MONETARY POLICY IN AN EQUILIBRIUM PORTFOLIO BALANCE MODEL

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Abstract

Standard theory shows that sterilized foreign exchange interventions do not affect equilibrium prices and quantities, and that domestic and foreign currency denominated bonds are perfect substitutes. This paper shows that when fiscal policy is not sufficiently flexible in response to spending shocks, exchange rates must adjust to restore budget balance. This exchange rate adjustment generates a capital gain or loss for holders of domestic currency denominated bonds and causes perfect substitutability to break down. Because of imperfect asset substitutability, uncovered interest rate parity no longer holds. Government balance sheet operations can be used as an independent policy instrument to target interest rates. Sterilized foreign exchange interventions should be most effective in developing countries, where fiscal volatility is large and where the fraction of domestic currency denominated government liabilities is small.

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1 Introduction

This paper presents a general equilibrium monetary portfolio balance model for a small open economy. It analyzes the effects of monetary policies on the currency composition of private sector portfolios, on the domestic-foreign interest rate differential, and on consumption. The paper makes two key contributions. First, it shows that there are general conditions under which a portfolio balance relationship holds in equilibrium, after endogenizing the effects of government tax and spending policies. Under such conditions domestic currency denominated government bonds are imperfect substitutes for foreign currency denominated bonds. Second, the paper provides a detailed analysis of the policy implications of a general equilibrium portfolio balance relationship. The implication for monetary policy is that it can affect not only the level of exchange rate depreciation and inflation, via a target path for the nominal anchor, but also interest rates and the volatility of exchange rate depreciation and inflation, via balance sheet operations. Interest rates in turn affect real allocations.

Central bank balance sheet operations in debt instruments that leave base money unchanged are generally referred to as sterilized foreign exchange interventions. We identify two factors that determine the degree of imperfect asset substitutability, and therefore the effectiveness of such operations in changing interest rates. The first factor is the volatility of exogenous fiscal spending shocks; shocks that induce budget balancing exchange rate movements instead of being financed by endogenous tax responses.[1] The more volatile such shocks, the wider the range of portfolio shares over which sterilized interventions have a large impact. The second factor is the government's initial balance sheet position; sterilized intervention has the largest effects on interest rates if there are only small outstanding

[1] The evidence presented in Click (1998) suggests that such shocks are indeed an important feature of the data. In a large cross-section of countries he finds that most permanent government spending is financed by conventional tax revenue. But transitory government spending (which has a high standard deviation in developing countries) is financed mainly by seigniorage.

amounts of domestic currency denominated government debt. This suggests that the conditions that give rise to this type of imperfect asset substitutability are most likely to be observed in developing countries.

The paper is motivated by a tension between economic theory and practice on the question of sterilized foreign exchange intervention. Most notably in developing countries, central bankers routinely intervene in foreign exchange markets with offsetting operations in domestic currency debt, with the intention of affecting interest rates and real activity without changing the money supply and therefore inflation. Their thinking may reflect older, partial equilibrium versions of portfolio balance theory such as Branson and Henderson (1985). The economics profession has challenged the validity of such models, and with it the effectiveness of sterilized foreign exchange interventions. We begin by summarizing this critique, and then develop our model.

The standard reference of modern open economy macroeconomics, Obstfeld and Rogoff (1996), dismisses portfolio balance theory as partial equilibrium reasoning because it omits the government budget constraint. This point is made most comprehensively in an important paper by Backus and Kehoe (1989).[2] Using only an arbitrage condition, they show that under complete asset markets, or under incomplete asset markets and a set of spanning conditions, changes in the currency composition of government debt require no offsetting changes in monetary and fiscal policies to satisfy both the government's and households' budget constraints. Consequently this 'strong form' of intervention is irrelevant for equilibrium allocations and prices. Weaker forms of government intervention in asset markets generally do require offsetting changes in monetary and/or fiscal policies to meet the government budget constraint. But because the impact of such 'weak form' interventions can as easily be attributed to these monetary and/or fiscal changes as to the intervention per se, sterilized intervention cannot be considered a separate, *third* policy instrument.

While this is a powerful theoretical argument, obtained under weak restrictions, it leaves

[2] See also Sargent and Smith (1988) on the irrelevance of open market operations in foreign currencies.

open the narrower yet practically very important question of precisely how 'weak form' interventions affect the economy. Answering this question requires taking a stance on the precise form of other government policies. One important consideration is that fiscal policy is generally not used as a short-term instrument for asset market intervention. Therefore, in the model, we assume tax and spending rules whose form is independent of such interventions. We can then ask how sterilized intervention affects equilibrium allocations and prices conditional on the form of these rules. In other words, we ask whether sterilized intervention can be effective as a *second* independent instrument of *monetary* policy, taking as given *fiscal* policy.

