregate demand, the shock to ΔF^* also has a direct impact on inflation that dampens the effect generated by the NER changes. In this more complex model, this happens for two different channels. First, a drop in international prices puts downward pressure to the domestic price of imports. Second, given the presence of imported inputs in the production of both X and N , a reduction in world prices will, ceteris paribus, reduce the marginal cost in these sectors, dampening also the response of inflation for both X and N . Thus, as in the simple model, it is expected to have a lower conditional ERPT for ΔF^* that for interest-rate-related shocks.

4.3 Conditional vs. Unconditional ERPT

We begin by computing the conditional ERPT associated with the three main shocks behind the fluctuation in the NER. We present the results for aggregate CPI (P), tradables (T), imported (M) and non-tradables (N), the last three excluding Food and Energy. In line with the previous discussion, the unconditional ERPTs generated by ΔF^* are significantly different from those implied by the shocks to the UIP and to the world interest rate R^W . For a horizon of 2 years, the conditional ERPT given a shock to international prices is less than 0.1 for total CPI, smaller than 0.05 for non-tradables, and close to 0.15 for both traded and imported goods.

Figure 12: Conditional ERPT



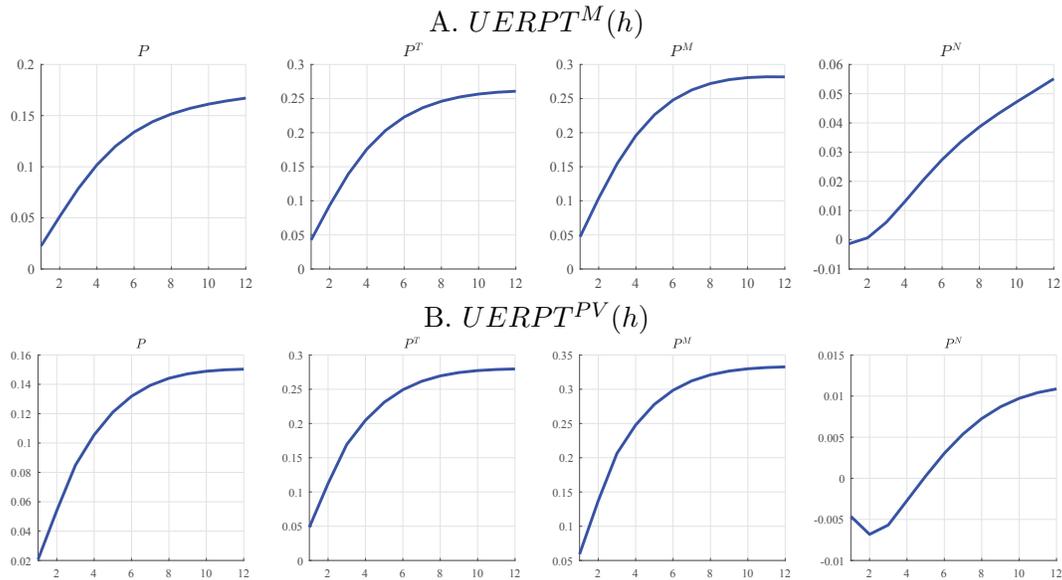
In sharp contrast, for the same horizon, the conditional ERPTs to the UIP shocks are much larger

²⁸The responses to shock to R^W and $C.P.$ in the quantitative model are similar to those originated by a UIP shock, and thus are omitted to save space.

for all prices: close to 0.5 for CPI, larger than 0.8 for tradables and importables, and near 0.2 for non-tradables. For the world-interest-rate shock the conditional ERPTs are somehow smaller, but still larger than those obtained after a shock in the trend of international prices.

Figure 13 displays both measures of unconditional ERPT we introduced in Section 2: panel A shows the weighted average of conditional ERPTs, while panel B displays that obtained using the Population VAR approach.²⁹ In line with our previous analysis, both measures of unconditional ERPT lie between those of the conditionals reported before.³⁰ Moreover, the empirical VAR literature using Chilean data estimates an ERPT close to 0.2% for total CPI after two years, with a similar value for tradables and close to 0.05 for non-tradables.³¹ These are close to the measures of unconditional ERPTs we report here.

Figure 13: Unconditional ERPT



Overall, the evidence presented in this section confirms the intuition developed with the simple model: conditional ERPTs are quite different from those obtained from aggregate ERPT measures comparable to those in the literature. Thus, using the results from the empirical literature would lead to a bias in the estimated dynamics of inflation following movements in the NER. In turn, the analysis of ERPT can be greatly improved by an assessment of which shock are behind the particular NER change, and the use of conditional ERPT measures.

4.4 ERPT and Expected Monetary Policy

Our second concern regarding the use of the ERPT obtained from the empirical literature is that it could mistakenly lead to think that actual and future monetary policy has little to say about the

²⁹The VAR is assumed to contain the following variables: world interest rate (R^W), foreign inflation (π^*), inflation of commodities (π^{Co*}) and imports (π^{M*}), growth of external GDP (Y^*), nominal depreciation rate (π^S), and inflations for CPI (π), tradables (π^T), importables (π^M) and non-tradables (π^N). These series are the same used in the empirical literature. The ERPT is computed using the shock for π^S in the Cholesky decomposition. We ran a VAR(2) based on the BIC criterion.

³⁰Although the measure $UERPT^M(h)$ includes all shocks, given the importance of ΔF^* , UIP and R^W to explain the volatility of the NER, they are the main drivers of this unconditional measure.

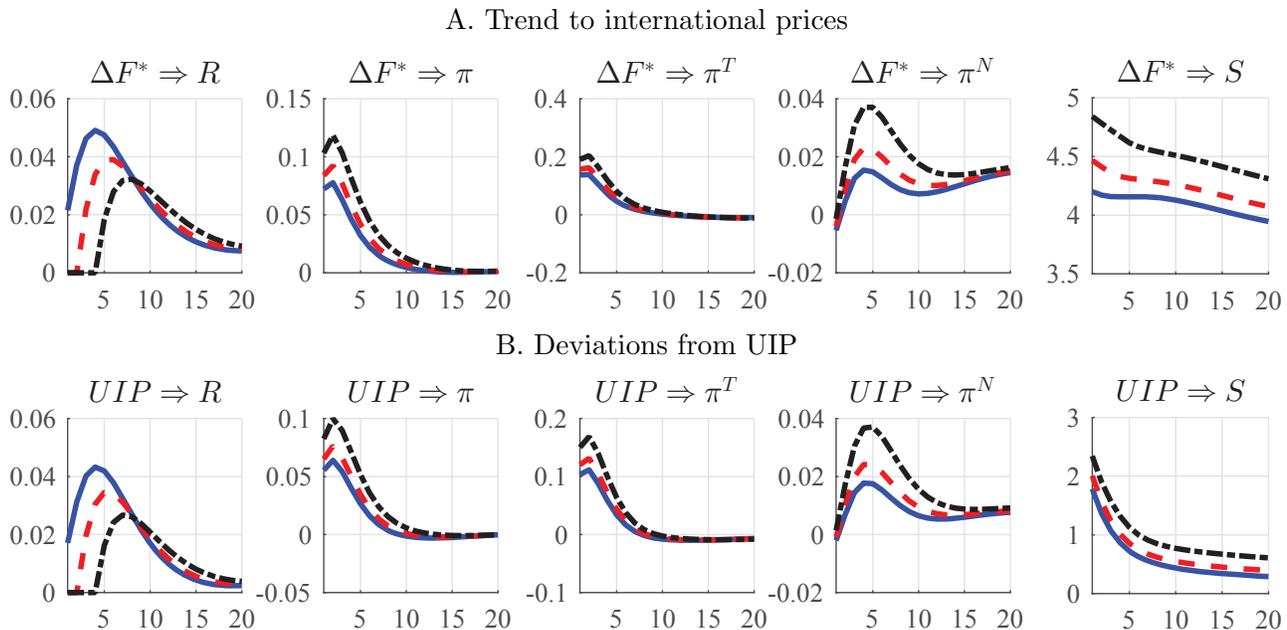
³¹See, for instance, Justel and Sansone (2015), Contreras and Pinto (2016), Albagli et al. (2015), among others.

behavior of both the NER and prices. Conceptually, this discussion is independent from the potential differences between conditional and unconditional ERPT; although we will see that quantitatively the source of the shock also matters for this discussion.

The starting point is to notice that, as discussed in Section 4.2, in the benchmark model the monetary policy rate increases (and it is expected to remain high) in response to the main shocks that depreciate the currency. We compare the benchmark ERPT, obtained with a path for the policy rate that follows the estimated rule, with alternative scenarios that deviate temporarily. In particular, as we did with the simple model, it is assumed that when the shock hits the economy the central bank announces that it will maintain the interest rate at its pre-shock level for T periods, and return to the estimated rule afterwards.

Figure 14 shows how the impulse-response functions change with these policy alternatives, for the main shocks that drive the NER. Relative to the baseline, these alternatives are more dovish, since a lower rate translates in higher inflation in all goods. At the same time, by the interest rate parity, a relatively lower policy rate path implies a more depreciated NER. Thus, as the ERPT is the ratio of the response of a price and the exchange rate, it is not ex-ante evident how it will change with these alternative policy paths.

Figure 14: IRF under alternative policy paths

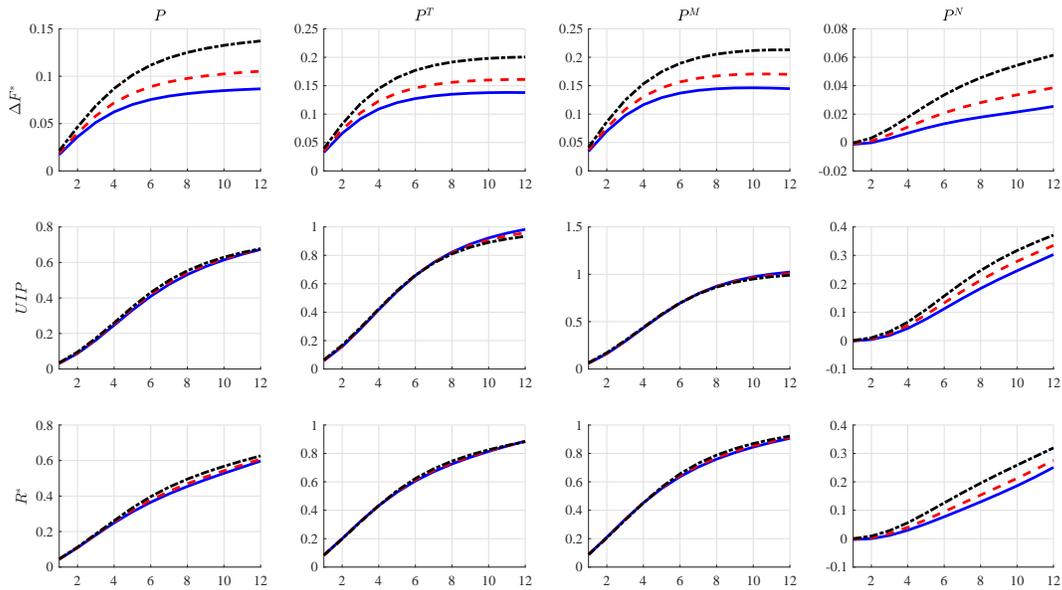


Note: The solid-blue line represents the benchmark case (when the policy rate follows the estimated rule), the dashed-red line is the case in which the rate is fixed for two periods, and the dashed-dotted-black line is when the rate is fixed for 4 periods. The variables shown are the policy rate, total, tradable and non-tradable inflations, and the nominal exchange rate.

Using these responses, Figure 15 shows the conditional ERPTs for these policy alternatives. When the shock to the trend in international prices hits the economy, the conditional ERPT varies significantly depending on the reaction of monetary policy. For instance, after two years, the ERPT to total CPI almost doubles if the policy rate remains fixed for a year; and the difference is even larger for non tradables. At the same time, conditional on shocks to either the UIP or the world interest rate, the ERPT measures do not seem to vary significantly as monetary policy changes; except for

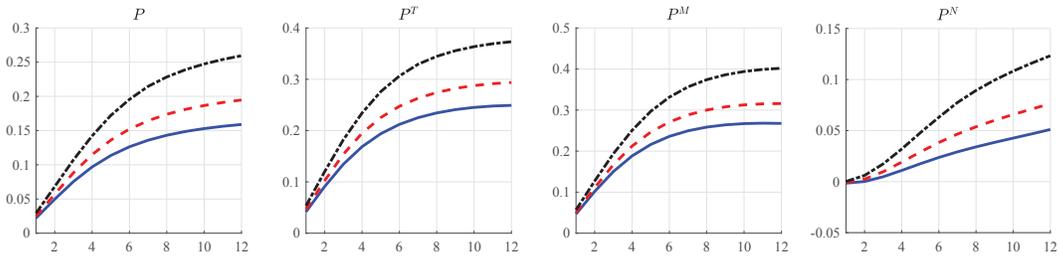
non-tradables where we can see some differences.

Figure 15: Conditional ERPT, under alternative policy paths



Note: See Figure 14

Figure 16: Unconditional ERPT, under alternative policy paths



Note: See Figure 14

In Figure 16 we compute the unconditional ERPT using the weighted average of conditional ones as in (7).³² As can be seen, influenced mainly by the behavior of the ERPT after the shock to international prices, the unconditional ERPT also increases with a more dovish policy. This comparison provides yet another reason to properly account for the source of the shock and to compute conditional ERPTs, as the effect of alternative policy paths will be relevant depending on the shock.

In sum, this analysis highlights that, in thinking about how monetary policy should react to shocks that depreciate the currency, a menu of policy options and their associated conditional ERPT should

³²In this computation, we exclude the monetary policy shock in all models, as it plays no role once we fix the policy rate, and we maintain the weights as in the baseline to isolate the changes only due to different dynamics with alternative policy paths. Moreover, the Population VAR measure of aggregate ERPT will not vary with this policy comparison, as the alternative paths for the interest rate will only affect the dynamics in the short run, without changing the population moments.

be analyzed. For some shocks, monetary policy has an important role to determine the final outcome of both inflation and the NER. As we have argued, this kind of analysis cannot be performed using the tools and results from the empirical literature literature, and the related literature using DSGE models has not analyzed the role of alternative policy paths for the ERPT.

5 Conclusions

This paper was motivated by the widespread use of ERPT measures generated by empirical, reduced-form methodologies for monetary-policy analysis. We analyzed two potential problems: the dependence of the ERPT on the shock hitting the economy (separating conditional and unconditional ERPT), and the influence of alternative expected paths of monetary policy. We first established the relationship between the ERPT measures used in the empirical literature with related objects obtained from general equilibrium models. We then used a simple model to conceptually understand how the two shortcoming that we highlight can arise even in simple models. Finally, to assess the quantitative importance of making these distinctions, we used a DSGE model estimated with Chilean data. We found that these distinctions are indeed relevant, and that a policy maker using the results from the empirical literature might be deciding using inappropriate tools.

Another way to frame this discussion in a more general context is the following. From the point of view of general equilibrium models, one can define alternative measures of what “optimal” policy means and then fully characterize how monetary policy should respond to particular shocks hitting the economy, in order to achieve the optimality criteria. In that discussion, structural parameters, the role of expectation formation, the nature of alternative driving forces, among other important details, will be relevant to determine the path that monetary policy should follow. However, as the empirical measure of the ERPT computed in the literature is, in one way or another, a conditional correlation and not a structural characteristic of the economy, all the relevant aspects of optimal monetary policy can be described without using the concept of ERPT at all. Thus, while the results of the empirical literature can be useful for other important discussions in International Macroeconomics, its relevance for monetary policy analysis is more limited.

Finally, the point we stress about the role of expected policy to determine the ERPT should be taken into account for actual policy making. To a large extent, the realized ERPT after a given NER movement can be influenced by monetary policy. However, the widespread use of empirical measures of ERPT for policy analysis, which completely omits this issue, indicates that this is not the way policy makers think about the ERPT. In that way, future research could study particular episodes of large depreciations to analyze to what extent the expected path of policy perceived at the time of the NER movement influenced the dynamics of inflation that followed.

6 References

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A ERPT in VARs and DSGE Models

A.1 Conditions for Exact Relationship

The linearized solution of a DSGE model takes the form

$$c_t = As_{t-1} + Be_t, \quad (9)$$

$$s_t = Cs_{t-1} + De_t, \quad (10)$$

where s_t is a $n \times 1$ vector of predetermined variables, both endogenous and exogenous, c_t is a $r \times 1$ vector of non-predetermined variables, e_t is a $m \times 1$ vector of i.i.d. exogenous shocks (with $E(e_t) = 0$, $E(e_t e_t') = I$, and $E(e_t e_j') = 0$ for $t \neq j$), while A , B , C and D are conformable matrices. The solution in (5) can be obtained by defining

$$y_t = \begin{bmatrix} c_t \\ s_t \end{bmatrix}, \quad F = \begin{bmatrix} 0 & A \\ 0 & C \end{bmatrix}, \quad Q = \begin{bmatrix} B \\ D \end{bmatrix}.$$

Let x_t be a $k \times 1$ vector collecting variables from either s_t or c_t , such that $x_t = S[c_t' s_t']' = Sy_t$ for an appropriate selection matrix S . From (9) and (10),

$$x_t = \bar{A}s_{t-1} + \bar{B}e_t, \quad (11)$$

with

$$\bar{A} = S \begin{bmatrix} A \\ C \end{bmatrix}, \quad \bar{B} = S \begin{bmatrix} B \\ D \end{bmatrix}.$$

If $k = m$ (i.e. the same number of variables in x than shocks in the model), under certain conditions stated in [Ravenna \(2007\)](#) a finite VAR representation for the vector x_t exists and takes the form

$$x_t = \Phi_1 x_{t-1} + \dots + \Phi_p x_{t-p} + \bar{B}e_t. \quad (12)$$

As long as the solution of the DSGE model is stationary, we can always find the $MA(\infty)$ representation of the vector x_t . Under the assumptions in [Ravenna \(2007\)](#), we can write it as,

$$x_t = \sum_{j=0}^{\infty} F_j \bar{B}e_{t-j}, \quad (13)$$

with $F_0 = I$ and $F_j = \bar{A}C^{j-1}D\bar{B}^{-1}$. Using this representation, the cumulative response of a variables in the position k in the vector x_t , h periods after a shock in the position i in the vector e_t is realized, is given by

$$CIRF_{k,i}^M(h) \equiv [F(h)\bar{B}]_{ki}, \quad (14)$$

where $F(h) \equiv \sum_{j=0}^h F_j$, and the notation X_{ij} indicates the element in the i th row, j th column of matrix X . Thus, the conditional ERPT after a shock i , for variable k , h periods ahead is given by

$$CERPT_{k,i}^M(h) \equiv \frac{CIRF_{k,i}^M(h)}{CIRF_{\pi^S,i}^M(h)},$$

i.e. the ratio of the cumulative response of variable k and that of the nominal depreciation (π_t^S), after

the i th shock.

At the same time, if the model (9)-(10) is the true data generating process, someone using the approach in the VAR-based literature will first estimate a reduced form VAR given by

$$x_t = \Theta_1 x_{t-1} + \dots + \Theta_p x_{t-p} + u_t. \quad (15)$$

Clearly, if the a finite VAR representation of the DSGE model exists and the lag-length is chosen properly, we have $\Theta_j = \Phi_j$ and $\Omega \equiv E(u_t u_t') = \bar{B} \bar{B}'$. The MA(∞) representation of this reduced-form is

$$x_t = \sum_{j=0}^{\infty} F_j u_{t-j}, \quad (16)$$

The Cholesky decomposition of Ω is a matrix P satisfying $\Omega = PP'$. The cumulative IRF after a shock corresponding to the nominal-depreciation equation is given by

$$CIRF_{k,\pi^S}^V(h) \equiv [F(h)P]_{k\pi^S}, \quad (17)$$

and the ERPT for variable k , h periods ahead, is computed as,

$$ERPT_k^V(h) \equiv \frac{CIRF_{k,\pi^S}^V(h)}{CIRF_{\pi^S,\pi^S}^V(h)},$$

To study the relationship between $ERPT_k^V(h)$ and $CERPT_{k,i}^M(h)$, assume the nominal depreciation (π_t^S) is ordered first in the vector x_t . Then, we can write the conditional ERPT as

$$CERPT_{k,i}^M(h) = \frac{[F(h)\bar{B}]_{ki}}{[F(h)\bar{B}]_{1i}} = \frac{F(h)_{k1}\bar{B}_{1i} + \dots + F(h)_{km}\bar{B}_{mi}}{F(h)_{11}\bar{B}_{1i} + \dots + F(h)_{1m}\bar{B}_{mi}} = \frac{\sum_{j=1}^m F(h)_{kj}\bar{B}_{ji}}{\sum_{j=1}^m F(h)_{1j}\bar{B}_{ji}}.$$

By the same token, the ERPT from the VAR is

$$ERPT_k^V(h) \frac{[F(h)P]_{k1}}{[F(h)P]_{11}} = \frac{F(h)_{k1}P_{11} + \dots + F(h)_{km}P_{m1}}{F(h)_{11}P_{11} + \dots + F(h)_{1m}P_{m1}} = \frac{\sum_{j=1}^m F(h)_{kj}P_{j1}}{\sum_{j=1}^m F(h)_{1j}P_{j1}}.$$

In addition, by the properties of the Cholesky decomposition, we have

$$P_{11} = (\Omega_{11})^{1/2}, \quad P_{j1} = \Omega_{j1}(\Omega_{11})^{1/2} \text{ for } j = 2, \dots, m.$$

Thus, the ERPT from the VAR can be written as

$$ERPT_k^V(h) = \frac{F(h)_{k1}\Omega_{11} + \dots + F(h)_{km}\Omega_{m1}}{F(h)_{11}\Omega_{11} + \dots + F(h)_{1m}\Omega_{m1}} = \frac{\sum_{j=1}^m F(h)_{kj}\Omega_{j1}}{\sum_{j=1}^m F(h)_{1j}\Omega_{j1}}.$$

Moreover, as $\Omega = \bar{B}\bar{B}'$, we have

$$\Omega_{ji} = \sum_{s=1}^m \bar{B}_{js}\bar{B}_{is}$$

Thus,

$$\begin{aligned}
ERPT^V(h) &= \frac{\sum_{j=1}^m F(h)_{kj} (\sum_{s=1}^m \bar{B}_{js} \bar{B}_{1s})}{\sum_{j=1}^m F(h)_{1j} (\sum_{s=1}^m \bar{B}_{js} \bar{B}_{1s})} = \frac{\sum_{s=1}^m \left(\sum_{j=1}^m F(h)_{kj} \bar{B}_{js} \right) \bar{B}_{1s}}{\sum_{s=1}^m \left(\sum_{j=1}^m F(h)_{1j} \bar{B}_{js} \right) \bar{B}_{1s}} \\
&= \frac{\sum_{s=1}^m CIRF_{k,s}^M(h) \bar{B}_{1s}}{\sum_{s=1}^m CIRF_{1,s}^M(h) \bar{B}_{1s}} = \frac{\sum_{s=1}^m CERPT_{k,s}^M(h) CIRF_{1,s}^M(h) \bar{B}_{1s}}{\sum_{s=1}^m CIRF_{1,s}^M(h) \bar{B}_{1s}} \\
&= \sum_{s=1}^m CERPT_{k,s}^M(h) \omega_s(h),
\end{aligned}$$

where $\omega_s(h) \equiv \frac{CIRF_{1,s}^M(h) \bar{B}_{1s}}{\sum_{s=1}^m CIRF_{1,s}^M(h) \bar{B}_{1s}}$.

To grasp some intuition on the weight $\omega_s(h)$, notice that at $h = 0$,

$$\omega_s(h) \equiv \frac{(\bar{B}_{1s})^2}{\sum_{s=1}^m (\bar{B}_{1s})^2},$$

i.e. the fraction of the one-step-ahead forecast-error-variance of the nominal exchange rate that is due to the shock s . In other words, the weight of the conditional ERPT given shock s depends on how important is this shock in explaining the fluctuations of the nominal exchange rate. For $h \geq 1$, the forecast-error variance is adjusted by the ratio of the response of the NER at period h relative to that at $h = 0$.

A.2 ERPT from the Population VAR

From the linearized solution of the DGSE model (5), provided stationarity, the variance-covariance matrix $\Sigma_0 \equiv E(y_t y_t')$ satisfies,

$$\Sigma_0 = F \Sigma_0 F' + Q Q', \quad (18)$$

which can be easily computed.³³ In addition, the matrix containing the auto-covariance of order p is $\Sigma_p \equiv E(y_t y_{t-p}') = F^p \Sigma_0$ for $p > 0$. Finally, we are interested in subset x_t of n variables from y_t , that will be included in the VAR model, defined as $x_t \equiv S y_t$ for an appropriate choice of S . In that case, we have

$$E(x_t x_{t-p}') = S E(y_t y_{t-p}') S' = S \Sigma_p S' \quad (19)$$

for $p \geq 0$.

The structural VAR(p) model for the vector x_t in (2)-(3) can be written in more compact form, defining the vector $X_t = [x_t' \ x_{t-1}' \ x_{t-p+1}']'$, in two alternative ways. Either,

$$x_t = \Phi X_{t-1} + P w_t, \quad (20)$$

where $\Phi = [\Phi_1 \ \dots \ \Phi_p]$ or,

$$X_t = \tilde{\Phi} X_{t-1} + U_t, \quad (21)$$

where,

$$\tilde{\Phi} = \begin{bmatrix} \Phi & \\ I_{n(p-1)} & 0_{n(p-1) \times n} \end{bmatrix}, \quad U_t = \tilde{P} w_t, \quad \tilde{P} = \begin{bmatrix} P \\ 0_{n(p-1) \times n} \end{bmatrix}.$$

Using (21) the IRF of the variables in the position j in the vector x_t to the shock associated with the variable in the position i , h periods after the shock, is given by the $\{j, i\}$ element of the matrix $\tilde{\Phi}^h \tilde{P}$. The cumulative IRF is just the element $\{j, i\}$ in the matrix $\sum_{s=0}^h \tilde{\Phi}^s \tilde{P}$.

An econometrician would proceed by choosing a lag order p in the VAR and estimate (20) by OLS. If she had available an infinite sample, she can estimate (20) using the population OLS; i.e. choosing $\hat{\Phi}$ to minimize,

$$E \left[(x_t - \hat{\Phi} X_{t-1})' (x_t - \hat{\Phi} X_{t-1}) \right].$$

This is equivalent to $\hat{\Phi}$ satisfying the first order condition,

$$E \left[(x_t - \hat{\Phi} X_{t-1}) X_{t-1}' \right] = 0,$$

which can be solved to obtain,

$$\hat{\Phi} = E(x_t X_{t-1}') [E(X_{t-1} X_{t-1}')]^{-1}, \quad (22)$$

³³For instance, $\text{vec}(\Sigma_0) = (I - F \otimes F)^{-1} \text{vec}(Q Q')$.

Similarly,

$$\begin{aligned}
\hat{\Omega} &= E(u_t u_t') = E \left[(x_t - \hat{\Phi} X_{t-1})(x_t - \hat{\Phi} X_{t-1})' \right] \\
&= E(x_t x_t') + \hat{\Phi} E(X_{t-1} X_{t-1}') \hat{\Phi}' - E(x_t X_{t-1}') \hat{\Phi}' - \hat{\Phi} E(X_{t-1} x_t') \\
&= E(x_t x_t') + E(x_t X_{t-1}') [E(X_{t-1} X_{t-1}')]^{-1} E(X_{t-1} x_t') - \\
&\quad E(x_t X_{t-1}') [E(X_{t-1} X_{t-1}')]^{-1} E(X_{t-1} x_t') - E(x_t X_{t-1}') [E(X_{t-1} X_{t-1}')]^{-1} E(X_{t-1} x_t') \\
&= E(x_t x_t') - E(x_t X_{t-1}') [E(X_{t-1} X_{t-1}')]^{-1} E(X_{t-1} x_t') = E(x_t x_t') - \hat{\Phi} E(X_{t-1} x_t') \quad (23)
\end{aligned}$$

In most applied cases, with finite samples, econometricians estimate the parameters of the VAR and use asymptotic theory to derive probability limits and limiting distributions to perform inference,³⁴ such as hypothesis testing or computing confidence bands. The case we want to analyze here is different, as we assume the DSGE model is the true data generating process, and we wish to compute the model that an econometrician would estimate with an infinite or population sample. This is equivalent to compute $\hat{\Phi}$ and $\hat{\Omega}$ in (22)-(23) using the population moments from the DSGE.

Given $x_t = Sy_t$, and recalling the definition of X_t , we have,

$$E(x_t x_t') = S \Sigma_0 S',$$

$$E(x_t X_{t-1}') = [E(x_t x_{t-1}') \ E(x_t x_{t-2}') \ \dots \ E(x_t x_{t-p}')] = [S \Sigma_1 S' \ S \Sigma_2 S' \ \dots \ S \Sigma_p S']$$

$$\begin{aligned}
E(X_{t-1} X_{t-1}') &= \begin{bmatrix} E(x_{t-1} x_{t-1}') & E(x_{t-1} x_{t-2}') & \dots & E(x_{t-1} x_{t-p}') \\ E(x_{t-2} x_{t-1}') & E(x_{t-2} x_{t-2}') & \dots & E(x_{t-2} x_{t-p}') \\ \vdots & \vdots & \ddots & \vdots \\ E(x_{t-p} x_{t-1}') & E(x_{t-p} x_{t-2}') & \dots & E(x_{t-p} x_{t-p}') \end{bmatrix} = \\
&\begin{bmatrix} E(x_t x_t') & E(x_t x_{t-1}') & \dots & E(x_t x_{t-p+1}') \\ E(x_{t-1} x_t') & E(x_{t-1} x_{t-1}') & \dots & E(x_{t-1} x_{t-p+2}') \\ \vdots & \vdots & \ddots & \vdots \\ E(x_{t-p+1} x_t') & E(x_{t-p+2} x_t') & \dots & E(x_t x_t') \end{bmatrix} = \begin{bmatrix} S \Sigma_0 S' & S \Sigma_1 S' & \dots & S \Sigma_{p-1} S' \\ S \Sigma_1' S' & S \Sigma_0 S' & \dots & S \Sigma_{p-2} S' \\ \vdots & \vdots & \ddots & \vdots \\ S \Sigma_{p-1}' S' & S \Sigma_{p-2}' S' & \dots & S \Sigma_0 S' \end{bmatrix}
\end{aligned}$$

which are all the elements required to compute $\hat{\Phi}$ and $\hat{\Omega}$.

A final comment relating the usual practice in the VAR literature. In most papers the vector x_t contains foreign variables. If the assumption of a small and open economy is used, it is generally assumed that the matrices Φ_j for $j = 1, \dots, p$ are block lower triangular: i.e. lags of domestic variables cannot affect foreign variables. In practice, this second constraint is implemented by estimating the matrices Φ_j by FGLS or FIML, applying the required restrictions. Here, however, if the DSGE model assumes that foreign variables cannot be affected by domestic variables, the auto-covariance matrices Σ_j will have zeros in the appropriate places, so that $\hat{\Phi}$ will display the same zero constraints the econometrician would impose.

³⁴For instance, (22) and (23) are the probability limits of the OLS estimators for Φ and Ω , by virtue of both the Law of Large Numbers and the Continuous Mapping Theorem.

B Simple DSGE Model Appendix

B.1 Optimality Conditions

B.1.1 Household

From the decision of final consumption, labor and bonds, and defining as λ_t the multiplier of the budget constraint, we have the first order conditions:

$$\begin{aligned} C_t^{-\sigma} - P_t \lambda_t &= 0 \\ -\xi(h_t)^\rho + W_t \lambda_t &= 0 \\ -\lambda_t + \beta E_t \lambda_{t+1} R_t &= 0 \\ -\lambda_t S_t + \beta E_t \lambda_{t+1} S_{t+1} R_t^* &= 0 \end{aligned}$$

In addition, the optimality conditions for the decision between tradable and non-tradable consumption are:

$$\begin{aligned} C_t^N &= \gamma \left(\frac{P_t^N}{P_t} \right)^{-\varrho} C_t \\ C_t^T &= (1 - \gamma) \left(\frac{P_t^T}{P_t} \right)^{-\varrho} C_t \end{aligned}$$

The price index of the consumption good is defined as:

$$P_t = [(1 - \gamma)(P_t^T)^{1-\varrho} + \gamma(P_t^N)^{1-\varrho}]^{\frac{1}{1-\varrho}}$$

B.1.2 Firms in N Sector

The aggregation creates a Δ variable in this case:

$$\begin{aligned} h_t &= \int_0^1 h_t(i) di = \Delta_t^{Nh} (Y_t^N)^{\frac{1}{1-\alpha_N}} \\ \Delta_t^{Nh} &= \int_0^1 \left(\frac{P_t(i)^N}{P_t^N} \right)^{-\frac{\epsilon_N}{1-\alpha_N}} di \end{aligned}$$

And the FOC of choosing prices optimally can be written in this case as:

$$\begin{aligned} f_t^{1,N} &= \frac{\epsilon_N - 1}{\epsilon_N} (P_t^{N,*})^{1-\epsilon_N} \frac{Y_t^N}{(P_t^N)^{-\epsilon_N}} + \beta \theta_N E_t \left(\frac{P_t^{N,*}}{P_{t+1}^{N,*}} \right)^{1-\epsilon_N} \Lambda_{t,t+1} \left[\left((\pi_t^N)^{\varrho_N} \pi_t^{1-\varrho_N} \right)^{\zeta_N} \bar{\pi}_{t+1}^{1-\zeta_N} \right]^{1-\epsilon_N} f_{t+1}^{1,N} \\ f_t^{2,N} &= \frac{1}{1 - \alpha_N} (P_t^{N,*})^{-\frac{\epsilon_N}{1-\alpha_N}} W_t \left[\frac{Y_t^N}{(P_t^N)^{-\epsilon_N}} \right]^{\frac{1}{1-\alpha_N}} + \beta \theta_N E_t \Lambda_{t,t+1} \left(\frac{P_t^{N,*}}{P_{t+1}^{N,*}} \right)^{-\frac{\epsilon_N}{1-\alpha_N}} \\ &\quad \left[\left((\pi_t^N)^{\varrho_N} \pi_t^{1-\varrho_N} \right)^{\zeta_N} \bar{\pi}_{t+1}^{1-\zeta_N} \right]^{-\frac{\epsilon_N}{1-\alpha_N}} f_{t+1}^{2,N} \end{aligned}$$

B.1.3 Market Clearing

All markets clear:

$$\begin{aligned} B_t &= 0 \\ Y_t^N &= \Delta_t^N C_t^N \end{aligned}$$

Which correspond to the local bonds market and goods market. The Δ_t^N variable is a measure of price dispersion in N .

The rest of the equations correspond to policy and foreign equations described in the text and to equations concerning the evolution of price indexes. In addition, we have the resource constraint:

$$S_t B_t^* = S_t P_t^{T,*} (Y_t^T - C_t^T) + S_t R_{t-1}^* B_{t-1}^*$$

And definitions of trade balance and real and nominal GDP:

$$\begin{aligned} TB_t &= P_t^T (Y_t^T - C_t^T) \\ GDP_t &= C_t + Y_t^T - C_t^T \\ P_t^Y GDP_t &= P_t C_t + TB_t \end{aligned}$$

B.2 Equilibrium Conditions

This sections describes the equilibrium conditions after the variables were redefined to make them stationary. The transformations made to the variables were: all lower case prices are the corresponding capital price divided by the CPI Index, with the exception of $p_t^{N,*} = P_t^{N,*} / P_t^N$, all inflation definitions are the corresponding price index divided by the price index in the previous period. And particular definitions are $\tilde{\lambda}_t = \lambda_t P_t$, $b_t^* = B_t^* / P_t^T$, $tb_t = TB_t / P_t$, $\tilde{f}_t^{1,N} = f_t^{1,N} / P_t^N$.

There are 22 endogenous variables,

$$\{C_t, \tilde{\lambda}_t, h_t, w_t, R_t^*, \pi_t^S, \pi_t, R_t, C_t^N, C_t^T, p_t^N, p_t^T, \Delta_t^{Nh}, Y_t^N, p_t^{N,*}, \pi_t^N, \tilde{f}_t^{1,N}, GDP_t, b_t^*, \Delta_t^N, p_t^Y, tb_t\}$$

and 3 shocks $\{\epsilon_t^m, \pi_t^*, R_t^W\}$.

$$C_t^{-\sigma} = \tilde{\lambda}_t \tag{B-EC.1}$$

$$\chi(h_t)^\varphi = \tilde{\lambda}_t w_t \tag{B-EC.2}$$

$$\tilde{\lambda}_t = \beta E_t \frac{\tilde{\lambda}_{t+1} R_t^* \pi_{t+1}^S}{\pi_{t+1}} \tag{B-EC.3}$$

$$\tilde{\lambda}_t = \beta E_t \frac{\tilde{\lambda}_{t+1} R_t}{\pi_{t+1}} \tag{B-EC.4}$$

$$C_t^N = \gamma (p_t^N)^{-\varrho} C_t \tag{B-EC.5}$$

$$C_t^T = (1 - \gamma) (p_t^T)^{-\varrho} C_t \quad (\text{B-EC.6})$$

$$1 = (1 - \gamma) (p_t^T)^{1-\varrho} + \gamma (p_t^N)^{1-\varrho} \quad (\text{B-EC.7})$$

$$h_t = \Delta_t^{Nh} (Y_t^N)^{\frac{1}{1-\alpha_N}} \quad (\text{B-EC.8})$$

$$\Delta_t^{Nh} = (1 - \theta_N) (p_t^{*,N})^{-\frac{\epsilon_N}{1-\alpha_N}} + \theta_N \left(\frac{\left((\pi_{t-1}^N)^{\varrho_N} \pi_{t-1}^{1-\varrho_N} \right)^{\zeta_N} \bar{\pi}^{1-\zeta_N}}{\pi_t^N} \right)^{-\frac{\epsilon_N}{1-\alpha_N}} \Delta_{t-1}^{Nh} \quad (\text{B-EC.9})$$

$$\begin{aligned} \tilde{f}_t^{1,N} &= \frac{\epsilon_N - 1}{\epsilon_N} (p_t^{N,*})^{1-\epsilon_N} Y_t^N + \\ &\beta \theta_N E_t \left(\frac{p_t^{N,*}}{p_{t+1}^{N,*}} \frac{1}{\pi_{t+1}^N} \right)^{1-\epsilon_N} \frac{\tilde{\lambda}_{t+1}}{\tilde{\lambda}_t} \left[\left((\pi_t^N)^{\varrho_N} \pi_t^{1-\varrho_N} \right)^{\zeta_N} \bar{\pi}^{1-\zeta_N} \right]^{1-\epsilon_N} \frac{\pi_{t+1}^N}{\pi_{t+1}} \tilde{f}_{t+1}^{1,N} \end{aligned} \quad (\text{B-EC.10})$$

$$\begin{aligned} \tilde{f}_t^{1,N} &= \frac{1}{1 - \alpha_N} (p_t^{N,*})^{-\frac{\epsilon_N}{1-\alpha_N}} \frac{w_t}{p_t^N} (Y_t^N)^{\frac{1}{1-\alpha_N}} + \\ &\beta \theta_N E_t \left(\frac{p_t^{N,*}}{p_{t+1}^{N,*}} \frac{1}{\pi_{t+1}^N} \right)^{-\frac{\epsilon_N}{1-\alpha_N}} \frac{\tilde{\lambda}_{t+1}}{\tilde{\lambda}_t} \left[\left((\pi_t^N)^{\varrho_N} \pi_t^{1-\varrho_N} \right)^{\zeta_N} \bar{\pi}^{1-\zeta_N} \right]^{-\frac{\epsilon_N}{1-\alpha_N}} \frac{\pi_{t+1}^N}{\pi_{t+1}} \tilde{f}_{t+1}^{1,N} \end{aligned} \quad (\text{B-EC.11})$$

$$\pi_t^N = \frac{p_t^N}{p_{t-1}^N} \pi_t \quad (\text{B-EC.12})$$

$$1 = (1 - \theta_N) (p_t^{*,N})^{1-\epsilon_N} + \theta_N \left[\left((\pi_{t-1}^N)^{\varrho_N} \pi_{t-1}^{1-\varrho_N} \right)^{\zeta_N} \bar{\pi}^{1-\zeta_N} \right]^{1-\epsilon_N} \left(\frac{1}{\pi_t^N} \right)^{1-\epsilon_N} \quad (\text{B-EC.13})$$

$$\left(\frac{R_t}{R} \right) = \left(\frac{\pi_t}{\pi} \right)^{\alpha_\pi} \left(\frac{GDP_t}{GDP} \right)^{\alpha_{gdp}} e^{\epsilon_t^m} \quad (\text{B-EC.14})$$

$$\frac{p_t^T}{p_{t-1}^T} = \frac{\pi_t^S \pi_t^*}{\pi_t} \quad (\text{B-EC.15})$$

$$R_t^* = R_t^W + \phi_B \left(e^{\bar{b} - b_t^*} - 1 \right) \quad (\text{B-EC.16})$$

$$Y_t^N = \Delta_t^N C_t^N \quad (\text{B-EC.17})$$

$$\Delta_t^N = (1 - \theta_N) (p_t^{*,N})^{-\epsilon_N} + \theta_N \left(\frac{\left((\pi_{t-1}^N)^{\varrho_N} \pi_{t-1}^{1-\varrho_N} \right)^{\zeta_N} \bar{\pi}^{1-\zeta_N}}{\pi_t^N} \right)^{-\epsilon_N} \Delta_{t-1}^N \quad (\text{B-EC.18})$$

$$tb_t = p_t^T (Y^T - C_t^T) \quad (\text{B-EC.19})$$

$$p_t^T b_t^* = tb_t + \frac{p_t^T}{\pi_t^*} R_{t-1}^* b_{t-1}^* \quad (\text{B-EC.20})$$

$$GDP_t = C_t + Y^T - C_t^T \quad (\text{B-EC.21})$$

$$p_t^Y GDP_t = C_t + tb_t \quad (\text{B-EC.22})$$

And the equations for the exogenous processes that are described in the text.

B.3 Steady state

The given endogenous are $\{h, p^T, s^{tb}\}$ and the exogenous variables or parameters calculated are $\{\pi^*, \xi, y^T\}$.

From (B-EC.16)

$$R^* = R^W$$

from (B-EC.14)

$$\pi = \bar{\pi}$$

from (B-EC.4)

$$R = \pi/\beta$$

from (B-EC.3)

$$\pi^s = \pi/(\beta R^*)$$

from (B-EC.12)

$$\pi^N = \pi$$

from (B-EC.13)

$$p^{*,N} = 1$$

from (B-EC.9), (B-EC.18)

$$\Delta^{Nh} = \Delta^N = 1$$

from (B-EC.15)

$$\pi^* = \pi/\pi^S$$

from (B-EC.7)

$$p^N = \left(\frac{1 - (1 - \gamma)(p^T)^{1-\varrho}}{\gamma} \right)^{\frac{1}{1-\varrho}}$$

from (B-EC.8)

$$Y^N = h^{1-\alpha_N}$$

from (B-EC.10)

$$\tilde{f}^{1,N} = \frac{\epsilon_N - 1}{\epsilon_N} (p^{N,*})^{1-\epsilon_N} Y^N \frac{1}{1 - \beta\theta_N}$$

from (B-EC.11)

$$w = \tilde{f}^{1,N} (1 - \beta\theta_N) (1 - \alpha_N) p^N \frac{1}{(p^{N,*})^{-\frac{\epsilon_N}{1-\alpha_N}} (Y^N)^{\frac{1}{1-\alpha_N}}}$$

from (B-EC.17)

$$C^N = Y^N$$

from (B-EC.5)

$$C = C^N (p^N)^\epsilon / \gamma$$

from (B-EC.6)

$$C^T = (1 - \gamma) (p^T)^{-\epsilon} C$$

from (B-EC.1)

$$\tilde{\lambda} = C^{-\sigma}$$

from (B-EC.2)

$$\chi = \tilde{\lambda} w / h^\varphi$$

from (B-EC.22)

$$p^Y GDP = C / (1 - s^{tb})$$

$$tb = s^{tb} p^Y GDP$$

from (B-EC.19)

$$y^T = \frac{tb}{p_t^T} + C^T$$

from (B-EC.20)

$$b^* = \frac{tb}{p_t^T (1 - R^* / \pi^*)}$$

from (B-EC.21)

$$GDP = C + Y^T - C^T$$

Finally the parameters

$$p^Y = \frac{p^Y GDP}{GDP}$$
$$\bar{b} = b^*$$

C Additional IRFs Baseline Model

Figure 17: IRFs to Monetary Shock for Alternative ρ_{ϵ^m}

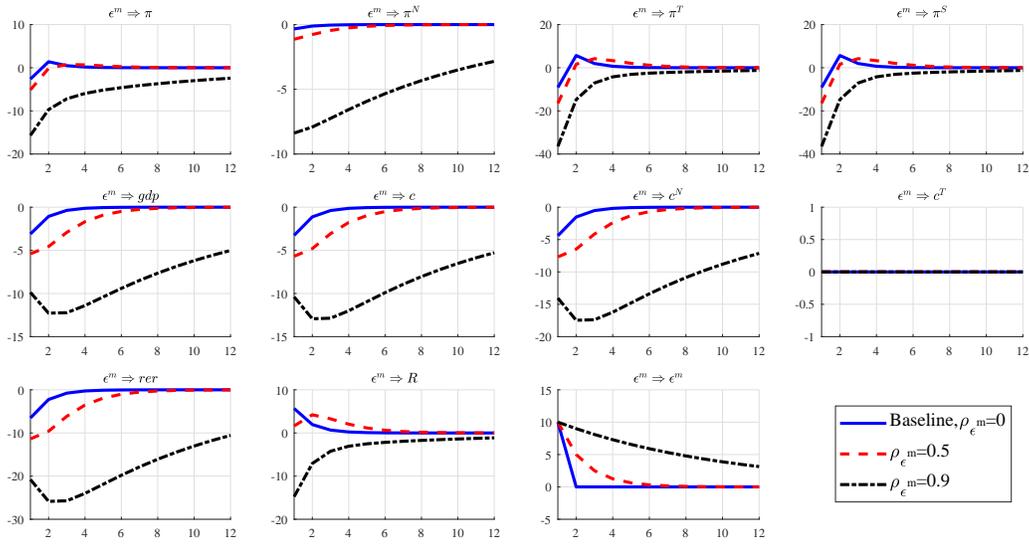


Figure 18: IRFs to External Inflation for Alternative periods with Fixed Interest Rate

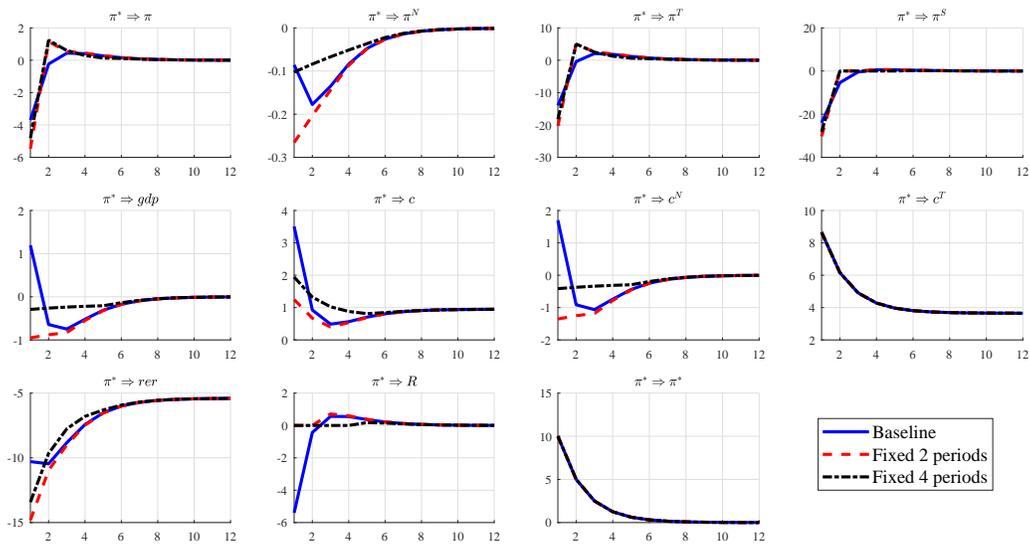


Figure 19: IRFs to External Interest Rate for Alternative periods with Fixed Interest Rate

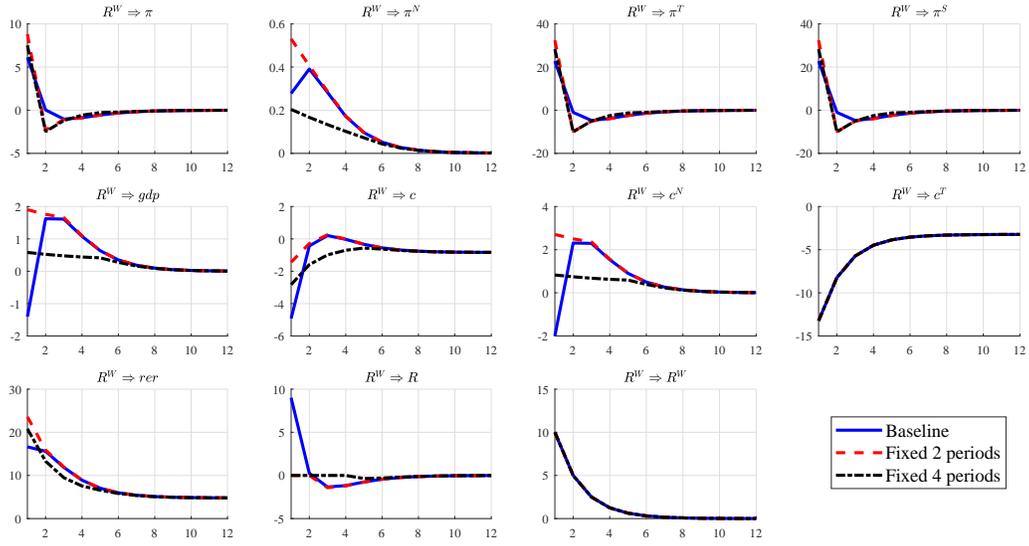


Figure 20: IRFs to Monetary Shock for Alternative Indexation

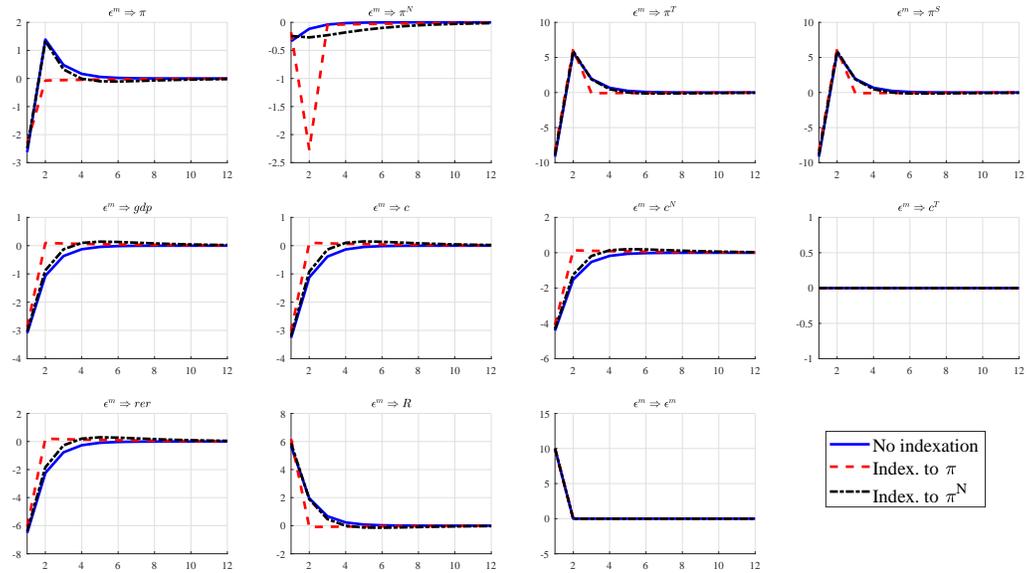


Figure 21: IRFs to External Inflation for Alternative Indexation

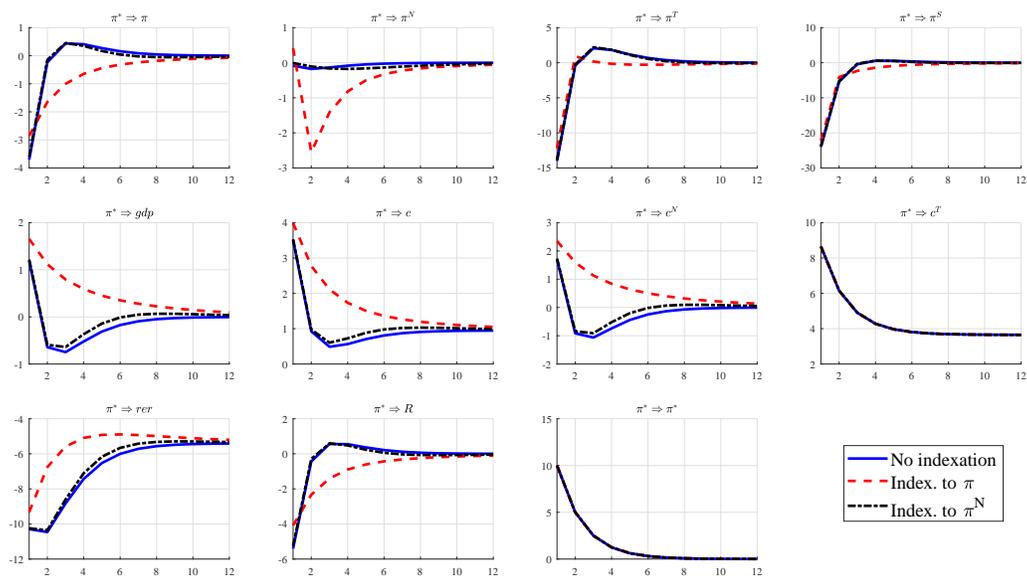
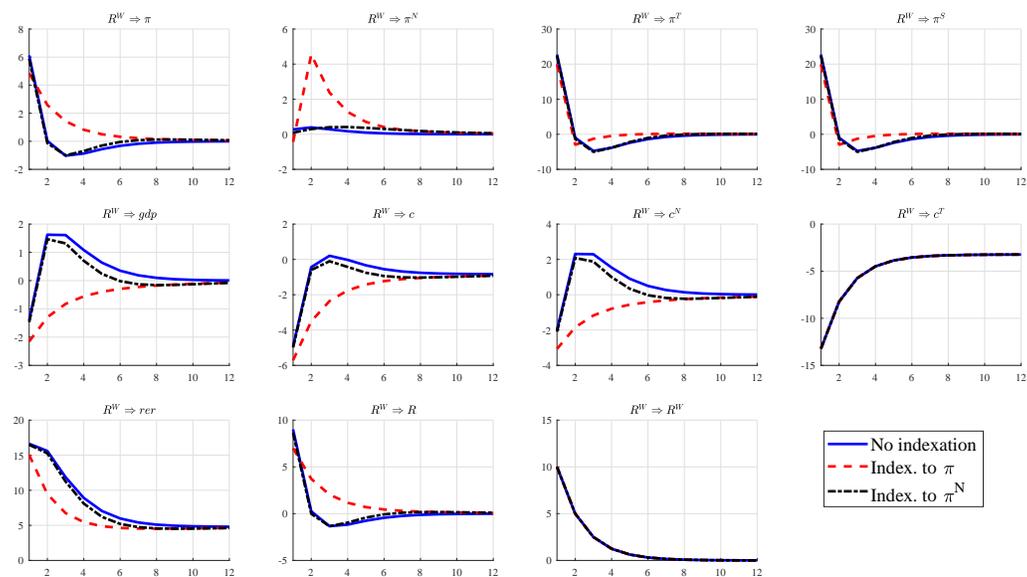


Figure 22: IRFs to External Interest Rate for Alternative Indexation



D Quantitative DSGE Model Appendix

This appendix has four sections. The first presents all agents in the model, their optimization problems and constraints, as well as the driving forces. The second describes the parametrization strategy and studies the goodness of fit of the model. The third derives the optimality conditions for the different agents. The final section presents the equilibrium conditions and the computation of the steady state.