Several papers such as Obstfeld (1982) and Grinols and Turnovsky (1994) have given a negative answer to that question. The latter show that while stochastic money growth gives rise to currency risk in partial equilibrium, this disappears once the fiscal use of stochastic seigniorage has been accounted for. In general equilibrium, domestic and foreign bonds are perfect substitutes, and a version of uncovered interest parity holds. Therefore, once a monetary policy rule is specified, sterilized intervention has no further effects on asset market equilibria. In this paper we show that these results depend on, first, the absence of exogenous fiscal spending shocks, and second, on the particular form of the fiscal policy rule used by these authors, full lump-sum redistribution of all government net revenue. While this is a convenient and frequently used assumption, it is extreme as a description of actual government behavior. When at least some fiscal spending is exogenous, domestic currency denominated government bonds become imperfect substitutes for foreign currency denominated bonds even in general equilibrium. Their portfolio share is determined by a portfolio balance equation, and sterilized intervention becomes an effective second instrument of monetary policy.

The empirical literature on the portfolio balance channel has produced mixed results. Sarno and Taylor (2001) contains an excellent survey. Studies done in the 1980s, summarized in Edison (1993), found very little evidence for the ability of sterilized intervention to affect

the foreign exchange risk premium. Since then the literature has been somewhat more supportive, especially since the key study by Dominguez and Frankel (1993) that found positive evidence for industrialized countries. Our theoretical model is able to rationalize such results, but it also concludes that a portfolio balance channel is likely to be most significant in developing countries, where the evidence so far, such as in Montiel (1993), is more limited but where sterilized intervention is more commonly practised.

Our paper is also related to the literature on interest rate risk premia. As shown in Lewis (1995), empirical risk premia have been both large in absolute value and highly variable in industrialized countries, and they are known to have been even larger in developing countries. An attempt at explaining that fact has to take into account both default and currency risk.[3] The focus of this paper is on currency risk. Engel (1992) and Stulz (1984) show that in flexible price monetary models monetary volatility per se will not give rise to any currency risk premium. And Engel (1999), using the frameworks of Obstfeld and Rogoff (1998, 2000) and Devereux and Engel (1998), shows that sticky prices are required to generate a risk premium. But the source of the risk premium in such models is the covariance of consumption and the exchange rate. This makes it difficult to rationalize large absolute-value risk premia because consumption is not very variable. A general equilibrium portfolio model such as ours introduces portfolio considerations as a second and potentially much more powerful source of interest rate differentials and risk premia.

The rest of the paper is organized as follows. Section 2 presents the model. Section 3 calibrates and estimates an example economy using Mexican data, and discusses policy implications. Section 4 concludes. Mathematical details are presented in two appendices.

[3] There is a well-established and growing literature on default risk. The early contributions include Eaton and Gersovitz (1981) and Aizenman (1989). More recent contributions include Kehoe and Perri (2002) and Kletzer and Wright (2000).

2 The Model

We consider a small open economy composed of a continuum of identical infinitely lived households and a government. We use a continuous time stochastic monetary portfolio choice model to derive households' optimal consumption and portfolio decisions.[4] Government behavior is characterized by a fiscal rule and a monetary rule.

2.1 Uncertainty

We fix a probability space $(\Omega, \mathcal{F}, P)$. A stochastic process is a measurable function $\Omega \times [0, \infty) : \mapsto \boldsymbol{R}$. The value of a process X at time t is the random variable written as X_t.

There are four sources of risk in this economy. We define a three-dimensional Brownian motion $B_t = [B_t^M \quad B_t^\alpha \quad B_t^r]'$, consisting of shocks B_t^M to the growth rate of the nominal money supply M_t, shocks B_t^α to the growth rate of velocity α_t, and shocks B_t^r to the real return on international bonds dr_t^b. We also define a one-dimensional Brownian motion W_t that represents shocks to the growth rate of exogenous government spending dG_t. The tribe $\mathcal{F}_t^{BW}$ includes every event based on the history of the above four Brownian motion processes up to time t. We complete the probability space by assigning probabilities to subsets of events with zero probability. We define $\mathcal{F}_t$ to be the tribe generated by the union of $\mathcal{F}_t^{BW}$ and the null sets. This leads to the standard filtration $\mathcal{F} = \{\mathcal{F}_t : t \geq 0\}$.