D.1 Model description

D.1.1 Households

There is a representative household that consumes, works, saves, invests and rents capital to the producing sectors. Her goal is to maximize,

$$E_0 \sum_{t=0}^{\infty} \beta^t \xi_t^\beta \left\{ \frac{(C_t - \phi_c \tilde{C}_{t-1})^{1-\sigma}}{1-\sigma} - \kappa_t \left(\xi_t^{h,X} \frac{h_t^{X1+\varphi}}{1+\varphi} + \xi_t^{h,N} \frac{h_t^{N1+\varphi}}{1+\varphi} \right) \right\}$$

where C_t is consumption and h_t^J for $J = \{X, N\}$ are hours worked in sector J . \tilde{C}_t denotes aggregate consumption (i.e. the utility exhibits external habits),³⁵ and $\kappa_t \equiv (\tilde{C}_t - \phi_c \tilde{C}_{t-1})^{-\sigma}$.³⁶ ξ_t^β and $\xi_t^{h,J}$ are preference shocks: the former affects inter-temporal decisions, while the latter is a labor supply shifter in sector $J = \{X, N\}$.

The budget constraint is

$$\begin{aligned} P_t C_t + S_t B_t^* + B_t + P_t^I I_t^N + P_t^I I_t^X &= h_t^{X,d} \int_0^1 W_t^X(j) \left(\frac{W_t^X(j)}{W_t^X} \right)^{-\epsilon_w} dj + \\ h_t^{N,d} \int_0^1 W_t^N(j) \left(\frac{W_t^N(j)}{W_t^N} \right)^{-\epsilon_w} dj &+ S_t R_{t-1}^* B_{t-1}^* + R_{t-1} B_{t-1} + P_t^N R_t^N K_{t-1}^N + \\ P_t^X R_t^X K_{t-1}^X + T_t + \Pi_t. \end{aligned}$$

Here P_t the price of the consumption good, S_t the exchange rate, B_t^* the amount of external bonds bought by the household in period t , B_t amount of local bonds bought by the household in t , P_t^I is the price of the investment good, I_t^J is investment in capital of the sector J , $h_t^{J,d}$ is labor demand in sector j , R_t^* is the external interest rate, R_t is the internal interest rate, R_t^J is the real rate from renting their capital to firms in sector J , P_t^J is the price of goods J , T_t are transfers made by the government and finally Π_t has all the profits of the firms in all sectors.

The formulation of the wage-setting problem follows [Schmitt-Grohe and Uribe \(2006\)](#). In this setup, households supply a homogeneous labor input that is transformed by monopolistically competitive labor unions into a differentiated labor input. The union takes aggregate variables as given and decides the nominal wage, while supplying enough labor to meet the demand in each market. The wage of each differentiated labor input is chosen optimally each period with a constant probability $1 - \theta_{WJ}$ for $J = \{X, N\}$. When wages cannot be freely chosen they are updated by $(\pi_{t-1})^{\zeta_{WJ}} \bar{\pi}^{1-\zeta_{WJ}}$, with π_{t-1} denoting previous-period CPI inflation and $\bar{\pi}$ the inflation target set by the Central Bank.

³⁵In equilibrium $\tilde{C}_t = C_t$.

³⁶This utility specification follows [Galí et al. \(2012\)](#), and it is designed to eliminate the wealth effect on the supply of labor while keeping separability between consumption and labor.

D.1.2 Consumption Goods

Consumption C_t is composed by three elements: core consumption (C_t^{NFE}), food (C_t^F) and energy (C_t^E). For simplicity, food and energy consumption are assumed exogenous and normalized to one (so total and core consumption are equal). In contrast the price of the consumption good will be a composite of the price of the core good, energy and food the following way:

$$P_t = (P_t^{NFE})^{1-\gamma_{FC}-\gamma_{EC}} (P_t^F)^{\gamma_{FC}} (P_t^E)^{\gamma_{EC}}$$

Where P_t^{NFE} is the price of core consumption, P_t^F is the price of food and P_t^E is the price of energy.³⁷ We further assume that the prices of both F and E relative to that of the tradable composite (T , defined below) follow exogenous processes (p_t^F and p_t^E respectively).³⁸

Core consumption is a composite of non-tradable consumption C_t^N and tradable consumption C_t^T , while the latter is composed by exportable C_t^X and importable C_t^M goods,

$$\begin{aligned} C_t^{NFE} &= \left[\gamma^{1/\varrho} (C_t^N)^{\frac{\varrho-1}{\varrho}} + (1-\gamma)^{1/\varrho} (C_t^T)^{\frac{\varrho-1}{\varrho}} \right]^{\frac{\varrho}{\varrho-1}} \\ C_t^T &= \left[\gamma_T^{1/\varrho_T} (C_t^X)^{\frac{\varrho_T-1}{\varrho_T}} + (1-\gamma_T)^{1/\varrho_T} (C_t^M)^{\frac{\varrho_T-1}{\varrho_T}} \right]^{\frac{\varrho_T}{\varrho_T-1}} \\ C_t^J &= \int_0^1 G(C_t^J(i), \xi_t^J) di \end{aligned}$$

Where ϱ and ϱ_T are elasticities of substitution between non-tradables and tradables, and between exportables and importables respectively. The last equation specifies that exportable, importable and non-tradable consumption are made of a continuum of differentiated goods in each sector, combined by an aggregator G , which we assume features a constant elasticity of substitution $\epsilon_J > 1$ for $J = \{X, M, N\}$. Moreover, it is assumed that the aggregator is subject to exogenous disturbances (ξ_t^J), generating markup-style shocks in the pricing decisions by firms as in [Smets and Wouters \(2007\)](#).

D.1.3 Capital and Investment Goods

The evolution of the capital stock in sector J is

$$K_t^J = \left[1 - \Gamma \left(\frac{I_t^J}{I_{t-1}^J} \right) \right] u_t I_t^J + (1 - \delta) K_{t-1}^J,$$

for $J = \{X, N\}$. It is assumed that installed capital is sector-specific, there are adjustment costs to capital accumulation with $\Phi'(\cdot) > 0$ and $\Phi''(\cdot) > 0$ and there is a shock u_t to the marginal efficiency of investment.³⁹

Households choose how much to invest in each type of capital, which constitutes the demand for investment. The supply of investment is assumed to be provided by competitive firms that have a technology similar to the consumption preferences of households, but with different weights and

³⁷The goal of this simplified specification is to be able to separate the dynamics of core and total inflation, without complicating significantly the supply side of the model.

³⁸The implicit assumption is that food and energy are made of tradable goods, although not all of them are strictly imported. This assumption is reasonable given the Chilean production structure of these goods.

³⁹We assume that u_t is the same for both sectors, as we do not have data on sectoral investment at a quarterly frequency.

elasticities of substitution,

$$I_t = \left[\gamma_I^{1/\varrho_I} (\tilde{I}_t^N)^{\frac{\varrho_I-1}{\varrho_I}} + (1-\gamma_I)^{1/\varrho_I} (\tilde{I}_t^T)^{\frac{\varrho_I-1}{\varrho_I}} \right]^{\frac{\varrho_I}{\varrho_I-1}}$$

$$\tilde{I}_t^T = \left[\gamma_{T,I}^{1/\varrho_{T,I}} (\tilde{I}_t^X)^{\frac{\varrho_{T,I}-1}{\varrho_{T,I}}} + (1-\gamma_{T,I})^{1/\varrho_{T,I}} (\tilde{I}_t^M)^{\frac{\varrho_{T,I}-1}{\varrho_{T,I}}} \right]^{\frac{\varrho_{T,I}}{\varrho_{T,I}-1}}$$

Similar to consumption, each investment \tilde{I}_t^J for $J = \{X, M, N\}$ is a continuum of the differentiated goods in each sector with the same elasticity of substitution as consumption, ϵ_J .

D.1.4 Firms

There are three sectors in addition to Commodities (assumed to be an endowment); exportable, importable and non-tradable. Firms in the importable sector buy an homogeneous good from foreigners and differentiate it, creating varieties which are demanded by households and firms. Firms in the exportable and non-tradable sector combine a value added created using labor and capital with a composite of the varieties sold by the importable sector to produce their final product.

Each firm in each sector supplies a differentiated product, generating monopolistic power. Given their marginal cost, they maximize prices a la Calvo with probability θ_J for $J = \{X, M, N\}$ of not being able to choose their price optimally each period. When not chosen optimally, the price is assumed to be updated according to: $[(\pi_{t-1}^J)^{\varrho_J} (\pi_{t-1})^{1-\varrho_J}]^{\zeta_J} \bar{\pi}^{1-\zeta_J}$, with π_{t-1}^J being inflation of sector J in the previous period. In this way, the indexation specification is flexible enough to accommodate both dynamic as well as static (i.e. steady-state) indexation, with a backward-looking feedback that can be related to either sector specific or aggregate inflation; and we let the data tell the appropriate values for ϱ_J and ζ_J in each sector.

D.1.5 Sector M

Each firm i in this sector produces a differentiated product from an homogeneous foreign input with the technology $Y_t^M(i) = M_t(i)$. The price of their input is given by $P_{m,t} = S_t P_t^{M*}$, where $P_{m,t}$ is the price of the good that is imported in local currency and P_t^{M*} is the price in foreign currency and is exogenously given.

D.1.6 Sector X and N

All firms in both sectors have the same format. Each firm i of sector J produces a differentiated product that is a combination of value added $V_t^J(i)$ and an importable input $M_t^J(i)$, which is a combination of a continuum of the goods sold by M sector and energy. They have the technology,

$$Y_t^J(i) = (V_t^J(i))^{\gamma_J} (M_t^J(i))^{1-\gamma_J},$$

where value added is produced by,

$$V_t^J(i) = z_t^J [K_{t-1}^J(i)]^{\alpha_J} [A_t^J h_t^{J,d}(i)]^{1-\alpha_J}.$$

z_t^J is a stationary technology shock, while A_t^J is a non-stationary stochastic trend in technology. To maintain a balance-growth path, we assume that both trends co-integrate in the long-run. In

particular, we assume that $a_t \equiv A_t^N/A_{t-1}^N$ is an exogenous process and A_t^X evolves according to,

$$A_t^X = (A_{t-1}^X)^{1-\Gamma_X} (A_t^N)^{\Gamma_X}$$

The factor demand for these firms can be solved in two stages:

1. Optimal production of $V_t^J(i)$: Firms are price takers, so they choose the optimal combination of capital and labor to minimize their cost,

$$\min_{K_{t-1}^J(i), h_t^d(i)} P_t^J R_t^J K_{t-1}^J(i) + W_t^J h_t^d(i) + \mu \left\{ V_t^J(i) - z_t^J [K_{t-1}^J(i)]^{\alpha_J} [A_t^J h_t^d(i)]^{1-\alpha_J} \right\}$$

2. Optimal production of $Y_t^J(i)$: The cost minimization in this case is,

$$\min_{M_t^J(i), V_t^J(i)} MC_t^{VJ} V_t^J(i) + P_t^{ME} M_t^J(i) + \mu \{ Y_t^J(i) - [V_t^J(i)]^{\gamma_J} [M_t^J(i)]^{1-\gamma_J} \}$$

where MC_t^{VJ} is the marginal cost of producing $V_t^J(i)$, which is the same for all firms, and P_t^{ME} is the price of a composite between a continuum of the importable goods sold by the M sector and energy; i.e.

$$P_t^{ME} = (P_t^M)^{1-\gamma_{EM}} (P_t^E)^{\gamma_{EM}}$$

As in the case of the household with Energy and Food, $M_t^J(i)$ can be interpreted as only the continuum of importable goods or the composite between energy and the importable goods, since firm take the quantity of energy as exogenous and so it has been normalized to one.

D.1.7 Commodity

The Commodity is assumed to be an exogenous and stochastic endowment, Y_t^{Co} which has its own trend A_t^{Co} that cointegrates with the other sectors, $A_t^{Co} = (A_{t-1}^{Co})^{1-\Gamma_{Co}} (A_t^N)^{\Gamma_{Co}}$. We assume $y_t^{Co} \equiv \frac{Y_t^{Co}}{A_{t-1}^{Co}}$ follows an exogenous process. The endowment is exported at the international price P_t^{Co*} . It is assumed that a fraction ϑ of commodity production is owned by the government and a fraction $(1 - \vartheta)$ is owned by foreigners.

D.1.8 Fiscal and Monetary Policy

The fiscal policy introduces an exogenous expenditure that is completely spent in non-tradable goods. The government receives part of the profits of the Commodity sector, can buy local bonds, B_t^G , and gives transfers to households, T_t . Its budget constraint is

$$\vartheta S_t P_t^{Co*} Y_t^{Co} + R_{t-1} B_{t-1}^G = P_t^N G_t + T_t + B_t^G$$

Similarly to the household, government expenditure is a composite of non-tradable varieties with elasticity of substitution ϵ_N . We assume $g_t \equiv \frac{G_t}{A_{t-1}^N}$ follows an exogenous process.

Monetary policy follows a Taylor-type rule of the form,

$$\left(\frac{R_t}{R} \right) = \left(\frac{R_{t-1}}{R} \right)^{\varrho_R} \left[\left(\frac{(\pi_t^{NFE})^{\alpha_\pi} \pi_t^{1-\alpha_\pi}}{\bar{\pi}} \right)^{\alpha_\pi} \left(\frac{GDP_t/GDP_{t-1}}{a} \right)^{\alpha_Y} \right]^{1-\varrho_R} e_t^m$$

where the variables without a time subscript are steady state values, π_t^{NFE} is core inflation, GDP_t is gross domestic product and e_t^m is a monetary shock.

D.1.9 Foreign Sector

The rest of the world sells the imported inputs at price $P_{m,t}^*$ and buys the exported products Y_t^X at the price set by local producers. It is assumed that the goods bought by foreigners share the same elasticity of substitution as the exportable good bought locally, ϵ_X . In contrast, the demand for the composite exportable is,

$$C_t^{X,*} = \left(\frac{P_t^X}{S_t P_t^*} \right)^{-\epsilon^*} Y_t^* \xi_t^{X*}.$$

Where P_t^* is the external CPI index, Y_t^* is external demand,⁴⁰ and ξ_t^{X*} is a disturbance to external demand; all of them assumed to be exogenous stochastic processes.

The closing device of the model is given by the equation for the international interest rate,

$$R_t^* = R_t^W \exp \left\{ \phi_B \left(\bar{b} - \frac{S_t B_t^*}{P_t^Y GDP_t} \right) \right\} \xi_t^{R1} \xi_t^{R2}. \quad (1)$$

In this way, the external rate relevant for the country is composed by three parts. The first part is R_t^W that represents the world interest rate (which in the data is matched with the LIBOR rate). The second part is the term $\exp \left\{ \phi_B \left(\bar{b} - \frac{S_t B_t^*}{P_t^Y GDP_t} \right) \right\} \xi_t^{R1}$, which represents the country premium (equal to the EMBI Chile), where ξ_t^{R1} is an exogenous shock.⁴¹ Finally, the third part is ξ_t^{R2} , which is a risk-premium shock that captures deviations from the EMBI-adjusted uncovered interest parity (UIP).

D.1.10 Driving Forces

The model features a total of 23 exogenous state variables. Those of domestic origin are consumption preferences (ξ_t^β), labor supply ($\xi_t^{H,N}$ and $\xi_t^{H,X}$), stationary productivity (z_t^H and z_t^X), the growth rate of the long-run trend (a_t), desired markups (ξ_t^N , ξ_t^X and ξ_t^M), endowment of commodities (y_t^{Co}), the relative prices of Food and Energy (p_t^F and p_t^E), efficiency of investment (u_t), government consumption (g_t), and monetary policy (e_t^m). In turn foreign driving forces are the world interest rate (R_t^W), foreign risk premium (ξ_t^{R1} and ξ_t^{R2}), international prices of commodities (P^{Co*}), imported goods (P_t^{M*}) and CPI for trade partners (P_t^*), demand for exports of X (ξ_t^{X*}), and GDP of trade partners (y_t^*). All these processes are assumed to be Gaussian in logs. Markup and monetary-policy shocks are i.i.d. while the rest, with the exception of international prices, are independent AR(1) processes.

As the model features a balanced growth path and preferences are such that relative prices are stationary, foreign prices should co-integrate, growing all at the same long-run rate.⁴² Defining inflation of foreign CPI as $\pi_t^* = \frac{P_t^*}{P_{t-1}^*}$, with steady state value of π^* , we propose the following model for international prices,

$$P_t^j = (\pi^* P_{t-1}^j)^{\Gamma_j} (F_t^*)^{1-\Gamma_j} u_t^j, \quad \text{with } \Gamma_j \in [0, 1), \quad \text{for } j = \{Co^*, M^*, *\}, \quad (2)$$

$$\Delta F_t^* \equiv \frac{F_t^*}{F_{t-1}^*}, \quad \frac{\Delta F_t^*}{\pi^*} = \left(\frac{\Delta F_{t-1}^*}{\pi^*} \right)^{\rho_{F^*}} \exp(\epsilon_t^{F^*}), \quad \text{with } \rho_{F^*} \in (-1, 1) \quad (3)$$

⁴⁰We assume $y_t^* \equiv \frac{Y_t^*}{A_{t-1}^N}$ follows an exogenous process.

⁴¹ GDP_t denotes gross domestic product and P_t^Y is the GDP deflator.

⁴²In other words, the co-integration vector between the log of any pair of these prices should be $(1, -1)$.

$$u_t^j = \left(u_{t-1}^j\right)^{\rho_j} \exp(\epsilon_t^j), \quad \text{with } \rho_j \in (-1, 1), \quad \text{for } j = \{Co*, M*, *\}, \quad (4)$$

where ϵ_t^i are i.i.d. $\mathcal{N}(0, \sigma_i^2)$ for $i = \{Co*, M*, *, F*\}$.

Under this specification, each price is driven by two factors: a common trend (F_t^*) and a price-specific shock (u_t^j). The parameter Γ_j determines how slowly changes in the trend affect each price. The presence of a common trend generates co-integration among prices (as long as $\Gamma_j < 1$), and the fact that the exponent in the trend and in the lagged price in (2) add-up to one forces relative prices to remain constant in the long run.⁴³ The usual assumption for these prices in DSGE models with nominal rigidities is obtained as a restricted version of this setup, imposing $\Gamma_j = 0$ for $j = \{Co*, M*\}$ and $\sigma_*^2 = 0$. In other words, the relative prices of both commodities and imports are driven by stationary AR(1) processes, while the inflation of commercial partners is a stationary AR(1) process. The specification in (2)-(4) generalizes this usual assumption in several dimensions. First, in the usual set up, the common trend of all prices is exactly equal to the CPI of commercial partners. This might lead to the wrong interpretation that inflation of commercial partners is an important driver of domestic variables, while in reality this happens because it represents a common trend in all prices. Second, the usual specification imposes that every change in the common trend has a contemporaneous one-to-one impact in all prices, while in reality different prices may adjust to changes in this common trend at different speeds. Finally, for our specific sample the data favors the general specification (2)-(4) relative to the restricted model.

Overall, the model features 24 exogenous disturbances, related to the 23 exogenous state variables previously listed plus the common trend in international prices.

⁴³If $\Gamma_j = 1$, each price is a random walk with a common drift π^* . Although this implies that in the long run all prices will grow at the same rate, they will not be co-integrated and relative prices may be non-stationary.

D.2 Parametrization Strategy and Goodness of Fit

The values of the parameters in the model are assigned by a combination of calibration and estimation. The resulting values are presented in the tables of Appendix D.2.1. Parameters representing shares in the different aggregate baskets and production functions are calibrated using input-output tables for Chile. In addition, we target several steady-state ratios to sample averages of their observable counterparts. For parameters that are not properly identified in our data set, we rely on studies estimating DSGE models for Chile. Finally, the parameters characterizing the dynamics of some of the external driving forces are calibrated by estimating AR(1) processes.

The remainder of the parameters are estimated using a Bayesian approach using the following series at quarterly frequency from 2001.Q3 to 2016.Q3:⁴⁴

- Real growth rate of: GDP , GDP^X (Agriculture, Fishing, Industry, Utilities, Transportation), GDP^N (Construction, Retail, Services), GDP^{Co} (Mining), private consumption (C), total investment (I), and government consumption (G).
- The ratio of nominal trade balance to GDP.
- Quarterly CPI-based inflation of π^N (services, excluding Food and Energy), π^T (goods. ex. Food and Energy), π^M (imported goods, ex. Food and Energy), π^F (Food) and π^E (Energy).
- The growth of nominal wages (π^{WX} and π^{WN}) measured as the cost per unit of labor (the CMO index), using sectors consistent with the GDPs definition.
- The nominal dollar exchange-rate depreciation (π^S) and the monetary policy rate (R).
- External: World interest rate (R^W , LIBOR), country premium (EMBI Chile), foreign inflation (π^* , inflation index for commercial partners, the IPE Index), inflation of Commodities prices (π^{Co*} , Copper price) and imports (π^{M*} , price index for imported of goods, the IVUM index), external GDP (Y^* , GDP of commercial partners).

All domestic observables are assumed to have a measurement error, with calibrated variance equal to 10% of the observable variance. Priors and posteriors are shown in Appendix D.2.1. When possible, priors are set centering the distributions around previous results in the literature. The estimated model is able to properly match the volatilities and first-order autocorrelation coefficients of the domestic observables, as can be seen in Table 3.

D.2.1 Calibrated and Estimated Parameters

⁴⁴The source is the Central Bank of Chile. Variables are seasonally adjusted using the X-11 filter, expressed in logs, multiplied by 100, and demeaned. All growth rates are changes from two consecutive quarters.

Table 3: Second Moments in the Data and in the Model

| Variable | St. Dev. (%) | | AC(1) | | | |
|----------------|--------------|-------|-------|-------|-------|-------|
| | Data | Model | Data | Model | Data | Model |
| ΔGDP | 0.9 | (0.1) | 1.1 | 0.5 | (0.2) | 0.5 |
| $\Delta CONS$ | 1.0 | (0.1) | 0.8 | 0.7 | (0.2) | 0.7 |
| ΔINV | 3.9 | (0.4) | 4.4 | 0.3 | (0.2) | 0.7 |
| ΔGDP^X | 1.5 | (0.1) | 1.5 | 0.2 | (0.1) | -0.1 |
| ΔGDP^N | 0.8 | (0.1) | 1.6 | 0.7 | (0.1) | 0.6 |
| TB/GDP | 5.5 | (0.5) | 5.2 | 0.8 | (0.1) | 0.9 |
| π | 0.7 | (0.1) | 0.6 | 0.6 | (0.2) | 0.7 |
| π^T | 0.7 | (0.1) | 0.8 | 0.6 | (0.2) | 0.8 |
| π^N | 0.4 | (0.1) | 0.4 | 0.7 | (0.2) | 0.9 |
| π^M | 0.8 | (0.1) | 0.8 | 0.7 | (0.2) | 0.8 |
| π^{WX} | 0.6 | (0.1) | 0.7 | 0.7 | (0.1) | 0.8 |
| π^{WN} | 0.4 | (0.0) | 0.4 | 0.8 | (0.2) | 0.9 |
| R | 0.4 | (0.0) | 0.6 | 0.9 | (0.2) | 0.9 |
| π^S | 5.2 | (0.8) | 5.7 | 0.2 | (0.2) | 0.0 |

Note: The variables are: the growth rates of GDP, private consumption, investment, and GDP in the X and N sectors, the trade-balance-to-output ratio, inflation for total CPI, tradables, non-tradables and imported, the growth rate of nominal wages in sector X and N , the monetary policy rate, and the nominal depreciation. Columns two to four correspond to standard deviations, while five to seven are first-order autocorrelations. For each of these moments, the three columns shown are: the point estimate in the data, GMM standard-errors in the data, and unconditional moment in the model at the posterior mode.

D.3 Optimality Conditions

D.3.1 Household

From the decision of final consumption, labor, bonds and capital and defining as λ_t the multiplier of the budget constraint, $\mu_t^J \lambda_t$ the multiplier of the capital accumulation equation for $J = \{X, N\}$ and as $\mu_t^{WJ} W_t^J \lambda_t$ the multiplier of the equalization of labor demand and supply, we have the first order conditions:

$$\begin{aligned}
& \xi_t^\beta (C_t - \phi_c \tilde{C}_{t-1})^{-\sigma} - P_t \lambda_t = 0 \\
& -\xi_t^\beta \kappa_t \xi_t^{h,X} (h_t^X)^\varphi + \mu_t^{WX} W_t^X \lambda_t = 0 \\
& -\xi_t^\beta \kappa_t \xi_t^{h,X} (h_t^N)^\varphi + \mu_t^{WN} W_t^N \lambda_t = 0 \\
& -\lambda_t + \beta E_t \lambda_{t+1} R_t = 0 \\
& -\lambda_t S_t + \beta E_t \lambda_{t+1} S_{t+1} R_t^* = 0 \\
& -\mu_t^J \lambda_t + \beta E_t \{ \lambda_{t+1} P_{t+1}^J R_{t+1}^J + \mu_{t+1}^J \lambda_{t+1} (1 - \delta) \} = 0 \\
& -\lambda_t P_t^I + \mu_t^J \lambda_t \left\{ \left[1 - \Gamma \left(\frac{I_t^J}{I_{t-1}^J} \right) \right] u_t + \left(-\Gamma' \left(\frac{I_t^J}{I_{t-1}^J} \right) \frac{1}{I_{t-1}^J} \right) u_t I_t^J \right\} + \\
& \beta E_t \left\{ \mu_{t+1}^J \lambda_{t+1} \left(-\Gamma' \left(\frac{I_{t+1}^J}{I_t^J} \right) \right) \left(-\frac{I_{t+1}^J}{(I_t^J)^2} \right) u_{t+1} I_{t+1}^J \right\} = 0
\end{aligned}$$

Table 4: Calibrated

| Para. | Descrip. | Value | Source |
|----------------|-------------------------------|-------|--|
| σ | Risk Aversion | 1 | Medina and Soto (2007) |
| φ | Inv. Frish elast. | 1 | Medina and Soto (2007) |
| γ | Share C^N in C^{NFE} | 0.62 | I-O Matrix, average 08-13 |
| γ_T | Share C^X in C^T | 0.23 | I-O Matrix, average 08-13 |
| γ_I | Share I^N in I | 0.62 | I-O Matrix, average 08-13 |
| γ_{TI} | Share I^X in I^T | 0.02 | I-O Matrix, average 08-13 |
| γ_{EC} | Share C^E in C | 0.09 | I-O Matrix, average 08-13 |
| γ_{FC} | Share C^F in C | 0.19 | I-O Matrix, average 08-13 |
| α_X | Capital in V.A. X | 0.66 | I-O Matrix, average 08-13 |
| α_N | Capital in V.A. N | 0.49 | I-O Matrix, average 08-13 |
| $1 - \gamma_X$ | Imports in Prod. X | 0.2 | I-O Matrix, average 08-13 |
| $1 - \gamma_N$ | Imports in Prod. M | 0.08 | I-O Matrix, average 08-13 |
| γ_{EM} | Share E in Interm. Imports | 0.09 | I-O Matrix, average 08-13 |
| s^{TB} | Ratio of TB to PIB | 0.05 | Average 01-15 |
| s^{PIB^N} | Ratio of PIB^N to PIB | 0.6 | Average 01-15 |
| s^{Co} | Ratio of Co to GDP | 0.1 | Average 01-15 |
| s^G | Ratio of G to GDP | 0.12 | Average 01-15 |
| ξ^{R1} | EMBI Chile (annual) | 1.015 | Average 01-15 |
| π | Inflation (annual) | 1.03 | Average 01-15 |
| a | Long-run growth (annual) | 1.016 | Average 01-15 |
| R^W | World Interest Rate (annual) | 1.045 | Average 01-15 |
| R | Monetary Policy Rate (annual) | 1.058 | Average 01-15 |
| δ | Capital depreciation | 0.01 | Medina and Soto (2007) |
| ϵ^j | Elast. of Subst. Varieties | 11 | Medina and Soto (2007) |

Table 5: Estimated Parameters

| Para. | Description | Dist. | Prior | | Posterior | |
|--------------------|-------------------------|-----------------|-------|-------|-----------|-------|
| | | | Mean | St.D. | Mode | St.D. |
| ϕ_C | Habits C | β | 0.65 | 0.2 | 0.879 | 0.03 |
| ϕ_I | Inv. Adj. Costs | \mathcal{N}^+ | 4 | 1 | 4.461 | 0.74 |
| θ_{WX} | Calvo W^X | β | 0.65 | 0.2 | 0.940 | 0.01 |
| ζ_{WX} | Din. Index. W^X | β | 0.5 | 0.27 | 0.066 | 0.11 |
| θ_{WN} | Calvo W^N | β | 0.65 | 0.2 | 0.969 | 0.01 |
| ζ_{WN} | Din. Index. W^N | β | 0.5 | 0.27 | 0.117 | 0.08 |
| ϱ | Sust. C^T, C^N | \mathcal{N}^+ | 0.9 | 1.5 | 0.171 | 0.85 |
| ϱ_I | Sust. I^T, I^N | \mathcal{N}^+ | 0.9 | 1.5 | 2.339 | 1.12 |
| θ_X | Calvo X | β | 0.5 | 0.27 | 0.600 | 0.07 |
| θ_M | Calvo M | β | 0.5 | 0.27 | 0.858 | 0.02 |
| θ_N | Calvo N | β | 0.5 | 0.27 | 0.952 | 0.01 |
| ϱ_X | Index. Own X | β | 0.5 | 0.27 | 0.887 | 0.22 |
| ϱ_M | Index. Own M | β | 0.5 | 0.27 | 0.662 | 0.28 |
| ϱ_N | Index. Own N | β | 0.5 | 0.27 | 0.775 | 0.11 |
| ζ_X | Din. Index. X | β | 0.5 | 0.27 | 0.919 | 0.17 |
| ζ_M | Din. Index. M | β | 0.5 | 0.27 | 0.541 | 0.18 |
| ζ_N | Din. Index. N | β | 0.5 | 0.27 | 0.817 | 0.10 |
| Γ_X | Adj. Trend X | β | 0.65 | 0.2 | 0.763 | 0.25 |
| Γ_{Co} | Adj. Trend Co | β | 0.65 | 0.2 | 0.772 | 0.25 |
| Policy Rule | | | | | | |
| ρ_R | Smoothing | β | 0.8 | 0.05 | 0.786 | 0.03 |
| α_π | Reaction to π | \mathcal{N}^+ | 1.7 | 0.1 | 1.630 | 0.09 |
| α_π^{SAE} | Reaction to π^{NFE} | β | 0.5 | 0.2 | 0.439 | 0.18 |
| α_y | Reaction to y | \mathcal{N}^+ | 0.125 | 0.05 | 0.145 | 0.05 |
| η^* | Elast. Ext. Dem. | \mathcal{N}^+ | 0.3 | 0.1 | 0.198 | 0.04 |

Note: Prior distributions: β Beta, \mathcal{N}^+ Normal truncated for positive values, IG Inverse Gamma, \mathcal{U} Uniform. The standard deviation of the posterior is approximated by the inverse Hessian evaluated at the posterior mode.

Table 6: Estimated Parameters, Coefficients Dynamics of Exogenous Processes

| Para. | Dist. | Prior | | Posterior | |
|----------------------------|---------------|-------|-------|-----------|-------|
| | | Mean | St.D. | Mode | St.D. |
| Dynamics of Driving Forces | | | | | |
| $\rho_{\xi\beta}$ | β | 0.65 | 0.2 | 0.777 | 0.08 |
| ρ_a | β | 0.35 | 0.15 | 0.286 | 0.16 |
| ρ_u | β | 0.65 | 0.2 | 0.545 | 0.11 |
| ρ_{z^X} | β | 0.65 | 0.2 | 0.910 | 0.06 |
| ρ_{z^N} | β | 0.65 | 0.2 | 0.693 | 0.10 |
| $\rho_{\xi^{X*}}$ | β | 0.65 | 0.2 | 0.871 | 0.05 |
| $\rho_{\xi^{R1}}$ | β | 0.65 | 0.2 | 0.946 | 0.02 |
| $\rho_{\xi^{R2}}$ | β | 0.65 | 0.2 | 0.734 | 0.12 |
| $\rho_{\xi^{hX}}$ | β | 0.65 | 0.2 | 0.829 | 0.08 |
| $\rho_{\xi^{hN}}$ | β | 0.65 | 0.2 | 0.919 | 0.05 |
| ρ_{p^A} | β | 0.65 | 0.2 | 0.973 | 0.02 |
| ρ_{p^E} | β | 0.65 | 0.2 | 0.895 | 0.05 |
| Γ_* | \mathcal{U} | 0.5 | 0.3 | 0.161 | 0.12 |
| Γ_{M^*} | \mathcal{U} | 0.5 | 0.3 | 0.488 | 0.08 |
| Γ_{Co^*} | \mathcal{U} | 0.5 | 0.3 | 0.304 | 0.12 |
| ρ_{F^*} | \mathcal{U} | 0 | 0.6 | 0.206 | 0.11 |
| ρ_* | \mathcal{U} | 0 | 0.6 | 0.737 | 0.15 |
| ρ_{M^*} | \mathcal{U} | 0 | 0.6 | 0.561 | 0.10 |
| ρ_{Co^*} | \mathcal{U} | 0 | 0.6 | 0.892 | 0.05 |
| ρ_{yCo} | β | 0.55 | 0.2 | 0.881 | 0.06 |

Table 7: Estimated Parameters, Standard Deviations Exogenous shocks

| Para. | Dist. | Prior | | Posterior | |
|----------------------|-----------------|-------|----------|-----------|-------|
| | | Mean | St.D. | Mode | St.D. |
| σ^{ξ^β} | \mathcal{N}^+ | 0.03 | 0.03 | 0.042 | 0.01 |
| σ^a | IG | 0.01 | ∞ | 0.004 | 0.00 |
| σ^u | \mathcal{N}^+ | 0.03 | 0.03 | 0.078 | 0.02 |
| σ^{z^X} | \mathcal{N}^+ | 0.01 | 0.03 | 0.009 | 0.00 |
| σ^{z^N} | \mathcal{N}^+ | 0.005 | 0.03 | 0.044 | 0.01 |
| σ^{ξ^X} | \mathcal{N}^+ | 0.1 | 0.3 | 0.006 | 0.06 |
| σ^{ξ^M} | \mathcal{N}^+ | 0.1 | 0.3 | 0.163 | 0.05 |
| σ^{ξ^N} | \mathcal{N}^+ | 0.1 | 0.3 | 0.726 | 0.18 |
| σ^{e^m} | \mathcal{N}^+ | 0.01 | 0.01 | 0.002 | 0.00 |
| $\sigma^{\xi^{X*}}$ | \mathcal{N}^+ | 0.01 | 0.01 | 0.021 | 0.00 |
| $\sigma^{\xi^{R1}}$ | \mathcal{N}^+ | 0.01 | 0.01 | 0.001 | 0.00 |
| $\sigma^{\xi^{R2}}$ | \mathcal{N}^+ | 0.01 | 0.01 | 0.004 | 0.00 |
| $\sigma^{\xi^{hN}}$ | \mathcal{N}^+ | 0.1 | 0.15 | 0.244 | 0.10 |
| $\sigma^{\xi^{hN}}$ | \mathcal{N}^+ | 0.1 | 0.15 | 0.165 | 0.09 |
| σ^{p^A} | \mathcal{N}^+ | 0.04 | 0.04 | 0.011 | 0.00 |
| σ^{p^E} | \mathcal{N}^+ | 0.02 | 0.02 | 0.025 | 0.00 |
| σ^{F*} | \mathcal{U} | 0.25 | 0.1443 | 0.028 | 0.00 |
| σ^* | \mathcal{U} | 0.25 | 0.1443 | 0.014 | 0.00 |
| σ^{M*} | \mathcal{U} | 0.25 | 0.1443 | 0.014 | 0.00 |
| σ^{Co*} | \mathcal{U} | 0.25 | 0.1443 | 0.120 | 0.01 |
| σ^{yCo} | \mathcal{N}^+ | 0.02 | 0.02 | 0.022 | 0.00 |

The last two equations for $J = \{X, N\}$. From the optimality conditions of choosing wages, we can write the first order conditions as:

$$\frac{\epsilon_W - 1}{\epsilon_W} W_t^{J,*} E_t \sum_{\tau=0}^{\infty} (\theta_{WJ} \beta)^\tau \lambda_{t+\tau} \left\{ \frac{h_{t+\tau}^{J,d}}{(W_{t+\tau}^J)^{-\epsilon_W}} (W_t^{J,*})^{-\epsilon_W} \left[a^\tau \prod_{s=1}^{\tau} ((\pi_{t+s-1}^J)^{\varrho_{WJ}} \pi_{t+s-1}^{1-\varrho_{WJ}})^{\zeta_{WJ}} \bar{\pi}_{t+s}^{1-\zeta_{WJ}} \right]^{1-\epsilon_W} \right\} =$$

$$E_t \sum_{\tau=0}^{\infty} (\theta_{WJ} \beta)^\tau \mu_{t+\tau}^{WJ} \lambda_{t+\tau} W_{t+\tau}^J \left\{ \frac{h_{t+\tau}^{J,d}}{(W_{t+\tau}^J)^{-\epsilon_W}} (W_t^{J,*})^{-\epsilon_W} \left[a^\tau \prod_{s=1}^{\tau} ((\pi_{t+s-1}^J)^{\varrho_{WJ}} \pi_{t+s-1}^{1-\varrho_{WJ}})^{\zeta_{WJ}} \bar{\pi}_{t+s}^{1-\zeta_{WJ}} \right]^{-\epsilon_W} \right\}$$

For $J = \{X, N\}$.

In addition, the optimality conditions for the decision between tradable and non-tradable consumption are:

$$C_t^N = \gamma \left(\frac{P_t^N}{P_t} \right)^{-\varrho} C_t$$

$$C_t^T = (1 - \gamma) \left(\frac{P_t^T}{P_t} \right)^{-\varrho} C_t$$

where it was used the fact that $C_t^{SAE} = C_t$.

And between the exportable and importable:

$$C_t^X = \gamma_T \left(\frac{P_t^X}{P_t^T} \right)^{-\varrho_T} C_t^T$$

$$C_t^M = (1 - \gamma_T) \left(\frac{P_t^M}{P_t^T} \right)^{-\varrho_T} C_t^T$$

D.3.2 Investment Good

The first order conditions between tradable and non-tradable investment can be written as:

$$\tilde{I}_t^N = \gamma_I \left(\frac{P_t^N}{P_t^I} \right)^{-\varrho_I} I_t$$

$$\tilde{I}_t^T = (1 - \gamma_I) \left(\frac{P_t^{T,I}}{P_t^I} \right)^{-\varrho_I} I_t$$

And between exportable and importable investment:

$$\tilde{I}_t^X = \gamma_{T,I} \left(\frac{P_t^X}{P_t^{T,I}} \right)^{-\varrho_{T,I}} \tilde{I}_t^T$$

$$\tilde{I}_t^M = (1 - \gamma_{T,I}) \left(\frac{P_t^M}{P_t^{T,I}} \right)^{-\varrho_{T,I}} \tilde{I}_t^T$$

D.3.3 Firms

The first order conditions are the same for each firm i in each sector and so the subscript will be omitted. First, given the marginal costs, the first order condition of the price setting can be written as:

$$\begin{aligned} \xi_t^J \frac{\epsilon_J - 1}{\epsilon_J} (P_t^{J,*})^{-\epsilon_J} \sum_{\tau=0}^{\infty} (\beta \theta_J)^\tau \Lambda_{t,t+\tau} \frac{1}{(P_{t+\tau}^J)^{-\epsilon_J}} Y_{t+\tau}^J \left[\prod_{s=1}^{\tau} \left((\pi_{t+s-1}^J)^{\varrho_J} \pi_{t+s-1}^{1-\varrho_J} \right)^{\zeta_J} \bar{\pi}_{t+s}^{1-\zeta_J} \right]^{1-\epsilon_J} = \\ (P_t^{J,*})^{-\epsilon_J - 1} \sum_{\tau=1}^{\infty} (\beta \theta_J)^\tau \Lambda_{t,t+\tau} MC_{t+\tau}^J \frac{1}{(P_{t+\tau}^J)^{-\epsilon_J}} Y_{t+\tau}^J \left[\prod_{s=1}^{\tau} \left((\pi_{t+s-1}^J)^{\varrho_J} \pi_{t+s-1}^{1-\varrho_J} \right)^{\zeta_J} \bar{\pi}_{t+s}^{1-\zeta_J} \right]^{-\epsilon_J} \end{aligned}$$

To get the marginal cost of each sector, we distinguish between the importable and the other sectors

- Sector M Cost minimization implies that their marginal cost is the same for all firms and is:

$$MC_t^M = P_{m,t}$$

Note the difference between the price set by the M sector, P_t^M , and the price of its input, $P_{m,t}$.

- Sector X and N

1. Optimal production of V_t^J : The first order conditions and the marginal cost are:

$$\begin{aligned} h_t^{J,d} &= \frac{V_t^J}{z_t^J (A_t^J)^{1-\alpha_J}} \left[\frac{1 - \alpha_J}{\alpha_J} \frac{P_t^J R_t^J}{W_t^J} \right]^{\alpha_J} \\ K_{t-1}^J &= \frac{V_t^J}{z_t^J (A_t^J)^{1-\alpha_J}} \left[\frac{\alpha_J}{1 - \alpha_J} \frac{W_t^J}{P_t^J R_t^J} \right]^{1-\alpha_J} \\ MC_t^{V,J} &= \frac{1}{z_t^J (A_t^J)^{1-\alpha_J}} (P_t^J R_t^J)^{\alpha_J} (W_t^J)^{1-\alpha_J} \left[\frac{1}{(1 - \alpha_J)^{1-\alpha_J} \alpha_J^{\alpha_J}} \right] \end{aligned}$$

2. Optimal production Y_t^J :

$$\begin{aligned} M_t^J &= Y_t^J(i) \left[\frac{1 - \gamma_J}{\gamma_J} \frac{MC_t^{V,J}}{P_t^{ME}} \right]^{\gamma_J} \\ V_t^J &= Y_t^J(i) \left[\frac{\gamma_J}{1 - \gamma_J} \frac{P_t^{ME}}{MC_t^{V,J}} \right]^{1-\gamma_J} \\ MC_t^J &= (MC_t^{V,J})^{\gamma_J} (P_t^{ME})^{1-\gamma_J} \left[\frac{1}{(1 - \gamma_J)^{1-\gamma_J} \gamma_J^{\gamma_J}} \right] \end{aligned}$$

D.3.4 Market Clearing

All markets clear:

$$\begin{aligned}
B_t &= B_t^G \\
I_t &= I_t^X + I_t^N \\
h_t^X &= \Delta_t^{WX} h_t^{X,d} \\
h_t^N &= \Delta_t^{WN} h_t^{N,d} \\
Y_t^X &= \Delta_t^X \left(C_t^X + \tilde{I}_t^X + C_t^{X,*} \right) \\
Y_t^M &= \Delta_t^M \left(C_t^M + \tilde{I}_t^M + M_t^X + M_t^N \right) \\
Y_t^N &= \Delta_t^N \left(C_t^N + \tilde{I}_t^N + G_t^N \right)
\end{aligned}$$

Which correspond to the local bonds market, the investment market, labor markets and goods market. The Δ variables are a measure of the dispersion in prices in the different markets.

The rest of the equations correspond to the policy and foreign equations described in the text.

D.4 Equilibrium Conditions

This sections describes the equilibrium conditions after the variables were redefined to make them stationary. The transformations made to the variables were: all lower case prices are the corresponding capital price divided by the CPI Index with the exception of $p_t^{Co,*}$ and p_t^{M*} which are divided by the foreign CPI price index and $p_t^{J,*} = P_t^{J,*}/P_t^J$. All lower case real variables (consumption, investment, capital, government expenditure, production, imports, productivity, output, foreign demand) are the upper case divided by A_{t-1} with the exception of $y_t^{Co} = Y_t^{Co}/A_{t-1}^{Co}$. All inflation definitions are the corresponding price index divided by the price index in the previous period. And particular definitions are: $\tilde{\xi}_t^{h,J} = \xi_t^{h,J}/A_{t-1}$, $\tilde{\mu}_t^J = \mu_t^J/P_t$, $b_t^* = B_t^*/(A_{t-1}P_t^*)$, $\tilde{f}_t^{1,J} = f_t^{1,J}/(A_{t-1}P_t^\sigma)$, $\tilde{f}_t^{1,WJ} = f_t^{1,WJ}/A_{t-1}^{1-\sigma}$, $\tilde{\lambda}_t = P_t\lambda_t/A_{t-1}^\sigma$, $w_t^J = W_t^J/(A_{t-1}P_t)$, $w_t^{J,*} = W_t^{J,*}/W_t^J$, $mc_t^J = MC_t^J/P_t^J$ and $mc_t^{V,J} = MC_t^{V,J}/P_t^J$ for $J = \{X, M, N\}$ or $J = \{X, N\}$ depending on the variable. In addition, new variables were defined as the real exchange rate, the trade balance, the gdp deflator among others.

There are 80 endogenous variables,

$$\begin{aligned}
\{ &c_t, \tilde{\lambda}_t, h_t^X, \mu_t^{WX}, w_t^X, h_t^N, \mu_t^{WN}, w_t^N, R_t, \pi_t, R_t^*, \pi_t^S, \tilde{\mu}_t^X, p_t^X, R_t^X, \tilde{\mu}_t^N, p_t^N, R_t^N, p_t^I, i_t^X, i_t^N, \\
&k_t^X, k_t^N, \tilde{f}_t^{1,WX}, w_t^{X,*}, h_t^{X,d}, \pi_t^X, \tilde{f}_t^{1,WN}, w_t^{N,*}, h_t^{N,d}, \pi_t^N, c_t^N, p_t^{SAE}, c_t^T, p_t^T, c_t^X, p_t^M, c_t^M, p_t^{T,I}, \\
&\tilde{i}_t^N, \tilde{i}_t^T, \tilde{i}_t^X, \tilde{i}_t^M, i_t, mc_t^M, y_t^M, m_t, p_{m,t}, v_t^X, a_t^X, v_t^N, mc_t^{V,X}, mc_t^{V,N}, y_t^X, p_t^{ME}, m_t^X, y_t^N, m_t^N, \\
&mc_t^X, mc_t^N, \tilde{f}_t^{1,X}, p_t^{X,*}, \tilde{f}_t^{1,M}, p_t^{M,*}, \pi_t^M, \tilde{f}_t^{1,N}, p_t^{N,*}, gdp_t, \pi_t^{SAE}, c_t^{X,*}, rer_t, \Delta_t^{WX}, \Delta_t^{WN}, \\
&\Delta_t^N, \Delta_t^X, \Delta_t^M, tb_t, a_t^{Co}, b_t^*, p_t^Y \}
\end{aligned}$$

and 23 shocks:

$$\{ \xi_t^\beta, a_t, \tilde{\xi}_t^{h,X}, \tilde{\xi}_t^{h,N}, \xi_t^N, \xi_t^N, \xi_t^N, \xi_t^A/p_t^T, p_t^E/p_t^T, u_t, z_t^X, z_t^N, g_t, e_t^m, y_t^*, \xi_t^{X,*}, \pi_t^*, p_t^{M*}, R_t^W, \xi_t^R, \xi_t^{R2}, p_t^{Co,*}, y_t^{Co} \}.$$

$$\xi_t^\beta \left(c_t - \phi_C \frac{c_{t-1}}{a_{t-1}} \right)^{-\sigma} = \tilde{\lambda}_t \quad (\text{EC.1})$$

$$\tilde{\xi}_t^{h,X} (h_t^X)^\varphi = \mu_t^{WX} w_t^X \quad (\text{EC.2})$$

$$\tilde{\xi}_t^{h,N} (h_t^N)^\varphi = \mu_t^{WN} w_t^N \quad (\text{EC.3})$$

$$\tilde{\lambda}_t = \beta a_t^{-\sigma} E_t \frac{\tilde{\lambda}_{t+1} R_t}{\pi_{t+1}} \quad (\text{EC.4})$$

$$\tilde{\lambda}_t = \beta a_t^{-\sigma} E_t \frac{\tilde{\lambda}_{t+1} R_t^* \pi_{t+1}^S}{\pi_{t+1}} \quad (\text{EC.5})$$

$$\tilde{\mu}_t^X \tilde{\lambda}_t = \beta a_t^{-\sigma} E_t \left\{ \tilde{\lambda}_{t+1} p_{t+1}^X R_{t+1}^X + \tilde{\mu}_{t+1}^X \tilde{\lambda}_{t+1} (1 - \delta) \right\} \quad (\text{EC.6})$$

$$\tilde{\mu}_t^N \tilde{\lambda}_t = \beta a_t^{-\sigma} E_t \left\{ \tilde{\lambda}_{t+1} p_{t+1}^N R_{t+1}^N + \tilde{\mu}_{t+1}^N \tilde{\lambda}_{t+1} (1 - \delta) \right\} \quad (\text{EC.7})$$

$$\begin{aligned} \tilde{\lambda}_t p_t^I = \tilde{\mu}_t^X \tilde{\lambda}_t & \left\{ 1 - \frac{\phi_I}{2} \left(\frac{i_t^X}{i_{t-1}^X} a_{t-1} - a \right)^2 - \phi_I \left(\frac{i_t^X}{i_{t-1}^X} a_{t-1} - a \right) \frac{i_t^X}{i_{t-1}^X} a_{t-1} \right\} u_t + \\ & \beta a_t^{-\sigma} E_t \tilde{\mu}_{t+1}^X \tilde{\lambda}_{t+1} \phi_I \left(\frac{i_{t+1}^X}{i_t^X} a_t - a \right) \left(\frac{i_{t+1}^X}{i_t^X} a_t \right)^2 u_{t+1} \end{aligned} \quad (\text{EC.8})$$

$$\begin{aligned} \tilde{\lambda}_t p_t^I = \tilde{\mu}_t^N \tilde{\lambda}_t & \left\{ 1 - \frac{\phi_I}{2} \left(\frac{i_t^N}{i_{t-1}^N} a_{t-1} - a \right)^2 - \phi_I \left(\frac{i_t^N}{i_{t-1}^N} a_{t-1} - a \right) \frac{i_t^N}{i_{t-1}^N} a_{t-1} \right\} u_t + \\ & \beta a_t^{-\sigma} E_t \tilde{\mu}_{t+1}^N \tilde{\lambda}_{t+1} \phi_I \left(\frac{i_{t+1}^N}{i_t^N} a_t - a \right) \left(\frac{i_{t+1}^N}{i_t^N} a_t \right)^2 u_{t+1} \end{aligned} \quad (\text{EC.9})$$

$$k_t^X = \left[1 - \frac{\phi_I}{2} \left(\frac{i_t^X}{i_{t-1}^X} a_{t-1} - a \right)^2 \right] u_t i_t^X + (1 - \delta) \frac{k_{t-1}^X}{a_{t-1}} \quad (\text{EC.10})$$

$$k_t^N = \left[1 - \frac{\phi_I}{2} \left(\frac{i_t^N}{i_{t-1}^N} a_{t-1} - a \right)^2 \right] u_t i_t^N + (1 - \delta) \frac{k_{t-1}^N}{a_{t-1}} \quad (\text{EC.11})$$

$$\begin{aligned} \tilde{f}_t^{1,WX} &= \frac{\epsilon_W - 1}{\epsilon_W} (w_t^{X,*})^{1-\epsilon_W} \tilde{\lambda}_t h_t^{X,d} + \\ & \theta_{WX} a_t^{1-\sigma} \beta E_t \left(\frac{w_t^{X,*}}{w_{t+1}^{X,*}} \frac{w_t^X}{w_{t+1}^X} \right)^{1-\epsilon_W} \left[\frac{a}{a_t} \frac{((\pi_t^X)^{\varrho_{WX}} \pi_t^{1-\varrho_{WX}}) \zeta_{WX} \bar{\pi}^{1-\zeta_{WX}}}{\pi_{t+1}} \right]^{1-\epsilon_W} \frac{w_{t+1}^X}{w_t^X} \tilde{f}_{t+1}^{1,WX} \end{aligned} \quad (\text{EC.12})$$

$$\begin{aligned}\tilde{f}_t^{1,WN} &= \frac{\epsilon_W - 1}{\epsilon_W} (w_t^{N,*})^{1-\epsilon_W} \tilde{\lambda}_t h_t^{N,d} + \\ &\theta_{WN} a_t^{1-\sigma} \beta E_t \left(\frac{w_t^{N,*}}{w_{t+1}^{N,*}} \frac{w_t^N}{w_{t+1}^N} \right)^{1-\epsilon_W} \left[\frac{a \left((\pi_t^N)^{\varrho_{WN}} \pi_t^{1-\varrho_{WN}} \zeta_{WN} \bar{\pi}^{1-\zeta_{WN}} \right)}{a_t \pi_{t+1}} \right]^{1-\epsilon_W} \frac{w_{t+1}^N}{w_t^N} \tilde{f}_{t+1}^{1,WN}\end{aligned}\quad (\text{EC.13})$$

$$\begin{aligned}\tilde{f}_t^{1,WX} &= \left(w_t^{X,*} \right)^{-\epsilon_W} \mu_t^{WX} \tilde{\lambda}_t h_t^{X,d} + \\ &\theta_{WX} a_t^{1-\sigma} \beta E_t \left(\frac{w_t^{X,*}}{w_{t+1}^{X,*}} \frac{w_t^X}{w_{t+1}^X} \right)^{-\epsilon_W} \left[\frac{a \left((\pi_t^X)^{\varrho_{WX}} \pi_t^{1-\varrho_{WX}} \zeta_{WX} \bar{\pi}^{1-\zeta_{WX}} \right)}{a_t \pi_{t+1}} \right]^{-\epsilon_W} \frac{w_{t+1}^X}{w_t^X} \tilde{f}_{t+1}^{1,WX}\end{aligned}\quad (\text{EC.14})$$

$$\begin{aligned}\tilde{f}_t^{1,WN} &= \left(w_t^{N,*} \right)^{-\epsilon_W} \mu_t^{WN} \tilde{\lambda}_t h_t^{N,d} + \\ &\theta_{WN} a_t^{1-\sigma} \beta E_t \left(\frac{w_t^{N,*}}{w_{t+1}^{N,*}} \frac{w_t^N}{w_{t+1}^N} \right)^{-\epsilon_W} \left[\frac{a \left((\pi_t^N)^{\varrho_{WN}} \pi_t^{1-\varrho_{WN}} \zeta_{WN} \bar{\pi}^{1-\zeta_{WN}} \right)}{a_t \pi_{t+1}} \right]^{-\epsilon_W} \frac{w_{t+1}^N}{w_t^N} \tilde{f}_{t+1}^{1,WN}\end{aligned}\quad (\text{EC.15})$$

$$1 = \theta_{WX} \left(\frac{w_{t-1}^X}{w_t^X} \frac{a}{a_{t-1}} \frac{\left((\pi_{t-1}^X)^{\varrho_{WX}} \pi_{t-1}^{1-\varrho_{WX}} \zeta_{WX} \bar{\pi}^{1-\zeta_{WX}} \right)}{\pi_t} \right)^{1-\epsilon_W} + (1 - \theta_{WX}) \left(w_t^{X,*} \right)^{1-\epsilon_W} \quad (\text{EC.16})$$

$$1 = \theta_{WN} \left(\frac{w_{t-1}^N}{w_t^N} \frac{a}{a_{t-1}} \frac{\left((\pi_{t-1}^N)^{\varrho_{WN}} \pi_{t-1}^{1-\varrho_{WN}} \zeta_{WN} \bar{\pi}^{1-\zeta_{WN}} \right)}{\pi_t} \right)^{1-\epsilon_W} + (1 - \theta_{WN}) \left(w_t^{N,*} \right)^{1-\epsilon_W} \quad (\text{EC.17})$$

$$c_t^N = \gamma \left(\frac{p_t^N}{p_t^{SAE}} \right)^{-\varrho} c_t \quad (\text{EC.18})$$

$$c_t^T = (1 - \gamma) \left(\frac{p_t^T}{p_t^{SAE}} \right)^{-\varrho} c_t \quad (\text{EC.19})$$

$$c_t^X = \gamma_T \left(\frac{p_t^X}{p_t^T} \right)^{-\varrho_T} c_t^T \quad (\text{EC.20})$$

$$c_t^M = (1 - \gamma_T) \left(\frac{p_t^M}{p_t^T} \right)^{-\varrho_T} c_t^T \quad (\text{EC.21})$$

$$1 = (p_t^{SAE})^{1-\gamma_{AC}-\gamma_{EC}} (p_t^A)^{\gamma_{AC}} (p_t^E)^{\gamma_{EC}} \quad (\text{EC.22})$$

$$1 = (1 - \gamma) \left(\frac{p_t^T}{p_t^{SAE}} \right)^{1-\varrho} + \gamma \left(\frac{p_t^N}{p_t^{SAE}} \right)^{1-\varrho} \quad (\text{EC.23})$$

$$1 = (1 - \gamma_T) \left(\frac{p_t^M}{p_t^T} \right)^{1-\varrho_T} + \gamma_T \left(\frac{p_t^X}{p_t^T} \right)^{1-\varrho_T} \quad (\text{EC.24})$$

$$p_t^I = \left(\gamma_I (p_t^N)^{1-\varrho_I} + (1 - \gamma_I) (p_t^{T,I})^{1-\varrho_I} \right)^{\frac{1}{1-\varrho_I}} \quad (\text{EC.25})$$

$$p_t^{T,I} = \left(\gamma_{T,I} (p_t^X)^{1-\varrho_{T,I}} + (1 - \gamma_{T,I}) (p_t^M)^{1-\varrho_{T,I}} \right)^{\frac{1}{1-\varrho_{T,I}}} \quad (\text{EC.26})$$

$$\tilde{i}_t^N = \gamma_I \left(\frac{p_t^N}{p_t^I} \right)^{-\varrho_I} i_t \quad (\text{EC.27})$$

$$\tilde{i}_t^T = (1 - \gamma_I) \left(\frac{p_t^{T,I}}{p_t^I} \right)^{-\varrho_I} i_t \quad (\text{EC.28})$$

$$\tilde{i}_t^X = \gamma_{T,I} \left(\frac{p_t^X}{p_t^{T,I}} \right)^{-\varrho_{T,I}} \tilde{i}_t^T \quad (\text{EC.29})$$

$$\tilde{i}_t^M = (1 - \gamma_{T,I}) \left(\frac{p_t^M}{p_t^{T,I}} \right)^{-\varrho_{T,I}} \tilde{i}_t^T \quad (\text{EC.30})$$

$$mc_t^M = \frac{p_{m,t}}{p_t^M} \quad (\text{EC.31})$$

$$y_t^M = m_t \quad (\text{EC.32})$$

$$h_t^{X,d} = \frac{v_t^X}{z_t^X (a_t^X)^{1-\alpha_X}} \left[\frac{1 - \alpha_X}{\alpha_X} \frac{p_t^X}{w_t^X} R_t^X \right]^{\alpha_X} \quad (\text{EC.33})$$

$$k_{t-1}^X = a_{t-1} \frac{v_t^X}{z_t^X (a_t^X)^{1-\alpha_X}} \left[\frac{\alpha_X}{1 - \alpha_X} \frac{w_t^X}{p_t^X} R_t^X \right]^{1-\alpha_X} \quad (\text{EC.34})$$

$$h_t^{N,d} = \frac{v_t^N}{z_t^N a_t^{1-\alpha_N}} \left[\frac{1 - \alpha_N}{\alpha_N} \frac{p_t^N}{w_t^N} R_t^N \right]^{\alpha_N} \quad (\text{EC.35})$$

$$k_{t-1}^N = a_{t-1} \frac{v_t^N}{z_t^N a_t^{1-\alpha_N}} \left[\frac{\alpha_N}{1 - \alpha_N} \frac{w_t^N}{p_t^N} R_t^N \right]^{1-\alpha_N} \quad (\text{EC.36})$$

$$mc_t^{V,X} = \frac{1}{z_t^X (a_t^X)^{1-\alpha_X}} \frac{(p_t^X R_t^X)^{\alpha_X} (w_t^X)^{1-\alpha_X}}{p_t^X} \left[\frac{1}{(1 - \alpha_X)^{1-\alpha_X} \alpha_X^{\alpha_X}} \right] \quad (\text{EC.37})$$

$$mc_t^{V,N} = \frac{1}{z_t^N a_t^{1-\alpha_N}} \frac{(p_t^N R_t^N)^{\alpha_N} (w_t^N)^{1-\alpha_N}}{p_t^N} \left[\frac{1}{(1 - \alpha_N)^{1-\alpha_N} \alpha_N^{\alpha_N}} \right] \quad (\text{EC.38})$$

$$v_t^X = y_t^X \left[\frac{\gamma_X}{1 - \gamma_X} \frac{p_t^{ME}}{mc_t^{V,X}} \frac{1}{p_t^X} \right]^{1-\gamma_X} \quad (\text{EC.39})$$

$$m_t^X = y_t^X \left[\frac{1 - \gamma_X}{\gamma_X} \frac{mc_t^{V,X}}{p_t^{ME}} p_t^X \right]^{\gamma_X} \quad (\text{EC.40})$$

$$v_t^N = y_t^N \left[\frac{\gamma_N}{1 - \gamma_N} \frac{p_t^{ME}}{mc_t^{V,N}} \frac{1}{p_t^N} \right]^{1 - \gamma_N} \quad (\text{EC.41})$$

$$m_t^N = y_t^N \left[\frac{1 - \gamma_N}{\gamma_N} \frac{mc_t^{V,N}}{p_t^{ME}} p_t^N \right]^{\gamma_N} \quad (\text{EC.42})$$

$$mc_t^X = (mc_t^{V,X})^{\gamma_X} \left(\frac{p_t^{ME}}{p_t^X} \right)^{1 - \gamma_X} \frac{1}{(1 - \gamma_X)^{1 - \gamma_X} \gamma_X^{\gamma_X}} \quad (\text{EC.43})$$

$$mc_t^N = (mc_t^{V,N})^{\gamma_N} \left(\frac{p_t^{ME}}{p_t^N} \right)^{1 - \gamma_N} \frac{1}{(1 - \gamma_N)^{1 - \gamma_N} \gamma_N^{\gamma_N}} \quad (\text{EC.44})$$

$$a_t^X = \left(\frac{a_{t-1}^X}{a_{t-1}} \right)^{1 - \Gamma_X} (a_t)^{\Gamma_X} \quad (\text{EC.45})$$

$$p_t^{ME} = (p_t^M)^{1 - \gamma_{EF}} (p_t^E)^{\gamma_{EF}} \quad (\text{EC.46})$$

$$\begin{aligned} \tilde{f}_t^{1,X} &= \xi_t^X \frac{\epsilon_X - 1}{\epsilon_X} \left(p_t^{X,*} \right)^{1 - \epsilon_X} y_t^X + \\ &\beta a_t^{1 - \sigma} \theta_X E_t \left(\frac{p_t^{X,*}}{p_{t+1}^{X,*}} \frac{p_t^X}{p_{t+1}^X} \right)^{1 - \epsilon_X} \frac{\tilde{\lambda}_{t+1}}{\tilde{\lambda}_t} \frac{\left[\left((\pi_t^X)^{\varrho_X} \pi_t^{1 - \varrho_X} \right)^{\zeta_X} \bar{\pi}^{1 - \zeta_X} \right]^{1 - \epsilon_X}}{\pi_{t+1}^{1 - \epsilon_X}} \frac{\pi_{t+1}^X}{\pi_{t+1}} \tilde{f}_{t+1}^{1,X} \end{aligned} \quad (\text{EC.47})$$

$$\begin{aligned} \tilde{f}_t^{1,M} &= \xi_t^M \frac{\epsilon_M - 1}{\epsilon_M} \left(p_t^{M,*} \right)^{1 - \epsilon_M} y_t^M + \\ &\beta a_t^{1 - \sigma} \theta_M E_t \left(\frac{p_t^{M,*}}{p_{t+1}^{M,*}} \frac{p_t^M}{p_{t+1}^M} \right)^{1 - \epsilon_M} \frac{\tilde{\lambda}_{t+1}}{\tilde{\lambda}_t} \frac{\left[\left((\pi_t^M)^{\varrho_M} \pi_t^{1 - \varrho_M} \right)^{\zeta_M} \bar{\pi}^{1 - \zeta_M} \right]^{1 - \epsilon_M}}{\pi_{t+1}^{1 - \epsilon_M}} \frac{\pi_{t+1}^M}{\pi_{t+1}} \tilde{f}_{t+1}^{1,M} \end{aligned} \quad (\text{EC.48})$$

$$\begin{aligned} \tilde{f}_t^{1,N} &= \xi_t^N \frac{\epsilon_N - 1}{\epsilon_N} \left(p_t^{N,*} \right)^{1 - \epsilon_N} y_t^N + \\ &\beta a_t^{1 - \sigma} \theta_N E_t \left(\frac{p_t^{N,*}}{p_{t+1}^{N,*}} \frac{p_t^N}{p_{t+1}^N} \right)^{1 - \epsilon_N} \frac{\tilde{\lambda}_{t+1}}{\tilde{\lambda}_t} \frac{\left[\left((\pi_t^N)^{\varrho_N} \pi_t^{1 - \varrho_N} \right)^{\zeta_N} \bar{\pi}^{1 - \zeta_N} \right]^{1 - \epsilon_N}}{\pi_{t+1}^{1 - \epsilon_N}} \frac{\pi_{t+1}^N}{\pi_{t+1}} \tilde{f}_{t+1}^{1,N} \end{aligned} \quad (\text{EC.49})$$

$$\begin{aligned} \tilde{f}_t^{1,X} &= \left(p_t^{X,*} \right)^{-\epsilon_X} mc_t^X y_t^X + \\ &\beta a_t^{1 - \sigma} \theta_X E_t \left(\frac{p_t^{X,*}}{p_{t+1}^{X,*}} \frac{p_t^X}{p_{t+1}^X} \right)^{-\epsilon_X} \frac{\tilde{\lambda}_{t+1}}{\tilde{\lambda}_t} \frac{\left[\left((\pi_t^X)^{\varrho_X} \pi_t^{1 - \varrho_X} \right)^{\zeta_X} \bar{\pi}^{1 - \zeta_X} \right]^{-\epsilon_X}}{\pi_{t+1}^{-\epsilon_X}} \frac{\pi_{t+1}^X}{\pi_{t+1}} \tilde{f}_{t+1}^{1,X} \end{aligned} \quad (\text{EC.50})$$

$$\begin{aligned} \tilde{f}_t^{1,M} &= \left(p_t^{M,*}\right)^{-\epsilon_M} m c_t^M y_t^M + \\ &\beta \alpha_t^{1-\sigma} \theta_M E_t \left(\frac{p_t^{M,*}}{p_{t+1}^{M,*}} \frac{p_t^M}{p_{t+1}^M} \right)^{-\epsilon_M} \frac{\tilde{\lambda}_{t+1}}{\tilde{\lambda}_t} \left[\frac{\left((\pi_t^M)^{\varrho_M} \pi_t^{1-\varrho_M} \right)^{\zeta_M} \bar{\pi}^{1-\zeta_M}}{\pi_{t+1}^{-\epsilon_M}} \right]^{-\epsilon_M} \frac{\pi_{t+1}^M}{\pi_{t+1}} \tilde{f}_{t+1}^{1,M} \end{aligned} \quad (\text{EC.51})$$

$$\begin{aligned} \tilde{f}_t^{1,N} &= \left(p_t^{N,*}\right)^{-\epsilon_N} m c_t^N y_t^N + \\ &\beta \alpha_t^{1-\sigma} \theta_N E_t \left(\frac{p_t^{N,*}}{p_{t+1}^{N,*}} \frac{p_t^N}{p_{t+1}^N} \right)^{-\epsilon_N} \frac{\tilde{\lambda}_{t+1}}{\tilde{\lambda}_t} \left[\frac{\left((\pi_t^N)^{\varrho_N} \pi_t^{1-\varrho_N} \right)^{\zeta_N} \bar{\pi}^{1-\zeta_N}}{\pi_{t+1}^{-\epsilon_N}} \right]^{-\epsilon_N} \frac{\pi_{t+1}^N}{\pi_{t+1}} \tilde{f}_{t+1}^{1,N} \end{aligned} \quad (\text{EC.52})$$

$$\pi_t^X = \frac{p_t^X}{p_{t-1}^X} \pi_t \quad (\text{EC.53})$$

$$\pi_t^M = \frac{p_t^M}{p_{t-1}^M} \pi_t \quad (\text{EC.54})$$

$$\pi_t^N = \frac{p_t^N}{p_{t-1}^N} \pi_t \quad (\text{EC.55})$$

$$\pi_t^{SAE} = \frac{p_t^{SAE}}{p_{t-1}^{SAE}} \pi_t \quad (\text{EC.56})$$

$$1 = (1 - \theta_X) \left(p_t^{*,X}\right)^{1-\epsilon_X} + \theta_X \left[\left((\pi_{t-1}^X)^{\varrho_X} \pi_{t-1}^{1-\varrho_X} \right)^{\zeta_X} \bar{\pi}^{1-\zeta_X} \right]^{1-\epsilon_X} \left(\frac{1}{\pi_t^X} \right)^{1-\epsilon_X} \quad (\text{EC.57})$$

$$1 = (1 - \theta_M) \left(p_t^{*,M}\right)^{1-\epsilon_M} + \theta_M \left[\left((\pi_{t-1}^M)^{\varrho_M} \pi_{t-1}^{1-\varrho_M} \right)^{\zeta_M} \bar{\pi}^{1-\zeta_M} \right]^{1-\epsilon_M} \left(\frac{1}{\pi_t^M} \right)^{1-\epsilon_M} \quad (\text{EC.58})$$

$$1 = (1 - \theta_N) \left(p_t^{*,N}\right)^{1-\epsilon_N} + \theta_N \left[\left((\pi_{t-1}^N)^{\varrho_N} \pi_{t-1}^{1-\varrho_N} \right)^{\zeta_N} \bar{\pi}^{1-\zeta_N} \right]^{1-\epsilon_N} \left(\frac{1}{\pi_t^N} \right)^{1-\epsilon_N} \quad (\text{EC.59})$$

$$\left(\frac{R_t}{R} \right) = \left(\frac{R_{t-1}}{R} \right)^{\varrho_R} \left[\left(\frac{(\pi_t^{SAE})^{\alpha_{\pi}^{SAE}} \pi_t^{1-\alpha_{\pi}^{SAE}}}{\bar{\pi}} \right)^{\alpha_{\pi}} \left(\frac{gdp_t a_{t-1} / gdp_{t-1}}{a} \right)^{\alpha_Y} \right]^{1-\varrho_R} c_t^m \quad (\text{EC.60})$$

$$c_t^{X,*} = \left(\frac{p_t^X}{rer_t} \right)^{-\epsilon^*} y_t^* \xi_t^{X,*} \quad (\text{EC.61})$$

$$\frac{rer_t}{rer_{t-1}} = \frac{\pi_t^S \pi_t^*}{\pi_t} \quad (\text{EC.62})$$

$$p_{m,t} = rer_t p_{m,t}^* \quad (\text{EC.63})$$

$$R_t^* = R_t^W \exp \left\{ \phi_B \left(\bar{b} - \frac{b_t^* rer_t}{p_t^Y gdp_t} \right) \right\} \xi_t^R \xi_t^{R2} \quad (\text{EC.64})$$

$$i_t = i_t^X + i_t^N \quad (\text{EC.65})$$

$$h_t^X = \Delta_t^{WX} h_t^{X,d} \quad (\text{EC.66})$$

$$h_t^N = \Delta_t^{WN} h_t^{N,d} \quad (\text{EC.67})$$

$$y_t^N = \Delta_t^N (c_t^N + g_t + \tilde{i}_t^N) \quad (\text{EC.68})$$

$$y_t^X = \Delta_t^X (c_t^X + \tilde{i}_t^X + c_t^{X,*}) \quad (\text{EC.69})$$

$$y_t^M = \Delta_t^M (c_t^M + \tilde{i}_t^M + m_t^X + m_t^N) \quad (\text{EC.70})$$

$$\Delta_t^{WX} = (1 - \theta_{WX}) (w_t^{X,*})^{-\epsilon_W} + \theta_{WX} \left(\frac{w_{t-1}^X}{w_t^X} \frac{a}{a_{t-1}} \frac{((\pi_{t-1}^X)^{\varrho_{WX}} \pi_{t-1}^{1-\varrho_{WX}})^{\varsigma_{WX}} \bar{\pi}^{1-\varsigma_{WX}}}{\pi_t} \right)^{-\epsilon_W} \Delta_{t-1}^{WX} \quad (\text{EC.71})$$

$$\Delta_t^{WN} = (1 - \theta_{WN}) (w_t^{N,*})^{-\epsilon_W} + \theta_{WN} \left(\frac{w_{t-1}^N}{w_t^N} \frac{a}{a_{t-1}} \frac{((\pi_{t-1}^N)^{\varrho_{WN}} \pi_{t-1}^{1-\varrho_{WN}})^{\varsigma_{WN}} \bar{\pi}^{1-\varsigma_{WN}}}{\pi_t} \right)^{-\epsilon_W} \Delta_{t-1}^{WN} \quad (\text{EC.72})$$

$$\Delta_t^X = (1 - \theta_X) (p_t^{*,X})^{-\epsilon_X} + \theta_X \left(\frac{((\pi_{t-1}^X)^{\varrho_X} \pi_{t-1}^{1-\varrho_X})^{\varsigma_X} \bar{\pi}^{1-\varsigma_X}}{\pi_t^X} \right)^{-\epsilon_X} \Delta_{t-1}^X \quad (\text{EC.73})$$

$$\Delta_t^M = (1 - \theta_M) (p_t^{*,M})^{-\epsilon_M} + \theta_M \left(\frac{((\pi_{t-1}^M)^{\varrho_M} \pi_{t-1}^{1-\varrho_M})^{\varsigma_M} \bar{\pi}^{1-\varsigma_M}}{\pi_t^M} \right)^{-\epsilon_M} \Delta_{t-1}^M \quad (\text{EC.74})$$

$$\Delta_t^N = (1 - \theta_N) (p_t^{*,N})^{-\epsilon_N} + \theta_N \left(\frac{((\pi_{t-1}^N)^{\varrho_N} \pi_{t-1}^{1-\varrho_N})^{\varsigma_N} \bar{\pi}^{1-\varsigma_N}}{\pi_t^N} \right)^{-\epsilon_N} \Delta_{t-1}^N \quad (\text{EC.75})$$

$$tb_t = \text{rer}_t p_t^{Co,*} y_t^{Co} \frac{a_{t-1}^{Co}}{a_{t-1}} + p_t^X c_t^{X,*} - p_{m,t} m_t \quad (\text{EC.76})$$

$$a_t^{Co} = \left(\frac{a_{t-1}^{Co}}{a_{t-1}} \right)^{1-\Gamma_{Co}} a_t^{\Gamma_{Co}} \quad (\text{EC.77})$$

$$\text{rer}_t b_t^* = tb_t + \frac{\text{rer}_t}{\pi_t^* a_{t-1}} R_{t-1}^* b_{t-1}^* - (1 - \vartheta) \text{rer}_t p_t^{Co,*} y_t^{Co} \frac{a_{t-1}^{Co}}{a_{t-1}} \quad (\text{EC.78})$$

$$gdp_t = c_t + g_t + i_t + c_t^{X,*} + y_t^{Co} \frac{a_{t-1}^{Co}}{a_{t-1}} - m_t \quad (\text{EC.79})$$

$$p_t^Y gdp_t = c_t + p_t^G g_t + p_t^I i_t + tb_t \quad (\text{EC.80})$$

D.4.1 Steady State

The given endogenous are: $\{R, h^X, h^N, p^X/p^I, p^M/p^I, s^{Co} = rer p^{Co,*} y^{Co}/(p^Y gdp), s^M = p_m y^M/(p^Y gdp), s^g = p^N g/(p^Y gdp)\}$ and the exogenous variables that are calculated endogenously are: $\{\beta, \tilde{\xi}^{h,N}, z^X, g, y^*, \pi^*, y^{Co}, \gamma, \bar{b}\}$.
By (EC.64) (assuming that the part inside the bracket is zero):

$$R^* = R^W \xi^R$$

By (EC.45)

$$a^X = a^{\frac{2\Gamma_X - 1}{\Gamma_X}}$$

By (EC.77)

$$a^{Co} = a^{\frac{2\Gamma_{Co} - 1}{\Gamma_{Co}}}$$

By (EC.60) and (EC.56) (assuming $\epsilon^m = 1$):

$$\pi^{SAE} = \pi = \bar{\pi}$$

By (EC.4):

$$\beta = \frac{a^\sigma \pi}{R}$$

By (EC.5):

$$\pi^S = \frac{a^\sigma \pi}{R^* \beta}$$

By (EC.62):

$$\pi^* = \frac{\pi}{\pi^S}$$

By (EC.63)-(EC.65):

$$\pi^X = \pi^M = \pi^N = \pi$$

By (EC.57)-(EC.59):

$$p^{X,*} = p^{M,*} = p^{N,*} = 1$$

By (EC.16)-(EC.17):

$$w^{X,*} = w^{N,*} = 1$$

By (EC.71)-(EC.75):

$$\Delta^{WX} = \Delta^{WN} = \Delta^X = \Delta^M = \Delta^N = 1$$

By (EC.47)-(EC.52)

$$mc^X = \frac{\epsilon_X - 1}{\epsilon_X}$$

$$mc^M = \frac{\epsilon_M - 1}{\epsilon_M}$$

$$mc^N = \frac{\epsilon_N - 1}{\epsilon_N}$$

By (EC.12)-(EC.15)

$$\mu^{WX} = \mu^{WN} = \frac{\epsilon_W - 1}{\epsilon_W}$$

By (EC.66)-(EC.67):

$$h^{X,d} = h^X$$

$$h^{N,d} = h^N$$

From the relative prices p^X/p^I and p^M/p^I , we get using (EC.24)-(EC.26) the relative prices:

$$\begin{aligned} \frac{p^{T,I}}{p^I} &= \left(\gamma_{T,I} \left(\frac{p^X}{p^I} \right)^{1-\varrho_{T,I}} + (1 - \gamma_{T,I}) \left(\frac{p^M}{p^I} \right)^{1-\varrho_{T,I}} \right)^{\frac{1}{1-\varrho_{T,I}}} \\ \frac{p^N}{p^I} &= \left(\frac{1 - (1 - \gamma_I) (p^{T,I}/p^I)^{1-\varrho_I}}{\gamma_I} \right)^{\frac{1}{1-\varrho_I}} \\ \frac{p^T}{p^I} &= \left[(1 - \gamma_T) \left(\frac{p^M}{p^I} \right)^{1-\varrho_T} + \gamma_T \left(\frac{p^X}{p^I} \right)^{1-\varrho_T} \right]^{\frac{1}{1-\varrho_T}} \end{aligned}$$

From (EC.8)-(EC.9):

$$\frac{\tilde{\mu}^X}{p^I} = \frac{\tilde{\mu}^N}{p^I} = 1/u$$

By (EC.6)-(EC.7):

$$\begin{aligned} R^X &= \frac{(\tilde{\mu}^X/p^I)(1 - \beta a^{-\sigma}(1 - \delta))}{\beta a^{-\sigma}(p^X/p^I)} \\ R^N &= \frac{(\tilde{\mu}^N/p^I)(1 - \beta a^{-\sigma}(1 - \delta))}{\beta a^{-\sigma}(p^N/p^I)} \end{aligned}$$

By (EC.31):

$$\frac{p_m}{p^I} = mc^M(p^M/p^I)$$

By (EC.63):

$$\frac{rer}{p^I} = \frac{p_m/p^I}{p_m^*}$$

It is further assumed that $p^A = p^E = p^T$, and so, we also have p^A/p^I and p^E/p^I . By (EC.46):

$$\frac{p^{ME}}{p^I} = \left(\frac{p^M}{p^I} \right)^{1-\gamma_{EF}} \left(\frac{p^T}{p^I} \right)^{\gamma_{EF}}$$

By (EC.43)-(EC.44):

$$\begin{aligned} mc^{V,X} &= \left(\frac{mc^X (p^X/p^I)^{1-\gamma_X} (1 - \gamma_X)^{1-\gamma_X} \gamma_X^{\gamma_X}}{(p^{ME}/p^I)^{1-\gamma_X}} \right)^{\frac{1}{\gamma_X}} \\ mc^{V,N} &= \left(\frac{mc^N (p^N/p^I)^{1-\gamma_N} (1 - \gamma_N)^{1-\gamma_N} \gamma_N^{\gamma_N}}{(p^{ME}/p^I)^{1-\gamma_N}} \right)^{\frac{1}{\gamma_N}} \end{aligned}$$

By (EC.38):

$$\frac{w^N}{p^I} = \left(\frac{mc^{V,N} z^N a^{1-\alpha_N} (p^N/p^I) (1 - \alpha_N)^{1-\alpha_N} \alpha_N^{\alpha_N}}{((p^N/p^I) R^N)^{\alpha_N}} \right)^{\frac{1}{1-\alpha_N}}$$

By (EC.3):

$$\frac{\tilde{\xi}^{h,N}}{p^I} = \frac{\mu^{WN}}{(h^N)^\varphi} \frac{w^N}{p^I}$$

Assuming that $\tilde{\xi}^{h,X} = \tilde{\xi}^{h,N}$, we also have $\tilde{\xi}^{h,X}/p^I$ and with (EC.2):

$$\frac{w^X}{p^I} = \frac{(\tilde{\xi}^{h,X}/p^I)(h^X)^\varphi}{\mu^{WX}}$$

By (EC.37):

$$z^X = \frac{((p^X/p^I)R^X)^{\alpha_X} (w^X/p^I)^{1-\alpha_X}}{mc^{V,X} (a^X)^{1-\alpha_X} (p^X/p^I)^{1-\alpha_X} \alpha_X^{\alpha_X}}$$

By (EC.33) and (EC.35):

$$v^X = h^{X,d} z^X (a^X)^{1-\alpha_X} \left[\frac{\alpha_X}{1-\alpha_X} \frac{w^X/p^I}{(p^X/p^I)R^X} \right]^{\alpha_X}$$

$$v^N = h^{N,d} z^N a^{1-\alpha_N} \left[\frac{\alpha_N}{1-\alpha_N} \frac{w^N/p^I}{(p^N/p^I)R^N} \right]^{\alpha_N}$$

By (EC.34) and (EC.36):

$$k^X = a \frac{v^X}{z^X (a^X)^{1-\alpha_X}} \left[\frac{\alpha_X}{1-\alpha_X} \frac{w^X/p^I}{(p^X/p^I)R^X} \right]^{1-\alpha_X}$$

$$k^N = a \frac{v^N}{z^N a^{1-\alpha_N}} \left[\frac{\alpha_N}{1-\alpha_N} \frac{w^N/p^I}{(p^N/p^I)R^N} \right]^{1-\alpha_N}$$

By (EC.39) and (EC.41):

$$y^X = v^X \left[\frac{\gamma_X}{1-\gamma_X} \frac{p^{ME}/p^I}{mc^{V,X}} \frac{1}{p^X/p^I} \right]^{-(1-\gamma_X)}$$

$$y^N = v^N \left[\frac{\gamma_N}{1-\gamma_N} \frac{p^{ME}/p^I}{mc^{V,N}} \frac{1}{p^N/p^I} \right]^{-(1-\gamma_N)}$$

By (EC.40) and (EC.42):

$$m^X = y^X \left[\frac{1-\gamma_X}{\gamma_X} \frac{mc^{V,X}}{p^{ME}/p^I} p^X/p^I \right]^{\gamma_X}$$

$$m^N = y^N \left[\frac{1-\gamma_N}{\gamma_N} \frac{mc^{V,N}}{p^{ME}/p^I} p^N/p^I \right]^{\gamma_N}$$

By (EC.47) and (EC.49):

$$\tilde{f}^{1,X} = \frac{\epsilon_X - 1}{\epsilon_X} \frac{y^X}{(1 - \beta a^{1-\sigma} \theta_X)}$$

$$\tilde{f}^{1,N} = \frac{\epsilon_N - 1}{\epsilon_N} \frac{y^N}{(1 - \beta a^{1-\sigma} \theta_N)}$$

By (EC.10)-(EC.11):

$$i^X = \frac{k^X}{u} \left(1 - \frac{1 - \delta}{a} \right)$$

$$i^N = \frac{k^N}{u} \left(1 - \frac{1 - \delta}{a} \right)$$

By (EC.65):

$$i = i^X + i^N$$

By (EC.27)-(EC.30):

$$\tilde{i}^N = \gamma_I \left(\frac{p^N}{p^I} \right)^{-\varrho_I} i$$

$$\tilde{i}^T = (1 - \gamma_I) \left(\frac{p^{T,I}}{p^I} \right)^{-\varrho_I} i$$

$$\tilde{i}^X = \gamma_{T,I} \left(\frac{p^X/p^I}{p^{T,I}/p^I} \right)^{-\varrho_{T,I}} \tilde{i}^T$$

$$\tilde{i}^M = (1 - \gamma_{T,I}) \left(\frac{p^M/p^I}{p^{T,I}/p^I} \right)^{-\varrho_{T,I}} \tilde{i}^T$$

When replacing equations (EC.68)-(EC.70) into equation (EC.80) (and using the identities of expenditures), one gets an alternative sum for nominal gdp :

$$p^Y gdp = p^X y^X + rer p^{Co,*} y^{Co} \frac{a^{Co}}{a} + p^N y^N + p^M y^M - p^M (m^X + m^N) - p_m m$$

which can also be written in terms of prices relative to investment:

$$\frac{p^Y}{p^I} gdp = \frac{p^X}{p^I} y^X + \frac{rer}{p^I} p^{Co,*} y^{Co} \frac{a^{Co}}{a} + \frac{p^N}{p^I} y^N + \frac{p^M}{p^I} y^M - \frac{p^M}{p^I} (m^X + m^N) - \frac{p_m}{p^I} m$$

And using s^{Co}, s^M :

$$\frac{p^Y}{p^I} gdp = \frac{\frac{p^X}{p^I} y^X + \frac{p^N}{p^I} y^N - \frac{p^M}{p^I} (m^X + m^N)}{1 - s^{Co} - s^M \frac{((p^M - p_m)/p^I)}{p_m/p^I}}$$

With this, we can get:

$$y^{Co} = \frac{s^{Co} (p^Y/p^I) gdp}{(rer/p^I) p^{Co,*} a^{Co}} \frac{a}{a^{Co}}$$

$$y^M = \frac{s^M (p^Y/p^I) gdp}{p_m/p^I}$$

$$g = \frac{s^g (p^Y/p^I) gdp}{p^N/p^I}$$

By (EC.51):

$$\tilde{f}^{1,M} = \frac{\epsilon_M - 1}{\epsilon_M} \frac{y^M}{(1 - \beta a^{1-\sigma} \theta_M)}$$

By (EC.32):

$$m = y^M$$

By (EC.68):

$$c^N = y^N - g - \tilde{i}^N$$

By (EC.70):

$$c^M = y^M - \tilde{i}^M - m^X - m^N$$

By (EC.21):

$$c^T = \frac{c^M}{1 - \gamma_T} \left(\frac{p^M/p^I}{p^T/p^I} \right)^{\varrho_T}$$

By (EC.20):

$$c^X = \gamma_T \left(\frac{p^X/p^I}{p^T/p^I} \right)^{-\varrho_T} c^T$$

By (EC.18)-(EC.19):

$$\gamma = \frac{(p^N/p^I)^{\varrho} c^N}{(p^T/p^I)^{\varrho} c^T + (p^N/p^I)^{\varrho} c^N}$$

By (EC.22)-(EC.23):

$$\frac{p^{SAE}}{p^I} = \left[(1 - \gamma) \left(\frac{p^T}{p^I} \right)^{1-\varrho} + \gamma \left(\frac{p^N}{p^I} \right)^{1-\varrho} \right]^{\frac{1}{1-\varrho}}$$

$$p^I = \left[\left(\frac{p^{SAE}}{p^I} \right)^{1-\gamma_{AC}-\gamma_{EC}} \left(\frac{p^T}{p^I} \right)^{\gamma_{AC}+\gamma_{EC}} \right]^{-1}$$

Now, we get all prices by multiplying the price relative to investment by p^I :
 $\{p^X, p^M, p^N, p^T, p^{T,I}, p^{SAE}, p^{ME}, rer, w^X, w^N, \tilde{\mu}^X, \tilde{\mu}^N, p_m, \tilde{\xi}^{h,N}\}$

By (EC.18):

$$c = \frac{1}{\gamma} (p^N)^{\varrho} c^N$$

(also check equation $c = c^T (p^T)^{\varrho} / (1 - \gamma)$)

By (EC.69):

$$c^{X,*} = y^X - \tilde{i}^X - c^X$$

By (EC.61):

$$y^* = \frac{c^{X,*}}{\xi^{X,*}} \left(\frac{p^X}{rer} \right)^{\epsilon^*}$$

By (EC.79):

$$gdp = c + g + i + c^{X,*} + y^{C_o} \frac{a^{C_o}}{a} - m$$

$$p^Y = \frac{p^Y gdp}{gdp}$$

By (EC.76):

$$tb = rer p^{C_o,*} y^{C_o} \frac{a^{C_o}}{a} + p^X c^{X,*} - p_m m$$

By (EC.78):

$$b^* = \frac{tb - (1 - \vartheta) rer p^{C_o,*} y^{C_o} \frac{a^{C_o}}{a}}{rer \left(1 - \frac{R^*}{\pi^* a} \right)}$$

By (EC.64) (part that was assumed zero):

$$\bar{b} = \frac{b^* rer}{p^Y gdp}$$

By (EC.1):

$$\tilde{\lambda} = \xi^\beta c^{-\sigma} \left(1 - \frac{\phi_C}{a}\right)^{-\sigma}$$

By (EC.14)-(EC.15):

$$\tilde{f}^{1, WX} = \frac{\mu^{WX} \tilde{\lambda} h^{X,d}}{1 - \theta_{WX} a^{1-\sigma} \beta}$$

$$\tilde{f}^{1, WN} = \frac{\mu^{WN} \tilde{\lambda} h^{N,d}}{1 - \theta_{WN} a^{1-\sigma} \beta}$$

Implications of Exhaustible Resources for Growth Accounting*

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PRELIMINARY

Abstract

Standard growth accounting (SGA) overlooks the role of exhaustible resources. This omission leads to overstating physical capital shares and to misleading total factor productivity (TFP). We quantify mining countries sources of economic growth over the high commodity prices period of 2002-2015. First, we conduct SGA over mining and non-mining sectors. We document the mining sector sources of economic growth are at odds with those of the non-mining sector. Second, we incorporate exhaustible resources (ore grade) into the analysis. Ore grade explains most of the difference between the mining and non-mining sectors. At the aggregate level, omitting ore grade overstates the contribution of capital and understates TFP growth. Finally, we study TFP gains arising from changes on the economy's sectoral composition. We document a negative composition gain between the mining and non-mining sectors and a positive composition gain within the non-mining sector.

JEL: O47, O5, Q32.

Keywords: Growth Accounting, Exhaustible Resources, Total Factor Productivity, Sectoral Reallocation.

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1. Introduction

Growth accounting exercises are a traditional workhorse of studies on economic growth. This methodology decomposes aggregate economic growth into contributions of factors of production: physical and human capital. Total factor productivity (TFP) is computed as the remaining component of growth not accounted for by the factors of production. This approach is appealing because of its simplicity to quantify the sources of economic growth. However, simplicity comes at the cost of overlooking some issues.¹ In this article, we focus on two of them. The first one relates to the omission of exhaustible natural resources. This is relevant for countries where natural resources are an important factor of production. Failing to incorporate this factor leads to incorrectly compute factors of production and TFP contributions to economic growth. In particular, omitting natural resources leads to overstating the contribution of physical capital. Moreover, the exhaustion of natural resources is attributed to TFP. A second methodological aspect arises when we incorporate economic sectors into the analysis. Changes on the economy's sectoral composition are expected to take place over time. Whenever the shares of physical and human capital differ across sectors, these changes cause TFP gains.² The sign of these gains, however, has to be empirically determined. Decomposing the economy's value added between exhaustible and non-exhaustible resource sectors, we expect the sign of the latter to be negative. Specifically, once natural resources are taken into account, the shares of physical and human capital are lower in the exhaustible than non-exhaustible resource sector. Hence, if sectoral physical and human capital are growing at the same rate, the lower participation of physical and human capital generates a negative TFP gain.

This paper offers an empirical analysis on these methodological issues. Our empirical application focuses on mining countries. We focus on the high metal and oil prices period

¹Barro (2000) provides a thorough discussion on the strengths and weaknesses of growth accounting.