The difference between B_t-shocks and W_t-shocks is critical for our results. Specifically, all shocks affect the real returns on domestic currency denominated government liabilities through the exchange rate. Therefore they affect the government budget constraint. The difference between B_t-shocks and W_t-shocks is the nature of the fiscal response. We assume that with respect to B_t-shocks the fiscal policy response is *endogenous*, meaning that the government redistributes the resulting net fiscal revenue back to households via lump-sum

[4] Useful surveys of the technical aspects of stochastic optimal control are contained in Chow (1979), Fleming and Rishel (1975), Malliaris and Brock (1982), Karatzas and Shreve (1991), and Duffie (1996). The seminal papers using this technique to analyze macroeconomic portfolio selection are Merton (1969, 1971) and Cox, Ingersoll and Ross (1985).

transfers. In contrast, W_t-shocks are *exogenous* shocks to fiscal policy, meaning that it is the exchange rate which adjusts to balance the government's budget. This in turn implies that money is endogenous with respect to such shocks, specifically that the money supply is adjusted to accommodate the exchange rate movements necessitated by fiscal balance.

Money Supply The nominal money supply follows a geometric Brownian motion with a drift process μ_t determined by the inflation target of monetary policy. There is an endogenous diffusion $\sigma^g_{M,t}$ with respect to W_t-shocks, and a constant, exogenous three dimensional diffusion $\sigma_M = [\sigma^M_M \quad \sigma^\alpha_M \quad \sigma^r_M]$ with respect to B_t-shocks. These represent exogenous financial market shocks that require changes in the money supply. Being an Itô process, M_t is continuous, which ensures exchange rate determinacy. We have

$$\frac{dM_t}{M_t} = \mu_t dt + \sigma_M dB_t + \sigma^g_{M,t} dW_t \quad . \tag{1}$$

We index endogenous drift and diffusion terms by time if they represent possibly time-varying monetary policy choices, or if they are functions of such choices.

Velocity of Money The process for velocity is similar to (1), except that velocity does not endogenously respond to fiscal shocks:

$$\frac{d\alpha_t}{\alpha_t} = \nu dt + \sigma_\alpha dB_t \quad . \tag{2}$$

International Bond Returns The real return on international bonds follows the process

$$dr^b_t = r dt + \sigma_r dB_t \quad . \tag{3}$$

It is assumed that the stochastic processes $d\log(M_t)$, $d\log(\alpha_t)$ and dr^b_t are correlated with variance-covariance matrix Σ.

Exogenous Fiscal Shocks Finally, exogenous government spending follows an Itô process with zero drift[5]:

$$\frac{dG_t}{a_t} = \sigma^g_g dW_t \quad , \tag{4}$$

[5] A nonzero drift would affect feasible choices for the inflation target. But because this does not affect the presence or transmission mechanism of a portfolio channel, we ignore it without loss of generality.

where a_t denotes aggregate household wealth. Fiscal spending shocks affect the resources available for private consumption. In order for this to represent a risk to households in general equilibrium, it must be true that government consumption is an imperfect substitute for private consumption. Below, we choose the simplest and most tractable assumption under which this is true, namely that government spending does not enter household utility.

Exchange Rates The nominal exchange rate E_t floats, and aggregate exchange rate risk cannot be hedged internationally.[6] All goods are tradable and the international price level is normalized to one. Assuming purchasing power parity, domestic goods prices P_t therefore satisfy $P_t = E_t$. Thus, while our discussion will be in terms of the exchange rate, this is everywhere interchangeable with the price level. The nominal exchange rate process E_t is endogenously determined as a function of the four exogenous stochastic processes. It follows a geometric Brownian motion with drift ε_t and diffusions $\sigma_{E,t}$ and $\sigma^g_{E,t}$:

$$\frac{dE_t}{E_t} = \varepsilon_t dt + \sigma_{E,t} dB_t + \sigma^g_{E,t} dW_t \quad . \tag{5}$$

We assume and later verify that the endogenous drift and diffusion terms are adapted processes satisfying $\int_0^T |\varepsilon_t| dt < \infty$, $\int_0^T \left(\sigma^x_{E,t}\right)^2 dt < \infty$ $(x = M, \alpha, r, g)$ almost surely for each T. The corresponding conditions for all exogenous or policy determined drift and diffusion processes hold by assumption - the exogenous terms are constants and policy choices are assumed to be bounded.

We use the following shorthand notation for diffusion terms, choosing terms relating to exchange rates and money as the example:

$$\begin{aligned}
\left(\sigma_{E,t}\right)^2 &= \left(\sigma^M_{E,t}\right)^2 + \left(\sigma^\alpha_{E,t}\right)^2 + \left(\sigma^r_{E,t}\right)^2 \ , \\
\sigma_M \sigma_{E,t} &= \sigma^M_M \sigma^M_{E,t} + \sigma^\alpha_M \sigma^\alpha_{E,t} + \sigma^r_M \sigma^r_{E,t} \ , \\
\left(\sigma_M - \sigma_{E,t}\right) &= \left[\left(\sigma^M_M - \sigma^M_{E,t}\right) \quad \left(\sigma^\alpha_M - \sigma^\alpha_{E,t}\right) \quad \left(\sigma^r_M - \sigma^r_{E,t}\right)\right] .
\end{aligned}$$

[6] As we will see, this may, but need not, imply that financial markets are incomplete.

2.2 Households

Preferences The representative household has time-separable logarithmic preferences[7] that depend on his expected lifetime path of tradable goods consumption $\{c_t\}_{t=0}^{\infty}$. It is convenient to model period utility in terms of consumption in excess of the constant endowment stream y.[8] We therefore have

$$\mathbb{E}_0 \int_0^{\infty} e^{-\beta t} \ln(c_t - y) dt \quad , \quad 0 < \beta < 1 \, , \tag{6}$$

where $\mathbb{E}_0$ is the expectation at time 0, and β is the rate of time preference.

Trading Household consumption c_t is financed from a constant endowment stream y and from the returns on three types of financial assets: (1) domestic currency denominated money M_t with a zero nominal return, (2) domestic currency denominated bonds Q_t with a nominal return $i_t^q dt$, and (3) international, foreign currency denominated bonds b_t with a real return dr_t^b. We denote the real stocks of money and domestic bonds by $m_t = M_t/E_t$ and $q_t = Q_t/E_t$, and total private financial wealth by $a_t = m_t + q_t + b_t$. Portfolio shares of money and domestic bonds will be denoted by $n_t^m = \frac{m_t}{a_t}$ and $n_t^q = \frac{q_t}{a_t}$. In order to determine the equilibrium portfolio share of domestic currency denominated assets in a small open economy, we follow Grinols and Turnovsky (1994) in assuming that these bonds are held exclusively by domestic residents. This is a good assumption for many developing countries, where the vast majority of claims held by foreigners tends to be denominated in dollars. Figure 1 illustrates this for the case of Mexico. We will return to the case of Mexico for our numerical example in Section 3.

[7] Logarithmic preferences are commonly used in the open economy asset pricing and portfolio choice literature for their analytical tractability, see e.g. Stulz (1984, 1987) and Zapatero (1995).

[8] Introducing the endowment stream is not essential for the theoretical model, but it is important to make a link between the model and the data, as described in Section 3. The issue is that in practice the financial assets that we model in detail represent a smaller share of household income than non-financial sources.

Taxation Households are subject to a lump-sum tax dT_t levied as a proportion of wealth a_t. This tax follows an Itô process with adapted drift process τ_t and diffusion process $\sigma_{T,t}$:

$$\frac{dT_t}{a_t} = \tau_t dt + \sigma_{T,t} dB_t \ . \tag{7}$$

The drift and diffusion terms will be determined in equilibrium from a balanced budget requirement for the government. We assume that $\int_0^T |\tau_t| dt < \infty$ and $\int_0^T (\sigma_{T,t})^2 \, dt < \infty$ almost surely for each T, and will later verify that this is satisfied in equilibrium. Note that taxes respond to B_t-shocks but not to W_t-shocks.

Budget Constraint The household budget constraint is given by

$$da_t = a_t \left[n_t^m dr_t^m + n_t^q dr_t^q + (1 - n_t^m - n_t^q) dr_t^b \right] + y dt - c_t dt - a_t [\tau_t dt + \sigma_{T,t} dB_t] - \Gamma_t dt \ , \tag{8}$$

where dr_t^i is the real rate of return on asset i. Using Itô's lemma we can derive the real returns in terms of tradable goods on money and domestic bonds as (see Appendix I):

$$dr_t^m = \left(-\varepsilon_t + (\sigma_{E,t})^2 + \left(\sigma_{E,t}^g\right)^2 \right) dt - \sigma_{E,t} dB_t - \sigma_{E,t}^g dW_t \quad , \tag{9}$$

$$dr_t^q = \left(i_t^q - \varepsilon_t + (\sigma_{E,t})^2 + \left(\sigma_{E,t}^g\right)^2 \right) dt - \sigma_{E,t} dB_t - \sigma_{E,t}^g dW_t \quad . \tag{10}$$

Note that the exchange rate affects these returns in two ways. First, a depreciation such as $\sigma_{E,t} dB_t > 0$ reduces the realized (ex-post) real return in terms of tradables. Second, by Jensen's inequality, larger exchange rate volatility $(\sigma_{E,t})^2$ increases their expected (ex-ante) real return.

The final term Γ_t in equation (8) represents a risk-premium on international borrowing, specified as

$$\Gamma_t = \mathfrak{I} \gamma a_t (n_t^m + n_t^q - 1)^2 \ , \tag{11}$$

where $\mathfrak{I}$ is an indicator variable, with $\mathfrak{I} = 1$ if $(n_t^m + n_t^q) > 1$ and $\mathfrak{I} = 0$ otherwise. Intuitively, households have to fund increasing purchases of government bonds by selling international bonds. When $(n_t^m + n_t^q) > 1$ they have to start borrowing from foreigners, who

demand a risk premium. Similar assumptions have become common in the open economy macroeconomics literature.[9] We will follow that literature in assuming a small risk premium γ. We adopt this risk premium mainly for technical reasons. It rules out multiple solutions for domestic interest rates at very high levels of foreign borrowing.