²This result is implied by Bernard and Jones (1996) productivity growth decomposition.

of 2002-2015 (Figure 1 shaded area). Our contribution is twofold. First, we quantify mining countries sources of economic growth. Second, we compare the sources of productivity growth when the economy is decomposed into exhaustible and non-exhaustible resource sectors, in contrast to non-exhaustible resource sectors. We pay special attention to quantify differences in the composition effects between these sectors.

Our analysis takes a bottom-up approach. First, we present growth accounting exercises at the sectoral level. We consider an economy constituted of two sectors: Depletable (mining) and non-depletable (non-mining) resource sectors. We quantify the contributions of productivities and factor of productions to value added growth. The concentration of metal that can be extracted from rocks, ore grade, is considered as an additional factor of production. Differences in the sectoral sources of economic growth reveal the relevance of ore grade. Next, we consider the contributions of reproducible and non-reproducible factors, and TFP growth to the aggregate economy. Finally, we decompose TFP growth within the aggregate economy and the non-mining sector into *pure productivity* and *composition* terms to characterize the latter across different levels of aggregation.

To highlight our findings we begin performing growth accounting over mining, non-mining, and aggregate sectors omitting ore grade. On a large number of mining countries we show the mining sector sources of economic growth are largely at odds with those of the non-mining one. The latter is important enough to affect the aggregate economy. Mining Solow's residual growth is largely negative, while non-mining Solow's residual growth is positive. The contribution of physical capital is much higher in the mining than non-mining sector. Mining Solow's residual growth induces aggregate Solow's residual growth to be low. In addition, for aggregate economic growth physical capital has a more important role than for the non-mining sector.

Once ore grade is considered the mining sector sources of economic growth are in accordance to those of the non-mining sector. For a subset of countries that we gather data on ore grade,

we find mining value added growth is 2.51 per cent. Ore grade massively contributes to value added growth, -1.85 per cent. As for the non-mining sector, the bulk of the difference relating to mining value added growth comes from ore grade. In regard to the aggregate economy, omitting ore grade overstates the contribution of capital and understates TFP growth by 13 and 53 per cent, respectively. Hence, for economies where exhaustible resources play an important role, neglecting them delivers a misleading account on the sources of economic growth. Finally, we document a negative *composition* term between the mining and non-mining sectors, 0.32 per cent, and a positive one within the non-mining sector, 0.35 per cent.

Our paper is part of the literature studying productivity on natural resources sectors. A set of articles document the role of ore grade as a key source of growth on mining value added. Looking at the Canadian mining sector, Wedge (1973) is the first to document the role of ore grade on mining value added. Lasserre and Ouellette (1988) examine productivity improvements when correcting for resource degradation in extractive sectors in Canada. By including ore grade as an index of resource quality in the production function, they show the importance of accounting for resource degradation. More recently, Arias and Rodríguez (2008) compute a measure of productivity, corrected by depletion of ore grade, on the coal sector in Spain. Zheng and Bloch (2014) provide related evidence for the Australian mining sector. With a focus on productivity improvements driven by periods of high competition, Aydin and Tilton (2000) and Schmitz Jr. (2005) study the sources of productivity gains in non-renewable resource sectors. These authors highlight the role of technological innovations as sources of labor productivity gains in the US copper and iron industries. Our article focuses on a sample of mining countries on a period of high metal and oil prices. We compare the different sources of value added growth between mining and non-mining sectors. First, we show the pitfalls of SGA on mining countries. We document the mining sector sources of economic growth are largely at odds with those of the non-mining sector. Because of the former sector's size its results are important enough to affect the aggregate economy.

Second, we present evidence that once ore grade is incorporated into the analysis the role of productivity and reproducible production factors are similar between the mining and non-mining sectors. The latter underscores the relevance of accounting for the missing production factor in mining countries.

This article relates as well to the recent literature that includes natural resources as input of aggregate production functions. Caselli and Feyrer (2007) and Monge-Naranjo et al. (2015) document the extent of the relevance of natural resources for developed and emerging economies. Ignoring them leads to overestimate the marginal product of physical capital. The latter occurs because non-labor income is incorrectly imputed to physical capital. Brandt et al. (2017) propose a measurement framework that accounts for the role of natural capital in productivity measurement. Our article incorporates depletable resources into the SGA framework. Our findings suggest natural resources are important to accurately compute the sources of economic growth.

2. Methodology

In this section we discuss the methodological aspects of our growth accounting exercise. Following a bottom-up approach, we introduce value added functions for the mining, non-mining, and aggregate sectors. We incorporate ore grade as an additional input to mining value added. Sectoral value added growth is decomposed into inputs and sector specific productivity contributions. Finally, productivity growth is decomposed into the sum of *pure productivity* and *composition* terms.

2.1. Sectoral Value Added Production Functions

To begin with, we describe the mining sector value added function. In addition to physical and human capital, ore grade is considered as an additional input. On the empirical side,

Young (1991) and Aguirregaviria and Luengo (2016) provide evidence that mining production depends crucially on ore grade.³ On the theory front, exhaustible resources models incorporate ore grade as state variable. The models predict an optimal extraction path exploiting deposits in sequence from high to low ore grades. High grade deposits are associated to lower marginal costs.⁴ A Cobb-Douglas value added function is consistent with such prediction. A general concern in regard to sectoral value added functions is letting them to depend on a limited number of inputs. If such limited number of inputs are separable with respect to the omitted ones, Sato (1976) shows that value added functions can be expressed depending on this limited number of inputs.⁵ Thus, we consider a mining value added function of the form

$$Y_{min t} = STFP_{min t} K_{min t}^{1-\alpha_{l min}-\alpha_{o min}} L_{min t}^{\alpha_{l min}} O_{min t}^{\alpha_{o min}} \quad (1)$$

where $Y_{min t}$, $STFP_{min t}$, $K_{min t}$, $L_{min t}$, and $O_{min t}$ denote mining value added, productivity, physical capital, human capital (hours and quality adjusted employment) and ore grade. $\alpha_{l min}$ and $\alpha_{o min}$ are the mining labor and natural resources shares on mining value added, respectively.

Regarding the non-mining sector, we consider as well a Cobb-Douglas value added function, but excluding ore grade. That is,

$$Y_{no min t} = STFP_{no min t} K_{no min t}^{1-\alpha_{l no min}} L_{no min t}^{\alpha_{l no min}} \quad (2)$$

where $STFP_{no min t}$, $K_{no min t}$, $L_{no min t}$, and $\alpha_{l no min}$ are sector specific productivity, physical

³Aguirregaviria and Luengo study has a large coverage of the mining sector. In particular, their dataset covers roughly 85 per cent of worldwide copper production over 1992-2010.

⁴Krautkraemer (1998) surveys extensions where this prediction is not necessarily true. For instance, when the resource price is stochastic the optimal response to a price increase can be to decrease extraction at a higher ore deposit and increase extraction at lower grade deposit.

⁵Recently, Herrendorf et al. (2015) use a similar argument to model sectoral value added functions.

and human capital, and the non-mining labor share, respectively.

Finally, we define aggregate value added as

$$Y_t = TFP_t K_t^{1-\alpha_1-\alpha_o} L_t^{\alpha_1} O_t^{\alpha_o}. \quad (3)$$

Taking first differences to the logarithm of Equations 1, 2, and 3, we approximate sectoral value added growth by

$$\Delta y_{mint} = \Delta stfp_{mint} + (1 - \alpha_{lmin} - \alpha_{omin}) \Delta k_{mint} + \alpha_{lmin} \Delta l_{mint} + \alpha_{omin} \Delta o_{mint} \quad (4)$$

$$\Delta y_{nomin} = \Delta stfp_{nomin} + (1 - \alpha_{lnomin}) \Delta k_{nomin} + \alpha_{lnomin} \Delta l_{nomin}, \quad (5)$$

$$\Delta y_t = \Delta tfp_t + (1 - \alpha_1 - \alpha_o) \Delta k_t + \alpha_1 \Delta l_t + \alpha_o \Delta o_t, \quad (6)$$

where lowercases are logarithm of level variables and Δx_t means $x_t - x_{t-1}$.

2.2. TFP Decomposition

TFP growth can be approximated by the sum of *pure productivity* and *composition* terms.

In Appendix C.1, we show the following approximation

$$\begin{aligned}
\Delta t f p_t \approx & \underbrace{\frac{Y_{min t-1}}{Y_{t-1}} \Delta s t f p_{min t} + \frac{Y_{no min t-1}}{Y_{t-1}} \Delta s t f p_{no min t}}_{\text{pure productivity}} + \\
& + \underbrace{\frac{Y_{min t-1}}{Y_{t-1}} \left((1 - \alpha_{l min} - \alpha_{o min}) \Delta k_{min t} - (1 - \alpha_1 - \alpha_o) \Delta k_t + \alpha_{l min} \Delta l_{min t} - \alpha_1 \Delta l_t \right)}_{\dots} \\
& + \underbrace{\alpha_{o min} \Delta o_{min t} - \alpha_o \frac{Y_{t-1}}{Y_{min t-1}} \Delta o_t}_{\text{composition}} + \\
& + \underbrace{\frac{Y_{t-1} No Min}{Y_{t-1}} \left((1 - \alpha_{l no min}) \Delta k_{no min t} - (1 - \alpha_1 - \alpha_o) \Delta k_t + \alpha_{l no min} \Delta l_{no min t} - \alpha_1 \Delta l_t \right)}_{\dots}.
\end{aligned} \tag{7}$$

The *pure productivity* term accounts for productivity gains within the mining and non-mining sectors. The *composition* term arises due to heterogeneous contributions of factors of production across sectors.⁶ An interesting case emerges when the factors of production are growing at the same rate. In particular, the heterogeneous contributions of factors of production implies the *composition* term will differ from zero. The *composition* term captures TFP gains due to changes on the economy's sectoral composition. Providing structural reasons to explain the size and sign of this term are beyond the aim of this article. Finally, the sum of *pure productivity* and *composition* terms is an approximation to Bernard and Jones (1996) TFP growth decomposition.⁷

We compare the sources of productivity growth between the aggregate and non-mining sectors. To do so we decompose non-mining productivity growth according to Equation 7. In particular,

⁶The term $\alpha_{o min} \Delta o_{min t} - \alpha_o \frac{Y_{t-1}}{Y_{min t-1}} \Delta o_t$ is close to zero. In particular, $\Delta o_{min t} = \Delta o_t$ and (in Section 4.2.1) α_o is calibrated by $\alpha_{o min} \frac{Y_{min t}}{Y_t}$ rendering $\alpha_o \frac{Y_{t-1}}{Y_{min t-1}} \approx \alpha_{o min}$.

⁷The *pure productivity* and *composition* terms are approximations to Bernard and Jones' Productivity Growth and Share Effects.

$$\Delta stfp_{no\ min\ t} \approx \sum_j \frac{Y_{j\ t-1}}{Y_{no\ min\ t-1}} \Delta stfp_{j,t} + \sum_j \frac{Y_{j\ t-1}}{Y_{no\ min\ t-1}} \left((1 - \alpha_j) \Delta k_{j\ t} - (1 - \alpha_{no\ min}) \Delta k_{no\ min\ t} \right) + \sum_j \frac{Y_{j\ t-1}}{Y_{no\ min\ t-1}} (\alpha_j \Delta l_{j\ t} - \alpha_{no\ min} \Delta l_{no\ min\ t}) ,$$

where j are economic sectors adding up to the non-mining sector.⁸ Moreover, each economic sector value added was assumed to follow a Cobb-Douglas function, $Y_{j\ t} = STF P_{j\ t} K_{j\ t}^{1-\alpha_j} L_{j\ t}^{\alpha_j}$.⁹ This is an appealing exercise because, once natural resources are taken into account, the shares of physical and human capital are lower in the mining than non-mining sector (see Section 4.2.1). Hence, for economies where exhaustible natural resources are important, the size of the *composition* term is expected to be quite different between the aggregate and non-mining sector.

3. Data

The main data sources of this study are National Statistics Departments (NSD) and Central Banks (CB). We focus on countries which mining sector represents at least a 5 per cent on aggregate value added. The countries included in the sample are Australia, Canada, Chile, Colombia, Ecuador, Indonesia, Malaysia, Mexico, Norway, Peru, and South Africa. At the time of writing this article, there is no available dataset of neither cross-country sectoral compensation of employees nor sectoral net capital stock. The latter forces us to use country

⁸The following economic sectors are considered: Agriculture, Manufacture, Energy, water, and gas, Construction, Retail and wholesales, Transport and communications, Business services, and Community services.

⁹Though Cobb-Douglas sectoral production functions may raise concerns in regard to being too restrictive, for our empirical application it seems a good approach. For our sample of countries, Appendix B shows that sectoral labor shares are relatively stable. Moreover, Bernard and Jones (1996) assume also Cobb-Douglas sectoral value added functions to carry out an exercise like ours. Finally, in a three sector (Agriculture, Manufacture, and Services) model Herrendorf et al. (2015) show that Cobb-Douglas sectoral production functions capture low frequency trends of the US economy as well as a constant elasticity of substitution production function.

specific data sources to carry out sectoral growth accounting exercises. Data on sectoral real and nominal value added, employment, sectoral compensation of employees as well as net capital stock are from NSD or CB. For specific details on the data sources and definitions of each country we refer the reader to Appendix A. Employment is adjusted by average hours worked as well as returns to education. We use NSD or CB data on sectoral average hours worked whenever available; otherwise, sectoral average hours worked are proxied by average hours worked from Penn World Tables 9 (Feenstra et al., 2015) as well as returns to education. Finally, our time frame is 2001-2015.

Ore grade series are from country specific data sources. We collect ore grade data for a handful of countries Australia, Canada, Chile, and Peru. At the mine level, ore grade is measured as the concentration of metal in ore. At the country level, ore grade is quantified as weighted (by ore mined) average of mine's ore grade. For the Australian case, where mining production is more diversified, we use Bloch et al. (2008) composite ore grade index.¹⁰ For Chile, where most mining production is copper based, we use copper's ore grade. Canada and Peru have a more diversified mining sector than Chile, unfortunately we just have data on copper's ore grade. Hence, aggregate ore grade is proxied by the copper one.

4. Results

We apply the methodology elaborated in Section 2 to a sample of mining countries. Our analysis considers a period characterized by high commodity prices. Assuming high commodity prices go in hand with expectations of price stability, we should observe increased resource depletion.¹¹ In what follows, we first conduct growth accounting exercises omitting the role of depletable resources. Second, we focus on the calibration of parameters α_{omin} and α_o . We show that ore grade accounts for the significant difference between the mining

¹⁰The composite ore grade index is a Törnqvist index based on the individual sub-sector yield indexes, and their relevant shares in the (annual) value of mining industry production.

¹¹For a theoretical survey on the determinants of depletion see Sweeney (1993).

and non-mining sectors value added growth. Finally, we decompose aggregate productivity growth into *pure productivity* and *composition* contributions. A negative composition term between mining and non-mining sectors highlights important factor reallocation dynamics when exhaustible resources are considered.

4.1. Standard Growth Accounting

We begin our analysis by conducting SGA over mining, non-mining and aggregate sectors.¹² Table 1 reports the results of the SGA exercise. Appendix B describes the labor shares to calculate sectoral productivities. Despite differences in magnitude qualitative results hold across countries. Our results suggest the sources of economic growth for the mining sector are largely at odds with those of the non-mining sector. Because of the mining sector large size, this result has an important impact on aggregate economic growth. For the mining sector the Solow’s residual growth is largely negative, while for the non-mining sector is positive. We focus on the average results for our sample of countries. Mining and non-mining value added grow 0.95 and 3.69 per cent, respectively. Mining Solow’s residual dramatically falls over the period by 5.32 per cent, whereas the non-mining sector exhibits strong growth, 1 per cent. The mining sector lowers aggregate Solow’s residual growth. Physical capital offsets Solow’s residual dynamics in the mining sector. Moreover, it plays a more important role on economic growth in the aggregate economy than in the non-mining sector. Excluding the mining sector, physical capital accumulation explains 47 per cent of mining countries’ economic growth. Once the mining sector is added, physical capital roughly explains three fifths of overall economic growth.

With respect to human capital, it appears to be as important to aggregate economic growth as to the non-mining sector. Human capital hardly accounts for mining activity. The latter is captured by a low sectoral labor share. Hence, it comes as no surprise human capital adding

¹²SGA exercises is equivalent to constrain $\alpha_{o\ min}$ and α_o to zero.

to economic growth approximately the same as it does to the non-mining sector.

Labor productivity growth exhibit the same sectoral patterns as the Solow's residual. Table 4 shows the results for labor productivity.¹³ Across countries and within the mining sector, labor productivity falls as much as the Solow's residual. For Canada, Chile and South Africa, the Solow's residual falls significantly more than labor productivity. This result might be attributed to SGA overstating the contribution of physical capital to value added growth. The next Sections document that whenever exhaustible resources are not taken into account in growth accounting exercises, Solow's residual growth is understated and capital accumulation is overstated.

4.2. Growth Accounting

4.2.1. Production Functions Calibration

We incorporate depletion of natural resources into the analysis. First, we calibrate the parameters on the mining value added function, Equation 1. Following the literature, we calibrate α_{lmin} as the (time series average) wage bill participation on mining value added. Ore grade's exponent, α_{omin} , is a non-standard parameter. Aguirregaviria and Luengo (2016) carry out structural estimations over Equation 1's exponents. To calibrate α_{omin} , we use their estimations.¹⁴ In particular, we follow a three steps procedure. First, we take α_{omin} as the average across their estimations, obtaining $1 - \alpha_{lmin} - \alpha_{omin}$ as residual. Second, we proceed in the opposite manner, we obtain $1 - \alpha_{lmin} - \alpha_{omin}$ as the average across their estimations, obtaining α_{omin} as residual. Finally, α_{omin} and $1 - \alpha_{lmin} - \alpha_{omin}$ are the average values

¹³We compute labor productivity for Colombia, Ecuador, and Indonesia as well. These countries do not report sectoral investment data.

¹⁴Under different specifications their estimates for α_{omin} are 0.59, 0.61, 0.66, 0.7, 0.74 and 0.77 (these values are close to Young (1991) estimates on the effect of ore grade on mining productivity.). As for $1 - \alpha_{lmin} - \alpha_{omin}$ their estimates are 0.13, 0.22, 0.24, 0.24, 0.33, and 0.37.

from the previous steps.¹⁵ As for the non-mining sector and all sectors within the non-mining sector, we calibrate $\alpha_{l\,no\,min}$ and α_j as the wage bill participation on sectoral value added. Table 2 shows the shares of physical and human capital we obtain. Noteworthy, in comparison to the non-mining sector, the shares of physical and human capital are lower in the mining sector. This result is explained by the high contribution of ore grade to the mining sector.

The exponents associated to physical capital and ore grade on the Cobb-Douglas aggregate production function deserve some explanations. To calibrate the capital share on a production function that accounts for non-reproducible physical capital, our approach resembles to Monge-Naranjo et al. (2015). Assuming sectors operate in a competitive environment under optimal conditions, the exponents on the Cobb-Douglas aggregate production functions may be expressed as weighted (by nominal sectoral value added share) average of each factor contribution to sectoral value added. Since ore grade affects aggregate output through mining, we can compute the share of ore grade weighting $\alpha_{o\,min}$ by the average nominal share of mining on value added. Finally, calibrating the labor share following the standard procedure in the literature, i.e. the ratio between the aggregate wage bill and value added, the capital share is obtained as residual.¹⁶

4.2.2. Sources of Economic Growth in the Mining and Non-mining Sectors

Over the period, depletion of ore grade lowers significantly mining value added. We turn to decomposing mining value added into productivity, physical and human capital, and ore grade contributions. Table 5 reports the contribution of each component for each country.

¹⁵An alternative to our calibration is considering Aguirregaviria and Luengo preferred estimate. However, since we constrain $\alpha_{l\,min}$ to be equal to the wage bill participation on value added, it is no longer clear what is the best estimate for $\alpha_{o\,min}$. Yet, our results are similar if we consider their preferred estimates. These results are available upon request.

¹⁶Monje-Naranjo et al.(2015) obtain similar values of factor shares for the aggregate economy. Casselli and Feyrer (2007) also estimate factor's contribution. Yet, their methodology overstates the contribution of natural resources (see Monje-Naranjo et al.(2015)).

Over the past fourteen years rapid ore grade decline, -1.98 per cent (factors of production period average are reported in Table 3) explains most of the difference between mining and non-mining value added growth. To put this result into perspective, if ore grade had remained constant, mining value added would have grown an average of 4.02 per cent, well over non-mining value added growth, 3.85 per cent.

In spite of ore grade reduction, physical capital accumulation and productivity gains prevent the decline of mining production. Mining investment explains a high physical capital annual growth of 5.41 per cent. Even though non-mining physical capital grows less than the mining physical capital, it contributes more to non-mining than mining value added. This result is accounted for by the higher physical capital share in the non-mining sector. Finally, mining productivity outperforms non-mining productivity growth.

Figure 2 depicts the annual contribution of each component to value added growth. Consistent with predictions of exhaustible resources models, we observe that depletion of ore grade is strong during the expansion-to-peak on metal prices, the period 2002-2011, and less so from there on. Figure 4 depicts that non-mining physical capital is the most important factor contributing to economic growth over the period 2002-2011. The latter is consistent with spillovers from mining to non-mining sectors.¹⁷

Mining Solow's residual severely distorts productivity growth. Mining Solow's residual may be expressed as $stfp_{mint} - \alpha_{omin}(k_{mint} - o_{mint})$. Hence, it absorbs the misspecification of mining value added function. The Solow's residual distortions are impressive. In particular, the contributions of productivity and physical capital to value added growth are distorted by a factor of -3.10 and 5 , respectively. Figure 4 shows the evolution of mining Solow's residual and the magnitude of its distortions. The largest distortion to $stfp_{mint}$ comes from overstating the contribution of physical capital to economic growth. Yet, omitting ore grade is important by itself.

¹⁷For a causal link on spillovers from mining to non-mining sectors see Fornero et al. (2015).

4.2.3. The Aggregate Economy

Accounting for exhaustible resources is relevant to assess mining countries sources of economic growth. Caselli and Feyrer (2007) and Monge-Naranjo et al. (2015) stress that accounting for natural resources is relevant to calibrate the economy's physical capital share. Thus, the role of natural resources matters for computing cross-country marginal returns to physical capital. As for growth accounting, exhaustible resources have an impact on physical capital and TFP contributions to economic growth. In particular, omitting exhaustible resources leads to overstate the contribution of physical capital and understate TFP growth.

The importance of ore grade to account for value added growth depends on the mining sector's size. Table 5 shows that depletion of ore grade contracted aggregate activity by 0.18 per cent on average. Yet, there are important differences across countries. For instance, ore grade in Chile and Peru, which share of the mining sector into the aggregate economy is larger, lead to an average output loss of -0.38 and -0.24 per cent, respectively. On the other end, depletion of ore grade barely accounts for Canada's value added growth. Figure 5 shows for Australia, Chile, and Peru, accounting for ore grade is of most importance over the period 2002-2011. Higher metal extraction rates imply larger distortions stemming from ore grade depletion.

Once the contribution of ore grade is taken into account, the aggregate sources of economic growth resemble to those of the non-mining sector. Table 5 shows the contributions of physical and human capital to aggregate value added growth. Physical capital has been the key source of mining countries value added growth. The latter accounts for 58.36 per cent of total value added growth. Productivity growth becomes as important as human capital. The former contributes 0.88 per cent to economic growth. For Australia and Canada TFP growth is lower than any convex combination of mining and non-mining productivity growth.¹⁸ In the

¹⁸This productivity paradox is extensively discussed in Fox (2012).

next Section we examine this result further.

SGA wrongly characterizes the contribution of TFP growth to economic growth. Ore grade omission leads to overstate and understate the contributions of physical capital and TFP to economic growth by 46 and 52 per cent, respectively. We decompose the Solow’s residual following the same approach as in Section 4.2.2. Figure 6 shows the results of decomposing the Solow’s residual. Our results indicate that overstating the physical capital share and omitting ore grade are distortions quantitatively important.

4.3. Accounting For Changes in Sectoral Composition

For Australia and Canada we reconcile a lower TFP growth than any convex combination of mining and non-mining sectoral productivity growth through a negative *composition* term. We trace back the negative *composition* term to the low contribution of reproducible factors to mining value added.¹⁹ Equation 7 shows that there is composition effects when mining (non-mining) physical or human capital (weighted by their respective share) grow at different rates than the aggregate economy. Table 5 shows a large gap between the contribution of reproducible factors in the mining sector relative to their contribution in the aggregate economy. Hence, the low contribution of reproducible factors to mining value added drives the negative, 0.32 per cent, *composition* term.

At the aggregate level, increased mining productivity growth falls behind the negative *composition* term. Aggregate productivity growth is the sum of *pure productivity* and *composition* terms. Average (weighted by $\frac{Y_{min,t-1}}{Y_{t-1}}$) productivity gains within the mining sector are smaller than the absolute value of the composition effect. Hence, aggregate TFP growth is mostly driven by non-mining productivity growth. This motivates us to further assess the channels of productivity growth within the non-mining sector.

¹⁹Sectoral capital stock within the non-mining sector is available until the year 2014. For this reason, the results of this Section are reported for the 2002-2014 period.

For the non-mining sector, TFP growth is mostly driven by *pure productivity* gains, 0.52 per cent, and to a lesser degree by *composition* gains, 0.35 per cent. Although productivity growth in the non-mining sector and the economy are quantitatively similar, the sources of this growth are different. The *composition* term is the main driver of productivity for the non-mining sector. While, by definition the *pure productivity* component drives the aggregate economy.

To summarize, our empirical application evidences that changes on the economy's sectoral composition is an important factor accounting for mining countries economic growth. The *composition* term is negative between the mining and non-mining sectors, while it is positive within the non-mining sector. Within the latter, the *composition* term accounts for a large share of non-mining productivity growth.

5. Conclusions

This paper contributed to the economic growth literature by examining the role of exhaustible natural resources for growth accounting. We presented a unified framework that incorporated exhaustible natural resources, and the role of changes on the economy's sectoral composition as sources of economic growth. We motivated our work performing SGA over mining, non-mining, and aggregate sectors on a sample of mining countries. With focus on the high metal and oil prices 2002-2015 period, we documented the mining sector sources of economic growth are at odds with those of the non-mining sector. Due to the mining sector large size, this result had an important effect on the sources of aggregate economic growth.

For countries that we collected data on ore grade, we showed its exhaustion can rationalize the mining sector value added growth rate. As for the non-mining sector, the bulk of the difference relating to mining value added growth was explained by ore grade. Ore grade depletion involved an average decline on aggregate value added of -0.18 per cent. The omis-

sion of ore grade led to overstate (understate) the contribution of physical capital (TFP) to economic growth by 13 (53) per cent. Additionally, we decomposed TFP and non-mining productivity growth into *pure productivity* and *composition* gains. The low contribution of reproducible factors to mining relative to the aggregate economy explained a lower *composition* term for the aggregate than the non-mining sector.

We close this article discussing some policy implications. Our article provides evidence that under high commodity prices depletion of natural resources plays a non-negligible role on mining countries. This result has implications for the design of policies aimed to manage commodity windfall revenues. In particular, our results give support to incorporate resource depletion on mining countries' fiscal rules.²⁰ In regard to the contribution of productivity and reproducible factors to aggregate economic growth, we conclude that they are well captured by their contribution to the non-mining sector. That is, the non-mining sector eases the challenges to perform growth accounting on mining countries.

²⁰For instance, Norway already considers oil reserves on its fiscal rule but Peru just considers commodity prices.

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Table 1: Growth Accounting.

| Sectors | Δy (1) | $\Delta stfp$ (2) | Δk (3) | Δl (4) |
|--|-------------------|----------------------|-------------------|-------------------|
| Australia | | | | |
| Mining | 4.47 | -4.61 | 7.41 | 1.66 |
| Non-mining | 2.94 | 0.93 | 1.20 | 0.80 |
| Economy | 3.04 | 0.46 | 1.84 | 0.73 |
| Canada | | | | |
| Mining | 0.85 | -5.04 | 5.53 | 0.36 |
| Non-mining | 2.09 | 0.08 | 1.18 | 0.83 |
| Economy | 1.99 | -0.18 | 1.34 | 0.83 |
| Chile | | | | |
| Mining | 0.50 | -8.67 | 8.84 | 0.33 |
| Non-mining | 4.68 | 1.69 | 1.94 | 1.05 |
| Economy | 4.09 | 0.54 | 2.61 | 0.94 |
| Malaysia | | | | |
| Mining | 0.34 | -8.7 | 8.54 | 0.5 |
| Non-mining | 5.53 | 2.21 | 1.99 | 1.33 |
| Economy | 4.97 | 1.18 | 2.59 | 1.2 |
| Mexico | | | | |
| Mining | -0.55 | -3.04 | 2.27 | 0.21 |
| Non-mining | 2.71 | 0.37 | 1.75 | 0.59 |
| Economy | 2.43 | 0.07 | 1.79 | 0.56 |
| Norway | | | | |
| Mining | -1.73 | -5.61 | 3.37 | 0.51 |
| Non-mining | 2.29 | 0.49 | 0.83 | 0.97 |
| Economy | 1.37 | -0.64 | 1.17 | 0.84 |
| Peru | | | | |
| Mining | 4.23 | -3.20 | 5.47 | 1.96 |
| Non-mining | 5.69 | 1.25 | 3.59 | 0.85 |
| Economy | 5.50 | 0.84 | 3.86 | 0.80 |
| South Africa | | | | |
| Mining | -0.51 | -3.64 | 2.07 | 1.06 |
| Non-mining | 3.58 | 1.01 | 1.31 | 1.26 |
| Economy | 3.15 | 0.54 | 1.37 | 1.24 |
| Average | | | | |
| Mining | 0.95 | -5.32 | 5.42 | 0.85 |
| Non-mining | 3.69 | 1.00 | 1.73 | 0.96 |
| Economy | 3.32 | 0.35 | 2.07 | 0.89 |
| Average: Australia, Canada, Chile, and Peru | | | | |
| Mining | 2.51 | -5.38 | 6.82 | 1.07 |
| Non-mining | 3.85 | 0.99 | 1.98 | 0.89 |
| Economy | 3.66 | 0.42 | 2.42 | 0.83 |

Notes: Decomposition of sectoral value added average 2002-2015 growth (Δy) into productivity ($\Delta stfp$), capital (Δk), and labor (Δl) contributions.

First row, Mining value added. The contributions of each factor are calculated from $y_{min t} = stfp_{min t} + (1 - \alpha_{l min}) k_{min t} + \alpha_{l min} l_{min t}$. Second row, Non-Mining value added. The contributions of each factor are calculated from $y_{no min t} = stfp_{no min t} + (1 - \alpha_{l no min}) k_{no min t} + \alpha_{l no min} l_{no min t}$. Third row, Economy value added. The contributions of each factor are calculated from $y_t = tfp_t + (1 - \alpha_l - \alpha_o) k_t + \alpha_l l_t + \alpha_o o_t$.

Columns (2), (3), (4), and (5) are time series averages of productivity, capital, and labor contributions respectively. Δx_t is $x_t - x_{t-1}$. Columns (2), (3), and (4) add up to column (1). 22

Table 2: Sectoral Production Function Shares: Non-Mining Sectors.

| Sectors | Physical Capital | Human Capital | Ore Grade |
|------------------|------------------|---------------|-----------|
| Australia | | | |
| Mining | 0.12 | 0.23 | 0.65 |
| Non-mining | 0.40 | 0.60 | – |
| Economy | 0.45 | 0.51 | 0.04 |
| Canada | | | |
| Mining | 0.14 | 0.21 | 0.65 |
| Non-mining | 0.43 | 0.57 | – |
| Economy | 0.43 | 0.56 | 0.01 |
| Chile | | | |
| Mining | 0.22 | 0.13 | 0.65 |
| Non-mining | 0.47 | 0.53 | – |
| Economy | 0.44 | 0.47 | 0.09 |
| Peru | | | |
| Mining | 0.16 | 0.19 | 0.65 |
| Non-mining | 0.63 | 0.37 | – |
| Economy | 0.57 | 0.34 | 0.09 |

Notes: Shares of physical and human capital, and ore grade on economic sectors and aggregate economy (first, second, and last column, respectively). Panel A corresponds to sectoral shares. Panel B corresponds to shares of non-mining sector and aggregate economy. The sum of physical and human capital, and ore grade share is one. The participation of human capital is computed as ratios between sectoral labor remunerations to value added. The participation of ore grade for the mining sector is computed in three steps. First, we obtain the average across ore grade parameters presented by Aguirregaviria and Luengo (2016) (0.59, 0.61, 0.66, 0.7, 0.74 and 0.77). Second, we compute the participation of capital as the average across Aguirregaviria and Luengo estimations (0.13, 0.22, 0.24, 0.24, 0.33, and 0.37), and obtain ore grade as a residual. The participation of ore grade of the mining sector is the average between these two steps. The participation of ore grade of the aggregate economy is computed as the product of the ore grade participation of the mining sector and the share of mining into aggregate value added. Physical capital share is computed as residual.

Table 3: Average Growth of Components of Value Added (2002-2015)

| Sectors | Physical Capital | Human Capital | Ore Grade |
|------------------|------------------|---------------|-----------|
| Australia | | | |
| Mining | 9.68 | 7.07 | -2.26 |
| Non-mining | 3.01 | 1.33 | - |
| Economy | 3.75 | 1.43 | -2.26 |
| Canada | | | |
| Mining | 6.99 | 1.71 | -1.22 |
| Non-mining | 2.71 | 1.47 | - |
| Economy | 3.07 | 1.47 | -1.22 |
| Chile | | | |
| Mining | 10.16 | 2.52 | -4.19 |
| Non-mining | 4.13 | 1.98 | - |
| Economy | 4.93 | 2.00 | -4.19 |
| Peru | | | |
| Mining | 6.75 | 10.33 | -2.67 |
| Non-mining | 5.71 | 2.29 | - |
| Economy | 5.85 | 2.37 | -2.67 |
| Average | | | |
| Mining | 8.40 | 5.41 | -1.98 |
| Non-mining | 3.89 | 1.77 | - |
| Economy | 4.40 | 1.82 | -1.98 |

Notes: Average growth rate, period 2002-2015, of sectoral (Mining, Non-Mining, and Aggregate Economy, first, second, and last row, respectively) physical and human capital, and ore grade.

Table 4: Labor Productivity Growth.

| Country | Mining (1) | Non-Mining (2) | Economy (3) |
|---------------------|---------------|-------------------|----------------|
| Australia | -3.04 | 1.12 | 1.14 |
| Canada | -0.65 | 0.80 | 0.70 |
| Chile | -1.97 | 2.34 | 1.75 |
| Colombia | 2.45 | 1.98 | 1.98 |
| Ecuador | -3.03 | 2.45 | 2.10 |
| Indonesia | -2.51 | 3.94 | 3.50 |
| Malaysia | -8.54 | 2.53 | 1.95 |
| Mexico | -3.12 | 1.29 | 0.99 |
| Norway | -6.44 | 1.15 | 0.17 |
| Peru | -5.64 | 3.65 | 3.40 |
| South Africa | -1.57 | 2.54 | 2.11 |
| Average | -3.09 | 2.16 | 1.80 |

Notes: Average sectoral labor productivity growth 2002-2015. Labor productivity is calculated from $\frac{Y_{s,t}}{N_{s,t}}$ where $Y_{s,t}$ and $N_{s,t}$ denote value added and number of workers and s is Mining, Non-Mining, and Economy sectors (columns 1, 2, and 3, respectively). Ecuador, Indonesia, Malaysia, South Africa's average spans 2007-2015, 2002-2014, 2002-2014, and 2004-2014, respectively.

Table 5: Augmented Growth Accounting.

| Sectors | Δy (1) | $\Delta stfp$ (2) | Δk (3) | Δl (4) | Δo (5) |
|------------------|-------------------|----------------------|-------------------|-------------------|-------------------|
| Australia | | | | | |
| Mining | 4.47 | 3.16 | 1.12 | 1.66 | -1.47 |
| Economy | 3.04 | 0.71 | 1.70 | 0.73 | -0.09 |
| Canada | | | | | |
| Mining | 0.85 | 0.30 | 0.99 | 0.36 | -0.80 |
| Economy | 2.00 | -0.12 | 1.30 | 0.83 | -0.01 |
| Chile | | | | | |
| Mining | 0.50 | 0.66 | 2.24 | 0.33 | -2.72 |
| Economy | 4.09 | 1.36 | 2.17 | 0.94 | -0.38 |
| Peru | | | | | |
| Mining | 4.23 | 2.92 | 1.08 | 1.96 | -1.73 |
| Economy | 5.50 | 1.60 | 3.34 | 0.80 | -0.24 |
| Average | | | | | |
| Mining | 2.52 | 1.76 | 1.36 | 1.08 | -1.68 |
| Economy | 3.65 | 0.88 | 2.13 | 0.82 | -0.18 |

Notes: Decomposition of sectoral value added average 2002-2015 growth (Δy) into productivity ($\Delta stfp$), capital (Δk), labor (Δl), and ore grade (Δo) contributions.

First row, Mining value added. The contributions of each factor are calculated from $y_{min t} = stfp_{min t} + (1 - \alpha_{l min} - \alpha_{o min})k_{min t} + \alpha_{l min}l_{min t} + \alpha_{o min}o_{min t}$. Columns (2), (3), (4), and (5) are time series averages of $\Delta stfp_{min t}$, $(1 - \alpha_{l min} - \alpha_{o min})\Delta k_{min t}$, $\alpha_{l min}\Delta l_{min t}$, and $\alpha_{o min}\Delta o_{min t}$ respectively.

Second row, Non-Mining value added. The contributions of each factor are calculated from $y_{no min t} = stfp_{no min t} + (1 - \alpha_{l no min})k_{no min t} + \alpha_{l no min}l_{no min t}$. Columns (2), (3), and (4), are time series averages of $\Delta stfp_{min t}$, $(1 - \alpha_{l min})\Delta k_{min t}$, and $\alpha_{l min}\Delta l_{min t}$, respectively.

Third row, Economy value added. The contributions of each factor are calculated from $y_t = tfp_t + (1 - \alpha_l - \alpha_o)k_t + \alpha_l l_t + \alpha_o o_t$. Columns (2), (3), (4), and (5) are time series averages of Δtfp_t , $(1 - \alpha_l - \alpha_o)\Delta k_t$, $\alpha_l \Delta l_t$, and $\alpha_o \Delta o_t$ respectively.

Δx_t is $x_t - x_{t-1}$. Columns (2), (3), (4), and (5) add up to column (1).

Table 6: TFP Growth Decomposition.

| Sectors | Productivity Growth (1) | Pure Productivity (2) | Composition (3) |
|------------------|----------------------------|--------------------------|--------------------|
| Australia | | | |
| Non-mining | 0.78 | 0.49 | 0.29 |
| Economy | 0.54 | 0.96 | -0.42 |
| Canada | | | |
| Non-mining | 0.10 | 0.08 | 0.02 |
| Economy | -0.06 | 0.13 | -0.18 |
| Chile | | | |
| Non-mining | 1.72 | 0.98 | 0.74 |
| Economy | 1.19 | 1.53 | -0.34 |
| Average | | | |
| Non-mining | 0.87 | 0.52 | 0.35 |
| Economy | 0.45 | 0.77 | -0.32 |

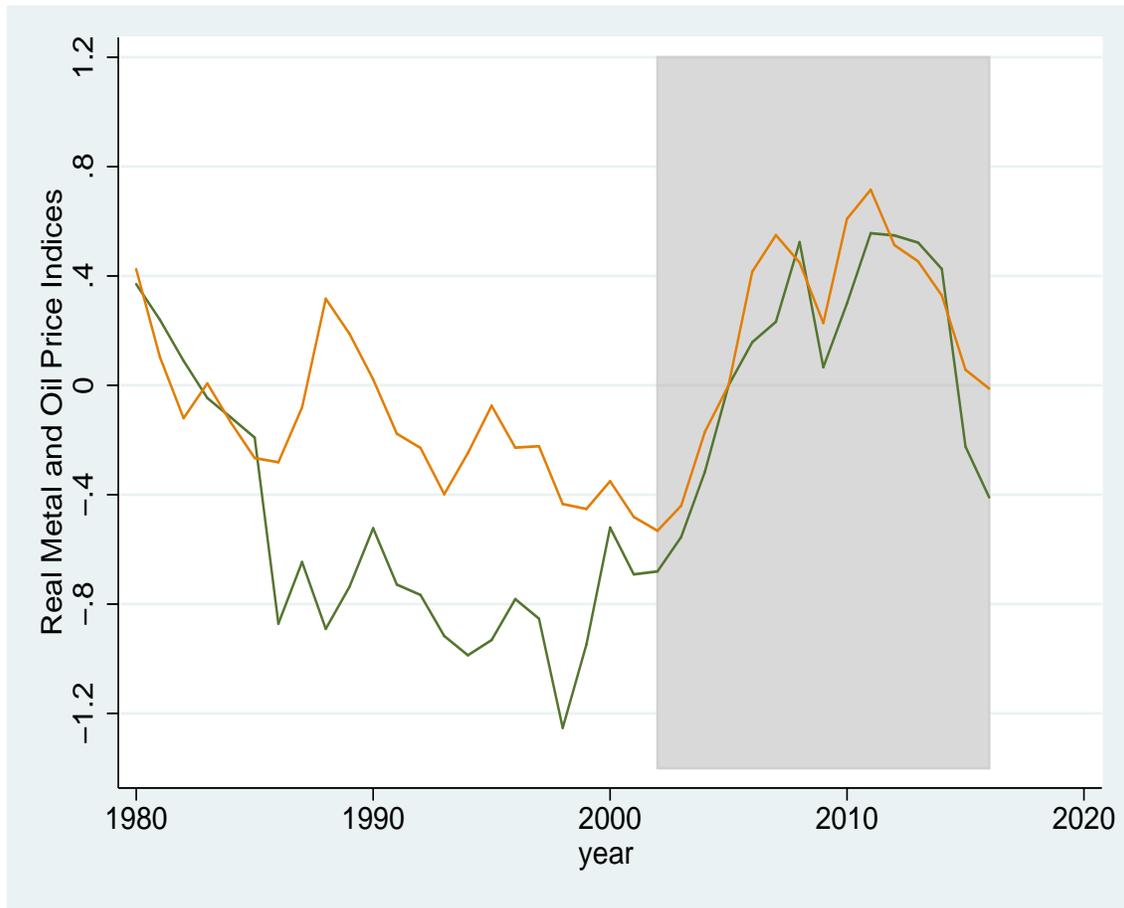
Notes: Decomposition of average sectoral productivity growth 2002-2014 into *pure productivity* and *composition* contributions.

First row, Non-Mining productivity. Columns *pure productivity* and *composition* are time series averages of $\sum_j \frac{Y_{j,t-1}}{Y_{no\ min\ t-1}} \Delta stfp_{j,t}$ and $\sum_j \frac{Y_{j,t-1}}{Y_{no\ min\ t-1}} \left((1 - \alpha_j) \Delta k_{j,t} - (1 - \alpha_{lno\ min}) \Delta k_{no\ min\ t} \right) + \sum_j \frac{Y_{j,t-1}}{Y_{no\ min\ t-1}} (\alpha_j \Delta l_{j,t} - \alpha_{lno\ min} \Delta l_{no\ min\ t})$, respectively.

Second row, Economy productivity. Columns *pure productivity* and *composition* are time series averages of $\frac{Y_{min\ t-1}}{Y_{t-1}} \Delta stfp_{min\ t} + \frac{Y_{no\ min\ t-1}}{Y_{t-1}} \Delta stfp_{no\ min\ t}$ and $\frac{Y_{min\ t-1}}{Y_{t-1}} \left((1 - \alpha_{l\ min} - \alpha_{o\ min}) \Delta k_{min\ t} - (1 - \alpha_1 - \alpha_o) \Delta k_t + \alpha_{l\ min} \Delta l_{min\ t} - \alpha_1 \Delta l_t + \alpha_{o\ min} \Delta o_{min\ t} - \alpha_o \frac{Y_{t-1}}{Y_{min\ t-1}} \Delta o_t \right) + \frac{Y_{no\ min\ t-1}}{Y_{t-1}} \left((1 - \alpha_{lno\ min}) \Delta k_{no\ min\ t} - (1 - \alpha_1 - \alpha_o) \Delta k_t + \alpha_{lno\ min} \Delta l_{no\ min\ t} - \alpha_1 \Delta l_t \right)$, respectively.

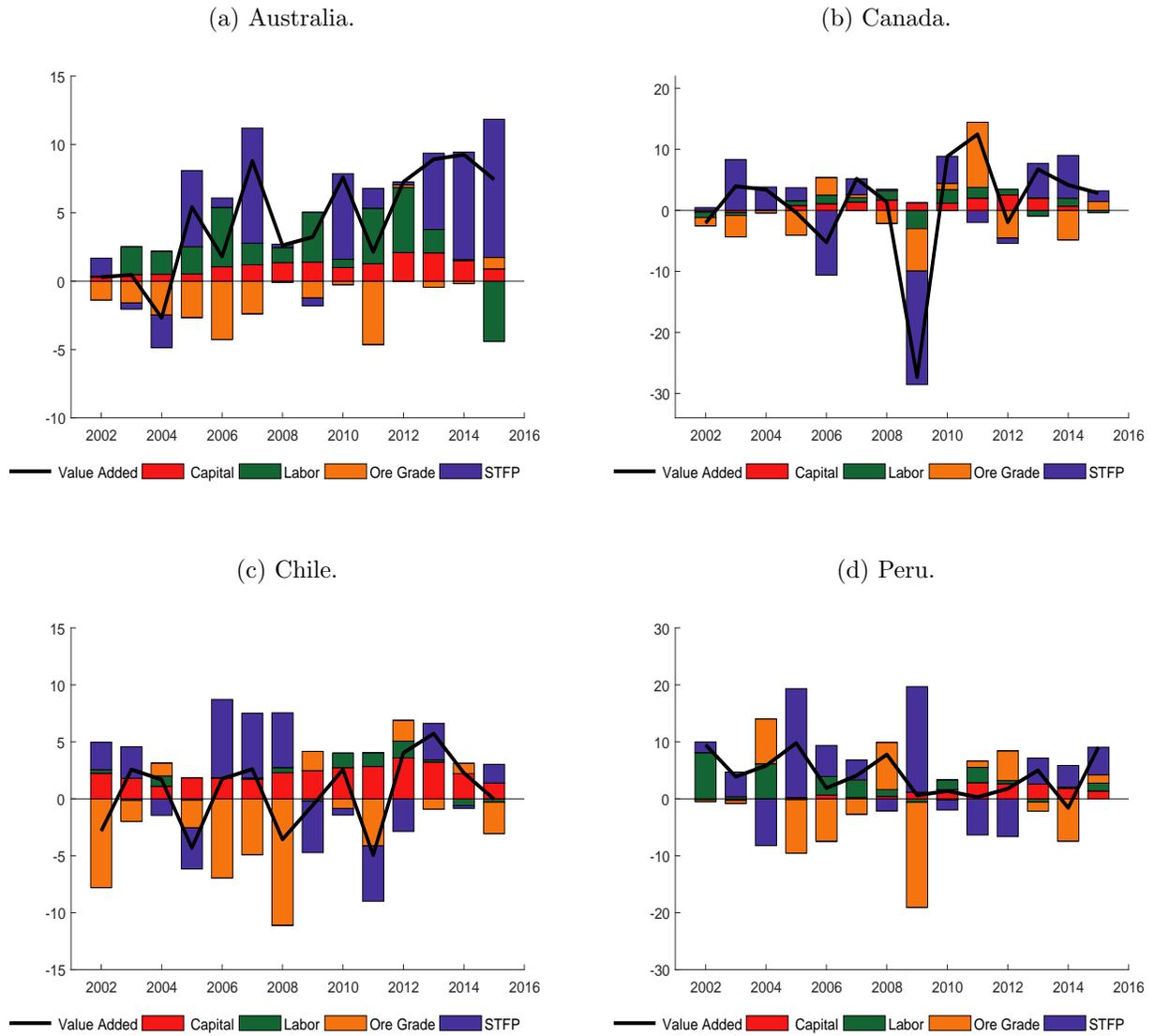
Δx_t is $x_t - x_{t-1}$. Columns (2) and (3) add up to column (1).

Figure 1: Real Metal and Oil Price Indices (1980-2016)



Notes: Real metal (solid yellow line) and oil (solid green line) price indices are logarithms of nominal metal and oil price indices deflated by the United States GDP deflator. The shaded area highlights the period 2002-2015.
Source: Authors' own calculation based on International Monetary Fund Primary Commodity Prices and United States Bureau of Economic Analysis.

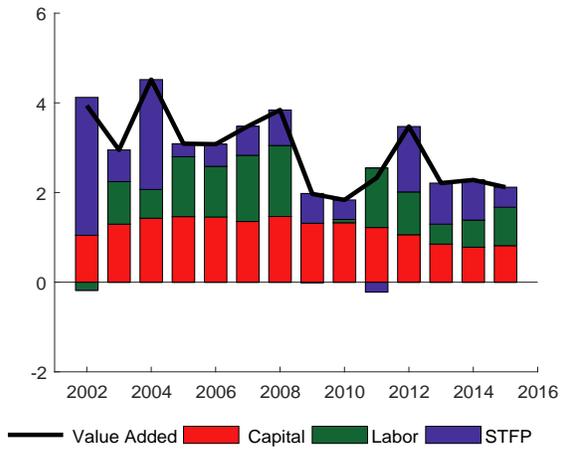
Figure 2: Growth Accounting: Mining Sector.