Cash Constraint Monetary portfolio choice models often introduce money into the utility function separably because this preserves the separability between portfolio and savings decisions found in Merton (1969, 1971). However, as pointed out by Feenstra (1986), without a positive cross partial between money and consumption the existence of money cannot be rationalized through transactions cost savings. We therefore use a cash constraint instead, and show that it is still possible to obtain analytical solutions. Specifically, consumers are required to hold real money balances equal to a time-varying multiple α_t of their net consumption expenditures $c_t - y$. This mirrors the appearance of the term $c_t - y$ in the utility function. We have

$$c_t - y = \alpha_t m_t = \alpha_t n_t^m a_t \quad . \tag{12}$$

The now very common treatment of the cash-in-advance constraint in Lucas (1990) has two aspects, a cash requirement aspect and an in-advance aspect. Our own treatment goes back to the earlier Lucas (1982), which uses only the cash requirement aspect. This is due to the difficulty of implementing the in-advance timing conventions in a continuous-time framework. In the continuous time stochastic finance literature, Bakshi and Chen (1997) have used the same device.

Portfolio Problem The household's portfolio problem is to maximize present discounted lifetime utility by the appropriate portfolio choice $\{n_t^m, n_t^q\}_{t=0}^{\infty}$:

$$\max_{\left\{n_t^m, n_t^q\right\}_{t=0}^{\infty}} \left\{ \mathbb{E}_0 \int_0^{\infty} e^{-\beta t} \ln\left(\alpha_t n_t^m a_t\right) dt \right\} \qquad s.t.$$

[9] Schmitt-Grohe and Uribe (2003) discuss computational reasons for adopting this device. Kollmann (2003) discusses calibration of the debt elasticity of interest rates based on international portfolio data.

$$
\begin{aligned}
da_t &= a_t \big\{ (r - \tau_t - \gamma \mathfrak{I}(n_t^m + n_t^q - 1)^2) dt \\
&\quad + n_t^m \left[(-\alpha_t - r - \varepsilon_t + (\sigma_{E,t})^2 + \left(\sigma_{E,t}^g\right)^2) dt - \sigma_{E,t} dB_t - \sigma_{E,t}^g dW_t \right] \\
&\quad + n_t^q \left[(i_t^q - r - \varepsilon_t + (\sigma_{E,t})^2 + \left(\sigma_{E,t}^g\right)^2) dt - \sigma_{E,t} dB_t - \sigma_{E,t}^g dW_t \right] \\
&\quad + (1 - n_t^m - n_t^q) \sigma_r dB_t - \sigma_{T,t} dB_t \big\} + y dt \ .
\end{aligned} \tag{13}
$$

We will solve this optimal portfolio problem recursively using a continuous time Bellman equation, as in Merton (1969, 1971). Let $V(a_t, t) = e^{-\beta t} J(a_t, t) \in C^2$ be a solution of the portfolio problem, and let $\dot{J} = \partial J(a_t, t)/\partial t$. Then the Hamilton-Jacobi-Bellman equation solves

$$
\begin{aligned}
\beta J - \dot{J} &= \sup_{n_t^m, n_t^q} \big\{ \ln\left(\alpha_t n_t^m a_t\right) + J_a a_t [\left(r - \tau_t - \gamma \mathfrak{I}(n_t^m + n_t^q - 1)^2\right) \\
&\quad + n_t^m \left(-\alpha_t - r - \varepsilon_t + (\sigma_{E,t})^2 + \left(\sigma_{E,t}^g\right)^2 \right) \\
&\quad + n_t^q \left(i_t^q - r - \varepsilon_t + (\sigma_{E,t})^2 + \left(\sigma_{E,t}^g\right)^2 \right)] \\
&\quad + \frac{1}{2} J_{aa} a_t^2 \Big[\left(n_t^m + n_t^q\right)^2 \left((\sigma_{E,t})^2 + \left(\sigma_{E,t}^g\right)^2 \right) + \left(1 - n_t^m - n_t^q\right)^2 (\sigma_r)^2 + (\sigma_{T,t})^2 \\
&\quad - 2 \left(n_t^m + n_t^q\right) \sigma_{E,t} \sigma_r + 2 \left(n_t^m + n_t^q\right)^2 \sigma_{E,t} \sigma_r \\
&\quad + 2 \left(n_t^m + n_t^q\right) \sigma_{E,t} \sigma_{T,t} - 2 \left(1 - n_t^m - n_t^q\right) \sigma_r \sigma_{T,t} \Big] \big\} \quad ,
\end{aligned} \tag{14}
$$

with boundary condition

$$
\lim_{\tau \to \infty} \ \mathbb{E}_0 \left[e^{-\beta \tau} \left| J(a_\tau, \tau) \right| \right] = 0 \ . \tag{15}
$$