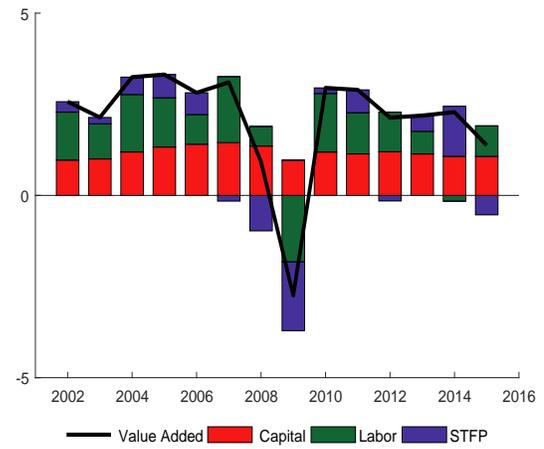
Notes: Decomposition of mining value added growth into productivity, physical and human capital, and ore grade contributions. Each factor contribution is calculated from $y_{mint} = stfp_{mint} + (1 - \alpha_{lmin} - \alpha_{omin})k_{mint} + \alpha_{lmin}l_{mint} + \alpha_{omin}o_{mint}$, where each term corresponds to the contribution of each factor (y , $stfp$, k , l , and o are logarithm of value added, productivity, physical and human capital, and ore grade, respectively). The red, green, orange, and blue bars are physical and human capital, ore grade, and productivity contributions. The bars add up to value added (solid black line).

Figure 3: Growth Accounting: Non-Mining Sector.

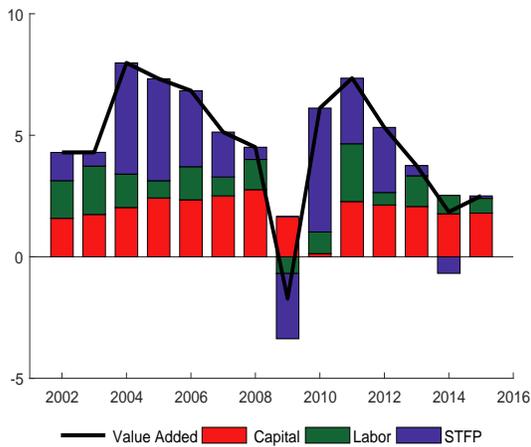
(a) Australia.



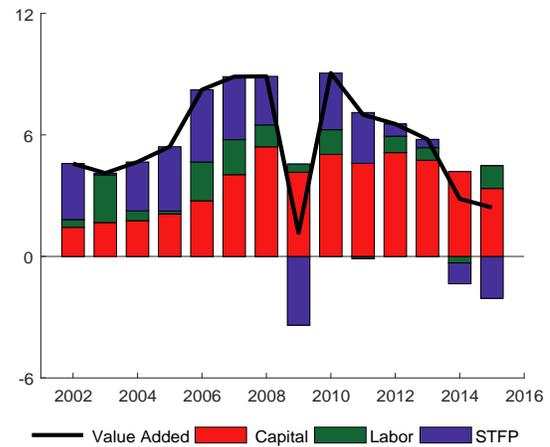
(b) Canada.



(c) Chile.



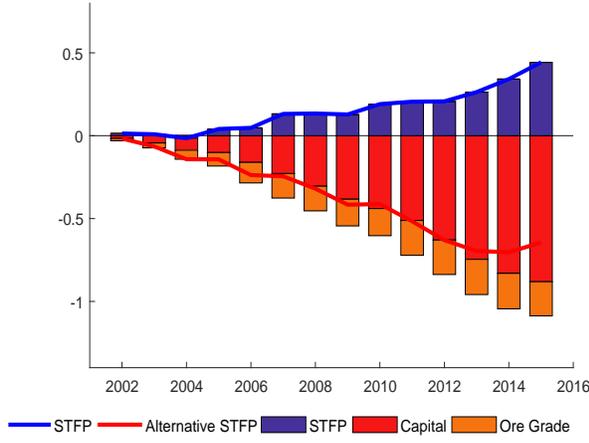
(d) Peru.



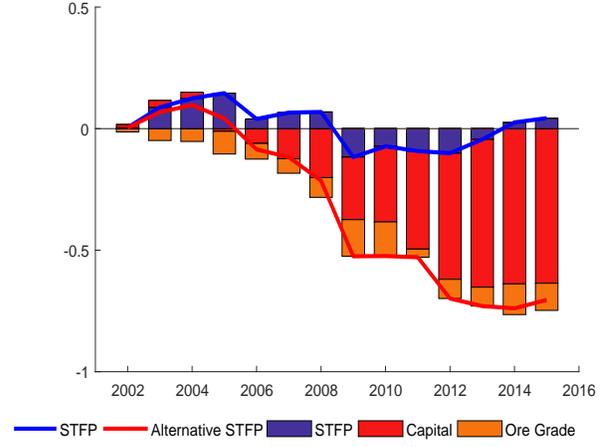
Notes: Decomposition of non-mining value added growth into productivity, physical and human capital contributions. Each factor contribution is calculated from $y_{no\ min\ t} = stfp_{no\ min\ t} + (1 - \alpha_{l\ no\ min})k_{no\ min\ t} + \alpha_{l\ no\ min}l_{no\ min\ t}$, where each term corresponds to the contribution of each factor (y , $stfp$, k , and l are logarithm of value added, productivity, physical and human capital, respectively). The red, green, and blue bars are physical and human capital, and productivity contributions. The bars add up to value added (solid black line).

Figure 4: Mining Productivity and Omitting of Ore Grade.

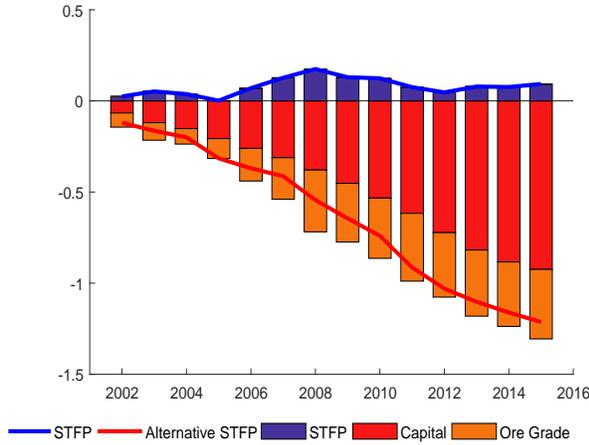
(a) Australia.



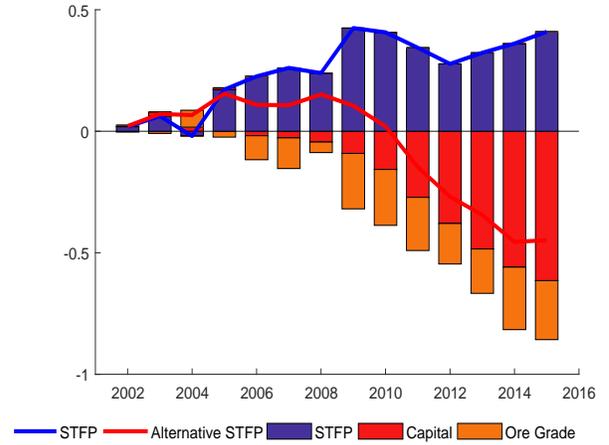
(b) Canada.



(c) Chile.



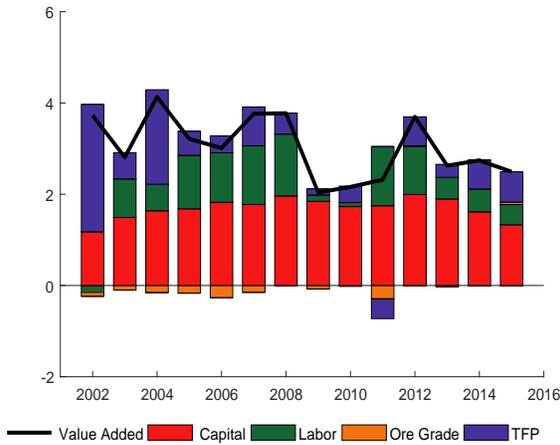
(d) Peru.



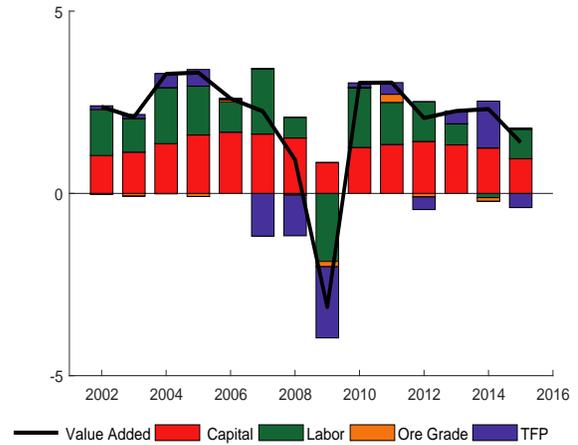
Notes: Ommiting ore grade and mining productivity. The blue line is logarithm of mining productivity. Mining productivity is calculated from $STFP_{min t} = \frac{Y_{min t}}{K_{min t}^{1-\alpha_{l min}} L_{min t}^{\alpha_{l min}} O_{min t}^{\alpha_{o min}}}$, where $Y_{min t}$, $STFP_{min t}$, $K_{min t}$, $L_{min t}$, and $O_{min t}$ denote mining value added, productivity, physical and human capital and ore grade, respectively. The red line is the logarithm of mining Solow's residual. The Solow's residual is calculated from $ASTFP_{min t} = \frac{Y_{min t}}{K_{min t}^{1-\alpha_{l min}} L_{min t}^{\alpha_{l min}}}$. The logarithm of $ASTFP_{min t}$ is $stfp_{min t} - \alpha_{o min} (k_{min t} - o_{min t})$, where lowercases are logarithms of level variables. The blue, red, and orange bars are $stfp_{min t}$, $-\alpha_{o min} k_{min t}$, and $\alpha_{o min} o_{min t}$, respectively, initial values are normalized to zero.

Figure 5: Growth Accounting: Aggregate Economy.

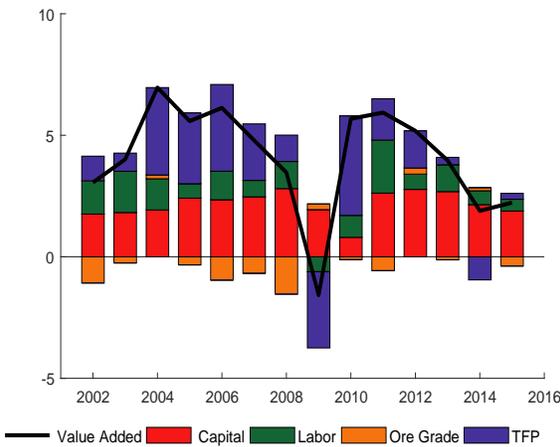
(a) Australia.



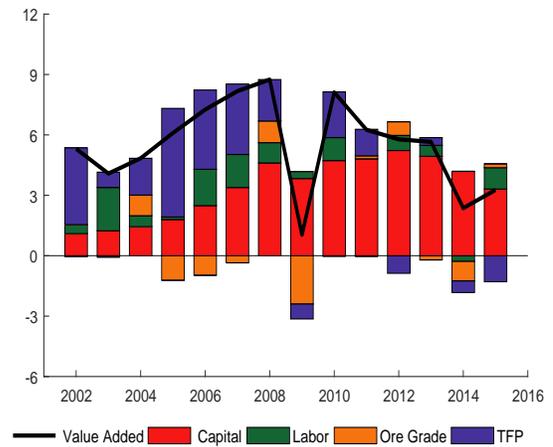
(b) Canada.



(c) Chile.



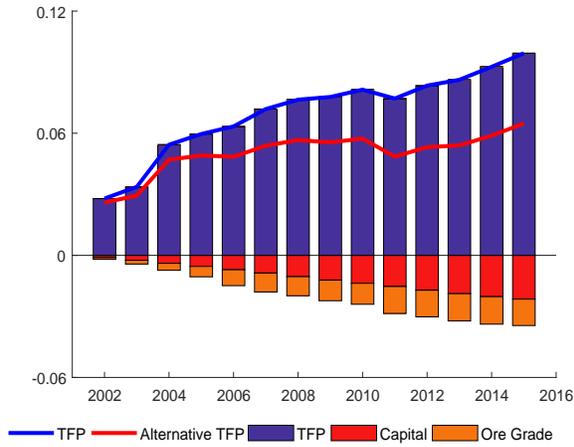
(d) Peru.



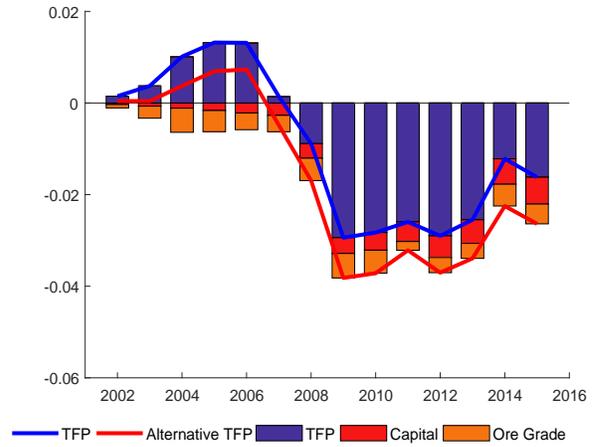
Notes: Decomposition of aggregate value added growth into productivity, physical and human capital, and ore grade contributions. Each factor contribution is calculated from $y_t = t f p_t + (1 - \alpha_l - \alpha_o) k_t + \alpha_l l_t + \alpha_o o_t$, where each term corresponds to the contribution of each factor (y , $stfp$, k , l , and o are logarithm of value added, productivity, physical and human capital, and ore grade, respectively). The red, green, orange, and blue bars are physical and human capital, ore grade, and productivity contributions. The bars add up to value added (solid black line).

Figure 6: TFP and Omitting Ore Grade (2002-2015)

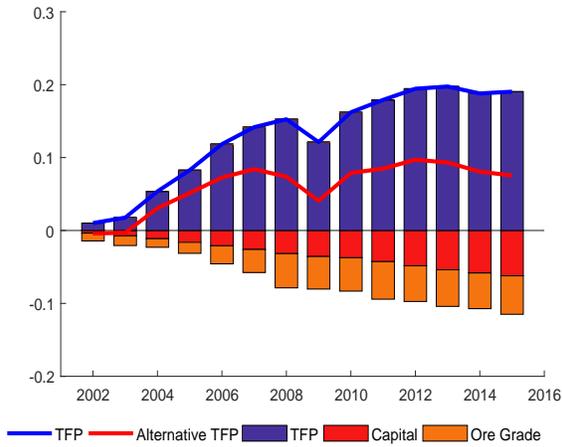
(a) Australia.



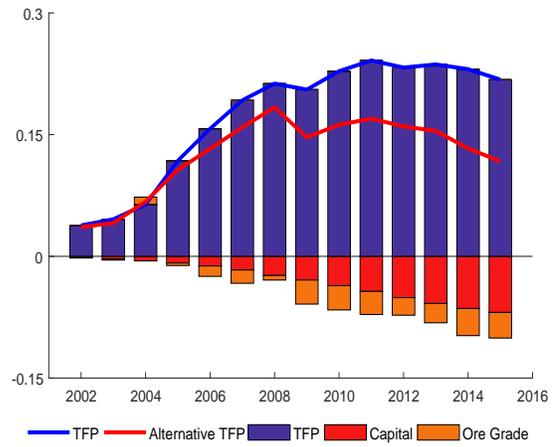
(b) Canada.



(c) Chile.



(d) Peru.



Notes: Ommiting ore grade and TFP. The blue line is logarithm of aggregate productivity. TFP is calculated from $TFP_t = \frac{Y_t}{K_t^{1-\alpha_1-\alpha_o} L_t^{\alpha_1} O_t^{\alpha_0}}$, where $Y_t, TFP_t, K_t, L_t,$ and O_t denote aggregate value added, TFP, physical and human capital and ore grade, respectively. The red line is the logarithm of Solow's residual. Solow's residual is calculated from $ATFP_t = \frac{Y_t}{K_t^{1-\alpha_1} L_t^{\alpha_1}}$. The logarithm of $ATFP_t$ is $tfp_t - \alpha_o(k_t - o_t)$, where lowercases are logarithms of level variables. The blue, red, and orange bars are $tfp_t, -\alpha_o k_t,$ and $\alpha_o o_t,$ respectively, initial values are normalized to zero.

Appendix A. Data Sources

Tables A1 describe the data sources for Australia, Canada, Chile, Colombia, Ecuador, Indonesia, Malaysia, Mexico, Norway, Peru, and South Africa.

For the Peruvian economy we constructed capital stock series for the aggregate economy and the mining sector using data on gross capital formation. To construct aggregate and mining capital stock series we follow Cspedes et al. (2016) and use the perpetual inventory method, assuming an annual depreciation rate of 5 per cent and value added growth of 3.9 per cent.

Appendix B. Sectoral Labor Shares Over Time and Countries

Table B1 reports mining, non-mining, and the economy's labor shares and its standard deviations for Australia, Canada, Chile, Malaysia, Mexico, Norway, Peru, and South Africa. Table B2 reports sectoral labor shares and its standard deviations for Australia, Canada, and Chile. The low standard deviations of the labor shares is consistent with our modelling choice of Cobb-Douglas sectoral value added functions.

Appendix C. TFP Decomposition

We turn to showing that TFP growth can be approximated by the sum of *pure productivity* and *composition* terms. Defining the economy value added, Y_t , as the sum of mining and non-mining value added, aggregate value added growth is

$$\frac{\Delta Y_t}{Y_{t-1}} = \frac{Y_{min\ t-1}}{Y_{t-1}} \frac{\Delta Y_{min\ t}}{Y_{min\ t-1}} + \frac{Y_{no\ min\ t-1}}{Y_{t-1}} \frac{\Delta Y_{no\ min\ t}}{Y_{no\ min\ t-1}}. \quad (C.1)$$

We approximate $\frac{\Delta Y_{mint}}{Y_{mint-1}}$ and $\frac{\Delta Y_{no mint}}{Y_{no mint-1}}$ using Equations 4 and 5. We substitute them back into Equation C.1. Then, we obtain

$$\begin{aligned} \frac{\Delta Y_t}{Y_{t-1}} &\approx \frac{Y_{mint-1}}{Y_{t-1}} (\Delta stf p_{mint} + (1 - \alpha_{lmin} - \alpha_{omin}) \Delta k_{mint} + \alpha_{lmin} \Delta l_{mint} + \alpha_{omin} \Delta o_{mint}) + \\ &+ \frac{Y_{no mint-1}}{Y_{t-1}} (\Delta stf p_{no mint} + (1 - \alpha_{lno min}) \Delta k_{no mint} + \alpha_{lno min} \Delta l_{no mint}) . \end{aligned} \quad (C.2)$$

Assuming the economy value added is generated according to Equation 3. Adding and subtracting $(1 - \alpha_1 - \alpha_0) \Delta k_t$, $\alpha_1 \Delta l_t$, and $\alpha_o \Delta o_t$ to Equation C.2 and re-arranging terms, one obtains.

$$\begin{aligned} \frac{\Delta Y_t}{Y_{t-1}} &\approx \underbrace{\frac{Y_{mint-1}}{Y_{t-1}} \Delta stf p_{mint} + \frac{Y_{no mint-1}}{Y_{t-1}} \Delta stf p_{no mint}}_{\text{pure productivity}} + \\ &+ \underbrace{\frac{Y_{mint-1}}{Y_{t-1}} \left((1 - \alpha_{lmin} - \alpha_{omin}) \Delta k_{mint} - (1 - \alpha_1 - \alpha_o) \Delta k_t + \alpha_{lmin} \Delta l_{mint} - \alpha_1 \Delta l_t \right)}_{\dots} \\ &+ \underbrace{\alpha_{omin} \Delta o_{mint} - \alpha_o \frac{Y_{t-1}}{Y_{mint-1}} \Delta o_t}_{\text{composition}} + \\ &+ \underbrace{\frac{Y_{t-1} \text{NoMin}}{Y_{t-1}} \left((1 - \alpha_{lno min}) \Delta k_{no mint} - (1 - \alpha_1 - \alpha_o) \Delta k_t + \alpha_{lno min} \Delta l_{no mint} - \alpha_1 \Delta l_t \right)}_{\dots} + \\ &+ \underbrace{(1 - \alpha_1 - \alpha_o) \Delta k_t + \alpha_1 \Delta l_t + \alpha_o \Delta o_t}_{\text{factors of production}} \end{aligned}$$

where the sum of the terms *pure productivity* and *composition* approximates to TFP growth.

References

Céspedes, N., Lavada, P. and N. Ramírez, (2016), Productividad en el Perú: Medición, Determinantes e Implicancias, Universidad del Pacífico, edition 1, nr 07-14.

Table A1: Variables and Data Sources

| Variable | Definition | Source |
|---------------------------|--|---|
| Australia | | |
| Capital stock | Non-residential capital stock, by industry, chain volume measures. | Table 58, Australian System of National Accounts, Australian Bureau of Statistics. |
| Compensation of employees | Compensation of Employees, by industry at current prices. | Table 38 and Table 48, Australian System of National Accounts, Australian Bureau of Statistics. |
| Employment | Employed persons by industry division of main job. | Table 04, Labour Force Survey, Australian Bureau of Statistics. |
| Hours worked | Hours actually worked in all jobs. | Labour Force Surveys, Australian Bureau of Statistics. |
| Labor quality index | Human capital index, based on years of schooling and returns to education, PWT9. | Feenstra, Robert C., Robert Inklaar and Marcel P.Timmer (2015). |
| Nominal and real GDP | Non-residential Gross Value Added (GVA) by industry at current and constant prices (chain volume). | Table 38 and Table 5, Australian System of National Accounts, Australian Bureau of Statistics. |
| Canada | | |
| Capital stock | Non-residential capital stock, by industry and asset, Canada, provinces and territories (year-to-date (averages)), annual. | Table 031 – 0005, Statistics Canada. |
| Compensation of employees | Compensation of employees, quarterly at current prices. | Table 379 – 0029, Table 380 – 0074, 384 – 0037, Statistics Canada. |
| Employment | Number of workers in the labor force. | Table 282 – 0008, Labour Force Survey, Statistics Canada. |
| Hours worked | Actual Hours worked, unadjusted for seasonality, annual. | Table 282 – 0027 and Table 282 – 0021, Labour Force Survey, Statistics Canada. |
| Labor quality index | Human capital index, based on years of schooling and returns to education, PWT9. | Feenstra, Robert C., Robert Inklaar and Marcel P.Timmer (2015). |
| Nominal and real GDP | Non-residential Gross Domestic Product at current and constant prices. | Table 379 – 0031, Table 379 – 0001, and Table 384 – 0037, Statistics Canada. |
| Chile | | |
| Capital stock | Real capital stock at constant prices. | Central Bank of Chile, reference 2008 and 2013. |
| Compensation of employees | Total labor remunerations of all sectors (including an imputation for the remuneration of self-employment). | National Accounts, Central Bank of Chile, reference 2008 and 2013. |
| Employment | Number of workers in the labor force. | National Statistics Institute, old and new Employment Surveys. |
| Hours worked | Average weekly hours. | National Statistics Institute, old and new Employment Surveys. Series joined formerly by the Central Bank of Chile. |
| Labor quality index | Human capital index, based on years of schooling and returns to education, PWT9. | Feenstra, Robert C., Robert Inklaar and Marcel P.Timmer (2015). |
| Nominal and real GDP | Gross Domestic Product at current and constant prices (chain volume). | Central Bank of Chile, reference 2008 and 2013. |
| Ore grade | Average ore grade. Calculated as weighted averages of mineral processing. | Chilean Copper Commission based on information of the main mining companies, which represent 99,6 per cent of total production (year 2015). |
| Colombia | | |
| Employment | Number of workers in the labor force. | Great Integrated Household Survey, Administrative National Statistics Department. |
| Real GDP | Real Gross Domestic Product. | National Accounts, Administrative National Statistics Department. |
| Ecuador | | |
| Employment | Number of workers in the labor force. | National Survey of Employment, Unemployment and Subemployment, National Institute of Census and Statistics. |
| Real GDP | Real Gross Domestic Product. | National Accounts, Central Bank of Ecuador. |

Table A1: Variables and Data Sources (Cont.)

| Variable | Definition | Source |
|-----------------------------|--|---|
| Indonesia | | |
| Employment | Number of workers in the labor force. | Statistics Indonesia. |
| Real GDP | GDP at constant market prices by industrial origin. | Statistics Indonesia. |
| Malaysia | | |
| Capital stock | Net capital stock at constant prices. | Department of Statistics Malaysia. |
| Hours worked | Average annual hours worked by persons engaged, PWT9. | Feenstra, Robert C., Robert Inklaar and Marcel P.Timmer (2015). |
| Labor quality index | Human capital index, based on years of schooling and returns to education, PWT9. | Feenstra, Robert C., Robert Inklaar and Marcel P.Timmer (2015). |
| Nominal and real GDP | Gross Value Added at current and constant prices. | Department of Statistics Malaysia. |
| Mexico | | |
| Capital stock | Net capital stock at constant prices. | National Institute of Statistics and Geografy. |
| Compensation of employees | Remuneration at Current prices. | National Institute of Statistics and Geografy. |
| Hours worked | Hours worked per employee. | National Institute of Statistics and Geografy. |
| Labor quality index | Human capital index, based on years of schooling and returns to education, PWT9. | Feenstra, Robert C., Robert Inklaar and Marcel P.Timmer (2015). |
| Nominal and real GDP | Gross Value Added at current and constant prices. | National Institute of Statistics and Geografy. |
| Norway | | |
| Capital stock | Capital stocks, by industry, at constant prices. | Table 9181 – 12, Statistics Norway. |
| Compensation of employees | Wages and salaries at current prices. | Table 9174 – 1, Statistics Norway. |
| Hours worked | Total hours worked for employees and self-employed (million work-hours). | Table 9174 – 1, Statistics Norway. |
| Labor quality index | Human capital index, based on years of schooling and returns to education, PWT9. | Feenstra, Robert C., Robert Inklaar and Marcel P.Timmer (2015). |
| Nominal and real GDP | Value added at current and constant. | Table 9170 – 3 and Table 9170 – 11, Statistics Norway. |
| Peru | | |
| Capital stock | Capital stock imputed through perpetual inventory method using data on gross capital formation at constant prices. | National Institute of Statistics and Information Technology. |
| Compensation of employees | Total labor remunerations of all sectors at current prices. | Data from National Accounts 2007, Central Reserve Bank of Peru. |
| Employment | Number of workers in the labor force. | Peru: Evolutions of Employment and Remuneration Indicators by State 2001 – 2010 and 2004 – 2015, National Institute of Statistics and Information Technology. |
| Hours worked | Average weekly hours. | Peru: Evolutions of Employment and Remuneration Indicators by State 2001 – 2010 and 2004 – 2015, National Institute of Statistics and Information Technology. |
| Labor quality index | Human capital index, based on years of schooling and returns to education, in PWT9. | Feenstra, Robert C., Robert Inklaar and Marcel P.Timmer (2015). |
| Nominal and real GDP | Gross Domestic Product at current and constant prices. | National Institute of Statistics and Information Technology and Central Reserve Bank of Peru. |
| Returns of physical capital | Depreciation rate and long term rate of growth of Gross Domestic Product to build capital stock. | Cespedes, Nikita., Pablo Lavado and Nelson Ramirez Rondan (2016). |

Table A1: Variables and Data Sources (Cont.)

| Variable | Definition | Source |
|---------------------------|---|---|
| South Africa | | |
| Capital stock | Non farms fixed capital stock at constant prices. | National accounts, South African Reserve Bank. |
| Compensation of employees | Non farms quarterly Compensation of Employees (R millions). | Statistics South Africa. |
| Employment | Non farms workers in the labor force. | Quarterly Employment Statistics, Statistics South Africa. |
| Hours worked | Average annual hours worked by persons engaged, PWT9 | Feenstra, Robert C., Robert Inklaar and Marcel P.Timmer (2015). |
| Labor quality index | Human capital index, based on years of schooling and returns to education, PWT9. | Feenstra, Robert C., Robert Inklaar and Marcel P.Timmer (2015). |
| Nominal and real GDP | Quarterly Non farms Gross Domestic Product by industry at current prices and constant prices. | Statistics South Africa. |

Table B1: Labor Share in Mining Latin-American Countries

| Country | Mining (1) | Non-Mining (2) | Economy (3) |
|---------------------|----------------|-------------------|----------------|
| Australia | 0.23 (0.04) | 0.60 (0.01) | 0.51 (0.02) |
| Canada | 0.21 (0.04) | 0.57 (0.00) | 0.56 (0.00) |
| Chile | 0.13 (0.02) | 0.53 (0.01) | 0.47 (0.01) |
| Malaysia | 0.05 (0.01) | 0.36 (0.01) | 0.32 (0.01) |
| Mexico | 0.07 (0.01) | 0.31 (0.02) | 0.30 (0.02) |
| Norway | 0.11 (0.04) | 0.61 (0.02) | 0.51 (0.04) |
| Peru | 0.19 (.) | 0.37 (.) | 0.34 (.) |
| South Africa | 0.44 (0.06) | 0.52 (0.02) | 0.52 (0.03) |
| Average | 0.18 | 0.48 | 0.44 |

Notes: First, second, and third row show labor shares of the Mining, Non-Mining, and Aggregate Economy respectively. First, second, and third columns present labor shares for Mexico and Peru. Labor shares are calculated as nominal compensation of employees divided by gross value added.

Table B2: Sectoral Labor Shares

| Sector | Chile (1) | Australia (2) | Canada (3) |
|------------------------------|----------------|------------------|----------------|
| Aggriculture | 0.42 (0.06) | 0.25 (0.03) | 0.30 (0.03) |
| Manufacture | 0.38 (0.01) | 0.57 (0.03) | 0.50 (0.02) |
| Energy, Water and Gas | 0.14 (0.03) | 0.34 (0.04) | 0.14 (0.01) |
| Construction | 0.57 (0.04) | 0.51 (0.02) | 0.50 (0.01) |
| Retail and Wholesale | 0.58 (0.02) | 0.64 (0.01) | 0.49 (0.01) |
| Transport and Communications | 0.40 (0.02) | 0.48 (0.03) | 0.46 (0.00) |
| Business Services | 0.45 (0.02) | 0.56 (0.02) | 0.53 (0.01) |
| Personal Services | 0.81 (0.01) | 0.80 (0.01) | 0.55 (0.01) |
| Average | 0.19 | 0.48 | 0.44 |

Notes: First, second, and third row show labor shares of the Mining, Non-Mining, and Aggregate Economy respectively. First, second, and third columns present labor shares for Mexico and Peru. Labor shares are calculated as nominal compensation of employees divided by gross value added.



Traspaso del tipo de cambio a precios en Chile: un análisis estructural

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1. INTRODUCCIÓN

Chile es una economía pequeña y abierta y como tal tiene acceso a una gran variedad de productos en el comercio internacional. Éstos tienen precios fijados en dólares y por lo tanto, al ingresar al país, su precio en pesos depende directamente del valor del tipo de cambio al cual se importan.

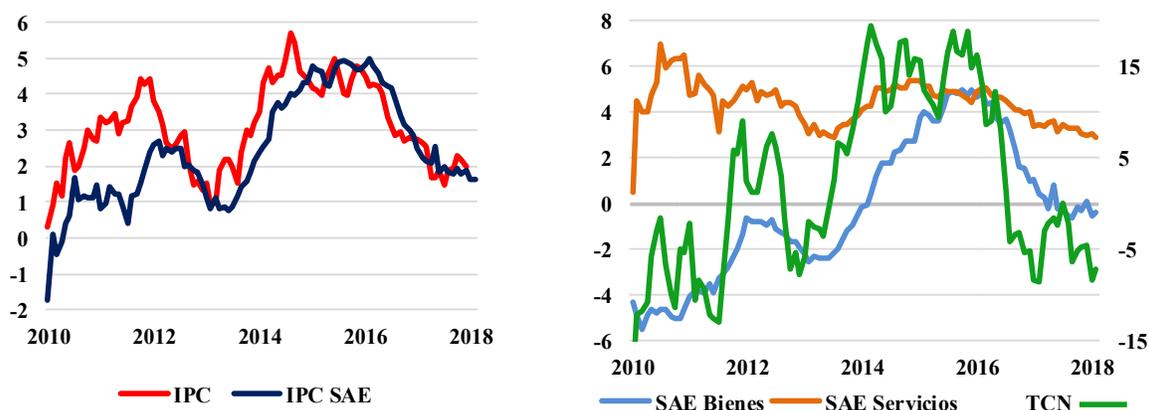
El Banco Central de Chile sigue un régimen de flotación cambiaria desde septiembre de 1999, con lo que el tipo de cambio fluctúa libremente¹. Esto ayuda a suavizar el ajuste de la economía real a shocks externos. Como contraparte, el tipo de cambio nominal (TCN) puede fluctuar fuertemente en ocasiones, afectando los precios de los productos importados y así la inflación.

Como muestra la figura 1, entre 2013 y 2015 hubo un fuerte aumento en la inflación total, explicada principalmente por el componente sin alimentos y energía (SAE) de la canasta. A su vez, la inflación SAE se explica mayormente por el componente de bienes, siendo la inflación de servicios bastante estable durante la muestra. El gráfico de la derecha muestra que el aumento de la inflación de bienes SAE está altamente correlacionado con el aumento experimentado en el TCN durante el mismo período, de 40% entre mayo de 2013 y diciembre de 2015. Lo anterior grafica la importancia que cambios en el TCN pueden tener en el aumento de los precios de los bienes SAE y del IPC total.

¹ Salvo algunas ocasiones en las que el Banco Central ha intervenido en el mercado cambiario de forma excepcional y transparente, cuando la trayectoria de la moneda se ha alejado de su valor de equilibrio.



Figura 1: Inflación 2010-2018



Nota: Ambos gráficos muestran la variación anual del IPC, IPC SAE en el gráfico de la izquierda y de IPC SAE Bienes, IPC SAE Servicios y TCN en el gráfico de la derecha.

Fuente: Banco Central de Chile.

Tal como lo muestra este ejemplo, una pregunta muy importante y recurrente en el ámbito de política monetaria es cuánto es el coeficiente de traspaso (o ERPT por sus siglas en inglés), del tipo de cambio a la inflación total y sus componentes². Por ejemplo, Contreras y Pinto (2016), en base a una metodología de Vectores Autorregresivos (VAR), calculan que el traspaso en Chile es de 0.15 a 1 año y 0.18 a dos años para el IPC total y alrededor de 0.1 y 0.13 para el IPC SAE.³

Un factor a considerar en la literatura que estima ERPTs es la gran variabilidad en los resultados encontrados⁴. Esto ha sido explicado por diversos factores, como por ejemplo el régimen de política, las variables incluidas en el análisis, entre otros. Una falencia de la metodología empírica que estima los ERPT, que generalmente no ha sido tratada, es que el TCN es en sí una variable endógena que responde a otros shocks, por lo que la relación

² Análisis previos se pueden ver en Banco Central de Chile (2014, 2016), Contreras y Pinto (2016), Albagli y otros (2015), Justel y Sansone (2015).

³ Es decir, una depreciación de 1% del TCN generaría, en promedio, un aumento de 0.15% (0.18%) del IPC en un plazo de 1 año (2 años) y de 0.1% (0.13%) del IPC SAE en el mismo plazo.

⁴ Ver por ejemplo Bravo y García (2002) para el caso de Chile.



entre el TCN y los precios, que se resume en el ERPT, puede depender del shock que inició el movimiento.

Este trabajo calcula ERPTs en base a un modelo dinámico y estocástico de equilibrio general (DSGE, por sus siglas en inglés) para el caso de Chile. Estos modelos proveen una solución natural al problema de endogeneidad, dado que permite el cálculo de la respuesta del TCN y de los precios (y por lo tanto del ERPT) a cada shock exógeno. Esto genera un ERPT condicional a cada tipo de shock, en contraste al ERPT incondicional calculado por la metodología empírica. Adicionalmente, este análisis permite evaluar si el ERPT depende de condiciones estructurales de la economía y del actuar de la política monetaria, lo que tampoco es posible con el análisis empírico.

En la sección 2 del trabajo se discute la diferencia entre las medidas empíricas y las condicionales e incondicionales calculadas en base al DSGE. La sección 3 describe brevemente el modelo DSGE ocupado en el análisis y los principales shocks que afectan al tipo de cambio. La sección 4 presenta una comparación entre traspaso condicional e incondicional. La sección 5 relaciona los coeficientes de traspaso con la reacción de la tasa de política monetaria. En la sección 6 se estudian las dinámicas ocurridas en Chile después de la depreciación cambiaria entre el 2013 y 2015. Finalmente, la sección 7 concluye.

2. RELACIÓN CON MEDIDAS DE LITERATURA EMPÍRICA⁵

La gran parte de la literatura empírica utiliza modelos VAR, donde se considera el vector x_t de variables observables que incluye entre ellas la depreciación cambiaria, π_t^z , la inflación de un bien o canasta de bienes j , π_t^j , y otras variables de control de origen doméstico y/o externo. Un modelo VAR(p) de forma reducida se puede escribir como:

$$x_t = \Phi_1 x_{t-1} + \dots + \Phi_p x_{t-p} + u_t$$

donde Φ_j para $j = 1, \dots, p$ son matrices de coeficientes a estimar y u_t es un vector de shocks de forma reducida *i.i.d.* con media cero y matriz varianza-covarianza Ω . Los shocks “estructurales” del modelo se definen como:

⁵ Hay varias medidas empíricas, pero se discutirán solo las basadas en modelos VAR.



$$u_t = Pw_t$$

donde P satisface $\Omega = PP'$ asumiendo que la varianza de w_t es la matriz identidad. En general la literatura asume que la matriz P es triangular inferior, obtenida de una descomposición de Cholesky aplicada a Ω . El ERPT h períodos en adelante está definido como:

$$ERPT^V(h) \equiv \frac{CIRF_{\pi^j, \pi^s}^V(h)}{CIRF_{\pi^s, \pi^s}^V(h)}$$

donde $CIRF_{k,i}^V(h)$ es la reacción acumulada de la variable k ante el shock en la posición asociada a la variable i , h períodos en adelante. Así el ERPT es el ratio entre la respuesta acumulada de la inflación y del cambio en el TCN ante un shock asociado a la ecuación del cambio en el TCN.

En el caso de un DSGE, la solución linearizada se puede escribir como:

$$y_t = Fy_{t-1} + Qe_t$$

donde y_t es un vector de las variables del modelo y e_t es un vector de shocks estructurales *i.i.d.* con media cero y matriz varianza-covarianza igual a la identidad. Las matrices F y Q son funciones de los parámetros del modelo. En este caso el ERPT condicional en el shock e_t^i para el precio j es:

$$CERPT_{j,i}^M(h) \equiv \frac{CIRF_{\pi^j, e^i}^M(h)}{CIRF_{\pi^s, e^i}^M(h)}$$

que es análogo a la definición anterior, excepto en que la respuesta se calcula ante el shock e_t^i en vez del shock asociado a la ecuación de TCN que no tiene una interpretación estructural.

Bajo varios supuestos, descritos en García-Cicco y García (2018), el ERPT calculado en base a un VAR es una suma ponderada de los ERPT condicionales, cuyos ponderadores dependen de la importancia del shock para explicar movimientos en el TCN. En base a este caso particular, se define una medida del ERPT incondicional para el precio j como:

$$UERPT_j^M(h) \equiv \sum_{i=1}^{n_e} CERPT_{j,i}^M(h)w_i(h)$$



donde $w_i(h)$ es una función de la fracción de la varianza del error de predicción del TCN en el horizonte h explicado por el shock i y n_e es el número de shocks en el DSGE.

De esta manera, al menos conceptualmente, resultados obtenidos con la metodología VAR pueden predecir cambios esperados en los precios ante un movimiento cambiario que son muy distintos de los implicados por el traspaso condicional. Para cuantificar si estas diferencias son relevantes en la práctica, estimamos un modelo DSGE con datos de Chile, que describimos a continuación.

3. MODELO DSGE Y SHOCKS QUE EXPLICAN EL TIPO DE CAMBIO NOMINAL

El modelo utilizado para realizar el análisis, que se encuentra descrito en detalle en García-Cicco y García (2018), contiene características que son relevantes para explicar las dinámicas observadas en la economía chilena; resaltando el rol de los efectos de fluctuaciones en el tipo de cambio en los precios locales y su dinámica esperada. Además se diferencian tipos de precios para así poder estudiar diferencias en sus ERPT, y poder comparar también con la literatura empírica.

Las características principales del modelo utilizado son:

- Cuatro bienes: *commodities*, otros exportables, importados, y no-transables. El *commodity* tiene una dotación exógena aleatoria y es vendido en su totalidad en el extranjero, los importados son comprados en el mercado internacional y tanto los exportables, como los no transables son producidos localmente utilizando capital, trabajo, energía y bienes importados.
- Los índices de precios definidos por el modelo incluyen: IPC, IPC SAE, IPC SAE-Bienes, IPC SAE-Servicios, Alimentos y Energía.
- Las dinámicas de fijación de precios permiten indexación a inflación pasada para precios de bienes y salarios. En particular, esto produce que el traspaso de tipo de cambio a precios locales de bienes importados sea rezagado.
- La política fiscal viene dada por un gasto exógeno, mientras que la política monetaria sigue una regla para la tasa de interés, del tipo de Taylor.



- Los hogares consumen bienes no transables, bienes transables SAE, alimento y energía. En cambio la inversión se compone de bienes no transables y transables SAE, y el gasto de gobierno sólo se gasta en no-transables.
- Las variables externas relevantes que enfrenta la economía son las tasas de interés, la demanda por los bienes exportables y los precios internacionales de *commodities*, de los bienes importados y un índice de precios externos de socios comerciales.
- El modelo contiene 21 variables exógenas y utiliza 22 variables observables (que incluye variables agregadas como sectoriales) para estimarse⁶. La muestra ocupada en la estimación es datos trimestrales desde el segundo trimestre de 2001 al tercer trimestre de 2016.

¿Qué shocks son importantes para explicar las fluctuaciones cambiarias? La tabla 1 muestra el porcentaje de la varianza de los movimientos cambiarios y de diversas inflaciones, atribuibles a los shocks más importantes para explicar las fluctuaciones del TCN. Como puede observarse, shocks a la tendencia de precios internacionales (F^*) explican cerca de 70% de la varianza del tipo de cambio, mientras que el shock a la paridad de tasas (UIP) determina cerca del 20% de la volatilidad cambiaria. Sólo estos dos shocks explican la mayor parte de los cambios en TCN (el 87%) y por lo tanto nos enfocaremos en estos dos para el resto del análisis.

Tabla 1: Descomposición de varianzas

| Dif. % en | Shock | | Suma |
|-----------|-------|-------|------|
| | UIP | F^* | |
| TCN | 18 | 69 | 87 |
| IPC | 15 | 6 | 21 |
| SAE-Bs | 23 | 9 | 32 |
| SAE-Svs | 13 | 6 | 19 |

Nota: Cada entrada indica el porcentaje de la varianza de la variable en cada fila, atribuible al shock indicado en la columna. Las variables en cada fila son las diferencias porcentuales trimestrales del tipo de cambio nominal, IPC, IPC SAE-Bienes e IPC SAE-Servicios. En cada columna, los shocks son: desviaciones de la paridad de tasas (UIP), tendencia de precios internacionales (F^*), y la suma de ambos.

Fuente: Elaboración propia.

⁶ Ver Anexo para lista de variables exógenas y observables y García-Cicco y García (2018) para más detalles.



Es importante notar que estos dos shocks también son relevantes para explicar la volatilidad de las diversas inflaciones, explicando en conjunto en torno a 20% de la correspondiente a la inflación total y SAE-Servicios, y 30% de la SAE-Bienes. Pero en términos relativos existen otros shocks que, si bien no son tan importantes para explicar movimientos cambiarios, sí lo son para las dinámicas de la inflación. Una forma alternativa de interpretar este resultado es que el esquema de tipo de cambio flexible permite absorber shocks nominales externos, reduciendo su impacto en variables domésticas locales como la inflación.

El shock a la tendencia (o factor común) de precios internacionales (F^*), como lo dice su nombre, afecta al mismo tiempo a todos los precios internacionales (medidos en dólares) que enfrenta Chile. Este shock captura cambios en el dólar multilateral, lo que se observa en el gráfico de la izquierda de la figura 2 que muestra el shock graficado junto a la variación del dólar multilateral⁷. Estas series tienen una correlación de 0.88. Cualitativamente, el efecto de una disminución en esta tendencia afectará a la economía por dos canales. Por una parte, este shock disminuye el ingreso obtenido de las exportaciones, dado que disminuye el precio internacional de los *commodities*, y además disminuye la demanda que enfrenta Chile por sus otros bienes exportables al disminuir el índice de precios de socios comerciales. Por otra parte, este shock disminuye el precio de los bienes que Chile importa, pero este efecto es dominado por el anterior dado que los precios locales de los bienes importados varían sólo gradualmente por existencia de rigideces de precios.⁸

El shock a la paridad de tasas captura desviaciones de la paridad de tasas descubierta (*UIP*), relacionados con la existencia de premios por los riesgos asociados a las fluctuaciones cambiarias. Como se ve en la figura 2, este shock está correlacionado con el diferencial de tasas de EE.UU. Se muestra que, si bien en muchas ocasiones el shock captura cambios esperados de las tasas en EE.UU., hay momentos en que captura otros factores. En términos cualitativos, los efectos de este shock son equivalentes a un shock a la tasa de interés

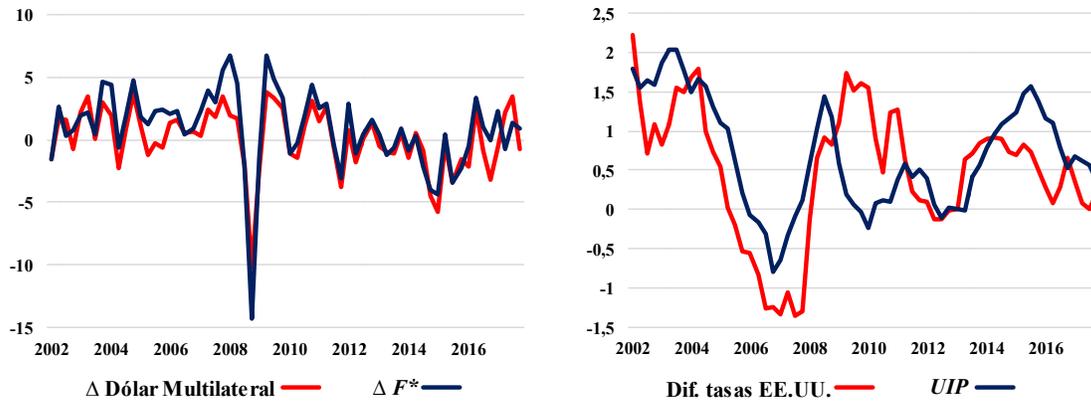
⁷ El dólar multilateral se mide como un promedio ponderado de los tipos de cambios de los principales socios comerciales de EE.UU.. Los tipos de cambio se miden como el valor en dólares de las monedas externas.

⁸ Existe un tercer efecto dado por la revalorización de la deuda externa, denominada en dólares. Al disminuir los precios externos, se aumenta la carga del pago de intereses en moneda local y además, al ser el shock persistente, aumenta la tasa de interés real de la deuda. En términos relativos, este efecto juega un rol menor al mencionado anteriormente.



externa. Ante un aumento en estos premios que elevan el costo de financiamiento externo, los efectos generados son cualitativamente similares a los de una disminución en la tendencia de los precios internacionales, al disminuir ambos shocks la demanda agregada.

Figura 2: Variables observables vs. shocks



Nota: El gráfico de la izquierda muestra la variación trimestral en el dólar multilateral y el shock a la tendencia de precios internacionales inferido por el modelo. El gráfico de la derecha muestra la diferencia de tasas entre la tasa de los bonos del tesoro de EE.UU. a 5 años y la tasa interbancaria federal de EE.UU. y el shock a la UIP inferido por el modelo.

Fuente: Reserva Federal de St. Louis y elaboración propia.

Aunque cualitativamente similares, es de esperar que el traspaso condicional a un shock en la tendencia de precios internacionales sea menor al generado por desviaciones de la paridad de tasas. Esto, pues si bien ambos shocks contraen la demanda agregada, el de los precios internacionales tiene un efecto en la inflación a través de los precios importados (tanto aquellos consumidos directamente, como por los insumos importados que se utilizan para producir otros bienes). De esta manera, si bien la contracción en la demanda genera una depreciación que es inflacionaria ante ambos shocks, cuando hay una disminución en los precios internacionales el efecto en la inflación es más acotado; y así el traspaso será menor.

4. TRASPASO CONDICIONAL VS. TRASPASO INCONDICIONAL



Según lo discutido anteriormente, a nivel teórico los traspasos condicionales pueden diferir del incondicional. Es de interés entonces estudiar cuantitativamente las diferencias entre éstos que surgen del modelo estimado. Dada la importancia de los shocks a la tendencia en los precios internacionales y a las desviaciones en la paridad de tasas, el análisis se centrará en comparar los traspasos condicionales para esos shocks con el traspaso incondicional. La siguiente tabla muestra los diferentes coeficientes de traspaso, a horizontes de 1, 4 y 8 trimestres, para los índices de precios IPC, SAE-Bienes y SAE-Servicios. También se incluye para comparación los obtenidos para estos mismos precios por Contreras y Pinto (2016) utilizando una metodología VAR.