The first order necessary conditions for optimality of n_t^q and n_t^m are

$$
\begin{aligned}
n_t^q + n_t^m &= \frac{\left(\frac{-J_a}{J_{aa} a_t} \right) \left(i_t^q - r - \varepsilon_t + (\sigma_{E,t})^2 + \left(\sigma_{E,t}^g\right)^2 \right)}{\left((\sigma_{E,t})^2 + \left(\sigma_{E,t}^g\right)^2 + (\sigma_r)^2 + 2 \sigma_{E,t} \sigma_r \right)} \\
&+ \frac{(\sigma_r)^2 + \sigma_{E,t} \sigma_r + 2\gamma \left(\frac{J_a}{J_{aa} a_t} \right) \mathfrak{I} \left(n_t^m + n_t^q - 1\right) - \sigma_{E,t} \sigma_{T,t} - \sigma_r \sigma_{T,t}}{\left((\sigma_{E,t})^2 + \left(\sigma_{E,t}^g\right)^2 + (\sigma_r)^2 + 2 \sigma_{E,t} \sigma_r \right)} \quad ,
\end{aligned} \tag{16}
$$

$$
\frac{1}{\alpha_t n_t^m a_t} = J_a (1 + \frac{i_t^q}{\alpha_t}) \quad . \tag{17}
$$

We revisit these optimality conditions in Section 2.4 after having solved for equilibrium taxation and the value function.

2.3 Government

Monetary Policy Monetary policy is characterized by two policy variables and by a technical condition on the government budget. First, primary control over the *level* of depreciation/inflation is achieved through a target path for the nominal anchor consistent with an inflation target. In our model this is simply a target path $\{\mu_t\}_{t=0}^{\infty}$ for money in equation (1). Second, we will show that control of the *volatility* of depreciation/inflation, and control of interest rates, can be achieved by setting a target path for the stock of nominal government debt $\{Q_t\}_{t=0}^{\infty}$. Furthermore, under our assumptions there is a monotonically increasing relationship between Q_t and i_t^q for all $i_t^q > 0$, so that there is an equivalent target path for the nominal interest rate on government debt $\{i_t^q\}_{t=0}^{\infty}$. As it turns out, this target also has a secondary effect on the level of depreciation/inflation ε_t. To show that the government can indeed control Q_t (or i_t^q) independently of μ_t requires that we find a determinate portfolio demand share for domestic currency bonds n_t^q in equation (16), after endogenizing fiscal policy.

Finally, we need a technical condition on the government budget. Discrete unanticipated policy changes will generally result in discontinuous jumps of the nominal exchange rate on impact[10], denoted $E_0 - E_{0-}$. Here 0_- stands for the instant before the announcement of a new policy at time 0. At such points the government could either spend the associated net seigniorage revenue, or it could fully redistribute it through a one-off transfer of international bonds. We assume the latter, to ensure that private financial wealth remains continuous upon the impact of any new policy. We denote international bonds held by the government by h_t,

[10] Subsequent discontinuous exchange rate jumps are ruled out by arbitrage.

and we denote asset transfers to compensate exchange rate jumps by $\Delta h_0 = -\Delta b_0$.[11] Then we can formalize the above as

$$(M_{0-} + Q_{0-}) \left(\frac{1}{E_0} - \frac{1}{E_{0-}} \right) = -\Delta b_0 = \Delta h_0 \quad . \tag{18}$$

Fiscal Policy The exogenous, spending component of fiscal policy is specified in (4) and the endogenous, lump-sum tax component in (7). We assume that the latter meets three requirements. First, the expected budget balance is always zero. Second, the budgetary effects of shocks to money, velocity and international interest rates (B_t-shocks) are instantaneously offset by lump-sum taxes. Third, endogenous lump-sum taxes do not adjust to react to exogenous fiscal spending shocks (W_t-shocks). Instead, the budget balancing role in response to such shocks falls to the exchange rate. This gives content to the exogeneity of these shocks.