Tabla 2: Coeficientes de traspaso condicionales e incondicionales estimados

| Horiz. | Cond. F^* | | | Cond. UIP | | |
|--------|-------------|--------|---------|-------------|--------|---------|
| | IPC | SAE-Bs | SAE-Svs | IPC | SAE-Bs | SAE-Svs |
| 1 | 0.02 | 0.03 | 0.00 | 0.04 | 0.07 | 0.00 |
| 4 | 0.05 | 0.07 | 0.02 | 0.26 | 0.40 | 0.09 |
| 8 | 0.06 | 0.08 | 0.03 | 0.54 | 0.75 | 0.29 |

| Horiz. | Incond. Modelo DSGE | | | Incond. VAR | | |
|--------|---------------------|--------|---------|-------------|--------|---------|
| | IPC | SAE-Bs | SAE-Svs | IPC | SAE-Bs | SAE-Svs |
| 1 | 0.03 | 0.06 | 0.00 | 0.06 | 0.06 | 0.00 |
| 4 | 0.10 | 0.15 | 0.03 | 0.15 | 0.14 | 0.06 |
| 8 | 0.14 | 0.21 | 0.07 | 0.18 | 0.18 | 0.07 |

Nota: Cada entrada muestra el traspaso indicado, para el precio que aparece en la primera fila, en el horizonte que se indica en la primera columna.

Fuente: Elaboración propia y Contreras y Pinto (2016).

En cuanto a la comparación de ambos traspasos condicionales, se observa que el shock a la tendencia de precios internacionales (F^*) genera un traspaso relativamente bajo, menor a 0.1 a 2 años para todos los índices. En otras palabras, una depreciación permanente de 10% se asociaría a un aumento de la inflación del IPC respecto a la meta de 0.5% a 1 año y menor a 1% acumulado en dos años. Además, los efectos inflacionarios de este shock tienden a ser rápidos, de manera que su efecto residual en la inflación proyectada a dos años, el cual es el horizonte relevante de política monetaria, es muy pequeño.



Este resultado contrasta con el traspaso condicional generado por un shock a la paridad de tasas (*UIP*), que a dos años genera un traspaso en torno a 0.6 para IPC, 0.8 para SAE-Bienes y 0.3 para SAE-Servicios. De esta manera, una depreciación permanente del 10%, se asociaría a un aumento en la inflación del IPC respecto a la meta de 2.5% a 1 año y de alrededor de 6% acumulados a dos años. El efecto inflacionario de este shock se produce de forma mucho más gradual. Esto lo hace más relevante para las decisiones de política, dado que gran parte de su efecto en precios ocurre entre los meses 12 y 24 posteriores al shock. Claramente, identificar la fuente del shock que genera el movimiento cambiario es de vital importancia para diagnosticar apropiadamente las consecuencias inflacionarias del mismo.

El traspaso *incondicional* generado por el modelo, que es comparable con los resultados obtenidos por Contreras y Pinto (2016), se ubica entre medio de los dos condicionales.⁹ De esta forma, los resultados basados en la metodología VAR por lo general entregarán predicciones incorrectas respecto a los movimientos esperados en los precios, generados por fluctuaciones cambiarias. El diagnóstico puede mejorarse utilizando un modelo de equilibrio general para distinguir el traspaso condicional correspondiente.

5. REACCIÓN DE POLÍTICA MONETARIA

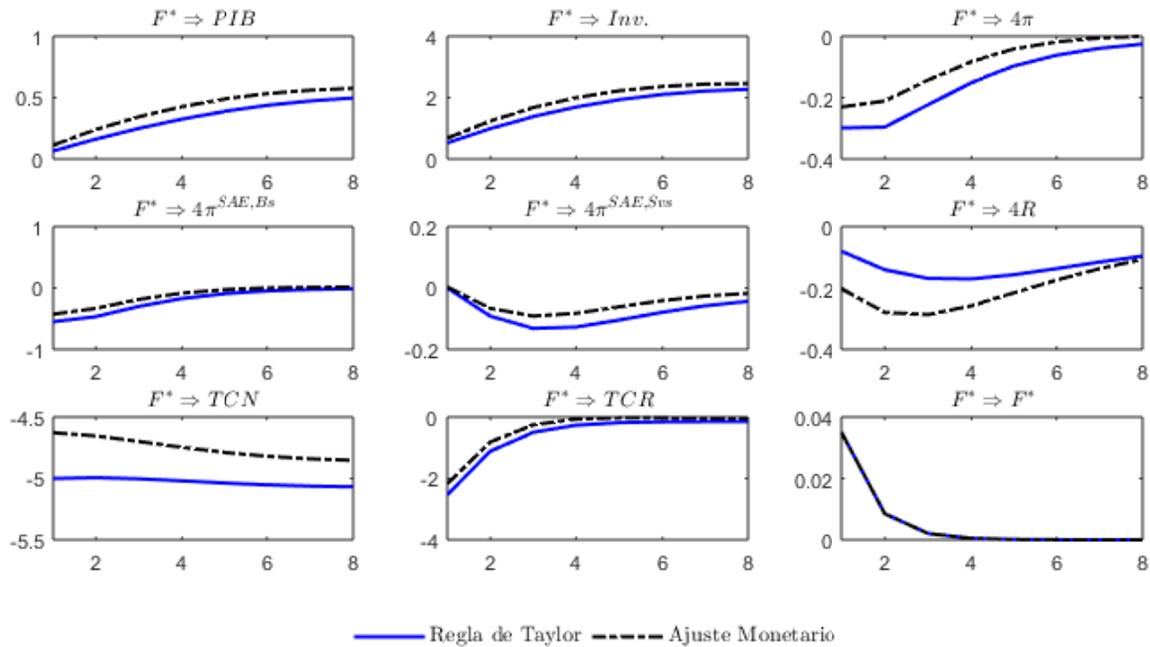
La magnitud y temporalidad del traspaso cambiario a precios asociado a los shocks anteriormente discutidos sugieren distintas reacciones de política monetaria. Además, distintas reacciones de la tasa de política monetaria va a afectar las reacciones de las variables endógenas como respuesta al shock y, por ende, el traspaso de tipo de cambio a precios. El modelo base asume que la tasa de política monetaria sigue una regla de Taylor simplificada en que la tasa de interés responde a la inflación y crecimiento contemporáneos. Para evaluar tanto la reacción de la tasa de interés ante distintos shocks, como el cambio de dinámica ante distintas reacciones de política monetaria, las figuras 3 y 4 muestran reacciones de variables endógenas ante un shock que, si se sigue la regla de Taylor asumida en el modelo, aprecia el tipo de cambio en impacto un 5%. Además muestra la reacción de

⁹ La comparación con los resultados de la literatura VAR es relevante pues indica que el modelo produce resultados similares a los de la literatura cuando éstos son contrastados utilizando estadísticos comparables (en este caso, el traspaso incondicional).



las mismas variables endógenas asumiendo una política monetaria que se ajusta para asegurar la convergencia de la inflación a dos años.

Figura 3: Efecto de política monetaria ante shock a la tendencia de precios internacionales



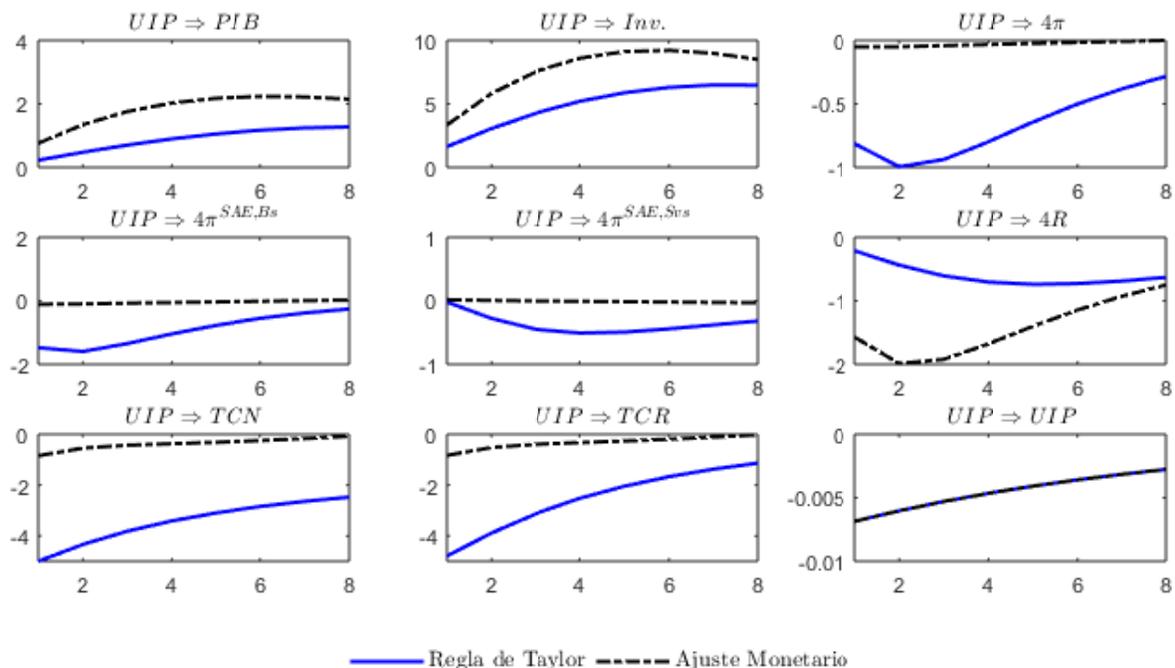
Nota: La línea azul muestra la respuesta ante un shock a la tendencia de precios internacionales asumiendo que la política monetaria sigue la regla de Taylor. La línea negra muestra la respuesta ante el mismo shock asumiendo que la tasa de política monetaria se ajusta para que la inflación converja a la meta en dos años. El shock es calibrado de forma que la depreciación cambiaria sea 5% si se sigue una regla de Taylor. Las variables graficadas son: PIB, Inversión, Inflación IPC, Inflación SAE Bienes, Inflación SAE Servicios, Tasa de interés, TCN, Tipo de cambio real y el shock.

Fuente: Elaboración propia.

Como se ve en la figura 3, ante un shock positivo a la tendencia de precios internacionales, cae la inflación en el corto plazo. A los dos años, sin embargo, la inflación siguiendo la regla de Taylor ya es muy cercana a la meta, por lo que para asegurar la convergencia a la meta de la inflación proyectada a dos años (la política graficada en negro), se requiere solo de un pequeño impulso. Esta política monetaria alternativa es entonces levemente más expansiva que la regla de Taylor, creando una expansión un poco mayor en el PIB y la inversión y menor reacción en el resto de las variables.



Figura 4: Efecto de política monetaria ante shock a la paridad de tasas



Nota: La línea azul muestra la respuesta ante un shock a la paridad de tasas asumiendo que la política monetaria sigue la regla de Taylor. La línea negra muestra la respuesta ante el mismo shock asumiendo que la tasa de política monetaria se ajusta para que la inflación converja a la meta en dos años. El shock es calibrado de forma que la depreciación cambiaria sea 5% si se sigue una regla de Taylor. Las variables graficadas son: PIB, Inversión, Inflación IPC, Inflación SAE Bienes, Inflación SAE Servicios, Tasa de interés, TCN, Tipo de cambio real y el shock.

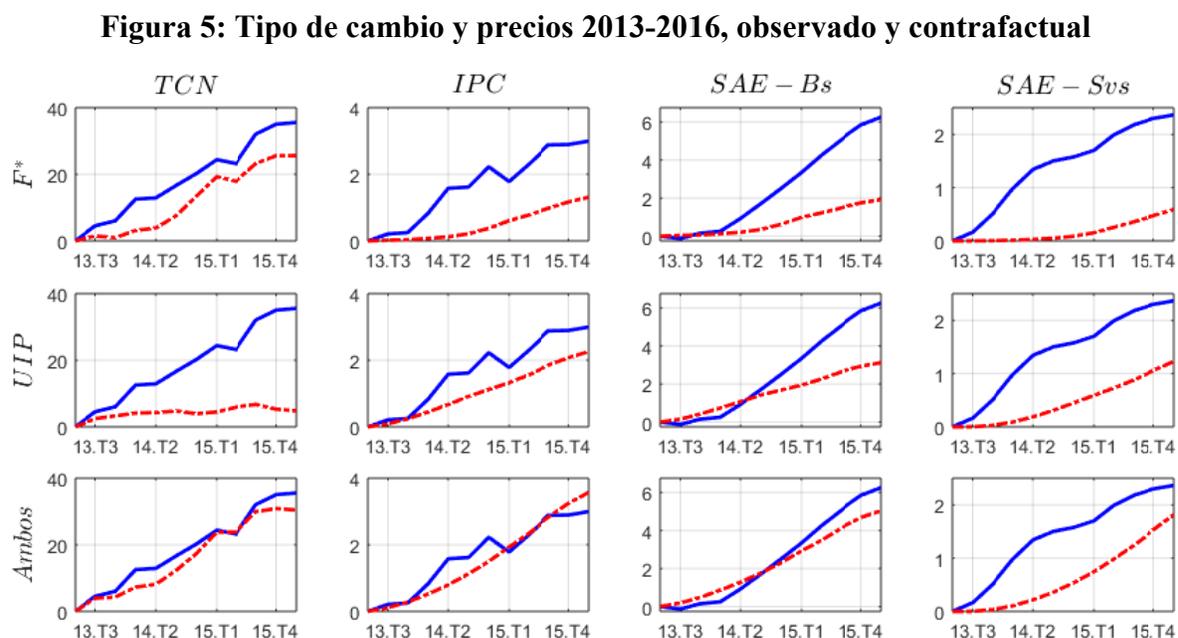
Fuente: Elaboración propia.

Ante un shock negativo a la paridad de tasas, en cambio, la figura 4 muestra que, dada la misma apreciación inicial que en el ejercicio anterior, al seguir una regla de Taylor la inflación disminuye considerablemente a corto y mediano plazo. Al cumplirse dos años, la inflación aún está lejos de la meta. Dado el traspaso alto de estos shocks, la política que asegura la convergencia de la inflación en dos años requiere una fuerte baja de la tasa de interés para así acotar la apreciación inicial y lograr la convergencia inflacionaria. Esta política monetaria alternativa difiere bastante de la prescrita por la regla de Taylor, produciendo efectos mucho más acotados en todas las variables nominales y mayores efectos en las variables reales.



6. DEPRECIACIÓN 2013-2015

Comenzando en junio de 2013, a raíz de las conversaciones sobre el *tapering* de la Reserva Federal de EE.UU., la mayoría de las monedas en el mundo se depreciaron fuertemente contra el dólar. En Chile, el tipo de cambio acumuló un aumento cercano al 40% entre el segundo trimestre de 2013 y el último trimestre de 2015; período que también coincidió con registros inflacionarios algo por encima de la meta. En esta sección utilizaremos la discusión conceptual anterior y el modelo estimado para tratar de discernir el rol que tuvieron los movimientos cambiarios en explicar las dinámicas observadas. En primer lugar, mostraremos que los dos shocks enfatizados anteriormente pueden explicar apropiadamente el movimiento cambiario observado en este período. Luego computaremos las trayectorias contrafactuales para los precios que hubiesen ocurrido si sólo estos shocks hubiesen estado presente, permitiendo así calcular qué parte de la inflación observada puede atribuirse a los shocks que afectaron al tipo de cambio. Los resultados se presentan en la figura 5.



Nota: La línea azul muestra el desvío porcentual acumulado (respecto a la tendencia muestral) de la variable



indicada en cada columna, comparado con su valor en el segundo trimestre de 2013. En cada columna, las variables son: tipo de cambio nominal (\$ por US\$), IPC, IPC SAE- Bienes e IPC SAE-Servicios. Las líneas rojas punteadas indican el sendero contrafactual de la misma variable que hubiese ocurrido si solo hubiese estado presente el shock indicado en cada fila (computados con el *Kalman smoother*). En cada fila, los shocks son: tendencia de precios internacionales (F^*), desviaciones de la paridad de tasas (*UIP*) y ambos a la vez.

Fuente: Elaboración propia y Banco Central de Chile.

En la primera columna de la figura se observa el cambio porcentual acumulado del tipo de cambio (línea azul), respecto a su valor en el segundo trimestre de 2013. Las líneas rojas muestran el sendero que hubiese seguido esa variable si solo uno de los shocks (o ambos en la tercera fila) hubiese estado presente. Mirando la primera fila, se observa que el shock a la tendencia en los precios internacionales (F^*) fue el principal determinante de la depreciación observada, particularmente a partir del primer trimestre de 2014. Por el contrario, en la segunda fila se aprecia que el shock a la paridad de tasas (*UIP*) afectó al tipo de cambio en los primeros trimestres luego del *tapering*, pero a partir de 2014 su efecto en el tipo de cambio fue marginal. Así, como se observa en la última fila, el efecto de ambos shocks combinados pueden dar cuenta de la evolución del tipo de cambio observada en ese período.

En la primera fila, columnas dos a cuatro, puede observarse cómo el shock a la tendencia de precios internacionales (F^*) afectó a los distintos índices de precios. Las líneas azules muestran los desvíos porcentuales acumulados (respecto a la tendencia muestral) del índice, comparado con su valor en el segundo trimestre de 2013; mientras que las rojas son los contrafactuales correspondientes. Aun cuando estos shocks dan cuenta de la mayoría de los movimientos cambiarios a partir 2014, su efecto en los precios fue moderado. Hacia fines de 2015, estos shocks explican alrededor de un tercio de los desvíos del IPC y de SAE-Bienes, y en torno a un quinto para SAE-Servicios. Estos resultados reflejan la discusión de la sección anterior; ya que el traspaso condicional de estos shocks es relativamente acotado.

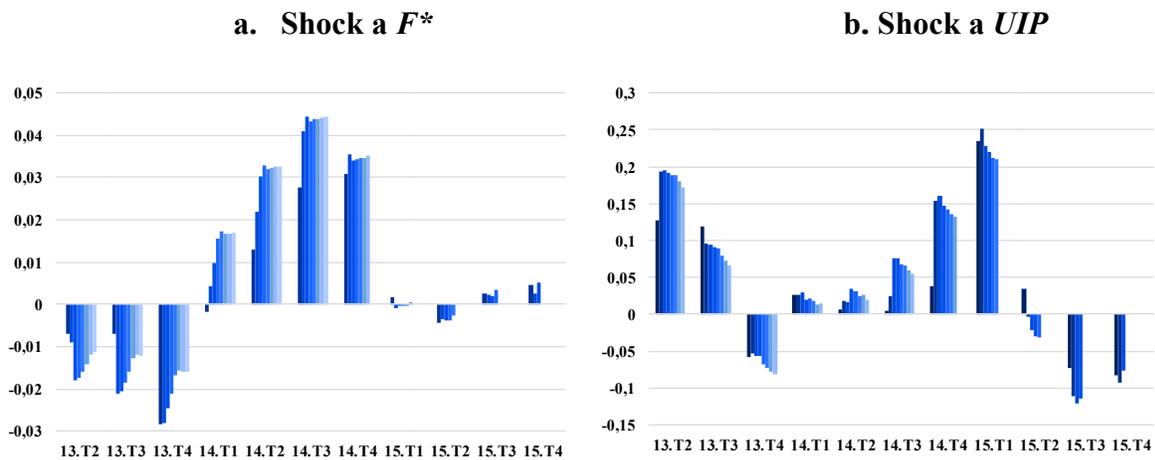
Pasando al efecto en los precios de los shocks a la paridad de tasas (*UIP*), en la segunda fila, columnas dos a cuatro, se observa que éstos pueden explicar cerca de dos tercios de los desvíos acumulado en el IPC hasta fines de 2015, y en torno a la mitad de la inflación acumulada para ambas SAE. Esto, pues si bien estos shocks solo afectaron al tipo de cambio durante el 2013, su traspaso condicional es más elevado y duradero.



Finalmente, la última fila de gráficos muestra que los shocks que determinaron los movimientos cambiarios en el período analizado pueden explicar en gran medida los movimientos observados en IPC y en SAE-Bienes. Por el contrario, la inflación de SAE-Servicios no estuvo tan relacionada con los movimientos cambiarios, en particular durante 2013 y 2014. Para esta variable, otros determinantes no relacionadas con las fluctuaciones cambiarias (principalmente factores de oferta en ese sector) fueron más relevantes para explicar su dinámica.

Este análisis sugiere que, sólo con los shocks inferidos hasta fines de 2013 y utilizando los conceptos de traspaso condicional, al menos la mitad de los desvíos de la inflación respecto a la meta experimentados en 2015 podrían haberse anticipado. Sin embargo, es importante destacar que la inferencia de shocks en tiempo real puede diferir de la presentada previamente. Esto se debe que los shocks predichos por el modelo, no sólo se afectan por datos pasados, sino además por datos futuros.

Figura 6: Revisión en proyección de inflación a 1 año



Nota: Los gráficos muestran los efectos de las revisiones de los shocks a F^* y a la UIP en la inflación proyectada a 1 año, medida en puntos porcentuales. El azul más oscuro muestra la revisión entre el primer trimestre en que se conocen los datos y el siguiente. El más claro muestra la revisión entre el primer trimestre y 8 trimestres después. Cada conjunto de columnas corresponde a la revisión del trimestre definido en el eje de abscisas.

Fuente: Elaboración propia.

La figura 6 muestra la revisión en la proyección de la inflación a 1 año dada por la revisión de los shocks a la tendencia en precios internacionales (izquierda) y a la paridad de tasas



(derecha) entre el segundo trimestre de 2013 y fines de 2015. Como se ve en el primer gráfico, los efectos de la revisión al shock en precios internacionales es menor, no sobrepasando 0,05% de inflación y en promedio es menor que 0.01%. En cambio, el efecto inflacionario de la revisión al shock a la paridad de tasas es mucho más elevado, situándose incluso sobre 0.2%, promediando 0.09%.

Se concluye que durante este episodio la revisión no fue cuantitativamente importante para los shocks a la tendencia en los precios internacionales, pero sí para los shocks a la paridad de tasas. Esta incertidumbre, sin embargo, disminuye considerablemente después de 1 a 2 trimestres. Luego de las dos primeras revisiones, la inferencia se acerca bastante a la que se obtiene con el set completo de información.

7. CONCLUSIÓN

En este trabajo presentamos una perspectiva complementaria a los estudios empíricos del traspaso cambiario, basado en un modelo DSGE. En particular, mostramos cómo la diferencia entre los conceptos de traspaso condicional (que depende del shock afectando a la economía) e incondicional (que se computa con modelos empíricos) es crucial a la hora de diagnosticar los efectos esperados en la inflación luego de grandes fluctuaciones cambiarias.

Utilizando el modelo DSGE estimado, mostramos que las diferencias entre estos conceptos de traspaso son cuantitativamente relevantes. Describimos además la relación entre política monetaria y coeficientes de traspaso. Tanto en relación al efecto del coeficiente de traspaso en la prescripción de política monetaria, como en la forma en que estas distintas políticas afectan de manera endógena a los coeficientes de traspaso. Además analizamos, a la luz del modelo, el episodio de depreciación ocurrido en Chile entre 2013 y 2015. En particular, enfatizamos que, dada la importancia del shock a la paridad de tasas en los meses inmediatamente posteriores al *tapering*, y que su traspaso condicional es relativamente más elevado, cerca de la mitad de la inflación ocurrida en ese período podría haberse anticipado a fines de 2013. Finalmente, resaltamos la importancia de las revisiones a la lectura de los shocks en tiempo real y como estas revisiones pueden alterar el análisis inicial.



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ANEXOS

Las variables exógenas son:

- Domésticos (12): Preferencias por consumo, oferta de trabajo de cada sector (exportable y no-transable), productividad de cada sector (exportable y no-transable), tendencia de largo plazo, dotación de *commodities*, precios de alimentos y de energía, eficiencia de los bienes de inversión, consumo público, y política monetaria.
- Externos (9): tasa de interés mundial libre de riesgo, riesgo país y premio por riesgo, precios internacionales de *commodities*, bienes importados, e IPC de socios comerciales, demanda por exportaciones, y PIB de socios comerciales.

Las variables observables son:

- Crecimiento real de: PIB, PIB-Exportable (Agropecuario-silvícola, Pesca, Industria, EGA, Transporte), PIB-No transable (Construcción, Comercio, Servicios), Consumo, Inversión. Ratio de Balanza Comercial a PIB.
- Inflaciones: SAE-Servicios, SAE-Bienes, Importada SAE, Alimentos y Energía.
- Crecimiento nominal de salarios de los sectores exportable y no-transable, para lo que se usa CMO nominal, sectores consistentes PIB.
- Gasto del gobierno, PIB de *Commodities*.
- Depreciación tipo de cambio nominal y Tasa de política monetaria.
- Externas: Tasa externa libre de riesgo (LIBOR), riesgo país (EMBI Chile), inflación externa (IPE), inflación de importaciones (IVUM), inflación de precios de *commodities* (precio del cobre) y PIB socios comerciales.

Channels of US Monetary Policy Spillovers to International Bond Markets ¹

Elias Albagli Luis Ceballos Sebastian Claro Damian Romero

Abstract

We document significant US monetary policy (MP) spillovers to international bond markets. Our methodology identifies US MP shocks as the change in short-term treasury yields around FOMC meetings, and traces their effects on international bond yields using panel regressions. We emphasize three main results. First, US MP spillovers to long-term yields have increased substantially after the global financial crisis. Second, spillovers are large compared to the effects of other events, and at least as large as the effects of domestic MP after 2008. Third, spillovers work through different channels, concentrated in risk neutral rates (expectations of future MP rates) for developed countries, but predominantly on term premia in emerging markets. In interpreting these findings, we provide evidence consistent with an *exchange rate channel*, according to which foreign central banks face a tradeoff between narrowing MP rate differentials, or experiencing currency movements against the US dollar. Developed countries adjust in a manner consistent with freely floating regimes, responding partially with risk neutral rates, and partially through currency adjustments. Instead, emerging countries display patterns consistent with FX interventions, which cushion the response of exchange rates but reinforce capital flows and their effects in bond yields through movements in term premia. Our results suggest that the endogenous effects of currency interventions on long-term yields should be added into the standard cost-benefit analysis of such policies.

JEL classification: E43, G12, G15.

Keywords: monetary policy spillovers, risk neutral rates, term premia.

1. Introduction

The conduct of monetary policy (MP) in many developed economies has changed in important ways since the global financial crisis. After reaching an effective zero lower bound, the focus shifted towards influencing long term yields, with significant efforts made by central banks in communicating their intentions to keep rates at zero for an extended period (forward guidance), and through large scale asset purchase programs (LSAP). The increased presence of the Fed, the ECB, and other central banks in fixed income markets has been reinforced by large portfolio flows from private investors, further contributing to the fast expansion of the world bond market in the last decade. This growth in size has also coincided with an increased presence of foreign investors in domestic bond markets, a change most noticeable for emerging market economies.²

While increased financial integration has multiple benefits, it also poses important challenges. In particular, it raises the question of whether the cost of funds in non-core economies can remain independent from developments in

¹The opinions and mistakes are the exclusive responsibility of the authors and do not necessarily represent the opinion of the Central Bank of Chile or its Board. We thank Jose Berrospide, Yan Carriere-Swallow, Diego Gianelli, Mauricio Hitschfeld, Alberto Naudon, Horacio Sapriza, Larry Summers, Rodrigo Vergara, and Vivian Yue for valuable comments and discussions, and Tobias Adrian for sharing the code used in Adrian et al. (2013).

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²See IMF (2014), and BIS (2015).

advanced countries, possibly undermining the ability of central banks to set appropriate monetary conditions given their domestic macroeconomic stance. This discussion is well captured by several studies assessing the international spillover effects from MP in the US and other large developed economies, including Rey (2015), Bruno and Shin (2015), and Obstfeld (2015), among many others.

There are several open questions that remain to be settled in this literature. First, there is a non-trivial problem of identification that makes it hard to assess whether comovements in yield curves are driven by causal effects from MP in advanced countries, or merely reflect common underlying economic forces. Second, there are few studies that test spillover effects on emerging market economies, mostly due to the lack of reliable, long-dated yield curve information. Third, to the extent that spillover effects are identified, there is little evidence about the specific channels at work. In particular, do movements in domestic long-term yields reflect the anticipation of future short-term rates that tend to follow MP changes in core economies, or do they result from changes in risk compensation due to portfolio rebalancing/risk-taking motives?

This paper contributes to the debate by presenting evidence of significant spillover of US MP into international bond yields. Our data includes 12 developed countries (henceforth, DEV) and 12 emerging market economies (henceforth, EME). In order to identify US MP shocks, we use the change in short-term treasuries (2-yr maturity in our baseline specification) within a narrow window centered around FOMC meetings. This identification strategy has been followed by several studies, most recently by Hanson and Stein (2015) in a setting similar to ours, and by Savor and Wilson (2014) to explain stock returns during days of macroeconomic announcements, including Fed meetings.³ We then test how shocks to US MP affect international bond yields at different maturities using panel data regressions. Because we wish to highlight the difference between DEV and EME, we run panel regressions for each group of countries separately. Our sample runs from January 2003 to December 2016, and we split it in October 2008 to mark the MP regime change due to the global financial crisis (see Gilchrist, Yue, and Zakrajsek, 2016).

To further understand spillover mechanisms, we decompose long-term yields for each country into a term premium (TP) and a risk neutral (RN) component, following the methodology of Adrian, Crump, and Moench (2013), but correcting for small sample bias as suggested by Bauer, Rudebusch, and Wu (2012). This allows us to determine whether US MP spillovers to other economies work by affecting market expectations of future domestic MP in those countries, or whether they reflect changes in risk compensation. Moreover, to put perspective on the economic magnitude of spillovers, we study the impact on yields of individual countries' domestic MP shocks, as well as other events including US and domestic releases of inflation, activity, and unemployment.

We highlight three main results. First, US MP spillovers are large for both DEV and EME, especially for the sub-sample after October 2008. Throughout this period, we estimate that a 100 bp increase in US short-term rates

³A similar event study is used in Gilchrist, Yue, and Zakrajsek (2016). Cochrane and Piazzesi (2002) and Bernanke and Kuttner (2005) use a related measure of US MP shocks, but focusing on shorter maturities –the 1-month eurodollar rate and Federal funds futures, respectively.

during MP meetings increases long-term rates in DEV and EME countries by 43 and 56 bp, respectively. In the earlier subsample, the elasticities are smaller in magnitude, particularly so for EME.

Second, spillovers are economically important compared to other events, and at least as large as the impact of domestic MP actions on long-term yields post October 2008. In particular, the point estimates of the effects of US MP on domestic long-term bond yields of DEV economies is roughly equivalent to the effect of domestic MP, but significantly larger than the effect of domestic MP in the case of EME in the second part of the sample. Moreover, US MP spillovers are comparable to the elasticity of long-term rates to 2-year yield changes around key domestic macroeconomic releases.

Third, there seem to be important differences in the mechanisms involved in the transmission of US MP when comparing different country groups. Based on the complete sample estimates, the contribution of the RN component (expectations of short-term rates) accounts for almost all the variation in yields for DEV economies, with a non-significant contribution of the TP component. For countries in the EME sample the effect is the opposite, with most of the variation in yields being driven by movements in TP. Digging deeper into the underlying mechanisms that could explain these patterns, we find little evidence of an *informational channel* –the notion that FOMC meetings could affect expected rates in other countries by communicating relevant information about the US macroeconomy, potentially correlated with conditions abroad. We argue that there are weak theoretical and empirical grounds for this view within our specific identification strategy.

We provide additional evidence that favors an *exchange rate channel*, according to which central banks face a tradeoff between narrowing interest differentials, or experiencing currency movements. Conceptually, the effects of US MP spillovers depend on the policy responses of central banks. As shown by Blanchard, Adler, and Carvalho Filho (2015), (sterilized) exchange rate interventions (FXI) dampen the exchange rate effects of capital inflows in reaction to US MP, but in doing so reinforce such inflows, compared to the alternative of adjusting domestic MP. In Appendix A, we extend their model to include long-term bonds and derive implications for exchange rates, capital flows, and long-term yields in response to US MP shocks under different policy reactions. Consistent with the theoretical predictions, our evidence suggests that central banks in DEV adjust in a manner consistent with freely floating regimes, absorbing shocks with both exchange rate and RN rate movements. EMEs, on the other hand, display patterns consistent with FXI, a behavior widely documented for the countries in our sample.⁴ These include weaker exchange rate effects, stronger capital inflows, and a stronger reaction of term premia. In contrast to the standard Mundell-Fleming paradigm in which effective FXI can in principle stabilize both short-term rates and the domestic currency –and thus present no apparent policy tradeoff– our results suggest FXI deflect the burden of adjustment into long term yields through changes in term premia, casting new light into their cost-benefit analysis.

There is a growing literature studying the effect of conventional and unconventional MP in the US post 2008.

⁴See Table B.12 in Appendix B for numerous references.

Hanson and Stein (2015) show that conventional Fed meetings have a significant impact on the long end of the US yield curve. Krishnamurthy and Vissing-Jorgensen (2011), Gagnon, Raskin, Remache, and Sack (2011), and Christensen and Rudebusch (2012), find large effects of unconventional MP announcements on US long-term yields. Several papers have also documented the international spillover effects of conventional US MP,⁵ and, more recently, the transmission of LSAP announcements.⁶

More closely related to our paper are the recent papers by Gilchrist, Yue, and Zakrajsek (2016), Hoffman and Takáts (2015), and IMF (2015), who put special emphasis on US MP spillovers to emerging countries. The main difference with these papers is our focus on the transmission mechanisms behind US MP spillovers. Indeed, the fact that the cost of credit at longer maturities in emerging markets could be partially disconnected from the expected path of MP decisions poses important challenges for central banks in these economies, and warns about additional, unintended consequences of FX interventions. Furthermore, by presenting evidence about the impact of own MP and economic releases, our paper helps to put into perspective the economic importance of spillover channels relative to other domestic and foreign events. Another difference, particularly with Hoffman and Takáts (2015) and IMF (2015), is the identification strategy. While they use a VAR methodology with recursive restrictions at monthly frequency to identify autonomous shocks on US long-term yields, we use event-study analysis based on narrow windows around Fed meetings to identify MP shocks.

The remainder of the paper is structured as follows. Section 2 describes the data and the main econometric specification, including the construction of US MP events and the decomposition of yield curve movements into RN and TP components. In section 3, we quantify US MP spillovers to international bond yields and their components, and contrast their magnitude with other economic events. Section 4 provides further analysis and evidence in order to interpret our results and identify specific mechanisms underlying US MP spillovers. Section 5 presents additional tests to check the robustness of our results to plausible deviations in sample choice, construction of the event study, and other methodological issues. Section 6 concludes.

2. Data description and identification strategy

2.1. Econometric specification

To estimate the effect of US MP spillovers, we test the following panel specification:

$$\Delta y_{j,t}^h = \alpha_{year}^h + \alpha_{month}^h + \beta^h MPR_t^{US} + \gamma^h MPR_{j,t}^{Own} + \sum_{n=1}^N \delta_n^h S_{n,t}^{US} + \sum_{n=1}^N \theta_n^h S_{j,n,t}^{Own} + \varepsilon_{j,t}^h \quad (1)$$

⁵See Craine and Martin (2008), Hausman and Wongswan (2011), and Georgiadis (2015).

⁶See Bauer and Neely (2014), and Bauer and Rudebusch (2014).

In equation (1), the main explanatory variable of interest is MPR_t^{US} : the change in the 2-yr US treasury yield between the closing of the business day before and the day after each meeting.⁷ The rationale for this measure, proposed by Hanson and Stein (2015), is that the actual Fed Funds Rate (FFR) changes are infrequent, and often anticipated by the market. Moreover, there could be relevant information at each meeting about the future course of MP that would be missed if one used only the contemporaneous FFR. For these reasons, they propose using a relatively short-maturity yield for capturing changes in the stance of future MP that could arise from information released during FOMC meetings. The other variables in the right hand side of equation (1) include $MPR_{j,t}^{Own}$: the change in country j 's 2-yr yield around an analogously defined 2-day window centered at its corresponding MP meeting; $S_{n,t}^{US}$: the change in 2-yr US yield around a 2-day window centered at each US economic release n (with n =CPI, IP, and unemployment); and $S_{j,n,t}^{Own}$: the change in country j 's 2-yr yield around a 2-day window centered at j 's economic release n (also, n =CPI, IP, and unemployment).

To control for other common events that might affect yields, we try several fixed-effects specifications and criteria for clustering standard errors. In our baseline specification, we include year- and month-fixed effects in each regression (α_{year}^h and α_{month}^h in equation (1)). We discuss robustness considerations in more detail in section 5.

We now turn to the left-hand side of equation (1). Because we are interested in the effect of US MP and other economic events on yields and their components, we use 3 different variables: the h -yr domestic bond yield (where the superscript h stands for maturity);⁸ the portion of this yield identified as the RN component (the expectations of future short-term interest rates); and the TP component. We focus the discussion below on 2-yr and 10-yr yields. In all specifications, $\Delta y_{j,t}^h$ is defined as the change in yields (or yield components) between the close of the business day after and the day before each meeting.⁹ Because we place special emphasis on the effects of US MP on EME and DEV, we run separate regressions for each group of countries. We also highlight the change in US MP spillovers over time by splitting the sample in two, with the first sub-sample including the period January 2003 up to (and including) October 2008.

2.2. Data sources and Identification issues

Our DEV sample comprises 12 countries: Australia, Canada, Czech Republic, France, Germany, Italy, Japan, New Zealand, Norway, Sweden, Switzerland, and the United Kingdom. The EME sample also includes 12 countries: Chile, Colombia, Hungary, India, Indonesia, Israel, Korea, Mexico, Poland, South Africa, Taiwan, and Thailand. Sample choice is limited by the availability of sufficiently rich yield curve data, as computation of yield components requires observing several yields along the term structure at each point in time. The resulting balanced panel runs

⁷For example, for the meeting that ended on October 29, 2014, the MP shock is the difference between the 2-yr treasury at the close of October 30, and the close of October 28.

⁸In the case of yields we use on the left-hand side the model-implied yield rather than the observed interest rates, which may not coincide due to measurement error in the affine model estimation. An estimation using actual yields changes only the coefficients associated to yields, but not their components. The differences are marginal (not reported).

⁹While specific countries will have longer/shorter windows before/after the announcement depending on time zone differences, it is always the case that the FOMC meeting is contained within the window.

from January 2003 through December 2016. Tables B.9 and B.10 in Appendix B provide further details.

Our identification strategy relies on two main premises. First, implicit in the use of MP calendar days is the notion that such events are quantitatively relevant to the dynamics of interest rate movements in the US.¹⁰ Table 1 reports moments of interest rate changes around different economic events. In the first sub-sample, the standard deviation of 2-yr US yields is larger around MP meetings than on non-meeting days, though the difference is marginally significant at 10% confidence levels. Post October 2008, the volatility of rates around meetings is significantly larger than non-event days (at 1% confidence). Similarly, macroeconomic releases are not associated with higher volatility in the earlier sample, but after 2008 unemployment releases, and to some extent CPI releases, exhibit significantly more rate volatility compared to non-event days. For DEV economies, interest rates on MP meeting days, and during CPI and unemployment releases, display significantly larger volatility than non-event days in both samples, and so do activity releases in the second part of the sample. For EME, volatility around economic releases is only significantly larger than non-event days post October 2008 for MP meetings, activity and unemployment releases.

Second, for the event to correctly measure US MP as a causal force affecting international yields, it should not be contaminated by other economic releases. Table B.11 in Appendix B shows that although Fed meetings are not always the only event moving yields on a given day, this is the case much more often than not: the overlap frequency between US MP meetings and all other country events is only about 7%.

TABLE 1: Changes in 2-yr yields around selected events

| | Pre Oct. 2008 | | | | | | Post Oct. 2008 | | | | | |
|--------------|---------------|-------|-------|---------|-------|----------|----------------|---------|-------|----------|-------|----------|
| | US | | DEV | | EME | | US | | DEV | | EME | |
| | mean | std | mean | std | mean | std | mean | std | mean | std | mean | std |
| No news | 0.07 | 8.94 | 0.04 | 6.43 | 0.29 | 19.31 | 0.05 | 4.35 | -0.25 | 7.35 | -0.31 | 10.01 |
| MPM | -0.22 | 9.50* | -0.86 | 9.73*** | -1.72 | 18.47* | -0.23 | 5.67*** | -1.24 | 11.07*** | -2.09 | 14.38*** |
| Inflation | -1.28 | 9.04 | 0.33 | 6.87** | 0.42 | 19.24 | -0.32 | 4.87* | -0.25 | 6.37** | -0.97 | 11.53*** |
| Activity | -1.86 | 9.04 | -0.40 | 5.32*** | 0.64 | 12.87*** | -0.19 | 4.51 | -0.60 | 8.41*** | -0.58 | 10.59** |
| Unemployment | 0.10 | 9.33 | 0.27 | 7.52*** | 1.12 | 8.41*** | -0.24 | 4.95*** | -0.27 | 7.93*** | -0.29 | 8.44*** |

The table shows the mean and the standard deviation of changes in 2-yr yields around economic releases. ***p-value < 1%, **p-value < 5%, and *p-value < 10%, denote the probability that volatility is higher in the corresponding event than in non-event days.

2.3. Decomposition of yields

To decompose interest rates into RN and TP components, we use the affine term-structure model of Adrian, Crump, and Moench (2013). We now briefly sketch their methodology (Appendix D provides further details). The model is characterized by the existence of K risk factors summarized in vector X_t , which follows a first-order VAR:

$$X_{t+1} = \mu + \Phi X_t + v_{t+1}, \quad v_{t+1} \sim N(0, \Sigma). \quad (2)$$

¹⁰The higher volatility of rates on event days is not a necessary condition for the identification strategy to be valid, but it supports the notion that Fed meetings are relevant events in yield curve movements.

It is further assumed that the short-term interest rate r_t is a linear function of the risk factors

$$r_t = \delta_0 + \delta_1' X_t, \quad (3)$$

and that there exists a unique stochastic discount factor given by

$$-\log M_{t+1} = r_t + \frac{1}{2} \lambda_t' \lambda_t + \lambda_t' v_{t+1}, \quad (4)$$

where the vector of risk prices (λ_t) is also linear in the risk factors: $\lambda_t = \lambda_0 + \lambda_1 X_t$. The risk factors also follow a Gaussian VAR under the risk-neutral probability measure \mathbb{Q} : $X_{t+1} = \mu^{\mathbb{Q}} + \Phi^{\mathbb{Q}} X_t + v_{t+1}^{\mathbb{Q}}$, where $\mu^{\mathbb{Q}} = \mu - \Sigma \lambda_0$ and $\Phi^{\mathbb{Q}} = \Phi - \Sigma \lambda_1$. Using this probability measure, the n -period zero coupon bond price corresponds to $P_t^n = E_t^{\mathbb{Q}}(\exp(-\sum_{h=0}^{n-1} r_{t+h}))$, and prices of bonds at different maturities can be written $P_t^n = \exp(\mathcal{A}_n + \mathcal{B}_n' X_t)$, where \mathcal{A}_n and \mathcal{B}_n are solved recursively. One can then compute model-implied yields as $y_t^n = -\frac{\log(P_t^n)}{n}$. By setting risk prices equal to zero, one can obtain the yields that would prevail under risk neutrality, \tilde{y}_t^n , a measure of pure expectations about future rates at different maturities –the risk-neutral (RN) component. The difference between model-implied yields and RN rates is defined as the term premium (TP) component, $tp_t^n \equiv y_t^n - \tilde{y}_t^n$.

To estimate the model, Adrian, Crump, and Moench (2013) exploit the predictability of excess bond returns found in earlier studies, such as Cochrane and Piazzesi (2005),¹¹ and propose a simple OLS procedure to estimate the market prices of risk, details of which are provided in Appendix D.

Bias correction. A potential issue encountered in the estimation of affine models is the assumption that the short-term interest rate follows a VAR(1) process. Bauer, Rudebusch, and Wu (2012) show that, due to the small-sample bias present in this type of estimations, OLS generates artificially lower persistence than the true process, understating the volatility of RN rates (and hence overstating the volatility of TP). We follow their advice and employ an indirect inference procedure. The idea of this method is to choose parameter values that yield a distribution of the OLS estimator with a mean equal to the OLS estimate in the actual data.¹²

3. International US MP spillovers in perspective

This section presents the main results of the paper. Part 3.1 documents the impact of US MP shocks on international bond yields and their components. In order to put these magnitudes in perspective, parts 3.2 and 3.3 provide further evidence about the impact of domestic MP shocks and other domestic economic releases (inflation, unemployment, and activity) on these variables.

¹¹See Gürkaynak and Wright (2012) for a comprehensive review of this literature.

¹²See the online Appendix of Bauer, Rudebusch, and Wu (2012) for details. The Matlab codes to apply the correction are available at <http://faculty.chicagobooth.edu/jing.wu/>.

3.1. Effect of regular Fed meetings

To build intuition about the regression design tested in equation (1), Figure 1 describes events during selected FOMC meetings. The plots include the change in US 2-yr yields (our measure of US MP shocks, depicted in white bars), as well as their impact on 10-yr yields (gray bars) and their components (dashed line: RN component; solid line: TP component). For each sub-sample of countries (DEV and EME), the series plotted correspond to simple averages across countries in each group.

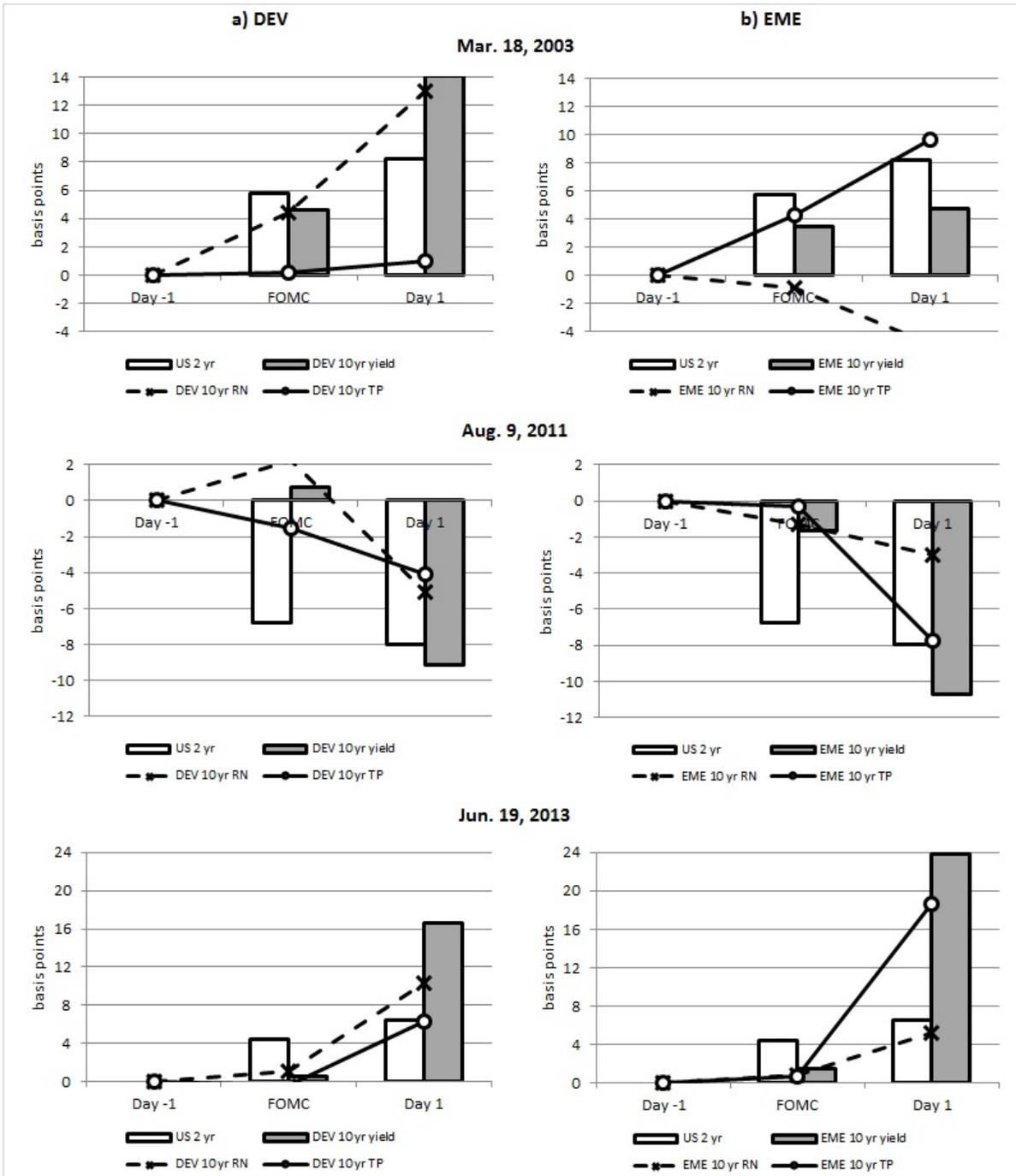
The upper panel plots the reaction of these variables during the meeting of March 18, 2003. Our measure of US MP shock is a positive 8.2 bp move, associated with a change in DEV 10-yr yields of about 14 bp, 13 of which correspond to the RN component. In contrast, the average effect in EME 10-yr yields, at about 5 bp, is explained by an increase in the TP component close to 9 bp, with a counteracting movement in the RN component. A similar pattern emerges for the meeting of August 9, 2011, which led to a market revision in 2-yr US yields of -8 bp. Of the -9.2 bp reaction in DEV 10-yr yields, more than half is explained by movements in the RN component, although in this episode the TP component does contribute a significant fraction. The slightly larger reaction in EME yields at -10.7 bp, on the other hand, is clearly dominated by the TP component. The third episode corresponds to the meeting of June 19, 2013, which increased US 2-yr rates in 6.5 bp. This shock had a comparably large effect of 16.7 bp in DEV 10-yr yields, of which more than 10 bp is accounted for by the RN component. The 24 bp effect in EME 10-yr yields is once again dominated by an increase in TP. While these are hand-picked cases, they capture the general pattern we document below: while overall yields in both groups of countries react similarly to US MP shocks, the action is dominated by the RN component for DEV, while TP is predominant for EME.

Table 2 presents the impact of US MP shocks in our baseline specification (the β^h coefficients in equation (1)), with panels a) and b) reporting the results for DEV and EME, respectively. The rows contain the effects on 2-yr yields, 10-yr yields, and the TP and RN components of 10-yr yields. The columns report the effects for the complete sample, the sub-sample ending in October 2008, and the sub-sample starting in December 2008.

We begin the discussion of the effects of US MP on DEV economies. For the full sample, a 100 bp US MP shock increases 2-yr rates abroad by 26 bp. For the 10-yr maturity, the effect is 34 bp. Comparing the pre and post October 2008 periods, the effect of US MP shocks on 2-yr yields has decreased from 32 to 17 bp. Interestingly, the effect is the reverse for 10-yr rates, for which spillovers have increased from 30 to 43 bp. These differences are statistically significant at 5% (not reported).

Focusing now on the composition of US MP spillovers on 10-yr yields, we see that the action is concentrated predominantly on the RN component. For the complete sample, a 100 bp shock in US MP is associated with a 33 bp increase in the RN component (significant at the 1% confidence level), virtually the whole effect in yields, while the contribution of the TP component is not statistically different from zero. Comparing the first and second sub-samples, we see that the TP component becomes statistically significant in the latter episode, although the RN component still explains more than half of the overall transmission of US MP to DEV yields.

FIGURE 1: US MP shocks and international bond yields during selected episodes



This figure plots the reaction of 10-yr yields (gray bars) and its components (RN component: dashed line; TP component: solid line) in response to changes in US 2-yr treasuries (white bars). The MP shock corresponds to the white bars at Day 1 (the difference between 2-yr yields at the closing of the day after and the day before the meeting). Panel a) and b) plot the average reaction across countries in the DEV and EME samples, respectively.

TABLE 2: Effects of US monetary policy

| | a) DEV | | | b) EME | | |
|-------------|---------------------|----------------------|---------------------|---------------------|---------------------|---------------------|
| | Full sample | Pre Oct. 2008 | Post Oct. 2008 | Full sample | Pre Oct. 2008 | Post Oct. 2008 |
| 2-yr yield | 0.263*** (0.023) | 0.318*** (0.028) | 0.173*** (0.038) | 0.160*** (0.041) | 0.100* (0.052) | 0.287*** (0.068) |
| 10-yr yield | 0.335*** (0.026) | 0.297*** (0.028) | 0.429*** (0.053) | 0.293*** (0.061) | 0.193*** (0.070) | 0.557*** (0.107) |
| RN (10-yr) | 0.331*** (0.032) | 0.390*** (0.040) | 0.234*** (0.053) | 0.054 (0.039) | 0.019 (0.050) | 0.136** (0.053) |
| TP (10-yr) | 0.005 (0.030) | -0.092*** (0.033) | 0.196*** (0.054) | 0.239*** (0.076) | 0.174** (0.088) | 0.421*** (0.132) |

The table shows the impact of US monetary policy events, corresponding to the β^h coefficient in equation (1). The regression is estimated separately for each group of countries: DEV and EME. Standard errors computed using Newey-West correction up to 40 lags (reported in parentheses). *** p-value < 1%, ** p-value < 5%, and * p-value < 10%.

For the EME group, a 100 bp US MP shock increases 2-yr rates about 16 bp in the full sample, an effect that increased from an insignificant 10 bp to a statistically significant 29 bp impact between the first and second estimation periods (a difference which is statistically significant at 1%). For the 10-yr maturity, the incremental effect across sub-periods is also noteworthy, growing from 19 bp to 56 bp per every 100 bp of US MP shocks (a difference also significant at 1%). Regarding the composition of US MP spillovers, these are now heavily tilted towards the TP component. For 10-yr yields, the full sample contribution of TP is 24 of the 29 bp total spillover effect (significant at 1%), while the 5 bp estimate for the RN component is not statistically significant. This dominance of the TP channel is evident in both sub-samples, although in the latter part the contribution of RN rates increases somewhat and is now marginally significant (at 5% confidence levels).

3.2. Effect of domestic MP

To gain perspective about the quantitative importance of US MP spillovers, Table 3 reports the impact of domestic MP meetings on yields (the γ^h coefficients in equation (1)), where the explanatory variable is the change in 2-yr domestic rates in a 2-day window centered at the business day corresponding to each country's MP meetings (hence, we report only the elasticity of 10-yr domestic yields). For the DEV group in panel a), we see that an increase of 100 bp of the domestic 2-yr rate is associated with a 37 bp increase in 10-yr yields in the full sample. The effect is decomposed into a highly significant increase of 78 bp in the RN component, partly offset by a reduction in TP of 42 bp. These magnitudes are relatively similar across sub-periods, although the second sub-sample shows a somewhat larger effect on yields. Importantly, the point estimates of the effects of US MP shocks are almost identical to those corresponding to domestic MP shocks in both sub-periods (a non-significant 1 bp difference in favor of domestic shocks in the earlier sample, and a non-significant 1 bp difference in favor of US MP shocks in the latter period).

For EME, per every 100 bp shock in domestic MP (2-yr domestic rates), 10-yr rates increase by 42 bp in the

complete sample, again explained by a larger increase in the RN component (61 bp), counteracted by a compression in the TP (20 bp). The effect is more pronounced in the earlier sample, at 52 bp, statistically larger than the corresponding effect of US MP shocks. In the second part of the sample, however, the effect of domestic MP drops to 33 bp, now statistically smaller (at 1% confidence) than the effect of US MP documented in Table 2.

TABLE 3: Effects of domestic monetary policy

| | a) DEV | | | b) EME | | |
|-------------|----------------------|----------------------|----------------------|---------------------|---------------------|---------------------|
| | Full sample | Pre Oct. 2008 | Post Oct. 2008 | Full sample | Pre Oct. 2008 | Post Oct. 2008 |
| 10-yr yield | 0.371*** (0.060) | 0.304*** (0.098) | 0.418*** (0.070) | 0.416*** (0.116) | 0.518*** (0.068) | 0.325** (0.164) |
| RN | 0.782*** (0.070) | 0.723*** (0.093) | 0.825*** (0.092) | 0.614*** (0.081) | 0.677*** (0.130) | 0.560*** (0.112) |
| TP | -0.412*** (0.089) | -0.419*** (0.102) | -0.407*** (0.134) | -0.198 (0.173) | -0.159 (0.180) | -0.236 (0.257) |

The table shows the impact of domestic monetary policy events, corresponding to the γ^h coefficients of equation (1). The regression is estimated separately for each group of countries: DEV and EME. Standard errors computed using Newey-West correction up to 40 lags (reported in parentheses). *** p-value < 1%, ** p-value < 5%, and * p-value < 10%.

It is also interesting to point out that for both DEV and EME groups, domestic policy consistently raises RN rates by a larger amount than 10-yr yields, with the TP component playing a counteracting effect. One interpretation of this pattern could be related to the effects of domestic MP on inflation risk. Indeed, Abrahams, Adrian, Crump, and Moench (2017) decompose forward nominal and real yield curves for US treasuries and estimate the impact of conventional MP. They find that a tightening of US MP has a significant negative effect on inflation term premia. While our decomposition cannot make the finer distinction between real and nominal term premia due to lack of systematic TIPS data in our sample of countries, the results of Table 3 are in principle consistent with the argument that an unanticipated tightening in MP reduces inflation risk, and therefore the risk compensation demanded by investors for holding nominal bonds, in a broader sample of countries.

In short, the evidence suggest that US MP shocks affect the long end of the yield curve at least as much, and in some cases even more so, than domestic monetary policy events. The predominant role played by the Fed in affecting international asset prices documented here is complementary to the findings of Brusa, Savor, and Wilson (2016). They find that international stock markets consistently command a positive risk premium in days of scheduled FOMC announcements, but not during announcement days of central banks different from the Fed, including their own.

3.3. Effect of domestic economic releases

As an additional exercise to put US MP spillovers in perspective, Table 4 reports the elasticity of 10-yr yields to changes in 2-yr yields around a 2-day window centered on domestic macroeconomic announcements, including inflation (CPI), activity (industrial production) and unemployment –the θ_n^h coefficients in equation (1). Panel

a) reports the results for the DEV group. In general, 2-yr yield movements around most economic releases have significant effects on 10-yr yields, with the transmission being larger in the case of unemployment and activity releases. In contrast, inflation releases in EME exhibit a larger comovement between short and long-term rates in the earlier sample, a pattern which is reversed in favor of activity and unemployment post October 2008.

TABLE 4: Effect of domestic economic releases

| a) DEV | Full sample | | | Pre Oct. 2008 | | | Post Oct. 2008 | | |
|-----------|---------------------|---------------------|----------------------|---------------------|---------------------|----------------------|---------------------|---------------------|----------------------|
| | 10-yr yield | RN | TP | 10-yr yield | RN | TP | 10-yr yield | RN | TP |
| Inflation | 0.361*** (0.085) | 0.662*** (0.170) | -0.301*** (0.096) | 0.351*** (0.055) | 0.812*** (0.053) | -0.461*** (0.049) | 0.362*** (0.135) | 0.561** (0.247) | -0.199 (0.126) |
| Activity | 0.509*** (0.050) | 0.819*** (0.111) | -0.310*** (0.109) | 0.444*** (0.048) | 0.796*** (0.063) | -0.353*** (0.059) | 0.520*** (0.066) | 0.820*** (0.144) | -0.300** (0.143) |
| Unempl. | 0.487*** (0.046) | 0.819*** (0.042) | -0.332*** (0.063) | 0.485*** (0.047) | 0.811*** (0.048) | -0.325*** (0.064) | 0.480*** (0.071) | 0.827*** (0.063) | -0.346*** (0.097) |

| b) EME | Full sample | | | Pre Oct. 2008 | | | Post Oct. 2008 | | |
|-----------|---------------------|---------------------|-------------------|---------------------|---------------------|-------------------|---------------------|---------------------|---------------------|
| | 10-yr yield | RN | TP | 10-yr yield | RN | TP | 10-yr yield | RN | TP |
| Inflation | 0.394*** (0.097) | 0.428*** (0.027) | -0.034 (0.100) | 0.404*** (0.064) | 0.424*** (0.049) | -0.020 (0.092) | 0.369** (0.153) | 0.424*** (0.029) | -0.056 (0.153) |
| Activity | 0.341** (0.133) | 0.312*** (0.089) | 0.030 (0.086) | 0.135 (0.122) | 0.253** (0.116) | -0.118 (0.091) | 0.640*** (0.049) | 0.394*** (0.083) | 0.246*** (0.081) |
| Unempl. | 0.400*** (0.079) | 0.507*** (0.076) | -0.107 (0.134) | 0.312* (0.170) | 0.530*** (0.120) | -0.218 (0.215) | 0.422*** (0.097) | 0.486*** (0.091) | -0.064 (0.179) |

The table shows the estimated impact of domestic economic releases, corresponding to the θ_n^h coefficients of equation (1). The regression is estimated separately for each group of countries: DEV and EME. Standard errors computed using Newey-West correction up to 40 lags (reported in parentheses). *** p-value < 1%, ** p-value < 5%, and * p-value < 10%.

All in all, the magnitudes of the effects are comparable to the impact of US MP on long-term yields, although their composition is different. As was the case for domestic MP events, we see a strong positive impact on RN rates, partly offset by a negative movement in TP.

4. Interpreting US MP spillover channels

Table 2 documents that, while the effects of US MP shocks to overall long-term yields is quantitatively similar across DEV and EME groups, the composition of yield changes differ, suggesting in principle different underlying spillover mechanisms. This section explores alternative explanations to account for these patterns.¹³

Two main hypotheses are generally mentioned as possible explanations for the comovement between US MP and international yields. According to the first, yield comovement during FOMC meetings could reflect an adjustment

¹³There is little evidence in the current literature to help narrow down the potential mechanisms behind the international transmission of interest rates. Bauer and Neely (2014) study the effects on foreign yields of LSAP's in the US, including a small sample of advanced economies and distinguishing between RN rates (which they dub the signaling channel), and TP. However, they do not investigate the economic mechanisms underlying their results.

of financial markets to the revelation of US macroeconomic conditions, potentially correlated with those of other countries. Under this *information channel*, the reaction of foreign yields anticipates MP moves in these countries due to commonality in underlying conditions, and should therefore not be interpreted as a spillover in the causal sense.

A second mechanism, which we refer to as the *exchange rate channel*, points to a more causal effect of US MP on the decision of other central banks. Under this mechanism, MP abroad might partially follow the Fed to avoid currency movements arising from interest rate differentials. Such response could be motivated by inflationary pressures from exchange rate pass-through and/or trade balance considerations. Sections 4.1 and 4.2 investigate these two hypotheses and provide additional evidence to establish their relative merits as possible explanations behind our results. Section 4.3 discusses the connection of our results with the broader international finance literature.

4.1. The information channel

Economic fundamentals –inflation, activity and/or unemployment– may be correlated between the US and other countries. If, in addition, FOMC meeting are times where information about US fundamentals is revealed to the markets, then one could expect MP rates in other countries to be correlated with Fed decisions. If this mechanism, which we refer to as the *information channel*, dominates the international transmission of US MP documented above, then such transmission should not be regarded as a spillover in the causal sense, but merely as comovement reflecting common underlying economic trends. To investigate the relevance of this channel, one must document i) whether there is a significant degree of comovement between US and other countries’ fundamentals, and ii) whether information about US fundamentals is indeed revealed at FOMC meetings.

The first condition has found support in the evidence. For much of the post financial crisis period, the US and other advanced economies –in particular the Eurozone, Japan, and the UK– displayed similar patterns of persistently low inflation and activity. More formally, Jotikasthira, Le, and Lundblad (2015) document that the observed comovement between yield curves in the US and other advanced countries’ (Germany and the UK) depend on common underlying factors. Specifically, interest rates depend on a set of macro variables, and those variables in Germany and the UK depend on both a global factor as well as a US factor, particularly so for inflation.

More problematic is to find support for the second condition –the revelation of fundamentals during FOMC meetings–, since we have chosen the event study around FOMC days precisely because these are days in which the main event is the meeting itself, having zero overlap with US economic releases and minimal overlap with events in other countries (see Table B.11, Appendix B). It is not obvious therefore how an informational mechanism would play out within our particular identification strategy. One possibility is that the market learns something about the state of the economy from the FOMC minutes that could not be anticipated from the processing of publicly available economic releases accumulated up to that point. This interpretation relies on some form of superior analysis or insight in the way the Fed processes commonly known information.

Several papers have formally studied whether Fed forecasts of macroeconomic variables can beat the market in a consistent fashion. While there is some evidence of forecasting superiority by the Fed in older studies, more recent

papers document a narrowing of this advantage post 2000.¹⁴ One could still argue the FOMC minutes may provide relevant signals (in the Bayesian sense) that are incorporated in market expectations as long as they have some forecasting power –whether or not it beats market forecasts. We now present two pieces of evidence that tend to downplay the role of this particular channel.

The first evidence is based on comparing the elasticity of international yields to US short-term rates in days of FOMC announcement compared to other days. Hanson and Stein (2015) argue that non-FOMC days should have a comparably higher share of macro news, vis-à-vis Fed’s reaction-function news (what the Fed will do about the macro news in terms of policy). Conversely, while FOMC days could still reveal macro information, they should have a relatively larger share of reaction-function news. Therefore, if the elasticity of long-term rates to short-term rate movements around FOMC days is driven by macro news, this elasticity should be even stronger during non-FOMC days. They find the opposite.

Based on a similar idea, we calculate the elasticity of long-term rates abroad to changes in US 2-yr yields around specific US macroeconomic release dates, including inflation (CPI), activity (IP), and unemployment announcements –the δ_n^h coefficients in equation (1). Notice that this is an even starker comparison than the one documented by Hanson and Stein (2015), since we select specific US macroeconomic release dates as a benchmark for comparing the elasticities with respect to FOMC days, whereas they use all non-FOMC days as control. Table 5 shows the results. For DEV, all US macroeconomic release dates show a significant comovement between US 2-yr and foreign 10-yr yields (with the bulk of the effects acting through the RN component), but the point estimates are all below the corresponding effects of US MP shocks reported in Table 2. In fact, difference tests reveal that the transmission of US short-term rates to DEV long-term yields is in general significantly larger during FOMC meetings than during US macroeconomic releases. The only exceptions are unemployment releases in the first half of the sample, and activity in the second part of the sample, where the larger coefficient associated with US MP shocks is not statistically significant at 5% confidence levels.

For EME countries, the effect of changes in the US 2-yr treasury around macroeconomic releases is generally not significant, with a few exceptions where small effects are found. Not surprisingly, we find that the impact of US MP on foreign bond yields is significantly higher than the corresponding effect of US macroeconomic releases.

This evidence is thus not supportive of the informational channel. Following the argument in Hanson and Stein (2015), the fact that international yields comove less with US interest rates during US economic releases (days with a larger share of US macro news) than during FOMC meetings suggests that the main driving force between such comovement must be unrelated to the revelation of US macroeconomic fundamentals.

¹⁴Romer and Romer (2000) document superior performance of Fed forecasts pre-1991, while Gavin and Mandal (2003), and Gamber and Smith (2009), find a deterioration in forecasting advantage when extending the sample up to the early 2000’s. Similarly, D’Agostino and Whelan (2008) find that extending the sample leads to forecasting superiority by the Fed only on very short-term (within the quarter) projections of inflation, but not on other macroeconomic variables or forecast horizons.

TABLE 5: Response of 10-yr yields during US economic releases

| a) DEV | Full sample | | | Pre Oct. 2008 | | | Post Oct. 2008 | | |
|--------------|---------------------|---------------------|----------------------|---------------------|---------------------|----------------------|---------------------|---------------------|-------------------|
| | 10-yr yield | RN | TP | 10-yr yield | RN | TP | 10-yr yield | RN | TP |
| US Inflation | 0.186*** (0.028) | 0.129*** (0.035) | 0.057 (0.036) | 0.209*** (0.033) | 0.173*** (0.044) | 0.036 (0.044) | 0.101** (0.049) | 0.031 (0.050) | 0.069 (0.054) |
| US Activity | 0.227*** (0.024) | 0.257*** (0.036) | -0.030 (0.038) | 0.179*** (0.027) | 0.231*** (0.042) | -0.052 (0.039) | 0.335*** (0.060) | 0.313*** (0.069) | 0.022 (0.093) |
| US Unempl. | 0.305*** (0.015) | 0.361*** (0.021) | -0.056*** (0.022) | 0.307*** (0.018) | 0.376*** (0.026) | -0.069*** (0.027) | 0.307*** (0.026) | 0.320*** (0.036) | -0.012 (0.033) |

| b) EME | Full sample | | | Pre Oct. 2008 | | | Post Oct. 2008 | | |
|--------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|--------------------|-------------------|--------------------|
| | 10-yr yield | RN | TP | 10-yr yield | RN | TP | 10-yr yield | RN | TP |
| US Inflation | -0.055 (0.063) | -0.011 (0.037) | -0.044 (0.073) | -0.027 (0.075) | -0.036 (0.047) | 0.009 (0.086) | -0.174* (0.105) | 0.055 (0.056) | -0.230* (0.132) |
| US Activity | 0.037 (0.054) | 0.038 (0.049) | -0.001 (0.064) | 0.006 (0.064) | 0.056 (0.062) | -0.050 (0.078) | 0.022 (0.100) | -0.045 (0.063) | 0.067 (0.104) |
| US Unempl. | 0.051* (0.031) | 0.036* (0.021) | 0.015 (0.038) | 0.042 (0.040) | 0.046* (0.027) | -0.004 (0.049) | 0.085** (0.040) | 0.023 (0.029) | 0.062 (0.050) |

The table shows the impact of US economic releases, corresponding to the δ_n^h coefficients of equation (1). The regression is estimated separately for each group of countries: DEV and EME. Standard errors computed using Newey-West correction up to 40 lags (reported in parentheses). *** p-value < 1%, ** p-value < 5%, and * p-value < 10%.

The second piece of evidence we present is based on testing directly whether yield changes during FOMC meetings affect macroeconomic variables in other countries.¹⁵ Here it is important to recognize that, beyond a signaling channel of future macroeconomic conditions, US yield changes may also affect macroeconomic conditions in a causal manner through tighter policy. But notice that these channels are, a priori, associated with opposite signs: while the signaling channel suggests a positive correlation between US yield changes and future macro conditions (i.e., the Fed is tightening policy because it anticipates better macro performance in the US, in turn correlated with activity and inflation abroad), the causal effect predicts a negative relation – a tighter Fed policy, all else equal, is contractionary for other economies, as has been widely documented.¹⁶

To test this hypothesis we need to adjust to a monthly-frequency empirical strategy to fit in the frequency of macroeconomic releases. We compute the monthly change in the 2-yr US yield and separate it into two components: the change around the FOMC meeting of that respective month (the same measure of US MP shock as above), and the difference between the total change in the rate during the month and the FOMC component. The idea is that the first component captures the surprise component in Fed policy during the month, while the second component incorporates all other information that affected interest rates during the month.¹⁷ That is, at each month t where

¹⁵We thank the referee for suggesting this test.

¹⁶See Kim (2001), and Canova (2005), among others.

¹⁷A related approach is followed by Bernanke and Kuttner (2005), who study the dynamic effects of the surprise component of FFR changes on equity returns using a VAR approach at monthly frequency (see section II of their paper).

there is an FOMC meeting, we have $\Delta US\ 2YR_t = FOMC_t + Rest_t$. We then regress different leads of activity and inflation in the countries included in each of our DEV and EME samples using monthly panel regressions. Specifically, we estimate the following model:

$$x_{j,t+h} = \alpha + \beta_1 * FOMC_t + \beta_2 * Rest_t + \gamma * x_{j,t} + \varepsilon_{j,t+h}, \quad (5)$$

where $x_{j,t+h}$ correspond to annual growth rates of realized macroeconomic variables at horizon $t+h$ for each country j (activity and inflation, depending on the regression). Table 6 summarizes the results. We find that increases in US 2-yr rates have a negative effect on future activity and inflation abroad, for both components of the overall change in yields. This suggests that the impact of higher US interest rates on foreign activity and inflation work predominantly through the standard channel –a higher interest rates in the US is contractionary for other countries, consistent with the literature on the international real spillovers of US MP.

Altogether, the evidence presented in this section suggests that, while impossible to completely rule out, the informational channel is unlikely to be the main driver behind the observed comovement between US 2-yr yields and international bond yields at longer maturities. We remark again that the evidence presented here should not be interpreted as against commonality in economic fundamentals between the US and other economies –well documented in other studies–, but merely against the interpretation that FOMC meetings are episodes where significant news about such fundamentals are revealed to the markets.

4.2. The exchange rate channel

By affecting the relative yield of dollar-denominated instruments, US MP drives changes in portfolio positions between US and international assets. In particular, an expansionary US MP shock will, for a given exchange rate, increase the demand for foreign bonds. Within the standard Mundell-Fleming paradigm, the equilibrium response in foreign yields and exchange rates will depend, in turn, on the reaction of foreign central banks. The more other central banks follow the Fed, the narrower the resulting yield differential and the more contained the appreciation of their currencies. We will refer to the effects of US MP shocks on foreign yields that result from this mechanism as the *exchange rate channel*.

As the evidence in section 3 suggests however, the adjustment not only takes place through changes in expected foreign MP (the RN channel), as there are relevant movements in bond term premia. Indeed, several recent papers have emphasized the “risk-taking” channel of US MP. According to this mechanism, an expansionary stance of US MP drives a search for yields in other assets, including longer-maturity US treasuries and higher risk securities (corporate bonds, MBS products), as well as foreign assets.¹⁸ The addition of term premia as a margin of adjustment

¹⁸See Hanson and Stein (2015), Krishnamurthy and Vissing-Jorgensen (2011), Bruno and Shin (2015), and Rey (2015). The risks being taken through larger international positions include currency risk (Gabaix and Maggiori, 2015) as well as default risk in the case of emerging countries.

TABLE 6: Response of international macroeconomic variables to US monetary policy

| a) DEV | | | | | | | | |
|--------|---------------|-----------|----------------|---------|---------------|-----------|----------------|--------|
| h | Inflation | | | | Activity | | | |
| | Pre Oct. 2008 | | Post Oct. 2008 | | Pre Oct. 2008 | | Post Oct. 2008 | |
| | FOMC | Rest | FOMC | Rest | FOMC | Rest | FOMC | Rest |
| 1 | -0.367** | 0.236*** | -0.046 | 0.100 | -3.004** | 0.219 | 3.353 | -1.999 |
| 2 | -0.062 | 0.170** | -0.083 | 0.350** | -2.274 | 1.349*** | -2.901 | 0.465 |
| 3 | 0.094 | 0.083 | -0.158 | 0.273 | -5.219*** | -0.505 | 0.603 | 1.830 |
| 4 | -0.026 | -0.107 | -1.099 | 0.281 | -3.682** | 1.913*** | 0.455 | 0.145 |
| 5 | -0.106 | -0.192** | -0.453 | 0.209 | -5.684*** | 0.301 | 0.096 | 1.867 |
| 6 | -0.460** | -0.305*** | -0.311 | 0.202 | -4.750*** | -0.654 | 8.753 | 3.771 |
| 7 | -1.141*** | -0.391*** | -0.753 | 0.158 | -4.988*** | -0.223 | 1.181 | -1.040 |
| 8 | -2.143*** | -0.427*** | -0.538*** | 0.221 | -4.967** | -2.338*** | 4.017 | 1.526 |
| 9 | -1.649*** | -0.252*** | -0.440** | 0.135 | -5.171*** | -1.904*** | 6.281 | 4.161 |
| 10 | -0.516* | -0.078 | -1.288** | 0.283* | -3.677** | -1.151 | 1.643 | 2.021 |
| 11 | 0.140 | -0.105 | -1.290* | 0.139 | -1.407 | -0.977* | -4.176 | 3.514* |
| 12 | -0.082 | -0.031 | -1.381* | -0.039 | 1.932 | -0.041 | -6.630 | -1.564 |

| b) EME | | | | | | | | |
|--------|---------------|----------|----------------|----------|---------------|-----------|----------------|-----------|
| h | Inflation | | | | Activity | | | |
| | Pre Oct. 2008 | | Post Oct. 2008 | | Pre Oct. 2008 | | Post Oct. 2008 | |
| | FOMC | Rest | FOMC | Rest | FOMC | Rest | FOMC | Rest |
| 1 | -0.066 | 0.338*** | 1.031 | -0.039 | -4.509** | 0.155 | -14.099*** | -2.041 |
| 2 | -0.035 | 0.375*** | 1.629 | 0.782*** | -2.249 | 2.384*** | -7.534 | -4.115*** |
| 3 | -0.191 | 0.385** | 1.063 | 0.757** | -6.189*** | -0.911 | -6.714* | -0.785 |
| 4 | -0.661 | 0.126 | 1.074 | 0.519 | -3.746** | 2.061*** | -14.261*** | -3.400** |
| 5 | -1.256*** | -0.124 | 1.091 | 0.605 | -7.087*** | 0.458 | -14.949*** | -3.970*** |
| 6 | -1.533*** | -0.309 | 0.941 | 0.686 | -0.076 | -1.110* | -0.209 | -0.815 |
| 7 | -1.555*** | -0.413* | 0.132 | 0.148 | -4.683** | -0.567 | 4.840 | -1.473 |
| 8 | -2.003*** | -0.398* | 0.989 | 0.397 | -3.023 | -3.129*** | -2.076 | -0.503 |
| 9 | -2.209*** | -0.357* | -0.037 | 0.466 | -6.318*** | -1.464** | -0.212 | -1.357 |
| 10 | -1.485** | -0.234 | -2.900* | -0.042 | -1.867 | -0.813 | 12.929*** | -0.817 |
| 11 | -0.363 | -0.004 | -1.873 | -0.108 | 2.743 | 0.043 | -3.996 | 2.279** |
| 12 | -0.397 | -0.021 | -2.329 | -0.194 | 7.329*** | 1.268* | 3.340 | 0.235 |

The table reports the impact of changes in the components of the US 2-yr rates defined in equation (??) for a given month (in bp), in effective inflation and activity data h -months ahead (also in bp) –the β_1 and β_2 coefficients in equation (5). Standard errors computed using Newey-West correction up to 40 lags (reported in parentheses). *** p-value < 1%, ** p-value < 5%, and * p-value < 10%.

makes the underlying transmission mechanisms less straightforward than in the standard Mundell-Fleming model. In particular, it is not obvious whether the relevant interest rate differential behind exchange rate pressures are expected MP rates (the RN component) or overall yields, nor why the reaction in yields components differs across country groups.

To provide a coherent interpretation of the *exchange rate channel* in the context of our previous results, Appendix A presents a model about the international transmission of US MP that extends the framework developed in Blanchard, Adler, and Carvalho Filho (2015). In that paper, imperfect substitutability between international assets drives capital flows across countries in response to interest rate differentials. Their analysis stresses how two main tools used by central banks to confront flows –standard MP and (sterilized) exchange rate interventions (FXI henceforth)– have different effects on interest rates, exchange rates, and the resulting capital inflows in equilibrium. To illustrate, consider the case of a capital inflow into country- j (for example, as a response to an expansionary US MP shock). If the central bank remains inactive, capital inflows that respond to interest differentials will be large, and so will be the appreciation of the domestic currency. In contrast, a MP response that narrows the interest rate differential would contain inflows and exchange rate pressures. Yet the central bank could confront the same situation through direct FXI (buying USD in this case), and may in principle control both exchange rate and short-term interest rate movements –to the extent that sterilized interventions have meaningful effects on the exchange rate. However, the authors show that such policy response will increase the resulting capital inflows in equilibrium, as the market stabilization mechanism that would normally act through a currency appreciation (and the ensuing expected depreciation) is inhibited by the intervention.

Our model extends this framework by including a long-term bond market in each country. This allows us to study the effects of US MP shocks on interest rates at longer maturities, as well as their RN and TP components. In the US bond market, long-term yields are connected to short-term policy rates both through RN rates and term premia, where this last term is influenced by a risk-taking factor. This risk-taking factor is in turn a negative function of US MP. The model assumes that overall capital inflows to other countries depend endogenously on interest rate differentials against the US in both short and long-term bonds. In particular, there are foreign investors in the long-term bond market whose demand is a positive function of yield differentials against the US, net of the expected depreciation of the domestic currency. Implicit in this assumption is the notion that US and international assets are imperfect substitutes, and that lower yields in US bonds incentivize larger risk-taking in foreign bonds. Also, MP in the receiving country responds to the exchange rate (i.e., is reduced following a currency appreciation against the USD), which can be rationalized from inflationary pressures (exchange rate pass-through) or trade balance concerns. In addition, the central bank may choose to intervene the FX market by buying/selling USD against capital inflows/outflows. The equilibrium of the model is pinned down by a balance of payments equilibrium condition in which capital inflows net of FXI must finance the trade balance deficit. In the equilibrium, the main objects of interest in the model are linear functions of US MP shocks.

We now briefly summarize the main results of the model, their implications for interpreting the evidence presented in Section 3, and the additional testable predictions they deliver (which we test below). Following a negative US MP shock that increases the global risk-taking factor, capital flows into the US and country- j 's long-term bond markets. The equilibrium level of capital inflows is a function of country- j 's prevailing interest rate differentials in both short- and long-term securities. The effect on the main endogenous variables depends, in turn, on the reaction of policy in the receiving country, as summarized in propositions 1 and 2 in the model of Appendix A, which we reproduce here for convenience.

Proposition 1: *In reaction to an expansionary US MP shock, a higher sensibility of domestic MP to exchange rate fluctuations in country- j will imply a) a weaker appreciation of the currency against the USD; b) a weaker response of capital inflows; c) a stronger effect in the RN component of long-term yields, and d) an ambiguous effect in the TP component of long-term yields.*

The intuition for these results is as follows. In response to a more expansionary US MP, a central bank that reacts more to the ensuing appreciation of the currency by changing its own MP will tend to narrow interest rate differentials. This will contain capital inflows (part b) and reduce the resulting appreciation of the currency (part a). The effects on the long-term bond market are less obvious, however. Because foreign investors in the domestic bond market trade off positive interest rate differentials against an expected depreciation of the domestic currency going forward, the equilibrium response in long-term yields will be larger whenever the initial appreciation is contained by the action of domestic MP. Hence, overall yields fall by more. On the other hand, a stronger reaction of domestic MP mechanically implies a larger response of expected MP into the future, implying a larger elasticity of the RN component of long-term yields (part c). The effect on the TP component, which is the difference between yields and the RN component, is therefore ambiguous (part d).

Proposition 2: *In reaction to an expansionary US MP shock, a higher degree of central bank FXI in country- j will imply a) a weaker appreciation of the currency against the USD; b) a stronger response of capital inflows; c) a weaker effect on the RN component of long-term yields, and d) a stronger effect in the TP component.*

To understand this prediction, notice that if central banks intervene more, any given level of capital inflows will have a weaker effect on the domestic currency (part a). Since a currency appreciation (and the ensuing expected depreciation) in response to foreign inflows is a market force that tends to deter such flows, FXI strengthen flows precisely by dampening the corrective response played by exchange rates (part b). At the same time, a weaker impact on the exchange rate implies a more muted response of the standard MP tool (for a given value of the MP response parameter), reducing the sensitivity of the RN component (part c). But this implies that the adjustment in domestic long-term yields, which drop even more under FXI due to the surge in capital inflows, must be made to a larger extent by a compression of the TP component (part d).

The evidence presented in Section 3 documents only the reaction of yields and their components to US MP shocks, and thus allows at least two different interpretations in the context of the model. First, according to proposition

1, the relatively weak response of RN rates in EME might reflect a lower sensitivity of domestic MP to currency movements in these countries relative to DEV. However, such policy reaction would imply a stronger response of exchange rates to US MP shocks in EME. The alternative hypothesis is that central banks in EME are more prone to use FXI. According to proposition 2, this would also explain a weaker response of RN rates, but now as a result of lower effective currency movements and not from a lower sensitivity of domestic MP to exchange rate fluctuations. In addition, such response would amplify the response of capital inflows to EMEs, generating unambiguously larger movements in long-term yields concentrated in the TP component.

A priori, the predictions from proposition 2 seem to square better with the empirical evidence. Indeed, central bank interventions in FX markets have been widely documented for emerging economies, where managed floats are much more common than in developed countries. Table B.12 in Appendix B includes a survey of the available evidence about FX intervention activity for all the countries in our sample, confirming this view. Moreover, recent literature shows that, once endogeneity issues are properly addressed (using high frequency intra-day data), interventions appear to be an effective exchange rate stabilizing tool, at least in the short term.¹⁹ This prediction is also consistent with the evidence reported in Section 3, which shows a stronger response to US MP shocks in the TP component of yields for EME relative to DEV.

To further distinguish between these predictions, we now provide evidence of the two additional endogenous variables not addressed thus far, namely the reaction of exchange rates and capital flows around US MP events. Table 7 shows the impact of US MP shocks on exchange rates. The results are from a regression that replaces the interest rate variables of the left-hand-side of equation (1) with the cumulative NER response for each country over the same interval around the FOMC meeting. The NER is in units of foreign currency per USD, so an increase is a depreciation against the dollar. We find highly statistically significant effects of US MP shocks on exchange rates for the DEV sample. Specifically, a 10 bp US MP shock would depreciate the exchange rate in the DEV sample by about 75 bp in the full sample, an effect that has increased from 55 bp in the first half to 109 bp in the period post October 2008. For EME, we also find statistically significant effects, although of smaller magnitude. The full sample coefficient is just 33 bp, increasing from 16 to 66 bp when comparing both sub-periods. In short, exchange rates react in the anticipated direction in both groups of countries, although the effect is roughly half as large for EME.²⁰

¹⁹In fact, all but three countries in the DEV sample follow clean floating regimes, and within these exceptions, both the Czech Republic and Switzerland have used the euro as a reference currency, making them clean floaters against the USD. For further evidence about FXI activity and its effectiveness in emerging markets see Sarno and Taylor (2001), Levy-Yeyati and Sturzenegger (2003), Husain, Mody, and Rogoff (2005), Menkhoff (2010), Ghosh, Ostry, and Chamon (2016), and Fratzscher, Gloede, Menkhoff, Sarno, and Stöhr (2017).

²⁰Evidence of weaker exchange rate effects in emerging countries is also found by Hausman and Wongswan (2011). Using an event study methodology similar to ours (for an earlier time period), they find that the USD depreciates following a US MP easing, but the effect is statistically significantly only against developed currencies.

TABLE 7: US monetary policy and exchange rates

| | Full sample | Pre Nov. 2008 | Post Nov. 2008 |
|-----|-------------------|-------------------|--------------------|
| DEV | 7.50*** (0.45) | 5.47*** (0.39) | 10.92*** (0.83) |
| EME | 3.52*** (0.44) | 1.93*** (0.49) | 6.66** (0.77) |

The table reports the impact of a 1 bp change in the US 2-yr rate on nominal exchange rate changes during the MP event window. The exchange rate is defined as units of the domestic currency per USD (an increase is a depreciation against the dollar). The coefficients are in bp. Standard errors computed using Newey-West correction up to 40 lags (reported in parentheses). *** p-value < 1%, ** p-value < 5%, and * p-value < 10%.

One possible concern with this empirical strategy is that exchange rates could anticipate MP shocks. Previous research has pointed out that FFR futures tend to correctly anticipate most of Fed policy changes (Cochrane and Piazzesi, 2002). A recent paper by Karnaukh (2016) documents that, while the anticipation in FFR futures happen several days in advance, the exchange rate reacts only about 2 days prior to the actual change (when the Fed tightens policy, the USD appreciates, and vice-versa). If exchange rates react in anticipation of our MP events, our 2-day window centered at the meeting could miss some of the action, and the results from the previous table would be misleading about the overall effects of US MP on foreign currencies.

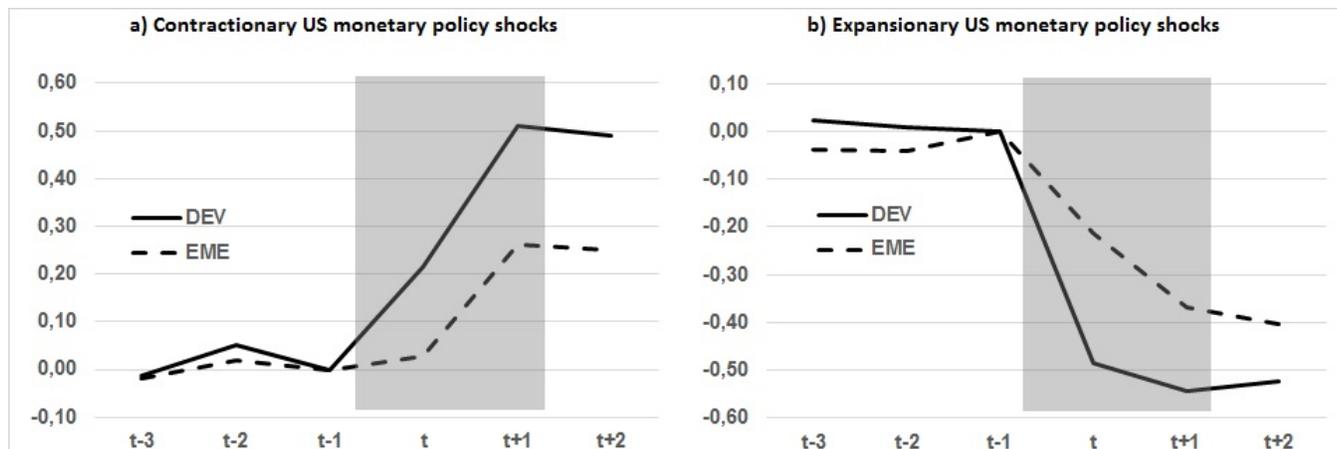
To address this concern, Figure 2 plots the cumulative reaction of the USD against the currencies in each country group over a wider window range (with respect to its value at the start of the window, $t-1$). Panel a) plots the average reaction over all episodes in which the US MP shock is positive, while panel b) presents the results for negative shocks (the effects on exchange rates are not normalized by the MP shock, so they should not be interpreted as elasticities, as in Table 7). Consistent with the coefficients in Table 7, the dollar appreciates for positive US MP shocks, and vice-versa. Crucial for our concern, the figure shows that prior to the beginning of the episode there is virtually no reaction in exchange rates. This is to be expected given the design of our event study, where MP shocks are defined as movements in short-term rates within the narrow window around FOMC meetings. Since this definition of MP shocks are, by construction, not anticipated by bond prices, they are not priced in by exchange rates either.²¹

Turning to flows, we run an event-study panel regression similar to the baseline exercise but using as dependent variable the net fund inflows into fixed-income securities for each country in the sample. We use EPFR data at weekly frequency, so the identification is less clean in this exercise than in the baseline regressions.²² We define the US MP surprise as the change in 2-yr treasury yields around the week of the FOMC meeting and compute the net

²¹We thank the anonymous referee for suggesting this test. To formalize the results presented in Figure 2, we run a similar regression but using a wider window of up to 5 days earlier than in the baseline regression, finding virtually identical cumulative effects on exchange rates. For space considerations we do not report this results here, but they are available upon request.

²²The data covers all fixed-income flows, including government and corporate bonds, as well as other fixed-income securities.

FIGURE 2: Exchange rate movements around US MP shocks



The figure plots the cumulative response (in percentage) of nominal exchange rates around FOMC meetings (with respect to its value at the close of day $t-1$), measured as domestic currency per USD (an increase is an appreciation of the dollar). Values correspond to simple averages across all events in the complete sample within a country group. We split episodes into positive (panel a) and negative (panel b) US MP shocks.

flows that occurs during the corresponding week. We use flows in levels, as well as normalized by nominal GDP and the value of bonds outstanding to control for the size of the corresponding fixed-income market.²³ Because systematic data on portfolio inflows is generally not available for the earlier sub-sample, we present results for the post October 2008 period only.

TABLE 8: US monetary policy and fixed-income flows

| Units | Deflator | DEV | EME |
|---------|-----------------|------------|-----------|
| MM USD | None | -154.971** | -92.682** |
| percent | GDP | -0.016** | -0.019* |
| percent | Government Debt | -0.041* | -0.057** |

The table reports the impact of a 1 bp change in the US 2-yr yield in the week of each FOMC meeting, on net fixed income flows using weekly data from EPFR. The regressions include year-month fixed-effects. Standard errors computed using Newey-West correction up to 40 lags (reported in parentheses).*** p-value < 1%, ** p-value < 5%, and * p-value < 10%.

The main results of this exercise are shown in Table 8. The effect of US MP shocks on portfolio flow levels is significant for both groups of countries, and actually larger for DEV. However, flows normalized by either GDP or amount of bonds outstanding reveal that the relative effects on flows is larger for EME, in particular when using bonds outstanding as deflator.²⁴

²³We use data on the stock of government debt denominated in domestic currency from the BIS: <http://www.bis.org/statistics/totcredit.htm>.

²⁴Ideally, flows should also be normalized by measures of bond market liquidity, which unfortunately are not available in a systematic manner for our sample. Arguably, adjusting for liquidity should reinforce the conclusions, to the extent that fixed-income markets in

This additional evidence helps drawing a more coherent interpretation about the mechanisms underlying the joint behavior of exchange rates, capital flows, and long-term yield components in reaction to US MP shocks. Consistent with proposition 2, the stronger reaction of the RN component in DEV and the dominance of the TP component in EME in response to US MP shocks seem to reflect different policy responses. In particular, more pervasive FXI in EME imply a more muted response of the exchange rate but an amplified response of capital flows and the TP component of long-term yields in response to US MP shocks. In the case of DEV, the absence of FXI is consistent with a stronger effect on the exchange rate, a weaker effect on flows, and a reaction of long-term yields concentrated in the RN component.

A natural question that arises is why some countries find it desirable and/or feasible to choose FXI as a policy response, while other countries –mostly developed economies, as documented in table B.12 in Appendix B– follow clean floats. Answers to this question can be found in several papers that study the predominance and effectiveness of FXI policies in different countries. Ghosh, Ostry, and Chamon (2016) conjecture that both the desirability and the feasibility of managing the exchange rate through sterilized interventions might differ between emerging and developed countries. Regarding their desirability, they note that exchange rate fluctuations tend to have larger macroeconomic effects in emerging countries for reasons that include more prevalent borrowing in foreign currency and financial markets with less scope for effective currency hedging. The resulting currency exposure of balance sheets in the financial and real sectors can prove highly disruptive in episodes of large exchange rate fluctuations. Besides from financial stability concerns, the evidence also generally documents a larger degree of exchange rate pass-through to domestic prices for emerging countries, suggesting currency interventions are used by central banks in these economies to help achieve their inflationary goals.²⁵ These arguments provide a rationale for the resistance to clean floating exhibited by many EMEs, explaining why they might be inclined to seek both MP independence and exchange rate stability through sterilized FXI.

With respect to its feasibility, Ghosh, Ostry, and Chamon (2016) argue that the size of central banks' foreign reserves, relative to normal currency transaction volumes, is typically much larger in emerging economies. This suggest that, using a relatively small fraction of their balance sheets, central banks in these countries can have a meaningful impact in the value of their currencies through direct FX interventions. For developed economies, in contrast, cross-border flows are likely to respond much more strongly to interest rate differentials against the US given the closer degree of asset substitutability. This implies that the size of interventions needed to make even a minor dent on the exchange rate may simply be too large to make it a viable option. This argument also features prominently in earlier papers such as Rogoff (1984) and Dominguez (1990), among others.

developed countries are generally viewed as more liquid.

²⁵See Bussière, Delle Chiaie, and Peltonen (2014), and Carranza, Galdon-Sanchez, and Gomez-Biscarri (2009).

4.3. Discussion

We now relate our findings with two important strands of literature in international finance. The first is the relation with the Mundell-Fleming paradigm as a benchmark to understand the effects of changes in international interest rates on domestic nominal and real variables in the presence of imperfect capital mobility. We briefly highlight the main differences between the predictions of that model and our framework regarding the effects of policy choices by central banks in dealing with international MP shocks. The second is the literature documenting the failure of the UIP condition –the so called forward discount puzzle. We briefly review some of its main findings, emphasizing the consistency with our results and the implications for the spillover mechanisms in our model.

In its simplest form, the Mundell-Fleming model with imperfect capital mobility predicts that a contractionary MP shock in core economies will affect nominal and real variables in a particular country depending on the reaction of its monetary authority. If the domestic central bank moves the MP rate one-to-one, the model predicts a complete stabilization of the exchange rate, but at a rather high cost to domestic output. In contrast, a central bank that keeps the domestic interest rate constant, and absent any form of FX intervention, will induce a pressure on capital outflows that will depreciate the domestic currency. In equilibrium, this improves the trade surplus. Flexible exchange rates hence play a role in cushioning part the negative effect of higher foreign interest rates by enhancing external demand. While the model in Appendix A does not include aggregate demand, its predictions on exchange rates align well with the standard framework in this case –the flexible exchange rate case– suggesting they would play a similar absorption role in a general equilibrium framework with endogenous output. Naturally, since our model includes a long-term bond market and allows for adjustment in term premia, it will deliver somewhat richer predictions regarding the effect of different MP actions at different segments of the yield curve. In its core predictions however, the general message regarding the tradeoffs involved in setting interest rates in response to MP spillovers abroad would not markedly differ from the standard model.

Where our model does depart from this framework is regarding the implications of FXI policies. If the domestic Central Bank wants to keep MP unchanged and at the same time limit the exchange rate adjustment through FXI, it must fully compensate for the capital outflow consistent with a lower interest rate differential. Since in the standard model aggregate demand depends only on short-term interest rates and exchange rates, this combination of policies would appear to be effective in stabilizing both nominal and real variables. In our model, the inclusion of a long-term bond market opens an additional channel that breaks this result. As discussed above (prediction 2 in section 4.2), while FXI can achieve both a stabilization of the MP rate and the exchange rate, they cannot control long-term yields. Our model highlights that stabilizing the currency through FXI will indeed amplify the effect of yield differentials on capital flows, thus enhancing the endogenous response of term premia. To the extent that aggregate demand depends on the whole structure of interest rates, this policy reaction will not be able to isolate the real economy from the external shock. This is the key mechanism that arises in our model which is absent from the Mundell-Fleming paradigm. We believe this additional mechanism should be added an important consideration

when evaluating the pros and cons of FXI policies.

Our results should also be contrasted with the literature documenting the forward discount puzzle, including Bansal and Dahlquist (2000) and Lustig, Roussanov, and Verdelhan (2014), among others. The latter show that a positive interest rate differential against the USD in a basket of advanced economies forecasts positive excess returns of these currencies. They propose a model in which high interest rates differentials against the USD occur when the US economy is hit by shocks which increase the volatility of the stochastic discount factor (SDF) relevant for US investors. In equilibrium, US investors require larger compensation for buying foreign bonds in these states of nature, which explains their higher returns.

At first glance, these studies appear to be in tension with the mechanism of our model. According to the forward discount puzzle, lower rates in the US are associated with higher, and not lower, risk premia in foreign currencies. One way of resolving this tension is by noticing that a low interest rate environment in the US and an expansionary US MP may well have different asset pricing implications. In line with the argument in Lustig, Roussanov, and Verdelhan (2014), a low interest rate environment may be the consequence of a relatively weak US macroeconomy, one in which US investors must be compensated with higher excess returns in order to invest in foreign instruments. But within this environment, a MP decision and/or communiqué by the Fed that is perceived more expansionary than what could be anticipated from economic fundamentals –the notion of MP shocks captured by our methodology– may well incentivize investors at the margin to build up larger positions in foreign securities offering higher returns, thus compressing foreign yields in the process.