The government's budget constraint is

$$a_t \tau_t dt + a_t \sigma_{T,t} dB_t + h_t dr_t^b = m_t dr_t^m + q_t dr_t^q + a_t \sigma_g^g dW_t \quad . \tag{19}$$

The assumption of expected budget balance implies that the government's net wealth $h_t - m_t - q_t$ does not change over time. Therefore we have $dh_t = dm_t + dq_t$. For simplicity we also assume the initial condition $h_{0-} = m_{0-} + q_{0-}$, which implies together with (18) that

$$h_t = m_t + q_t \quad \forall t \geqq 0 \quad . \tag{20}$$

Condition (20) therefore states that the consolidated government's net domestic currency denominated liabilities are fully backed by international bonds.[12] Given perfect international capital mobility, the assumption of instantaneous redistribution in (19) is not restrictive. It is

[11] Note that Δh_0 need not equal $h_0 - h_{0-}$, because the policy itself may in addition involve the purchase or sale of foreign exchange reserves against domestic money or bonds at the new exchange rate E_0.

[12] This formulation treats government issued and central bank issued domestic currency bonds as perfect substitutes, so that q_t could represent either debt class. Note that q_t could be negative and represent government claims on the private sector. In that case h_t could also be negative. Given that the model makes no distinction between government and the central bank, we will refer to all policies, fiscal and monetary, as being carried out by government.

equivalent to redistribution over households' infinite lifetime combined with instantaneous capitalization by households of the expected redistribution stream. Our treatment is analytically more convenient.

To determine the drift τ_t and diffusion $\sigma_{T,t}$ of the tax process dT_t, and the diffusion $\sigma^g_{E,t}$ of the exchange rate process, we equate terms in (19) using (3), (9), (10) and (20), and we use our three requirements for lump-sum taxes. We obtain the following:

$$\tau_t = n^q_t i^q_t - \left(n^m_t + n^q_t\right)\left(r + \varepsilon_t - \left(\sigma_{E,t}\right)^2 - \left(\sigma^g_{E,t}\right)^2\right) \quad , \tag{21}$$

$$\sigma_{T,t} = -\left(n^m_t + n^q_t\right)\left(\sigma_{E,t} + \sigma_r\right) \quad , \tag{22}$$

$$\sigma^g_{E,t} = \frac{\sigma^g_g}{\left(n^m_t + n^q_t\right)} \quad . \tag{23}$$

The first condition ensures that the expected budget balance is always zero. The second condition represents the endogenous response of lump-sum taxes to B_t-shocks. The third condition is critical. It represents the endogenous response of the exchange rate to exogenous fiscal spending shocks (W_t-shocks). Fiscally induced exchange rate volatility is increasing in the volatility of the fiscal shocks themselves, but it is decreasing in the amount of nominal government liabilities held in household portfolios. This is because a larger stock of nominal liabilities that can be revalued by nominal exchange rate movements represents a larger base of the stochastic inflation tax.[13]

Definition 1. *A feasible government policy is an initial net compensation Δh_0 and a list of stochastic processes $\{\mu_t, Q_t, \tau_t, \sigma_{T,t}\}_{t=0}^{\infty}$ such that, given a list of stochastic processes $\{\varepsilon_t, \sigma_{E,t}, \sigma^g_{E,t}, n^m_t, n^q_t\}_{t=0}^{\infty}$, initial conditions $b_{0-}, h_{0-}, M_{0-}, Q_{0-}$ and E_{0-},*

[13] This result is consistent with the empirical results of Reinhart, Rogoff and Savastano (2003), who find that inflation is consistently more variable in countries with a high degree of liability dollarization, including government liability dollarization.

and an initial exchange rate jump $E_0 - E_{0-}$, the conditions (21), (22), (23) and (18) are satisfied at all times.

In all our policy experiments in Section 3 we will assume that $\{\mu_t, Q_t\}_{t=0}^{\infty}$ are deterministic sequences.

2.4 Equilibrium, Current Account and Interest Rate Differential

Equilibrium in the small open economy is defined as follows:

Definition 2. *An equilibrium is a set of initial conditions $\{b_{0-}, h_{0-}, M_{0-}, Q_{0-}, E_{0-}\}$, exogenous stochastic processes $\{B_t, W_t\}_{t=0}^{\infty}$, an allocation consisting of stochastic processes $\{c_t, b_t, h_t, Q_t, M_t\}_{t=0}^{\infty}$, a price system consisting of an initial exchange rate jump $E_0 - E_{0-}$ and stochastic processes $\{\varepsilon_t, \sigma_{E,t}, \sigma_{E,t}^g\}_{t=0}^{\infty}$, and a feasible government policy such that, given the initial conditions, the exogenous stochastic processes, the feasible government policy and the price system, the allocation solves households' problem of maximizing (6) subject to (8) and (12).*

The condition $h_t = m_t + q_t \ \forall t$ ensures that $a_t = b_t + h_t \ \forall t$, i.e. private assets at any point are equal to the economy's net international bonds. Then the current account can be derived by consolidating households' and the government's budget constraints (8) and (19):

$$da_t = (ra_t + y - c_t)\,dt + a_t\sigma_r dB_t - a_t\sigma_g^g dW_t - a_t\gamma\mathfrak{I}(n_t^m + n_t^q - 1)^2 \quad . \tag{24}$$