This interpretation is also consistent with a USD that depreciates following an expansionary US MP shock. Our results of section 4.2, as well as evidence from a large literature that investigates the dynamic effects of US MP shocks on exchange rates, suggest that this is indeed the case.²⁶ While these papers robustly find exchange rate movements in such direction, their different identification strategies translate into varying results regarding the persistence of exchange rate dynamics –that is, whether the exchange rate exhibits immediate or delayed overshooting–, and thus into distinct predictions for the forward discount puzzle.

In short, as long as an expansionary US MP shock results in an inflow of capital into other countries –and that such inflow in turn depends on the policy reaction by the domestic monetary–, our qualitative predictions regarding the impact on long-term yields would remain largely unchanged, irrespective of whether the depreciation of the USD is sudden or gradual. We believe our empirical results, as well those of related papers that trace the effects of identified US MP shocks, are generally consistent with this view, and not in contradiction with the forward premium puzzle literature.

²⁶See Clarida and Galí (1994), Eichenbaum and Evans (1995), Kim and Roubini (2000), and Scholl and Uhlig (2008), among others.

5. Robustness

We now briefly describe different robustness checks we perform to our baseline econometric specification. For space considerations, we focus mostly on the coefficients related to US MP spillovers for overall 10-yr yields and their components. The main tables are included in Appendix C.

A first robustness check involves sample selection. To ensure that our main results are not driven by outliers, we run equation (1) iteratively excluding one country from each group (for example, we run the regressions for DEV without Japan, then put Japan back in and exclude Sweden, and so forth). These results are reported in Table C.13. The main conclusions remain unaltered, namely, US MP spillover effects are larger in the post October 2008 data, with similar point estimates for both DEV and EME samples. Moreover, these effects are much more tilted towards changes in the TP component in the case of EME.

The second set of robustness tests include different fixed effects in the panel regression of equation (1), as well as alternative windows for clustering standard errors (in this case, the differences arise only in the significance of point estimates). These results are reported in Table C.14. For ease of comparison, the third column of the table reproduces the spillover effects on long-term yields in the baseline regression from Table 2. The point estimates from using alternative fixed-effects change only marginally. While the significance of the coefficients drop in some specifications, it is always the case that the impact of US MP shocks on long-term yields is significant at 5% confidence levels, and its point estimate larger in the post October 2008 period. In the DEV sample, the effect of US MP shocks on RN rates is always associated with a larger point estimate than the effect on TP, and the significance of the former effect is always larger than a 5% p-value, while in some specifications the significance on TP falls below the 5% threshold. For EME, the point estimate on TP is always larger than the effect on the RN component (both significant at 5% across specifications). Thus, our main conclusions are maintained in these exercises.

A third robustness exercise deals with the methodology for decomposing yields into their RN and TP components. In Table C.15 we reproduce our main regression in Table 2 using the affine term-structure model of Joslin, Singleton, and Zhu (2011). Its main difference with the methodology of Adrian, Crump, and Moench (2013) is that the prices of risk associated with the factors driving the yield curve are estimated jointly with the parameters of the VAR in equation (2) using maximum likelihood.²⁷ Our main quantitative and qualitative results regarding the relative contribution of yield components for both the DEV and EME samples remain unaltered under this alternative decomposition methodology.

A fourth robustness check involves using a tighter window for defining the US MP shock. Indeed, the choice of the appropriate window involves non trivial tradeoffs: while shorter windows help identification by reducing overlap with other events, they also allow less time for the market to digest the relevant information that may be contained in FOMC minutes. Table C.16 reports the regression results of Table 2, but defining the US MP shock as the change

²⁷For further discussion of the differences between methodologies, see Section 2.5 of Adrian, Crump, and Moench (2013).

in the 2-yr US treasury between (the closing of) the day before and the same day of the FOMC meeting (as opposed to the day after the FOMC statement). Once again, the main qualitative results are maintained, with very minor differences in the point estimates.

As the final robustness exercise, we use alternative definitions of the interest rate chosen as a measure of US MP shocks. Table C.17 replicates the main regression results of Table 2, but using the change of the 1-yr treasury around the FOMC meeting, as opposed to the 2-yr treasury used in the baseline specification. In general, the point estimates are larger, but the qualitative results from the baseline regression remain unaltered. Essentially, the 1-yr and 2-yr treasury yields have a very strong correlation (0.76 in the complete sample), but the standard deviation of the former is about 60% of the latter in the post October 2008 period, which explains the larger estimated elasticities when the 1-yr rate is used. We prefer to use the 2-yr rate in our baseline regressions as it is more likely to capture the stance of US MP in the medium term. This is especially relevant post October 2008, when changes in the tone of Fed policy often did not involve revisions in market expectations about the FFR in the coming 12 months.²⁸ Other authors have used changes in the short-term FFR futures (typically the next month contract) as an alternative measure of MP shocks, either directly (as in Bernanke and Kuttner, 2005), or indirectly as instruments (Gertler and Karadi, 2015). Table C.18 contains the results from using 1 year-ahead FFR futures. Alternative 1 defines the MP shock as the change in the futures around the 2-day window, while Alt. 2 uses the change in futures as an instrument for the change in the 2-year yield. Results are quantitatively quite similar to the baseline regression.²⁹

6. Conclusions

We document the presence of significant US monetary policy spillovers to domestic bond markets in a sample of 24 countries, including 12 developed and 12 emerging market economies. We rely on an event study methodology where US monetary policy shocks are identified with the response of short-term US treasury yields within a narrow window of FOMC meetings, and trace its consequences on international bond yields using panel regressions. We decompose yields for each individual country into a risk-neutral component, which captures the expected evolution of short-term rates, and bond term premia, in order to better understand the channels underlying such transmission.

We find that US MP spillovers are statistically and economically significant for both developed and emerging market economies, and have become relatively larger after the global financial crisis. These spillovers are comparable in magnitude with the impact of other economic events that move international yield curves, including domestic monetary policy shocks and economic releases in each country.

²⁸This is particularly the case in some FOMC statements associated with *forward guidance*. For example, in the FOMC meeting of Aug. 2011, the press release stated: “The Committee currently anticipates that economic conditions... are likely to warrant exceptionally low levels for the federal funds rate at least through mid-2013.” At that meeting, the 1-yr rate fell only 3 bp, less than half the effect on the 2-yr rate. Furthermore, the 2-yr maturity is also used in other related studies, such as Hanson and Stein (2015) and Gilchrist, Yue, and Zakrajsek (2016), which makes results easier to compare.

²⁹We prefer the use of the 1-year ahead FFR future due to the aforementioned reason that shorter maturity contracts (as used by Bernanke and Kuttner, 2005) are essentially flat for a considerable part of the post-2008 sample.

While the size of spillovers is comparable across country groups, our results suggest they operate through different mechanisms, being concentrated in the risk-neutral component of yields (expected policy rates) in the case of developed economies, but predominantly on term premia for emerging countries. We test two alternative theories as possible explanations. The evidence presented is in general not supportive of an *information channel*, through which FOMC meetings reveal US economic fundamentals that might correlate with conditions abroad. We find more support for a *exchange rate channel*, according to which changes in Fed policy (as anticipated by the market) present a tradeoff to foreign central banks between narrowing interest rate differentials and experiencing exchange rate movements.

Importantly, the evidence suggests that developed and emerging countries react to this tradeoff with different tools. In particular, the patterns of relatively weak exchange rate movements, stronger sensitivity of capital inflows into domestic fixed-income markets, and a response of long-term yields tilted towards term premia, suggests emerging economies respond to US MP shocks and the ensuing capital flows by intervening the FX market, a behavior documented in numerous studies. Developed countries, on the other hand, display patterns associated with monetary policy responses under flexible exchange rate regimes –weaker capital flows, stronger exchange rate effects, and yield movements tilted towards risk-neutral rates. These results suggest that while FXI can be effective in stabilizing both short-term interest rates and exchange rates in some countries, they deflect the burden of adjustment into long term yields through endogenous changes in term premia.

With this evidence in hand, we conclude that bond markets around the globe are quite responsive to US monetary policy shocks. However, the evidence suggests that the effects on capital flows and domestic asset prices depend importantly on the set of tools through which foreign monetary authorities respond to these shocks, at least as expected by financial market participants. In particular, our results cast new light into the cost-benefit analysis behind the desirability of currency intervention policies.

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Appendix

Appendix A. A model of US MP Spillovers

This appendix develops a model to understand the international transmission of US MP and guide the interpretation of the results documented in the main text. The building blocks of the model follow Blanchard, Adler, and Carvalho Filho (2015), who consider the effects of international capital flows on domestic exchange and interest rates as a function of country-specific policies, including MP and (sterilized) foreign exchange interventions (FXI).

We augment that model to capture the following key features. First, we assume that US MP affects investment flows into fixed income markets through to a *risk-taking channel*, modeled as a price-inelastic demand component for long-term bonds in the US. Second, in each country, fund flows are allocated both in the short-term money market (at the MP rate) and in the long-term bond market, depending on the yield differential relative to its US equal maturity bond, net of expected fluctuations in the value of the domestic currency. As in Blanchard, Adler, and Carvalho Filho (2015), central banks react to shocks with two policy choices: standard MP (equal to the interest rate of short-term, domestic bonds) and (sterilized) FXI. In equilibrium, the nominal exchange rate, as well as yields and their components, are pinned down by the balance of payments equilibrium condition. We now provide the details of the model.

US MP and long-term US yields

US MP follows an autoregressive process, normalized at a long-run mean of zero,

$$i_t^* = m_t^*, \quad \text{with } m_t^* = \rho \cdot m_{t-1}^* + \varepsilon_t^*. \quad (\text{Appendix A.1})$$

US MP affects the evolution of a “risk-taking factor” z_t^* through

$$z_t^* = -i_t^*. \quad (\text{Appendix A.2})$$

Besides from the short-term bond that yields the MP rate i_t^* , there is a long-term bond market composed of h -year zero coupon bonds (i.e., $h = 10$ years in our empirical setup). The demand for US h -yr zero-coupon bonds has an endogenous component that depends positively on the yield (negatively on the price), and a price-inelastic component given by z_t^* . For simplicity, we normalize bond supply to zero, leading to a bond-market equilibrium condition

$$0 = \beta^* y_t^{*(h)} + z_t^*. \quad (\text{Appendix A.3})$$

The h -year yield in (Appendix A.3) and its decomposition into RN and TP components is then given by

$$y_t^{*(h)} = m_t^*/\beta^* = RN_t^{*(h)} + TP_t^{*(h)}, \quad \text{with} \quad RN_t^{*(h)} \equiv \frac{1}{h} E \left[\sum_{s=0}^{h-1} i_{t+s}^* | \Omega_t \right]. \quad (\text{Appendix A.4})$$

Ω_t denotes the information set, common to all agents, which consists of all current state variables. Using equations (Appendix A.1) through (Appendix A.4) we arrive at

$$RN_t^{*(h)} = m_t^* \left(\frac{1 - \rho^h}{h(1 - \rho)} \right), \quad \text{and} \quad (\text{Appendix A.5})$$

$$TP_t^{*(h)} = m_t^* \left(\frac{1}{\beta^*} - \frac{1 - \rho^h}{h(1 - \rho)} \right). \quad (\text{Appendix A.6})$$

Country- j block

The net private capital inflows (NPKI) into country j consist of foreign portfolio allocation into short-term (1-year) and long-term (h -year) bonds. Each flow is proportional to the bond yield differential with respect to its US equal-maturity counterpart, net of the expected depreciation rate of j 's currency over the corresponding horizon (we omit j -superscripts below for notational simplicity). Assuming the same elasticity of flows to yield differentials across maturities, the level of NPKI is given by

$$NPKI_t = \underbrace{\alpha (i_t - i_t^* - (e_t - E[e_{t+1} | \Omega_t]))}_{\text{allocation into short-term bond}} + \underbrace{\alpha (y_t^{(h)} - y_t^{*(h)} - (e_t - E[e_{t+h} | \Omega_t]))}_{\text{allocation into long-term bond}}, \quad (\text{Appendix A.7})$$

where e_t is the (log of) value of one unit of domestic currency (an increase in e_t stands for an appreciation against the US dollar).

The interest rate of the 1-year bond is set by the central bank according to the rule

$$i_t = -d \cdot e_t + m_t, \quad \text{with} \quad m_t = \psi \cdot m_{t-1} + \varepsilon_t. \quad (\text{Appendix A.8})$$

Equation (Appendix A.8) captures in a stylized manner the reaction function of domestic central banks to exchange rate movements. To stabilize the currency, central banks raise MP rates following a depreciation against the US dollar, and vice-versa. This stabilization motive, whose strength is captured by the parameter d , could reflect domestic MP reaction to inflationary pressures (due to exchange rate pass-through). It can also be rationalized as a direct exchange rate objective, due to trade balance and/or financial stability considerations.³⁰

³⁰Implicitly, the central bank adjusts the supply of short-term bonds in order to reach the desired one-period rate.

Besides traditional MP, the central bank in country j may choose to stabilize the currency by directly intervening the FX market in the opposite direction of the net private capital flows. Following Blanchard, Adler, and Carvalho Filho (2015), we assume an offset parameter ϕ , such that

$$FXI_t = -\phi \cdot NPKI_t, \quad (\text{Appendix A.9})$$

and we assume that the trade balance depends negatively on the value of the domestic currency,

$$CA_t = -\gamma \cdot e_t. \quad (\text{Appendix A.10})$$

We can now write the balance of payments equilibrium condition as

$$NPKI_t + FXI_t + CA_t = 0. \quad (\text{Appendix A.11})$$

We close the model with the domestic long-term bond market. We assume that domestic investors respond positively to long-term yields with elasticity β , irrespective of exchange rate dynamics (for example, pension funds targeting returns in domestic currency). Foreign investors can also purchase domestic long-term bonds. In particular, their demand responds positively to yield differentials against US long-term bonds, net of the expected depreciation of the domestic currency, with elasticity α (i.e., the long-term component of NPKI in equation (Appendix A.7)). This gives the following bond market-clearing condition:

$$0 = \beta \cdot y_t^{(h)} + \alpha \left(y_t^{(h)} - y_t^{*(h)} - (e_t - E[e_{t+h}|\Omega_t]) \right). \quad (\text{Appendix A.12})$$

Equation (Appendix A.12) states that an increase in the foreign demand for domestic bonds (due to a positive yield differentials against the h -year US bond) must be accommodated by a lower demand from domestic investors, inducing a fall in yields in equilibrium. This condition therefore links domestic yield movements with developments in the US long-term bond market.³¹

Equilibrium characterization

We now solve for the main objects of interest in our model, namely the exchange rate, long-term bond yields and their decomposition into RN and TP components, and the resulting equilibrium flows into fixed income markets as a function of the state variables. Because we are concerned only with the effects of US MP shocks, we focus on the special case where domestic MP shocks have zero variance. The relevant state variable in this case is thus only

³¹For simplicity, we have abstracted from local supply conditions as they are not at the core of the results we wish to highlight, although the model can be extended in this dimension with little extra complexity.

m_t^* .³²

Using (Appendix A.12) and (Appendix A.8) in the capital market equilibrium condition (Appendix A.11), we can solve for the exchange rate by iterating forward the time $t + s$ expectation of future exchange rates as a function of m_t^* . Letting $a \equiv \alpha/(\alpha + \beta)$ and $b \equiv \beta/(\alpha + \beta)$ denote the relative demand elasticity of domestic and foreign investors, we obtain

$$e_t = -m_t^* \left(\frac{(1 - \phi) \left(\alpha + a \frac{\beta}{\beta^*} \right)}{\gamma + \alpha(1 - \phi)(1 + d - \rho + b(1 - \rho^h))} \right). \quad (\text{Appendix A.13})$$

Intuitively, a tightening of US MP following an increase in m_t^* leads to a negative interest rate differential in both short- and long-term bonds. This leads to a retreat of flows which translates into a depreciation of the domestic currency (terms α and $a\beta/\beta^*$ in the numerator of the expression post-multiplying m_t^*).

We now use (Appendix A.13) in (Appendix A.11) to back out NPKI,

$$NPKI_t = -m_t^* \left(\frac{\gamma \left(\alpha + a \frac{\beta}{\beta^*} \right)}{\gamma + \alpha(1 - \phi)(1 + d - \rho + b(1 - \rho^h))} \right). \quad (\text{Appendix A.14})$$

NPKI follow the same logic described for the exchange rate. In particular, a tightening of US MP leads to negative foreign flows due to interest rate differentials. Indeed, the capital account equilibrium condition implies that NPKI must be equal to the exchange rate depreciation, multiplied by the ratio $\gamma/(1 - \phi)$, which accounts for the impact of the exchange rate on the trade balance, net of central bank interventions.

The domestic long-term bond market is solved by iterating forward the h -period expectation of e_{t+h} ,

$$y_t^{(h)} = m_t^* \left(\frac{a}{\beta^*} - \frac{(1 - \phi)(1 - \rho^h)a \left(\alpha + a \frac{\beta}{\beta^*} \right)}{\gamma + \alpha(1 - \phi)(1 + d - \rho + b(1 - \rho^h))} \right). \quad (\text{Appendix A.15})$$

Expression (Appendix A.15) shows that a tightening of US MP affects domestic long-term yields through two separate forces. The first is the direct effect of US MP on US long-term yields, which increase due to the contraction in the global risk-taking factor. Domestic yields must also rise in response to the fall in foreign demand. The second term is the offset implied by the currency depreciation, which is thereafter expected to appreciate and provide a positive return, partly dampening the impact on yields of the first element.

To further understand the impact on yield components, we iterate forward the expectations of future exchange rates

³²An extension of the model with domestic MP shocks is available upon request.

and domestic MP, which gives the RN component of h -year bond yields,

$$RN_t^{(h)} = m_t^* \left(\frac{d(1-\phi) \left(\alpha + a \frac{\beta}{\beta^*} \right)}{\gamma + \alpha(1-\phi)(1+d-\rho + b(1-\rho^h))} \frac{(1-\rho^h)}{h(1-\rho)} \right). \quad (\text{Appendix A.16})$$

The logic behind expression (Appendix A.16) is as follows. An increase in m_t^* raises US MP, which depreciates the domestic currency due to the impact on foreign flows. Domestic policy reacts to the depreciation of the currency by increasing rates in a proportion d of the contemporaneous depreciation. The ratio $(1-\rho^h)/(h(1-\rho))$ is the expected average effect on the domestic MP rate from a contemporaneous increase in m_t of one unit in response to the shock m_t^* .

To solve for the TP component in long-term yields, we subtract the RN component from (Appendix A.16) into the yield expression (Appendix A.15) to get

$$TP_t^{(h)} = m_t^* \left(\frac{a}{\beta^*} - \frac{(1-\phi)(1-\rho^h) \left(\alpha + a \frac{\beta}{\beta^*} \right)}{\gamma + \alpha(1-\phi)(1+d-\rho + b(1-\rho^h))} \left(\frac{a(h(1-\rho) + d) + d \cdot b}{h(1-\rho)} \right) \right) \quad (\text{Appendix A.17})$$

Expression (Appendix A.17) shows two terms post-multiplying m_t^* . The first comes from the direct effect of US MP on the US h -year yield, which increases due to the contraction in the risk-taking factor. All else equal, this leads to a retreat of foreign demand for domestic long-term bonds, raising domestic yields in a magnitude that depends on the relative elasticity of bond demand by foreign and domestic investors (parameter a). The second effect captures the response of expected domestic MP in reaction to the depreciation of the currency, acting as an offset to the increase in the term premium by raising the RN component in (Appendix A.16).

US MP spillovers: the role of country-specific characteristics

We now briefly describe how the main objects of interest in the model can be used to interpret the evidence presented in sections 3 and 4. In particular, inspection of equations (Appendix A.13) through (Appendix A.17) reveal several comparative statics regarding the impact of US MP shocks on endogenous model variables, as a function of country-specific characteristics.

While in principle all parameters of the country-specific bloc of the model can vary between economies, we will focus on the two parameters describing policy reaction: the response of traditional MP to exchange rate movements, d , and the degree of FXI, ϕ . The next two propositions highlight the comparative statics from varying these parameters, specifically how they affect the response of the main endogenous variables to US MP shocks.

Proposition 1: *In reaction to a more expansionary US MP, a higher sensibility of domestic MP to exchange rate fluctuations will imply a) a weaker appreciation of the domestic currency against the USD; b) a weaker response of capital inflows; c) a stronger effect in the RN component of domestic long-term yields, and d) a weaker effect in the*

TP component of yields whenever

$$\frac{\gamma + \alpha(1 - \phi)(1 - \rho + b(1 - \rho^h))}{\alpha(1 - \phi)} > ah(1 - \rho). \quad (\text{Appendix A.18})$$

The proof is immediate by taking the corresponding derivatives of the terms multiplying m_t^* in equations (Appendix A.13) through (Appendix A.17) with respect to d , the parameter capturing the response of domestic MP to exchange rate movements. Following a more expansionary US MP, a central bank that reacts more to the ensuing appreciation of the currency will tend to narrow interest rate differentials, thus containing the movement in the exchange rate (part a), since lower interest differentials keep capital inflows more contained (part b). Also, and by construction, a stronger reaction of domestic MP implies a larger response of expected MP into the future, implying a larger elasticity of the RN component of long-term yields (part c). The effect on the TP component is ambiguous, however, since a more contained response of the exchange rate implies that a larger effect in long-term yields is needed to accommodate the surge in foreign bond demand. When the inequality in expression (Appendix A.18) holds, the first effect dominates (i.e., the reaction of RN rates is relatively large), leading to a weaker overall elasticity of the TP component to US MP shocks.

Proposition 2: *In reaction to a more expansionary US MP, a higher degree of central bank FXI in country- j will imply a) a milder appreciation of the domestic currency against the USD; b) a stronger response of capital inflows; c) a milder effect on the RN component of long-term yields (through expected changes in domestic MP); and d) a stronger effect in the TP component of long-term yields.*

The proof of this proposition is also immediate by taking the derivative of the terms multiplying m_t^* in equations (Appendix A.13) through (Appendix A.17) with respect to ϕ . Intuitively, if central banks intervene more, any given level of NPKI has a milder effect on the domestic currency (part a). Since a currency appreciation (and the ensuing expected depreciation) in response to foreign inflows is a market force that tends to deter such flows, FXI by central banks strengthen flows precisely by dampening the corrective response played by the exchange rate (part b). At the same time, a weaker impact on the exchange rate implies a more muted response of the standard MP tool (for a given MP response parameter d), reducing the sensitivity of the RN component (part c). But this implies that the adjustment in domestic long-term yields must be made to a larger extent by a compression of the TP component (part d).

Appendix B. Economic indicators

This appendix provides further details on the construction of our dataset, and summarizes some basic descriptive statistics. Table B.9 lists the countries considered and the number of events for each category.

TABLE B.9: Countries and Economic Releases

| Code | Country | Classification | Number of Releases | | | |
|------|----------------|----------------|--------------------|-----|----------|-----|
| | | | MPM | CPI | Activity | Ump |
| USA | United States | DEV | 113 | 160 | 167 | 726 |
| AUS | Australia | DEV | 107 | 54 | 55 | 167 |
| CAD | Canada | DEV | 112 | 167 | 167 | 167 |
| CZE | Czech Republic | DEV | 131 | 167 | 167 | 0 |
| FRA | France | DEV | 165 | 167 | 167 | 33 |
| GER | Germany | DEV | 165 | 143 | 54 | 166 |
| ITA | Italy | DEV | 165 | 159 | 118 | 50 |
| JPN | Japan | DEV | 182 | 166 | 125 | 163 |
| NZL | New Zealand | DEV | 111 | 44 | 55 | 56 |
| NOR | Norway | DEV | 108 | 167 | 132 | 164 |
| SWE | Sweden | DEV | 91 | 167 | 147 | 108 |
| SWI | Switzerland | DEV | 48 | 167 | 50 | 167 |
| UKG | United Kingdom | DEV | 169 | 163 | 167 | 167 |
| CHI | Chile | EME | 167 | 164 | 164 | 165 |
| COL | Colombia | EME | 163 | 96 | 99 | 117 |
| HUN | Hungary | EME | 160 | 144 | 145 | 110 |
| IND | India | EME | 62 | 47 | 39 | 0 |
| IDO | Indonesia | EME | 133 | 150 | 49 | 0 |
| ISR | Israel | EME | 153 | 115 | 30 | 0 |
| KOR | Korea | EME | 166 | 126 | 142 | 79 |
| MEX | Mexico | EME | 108 | 217 | 167 | 134 |
| POL | Poland | EME | 148 | 167 | 167 | 166 |
| SOA | South Africa | EME | 85 | 167 | 120 | 23 |
| TWN | Taiwan | EME | 52 | 123 | 164 | 115 |
| THA | Thailand | EME | 80 | 95 | 43 | 0 |

This table shows the number of economic releases considered for each country, based on Bloomberg's Surveys. The country classification as developed/emerging economy is based on the criteria followed by the International Monetary Fund, United Nations, MSCI and DJI. Columns 4 to 6 show the number of monetary policy meetings (MPM), inflation releases (CPI), economic activity releases (Activity), and unemployment (Ump). A value of zero is reported when coverage by Bloomberg is not systematic.

Table B.10 shows the economic indicators used to identify macroeconomic release days, as described in subsection 2.2. The three columns show the sources for CPI, Activity, and Unemployment, for all countries, with the corresponding release frequency in parentheses. (Q): quarterly, (M): monthly, (B): bi-weekly and (W): weekly. N/A: not available.

TABLE B.10: Economic releases description

| | CPI | Activity | Unemployment |
|-----|---------------------------|---------------------------------|-------------------------------|
| USA | CPI Urban Consumers (M) | Industrial Production YoY (M) | Initial Jobless Claims SA (W) |
| AUS | CPI All Groups Goods (Q) | GDP YoY (Q) | Unemployment rate SA (M) |
| CAD | CPI YoY (M) | GDP All industries (M) | Unemployment rate SA (M) |
| CZE | CPI YoY (M) | Industrial Production YoY (M) | N/A (N/A) |
| FRA | CPI EU Harmonized YoY (M) | Industrial Production YoY (M) | Unemployment rate SA (M) |
| GER | CPI EU Harmonized YoY (M) | GDP YoY (Q) | Unemployment rate SA (M) |
| ITA | CPI EU Harmonized YoY (M) | Industrial Production YoY (M) | Unemployment rate SA (M) |
| JPN | CPI Nationwide YoY (M) | Industrial Production YoY (M) | Unemployment rate SA (M) |
| NZL | CPI All Groups (Q) | GDP YoY (Q) | Unemployment rate SA (Q) |
| NOR | CPI YoY (M) | Industrial Production YoY (M) | Unemployment rate SA (M) |
| SWE | CPI Headline YoY (M) | Industrial Production YoY (M) | Unemployment rate SA (M) |
| SWI | CPI YoY (M) | GDP YoY (Q) | Unemployment rate SA (M) |
| UKG | CPI EU Harmonized YoY (M) | Industrial Production YoY (M) | Claimant Count Rate SA (M) |
| CHI | CPI YoY (M) | Monthly Economic Index (M) | Unemployment rate SA (M) |
| COL | CPI YoY (M) | Industrial Production YoY (M) | Unemployment rate SA (M) |
| HUN | CPI YoY (M) | Industrial Production YoY (M) | Unemployment rate SA (M) |
| IND | CPI YoY (M) | GDP YoY (Q) | N/A (N/A) |
| IDO | CPI YoY (M) | GDP YoY (Q) | N/A (N/A) |
| ISR | CPI YoY (M) | GDP YoY (Q) | N/A (N/A) |
| KOR | CPI YoY (M) | Industrial Production YoY (M) | Unemployment rate SA (M) |
| MEX | Biweekly CPI (B) | Industrial Production YoY (M) | Unemployment rate SA (M) |
| POL | CPI YoY (M) | Industrial Goods & Services (M) | Unemployment rate SA (M) |
| SOA | CPI YoY (M) | Manufacturing Production (M) | Unemployment rate SA (Q) |
| TWN | CPI YoY (M) | Industrial Production YoY (M) | Unemployment rate SA (M) |
| THA | CPI YoY (M) | GDP YoY (Q) | N/A (N/A) |

Table B.11 presents the overlap frequency of US MP meetings with other events in the sample.

TABLE B.11: Economic releases overlap

| a) DEV | | | | | |
|-----------------|-------------|-----------|----------|--------------|-------|
| | Domestic MP | Inflation | Activity | Unemployment | Total |
| US MP | 3.69 | 4.57 | 3.24 | 3.98 | 7.08 |
| US inflation | 2.74 | 5.38 | 1.42 | 2.69 | 6.75 |
| US activity | 2.30 | 4.59 | 1.65 | 3.04 | 5.99 |
| US unemployment | 0.78 | 3.59 | 4.05 | 3.51 | 5.74 |
| b) EME | | | | | |
| | Domestic MP | Inflation | Activity | Unemployment | Total |
| US MP | 2.65 | 2.88 | 2.36 | 2.73 | 7.30 |
| US inflation | 3.48 | 3.64 | 4.17 | 0.79 | 6.43 |
| US activity | 2.54 | 5.14 | 3.74 | 0.20 | 6.19 |
| US unemployment | 3.29 | 2.72 | 2.79 | 2.63 | 6.12 |

The table shows the overlap frequency (in percentage points) between the number of domestic releases of the variable in the column and the corresponding events in the US, in each row. For example, 3.69% in column 1, row 1, equals the number of own MP summed across the 12 countries in the DEV sample which also occur during a US MPM window, divided by 113×12 country-episodes (where 113 is the number of US MPM, and 12 is the number of countries in each group included in the panel regressions).

Table B.12 presents different statistics to characterize the central bank FXI activity. Because many countries that actively intervene do not disclose information (Fratzscher et al., 2017), the statistics reported here will tend to underestimate the extent of FXI, particularly so for countries with managed floating regimes (classified here as “floating”).

TABLE B.12: Foreign exchange interventions

| Country | FX regime (IMF) | Regular FXI | Public FXI | Recent episodes | References |
|------------|------------------------|-------------|------------|-----------------|--------------------|
| DEV | | | | | |
| AUS | Free floating | No | No | November, 2008 | (7), (9), (10) |
| CAD | Free floating | No | Yes | September, 1998 | (7) |
| CZE | Stabilized arrangement | Yes | Yes | | (7) |
| FRA | Free floating | No | No | | |
| GER | Free floating | No | No | | |
| ITA | Free floating | No | No | | |
| JPN | Free floating | No | No | October, 2011 | (5), (6), (9) |
| NZL | Floating | No | No | June, 2007 | (3), (7) |
| NOR | Free floating | No | No | March, 2001 | (2), (7) |
| SWE | Free floating | No | No | | (7) |
| SWI | Floating | No | No | | (5), (7) |
| UKG | Free floating | No | No | March, 2011 | (7) |
| EME | | | | | |
| CHI | Free floating | No | Yes | January, 2011 | (1), (3), (7), (8) |
| COL | Floating | No | Yes | October, 2015 | (1), (3), (7), (8) |
| HUN | Floating | No | No | September, 2011 | (3), (4) |
| IND | Floating | No | No | January, 2013 | (4) |
| IDO | Floating | No | No | April, 2017 | (3), (4) |
| ISR | Floating | No | Yes | December, 2015 | (1), (3), (4), (7) |
| KOR | Floating | No | No | February, 2017 | (3), (4), (5) |
| MEX | Free floating | No | Yes | February, 2017 | (1), (3), (7), (8) |
| POL | Free floating | No | No | December 2011 | (3), (4), (7) |
| SOA | Floating | Yes | Yes | | (3), (4), (7) |
| TWN | Manage peg | No | No | February, 2017 | (5) |
| THA | Floating | No | No | December, 2012 | (3), (4) |

References: (1) Adler and Tovar (2014); (2) Alstadheim (2016); (3) BIS (2005); (4) BIS (2013); (5) Department of Treasury (2017); (6) Fatum (2015); (7) Fratzscher, Gloede, Menkhoff, Sarno, and Stöhr (2017); (8) Fuentes, Pincheira, Julio, Rincon, Garcia, Zerecero, Vega, Lahura, and Moreno (2014); (9) Kearns and Rigobon (2005); (10) Newman, Potter, and Wright (2011)

Notes: FX regime corresponds to the International Monetary Fund arrangement (IMF, 2016). Regular FXI takes the value Yes if the country has an organized intervention schedule during the sample period, and No otherwise. Public FXI takes the value Yes if the country publishes information on actual interventions, and No otherwise. Recent episodes show information about FXI against the U.S. dollar only. CZE, SWE and SWI intervened during our sample period but against the euro.

Appendix C. Robustness

This appendix presents the results from the robustness exercises discussed in Section 5.

TABLE C.13: Effects of removing individual countries

| a) DEV | | | | | | |
|------------------|---------------|----------|-----------|----------------|----------|----------|
| Country excluded | Pre Oct. 2008 | | | Post Oct. 2008 | | |
| | 10-yr yield | RN | TP | 10-yr yield | RN | TP |
| AUS | 0.283*** | 0.403*** | -0.121*** | 0.426*** | 0.230*** | 0.196*** |
| CAD | 0.296*** | 0.376*** | -0.080** | 0.391*** | 0.218*** | 0.172*** |
| CZE | 0.303*** | 0.419*** | -0.116*** | 0.457*** | 0.260*** | 0.197*** |
| FRA | 0.291*** | 0.354*** | -0.063* | 0.428*** | 0.231*** | 0.197*** |
| GER | 0.294*** | 0.379*** | -0.085** | 0.414*** | 0.241*** | 0.174*** |
| ITA | 0.297*** | 0.381*** | -0.084** | 0.438*** | 0.259*** | 0.179*** |
| JPN | 0.319*** | 0.423*** | -0.105*** | 0.456*** | 0.252*** | 0.204*** |
| NZL | 0.276*** | 0.345*** | -0.069** | 0.432*** | 0.203*** | 0.229*** |
| NOR | 0.304*** | 0.419*** | -0.115*** | 0.439*** | 0.251*** | 0.188*** |
| SWE | 0.298*** | 0.404*** | -0.107*** | 0.424*** | 0.210*** | 0.215*** |
| SWI | 0.311*** | 0.401*** | -0.090** | 0.430*** | 0.252*** | 0.178*** |
| UKG | 0.296*** | 0.372*** | -0.076** | 0.416*** | 0.194*** | 0.222*** |

| b) EME | | | | | | |
|------------------|---------------|--------|---------|----------------|----------|----------|
| Country excluded | Pre Oct. 2008 | | | Post Oct. 2008 | | |
| | 10-yr yield | RN | TP | 10-yr yield | RN | TP |
| CHI | 0.189** | 0.020 | 0.169* | 0.591*** | 0.157*** | 0.434*** |
| COL | 0.141*** | 0.048 | 0.093 | 0.551*** | 0.148*** | 0.403*** |
| HUN | 0.217*** | -0.007 | 0.223** | 0.560*** | 0.114** | 0.446*** |
| IND | 0.194** | 0.013 | 0.181* | 0.562*** | 0.123** | 0.439*** |
| IDO | 0.203*** | 0.026 | 0.177* | 0.484*** | 0.126** | 0.358*** |
| ISR | 0.191*** | 0.021 | 0.170** | 0.577*** | 0.147*** | 0.430*** |
| KOR | 0.193** | 0.012 | 0.181* | 0.573*** | 0.137** | 0.437*** |
| MEX | 0.200*** | 0.016 | 0.184* | 0.520*** | 0.122** | 0.398*** |
| POL | 0.195** | 0.009 | 0.186* | 0.568*** | 0.173*** | 0.395*** |
| SOA | 0.200*** | 0.049 | 0.152* | 0.571*** | 0.120** | 0.451*** |
| TWN | 0.193** | 0.004 | 0.189** | 0.604*** | 0.139** | 0.465*** |
| THA | 0.199*** | 0.018 | 0.181* | 0.517*** | 0.121** | 0.396*** |

The table estimates (1) using alternative samples that iteratively remove individual countries. Standard errors computed using Newey-West correction up to 40 lags. *** p-value < 1%, ** p-value < 5%, and * p-value < 10%.

TABLE C.14: Alternative fixed effects and clusters

| Sample | yields | Baseline | a) DEV | | | | | |
|----------------|---------------|-----------|----------------------------|-------------|----------|-----------|----------|----------|
| | | | 0-yr yield | 10-yr yield | 0.291*** | 0.294*** | 0.294*** | 0.297** |
| Pre Oct. 2008 | 10-yr yield | 0.297*** | 0.291** | 0.291*** | 0.294*** | 0.294*** | 0.297** | 0.295*** |
| Pre Oct. 2008 | RN | 0.390*** | 0.387*** | 0.387*** | 0.388*** | 0.388*** | 0.390*** | 0.390*** |
| Pre Oct. 2008 | TP | -0.092*** | -0.097 | -0.097** | -0.094 | -0.094*** | -0.092 | -0.090** |
| Post Oct. 2008 | 10-yr yield | 0.429*** | 0.424** | 0.424*** | 0.438** | 0.438*** | 0.429** | 0.429*** |
| Post Oct. 2008 | RN | 0.234*** | 0.222** | 0.222*** | 0.225*** | 0.225*** | 0.234*** | 0.231*** |
| Post Oct. 2008 | TP | 0.196*** | 0.203* | 0.203** | 0.213* | 0.213** | 0.196* | 0.198** |
| Sample | yields | Baseline | b) EME | | | | | |
| Pre Oct. 2008 | 10-yr yield | 0.193*** | 0.182 | 0.182** | 0.197 | 0.197*** | 0.193 | 0.193** |
| Pre Oct. 2008 | RN | 0.019 | 0.015 | 0.015 | 0.019 | 0.019 | 0.019 | 0.019 |
| Pre Oct. 2008 | TP | 0.174** | 0.167 | 0.167* | 0.178 | 0.178* | 0.174 | 0.174* |
| Post Oct. 2008 | 10-yr yield | 0.557*** | 0.524*** | 0.524*** | 0.544*** | 0.544*** | 0.557** | 0.556*** |
| Post Oct. 2008 | RN | 0.136** | 0.145*** | 0.145*** | 0.139*** | 0.140*** | 0.136*** | 0.135*** |
| Post Oct. 2008 | TP | 0.421*** | 0.379** | 0.379** | 0.405** | 0.404** | 0.421** | 0.421** |
| Controls | | Baseline | Fixed effects and clusters | | | | | |
| FE | Country | N | N | N | Y | N | N | N |
| FE | Year | Y | N | N | Y | N | Y | Y |
| FE | Month | Y | N | N | N | N | N | N |
| FE | Country-Year | N | N | N | N | Y | N | N |
| FE | Country-Month | N | N | N | N | N | Y | Y |
| Cluster | Year | Y | N | N | Y | N | Y | N |
| Cluster | Month | N | N | Y | N | Y | N | Y |

The table estimates (1) using alternative fixed effects and windows for clustering standard errors. *** p-value < 1%, ** p-value < 5%, and * p-value < 10%.

TABLE C.15: Alternative term-structure decomposition

| | a) DEV | | | b) EME | | |
|-------------|---------------------|----------------------|---------------------|---------------------|--------------------|---------------------|
| | Full sample | Pre Oct. 2008 | Post Oct. 2008 | Full sample | Pre Oct. 2008 | Post Oct. 2008 |
| 2-yr yield | 0.254*** (0.024) | 0.317*** (0.029) | 0.150*** (0.037) | 0.154*** (0.040) | 0.102** (0.051) | 0.267*** (0.068) |
| 10-yr yield | 0.322*** (0.025) | 0.292*** (0.027) | 0.399*** (0.051) | 0.272*** (0.058) | 0.163** (0.066) | 0.556*** (0.102) |
| RN (10-yr) | 0.345*** (0.033) | 0.399*** (0.042) | 0.261*** (0.052) | 0.076** (0.034) | 0.045 (0.044) | 0.145*** (0.049) |
| TP (10-yr) | -0.023 (0.029) | -0.107*** (0.034) | 0.138*** (0.050) | 0.196*** (0.065) | 0.118* (0.070) | 0.411*** (0.120) |

The table estimates (1) using the term-structure decomposition of Joslin et al. (2011) for computing yield components. Standard errors computed using Newey-West correction up to 40 lags (reported in parentheses). *** p-value < 1%, ** p-value < 5%, and * p-value < 10%.

TABLE C.16: Alternative US MP shock: changes in 2-yr yields around a 1-day window

| | a) DEV | | | b) EME | | |
|-------------|---------------------|---------------------|---------------------|---------------------|--------------------|---------------------|
| | Full sample | Pre Oct. 2008 | Post Oct. 2008 | Full sample | Pre Oct. 2008 | Post Oct. 2008 |
| 2-yr yield | 0.219*** (0.024) | 0.244*** (0.030) | 0.186*** (0.038) | 0.202*** (0.041) | 0.135** (0.053) | 0.322*** (0.071) |
| 10-yr yield | 0.248*** (0.028) | 0.170*** (0.029) | 0.445*** (0.052) | 0.271*** (0.064) | 0.142** (0.070) | 0.604*** (0.123) |
| RN (10-yr) | 0.246*** (0.034) | 0.266*** (0.043) | 0.229*** (0.052) | 0.054 (0.041) | 0.023 (0.051) | 0.108* (0.063) |
| TP (10-yr) | 0.003 (0.034) | -0.095** (0.040) | 0.216*** (0.052) | 0.216*** (0.078) | 0.119 (0.084) | 0.495*** (0.155) |

The table estimates (1) using an alternative window of a single day (the closing of the FOMC meeting day vs. the day before). Standard errors computed using Newey-West correction up to 40 lags (reported in parentheses). *** p-value < 1%, ** p-value < 5%, and * p-value < 10%.

TABLE C.17: Alternative US MP shock: 1-yr yield changes

| | a) DEV | | | b) EME | | |
|-------------|---------------------|----------------------|---------------------|---------------------|---------------------|---------------------|
| | Full sample | Pre Oct. 2008 | Post Oct. 2008 | Full sample | Pre Oct. 2008 | Post Oct. 2008 |
| 1-yr yield | 0.145*** (0.024) | 0.136*** (0.025) | 0.222*** (0.057) | 0.205** (0.082) | 0.204** (0.092) | 0.276*** (0.093) |
| 10-yr yield | 0.148*** (0.035) | 0.078** (0.031) | 0.788*** (0.089) | 0.338*** (0.097) | 0.287*** (0.101) | 0.995*** (0.192) |
| RN (10-yr) | 0.207*** (0.040) | 0.181*** (0.041) | 0.440*** (0.096) | 0.059 (0.063) | 0.046 (0.068) | 0.266*** (0.102) |
| TP (10-yr) | -0.059* (0.033) | -0.103*** (0.033) | 0.348*** (0.100) | 0.279*** (0.091) | 0.241*** (0.093) | 0.728*** (0.234) |

The table estimates (1) using the change in the 1-yr US treasury yield around FOMC meetings (2-day window) as a measure of US MP shocks. Standard errors computed using Newey-West correction up to 40 lags (reported in parentheses). *** p-value < 1%, ** p-value < 5%, and * p-value < 10%.

TABLE C.18: Alternative US monetary policy shock: 1-year ahead FFR futures

| | a) DEV | | | b) EME | | |
|-------------|-------------|---------------|----------------|-------------|---------------|----------------|
| | Full sample | Pre Oct. 2008 | Post Oct. 2008 | Full sample | Pre Oct. 2008 | Post Oct. 2008 |
| 2-yr yield | | | | | | |
| baseline | 0.263*** | 0.318*** | 0.173*** | 0.160*** | 0.100* | 0.287*** |
| Alt. 1 | 0.249*** | 0.244*** | 0.282*** | 0.196*** | 0.136*** | 0.327*** |
| Alt. 2 | 0.262*** | 0.317*** | 0.174*** | 0.160*** | 0.099 | 0.287*** |
| 10-yr yield | | | | | | |
| baseline | 0.335*** | 0.297*** | 0.429*** | 0.293*** | 0.193*** | 0.557*** |
| Alt. 1 | 0.259*** | 0.196*** | 0.435*** | 0.237*** | 0.127** | 0.558*** |
| Alt. 2 | 0.334*** | 0.295*** | 0.435*** | 0.293*** | 0.193*** | 0.558*** |
| RN (10-yr) | | | | | | |
| baseline | 0.331*** | 0.390*** | 0.234*** | 0.054 | 0.019 | 0.136** |
| Alt. 1 | 0.284*** | 0.272*** | 0.331*** | 0.048 | 0.028 | 0.091* |
| Alt. 2 | 0.331*** | 0.389*** | 0.239*** | 0.054 | 0.019 | 0.135** |
| TP (10-yr) | | | | | | |
| baseline | 0.005 | -0.092*** | 0.196*** | 0.239*** | 0.174** | 0.421*** |
| Alt. 1 | -0.025 | -0.076** | 0.104** | 0.189*** | 0.099 | 0.467*** |
| Alt. 2 | 0.003 | -0.094*** | 0.196*** | 0.239*** | 0.174 | 0.424*** |

The table estimates (1) using alternative specifications of the US monetary policy shock. Alt. 1 replaces changes in the US 2-yr by changes in the 1-yr FFR future. Alt. 2 instruments changes in the US 2-yr rate with changes in the 1-yr FFR future. Each panel shows results for different dependent variables. The regression is estimated separately for each group of countries: DEV and EME. Standard errors reported in parentheses. *** p-value < 1%, ** p-value < 5%, and * p-value < 10%.

Appendix D. Affine Model estimation

Using equations (2) through (4), it can be shown that the coefficients in the term-structure recursion satisfy

$$\mathcal{A}_{n+1} = \mathcal{A}_n + (\mu^{\mathbb{Q}})' \mathcal{B}_n + \frac{1}{2} \mathcal{B}_n' \Sigma \Sigma' \mathcal{B}_n - \delta_0 \quad (\text{Appendix D.1})$$

$$\mathcal{B}_{n+1} = (\phi^{\mathbb{Q}})' \mathcal{B}_n - \delta_1 \quad (\text{Appendix D.2})$$

with initial values $\mathcal{A}_0 = \mathcal{B}_0 = 0$. Thus, the model-implied yields are $y_t^n = -\frac{\log(P_t^n)}{n} = A_n + B_n' X_t$, with $A_n = \frac{\mathcal{A}_n}{n}$ and $B_n = \frac{\mathcal{B}_n}{n}$. On the other hand, the risk-neutral yield (the yields that would be obtained if investors priced bonds under risk neutrality) corresponds to:

$$\tilde{y}_t^n = \tilde{A}_n + \tilde{B}_n' X_t \quad (\text{Appendix D.3})$$

$$\tilde{\mathcal{A}}_{n+1} = \tilde{\mathcal{A}}_n + \mu' \tilde{\mathcal{B}}_n + \frac{1}{2} \tilde{\mathcal{B}}_n' \Sigma \Sigma' \tilde{\mathcal{B}}_n - \delta_0 \quad (\text{Appendix D.4})$$

$$\tilde{\mathcal{B}}_{n+1} = \Phi' \tilde{\mathcal{B}}_n - \delta_1 \quad (\text{Appendix D.5})$$

The risk-neutral yield denoted in (Appendix D.3) essentially reflects the expected path of the future monetary policy rate, and the difference between model-implied yields and risk neutral rates gives the term premium component, at each corresponding maturity.

One of the innovations proposed by Adrian, Crump, and Moench (2013) regards the way in which market prices of risk are calculated. To obtain those prices, the authors propose the following three-step procedure:

1. Estimate the VAR(1) process for the observable state variables given by (2). With these estimates, collect residuals in vector \hat{V} and compute its variance-covariance matrix ($\hat{\Sigma} = \hat{V} \hat{V}' / T$).
2. Construct the log excess holding return of a bond maturing in n periods as:

$$rx_{t+1}^{n-1} = \log P_{t+1}^{n-1} - \log P_t^n - r_t, \quad n = 2, \dots, N \quad (\text{Appendix D.6})$$

where P_t^n is the price of an n period bond, r_t is the risk-free rate, and N is the maximum maturity considered. In this regard, the main difference between Adrian, Crump, and Moench (2013) and Cochrane and Piazzesi (2005) is that the latter work with one-year excess return while the former uses one-month excess returns. Stacking the system across the N maturities and T time periods we can construct the vector rx and run the following regression:

$$rx = \alpha \iota_T' + \beta' \hat{V} + cX_- + E \quad (\text{Appendix D.7})$$

where ι_T is T vector of ones and X_- is the lagged value of factors. The idea of this regression is to recover the

fundamental components of the data generating process of the log excess holding return. Adrian, Crump, and Moench (2013) shows that the decomposition of these returns can be written as:

$$rx = \text{Expected return} + \text{Priced return innovation} + \text{Return pricing error}$$

After running (Appendix D.7), collect residuals in the $N \times T$ matrix \hat{E} and estimate the return pricing error variance as $\hat{\sigma}^2 = \text{tr}(\hat{E}\hat{E}')/NT$.

3. Using the estimated parameters in (Appendix D.7), compute the market prices of risk as:

$$\hat{\lambda}_0 = (\hat{\beta}\hat{\beta}')^{-1}\hat{\beta}[\hat{a} + \frac{1}{2}(\hat{B}^*\text{vec}(\hat{\Sigma}) + \hat{\sigma}^2)] \quad (\text{Appendix D.8})$$

$$\hat{\lambda}_1 = (\hat{\beta}\hat{\beta}')^{-1}\hat{\beta}\hat{c} \quad (\text{Appendix D.9})$$

where $\hat{B}^* = [\text{vec}(\beta^1\beta^{1'}), \dots, \text{vec}(\beta^N\beta^{N'})]'$ and β^i is the covariance between log excess holding return at maturity n and the VAR innovations.

With this procedure, we are able to solve equations (Appendix D.1) through (Appendix D.5). The difference between fitted yields and risk-neutral yields corresponds to the term premium component.