Value Function We can now derive a closed form expression for the household value function. The solution proceeds by first substituting (16), (17), (21), (22) and (23), which contain the terms J_a and J_{aa}, back into the Hamilton-Jacobi-Bellman equation (14). That equation is then solved for J by way of a conjecture and verification. Given the logarithmic form of the utility function a good conjecture is

$$J(a_t, t) = x\left[\ln(a_t) + \ln(X(t;\chi_t))\right] \quad , \tag{25}$$

where x and $X(t;\chi_t)$ are to be determined in the process of verifying the conjecture, and where χ_t is the set of exogenous policy and shock processes. The verification is relegated to

Appendix II. We show there that

$$x = \beta^{-1} \quad . \tag{26}$$

Therefore, using (21) and (22), the first-order conditions (16) and (17) become

$$c_t = y + \frac{\beta a_t}{(1 + (i_t^q/\alpha_t))} \quad , \tag{27}$$

$$n_t^q + n_t^m = \frac{\left(i_t^q - r - \varepsilon_t + (\sigma_{E,t})^2 + \left(\sigma_{E,t}^g\right)^2 + (\sigma_r)^2 + \sigma_{E,t}\sigma_r + 2\gamma\mathfrak{I}\right)}{\left(\left(\sigma_{E,t}^g\right)^2 + 2\gamma\mathfrak{I}\right)} \quad . \tag{28}$$

Equation (27) is a standard condition in this model class. It states that consumption in excess of the flow endowment is proportional to wealth and, because of the cash constraint, negatively related to nominal interest rates.

The general equilibrium portfolio balance equation (28) is the key equation of this paper. It shows that the portfolio share of domestic currency denominated assets is determinate even after taxes have been endogenized. In the following discussion we ignore the risk premium term $2\gamma\mathfrak{I}$, which in our calibration is both very small and enters only at very high levels of government borrowing.

Interest Rate Differential Assume for the moment that the volatility of exogenous fiscal spending is zero ($\sigma_g^g = 0$). Then (28) in conjunction with (23) would imply that

$$i_t^q = r + \varepsilon_t - (\sigma_{E,t})^2 - (\sigma_r)^2 - \sigma_{E,t}\sigma_r \quad . \tag{29}$$

Endogenizing taxes in the complete absence of exogenous fiscal spending therefore results in a version of uncovered interest parity, the only difference being Jensen's inequality terms relating to exchange rate and interest rate volatility. Because the portfolio share $(n_t^m + n_t^q)$ is indeterminate, the currency composition of the government's balance sheet is irrelevant. This is a version of the result of Grinols and Turnovsky (1994) and others discussed in the Introduction. Full lump-sum redistribution of the net seigniorage revenues resulting from shocks fully insures agents against exchange rate risk in equilibrium. Private

agents may lose from exchange rate movements at the expense of the government, but the economy as a whole does not. Therefore, neither do private agents after the government returns to them what it gained at their expense. A market for hedging exchange rate risk turns out to be redundant.

With exogenous fiscal spending shocks ($\sigma_g^g > 0$) we obtain a very different result. A spending shock $dW_t > 0$ is a net resource loss to households because government spending does not enter private utility. The government passes this loss on to holders of domestic currency denominated assets through exchange rate movements, and this exchange rate risk is the source of imperfect asset substitutability. Equation (29) becomes

$$i_t^q = r + \varepsilon_t - (\sigma_{E,t})^2 - (\sigma_r)^2 - \sigma_{E,t}\sigma_r - \left(\sigma_g^g\right)^2 \frac{\left(1 - n_t^m - n_t^q\right)}{(n_t^m + n_t^q)^2} \quad . \tag{30}$$

The size of the additional risk discount depends on exogenous fiscal spending volatility σ_g^g, but also on the endogenous portfolio share of domestic assets $n_t^m + n_t^q$. The latter can, in this environment, be controlled through a second instrument of monetary policy.

Second Policy Instrument To understand the transmission channel of monetary policy in this economy, let us first think of the interest rate i_t^q as the government's policy instrument. There are two complementary effects of raising i_t^q. First, by equation (28) a higher i_t^q raises (ceteris paribus) the *mean* return on domestic government bonds and therefore their portfolio share $(n_t^m + n_t^q)$. Second, by equation (23), a higher portfolio share further reduces the *risk* of holding domestic bonds, thereby reinforcing the effect of the higher mean return. The result is a monotonically increasing relationship between i_t^q and $(n_t^m + n_t^q)$, and a monotonically decreasing relationship between i_t^q and the risk discount. The effects of lowering risk become much more significant at high portfolio shares and interest rates. A given increase in interest rates therefore induces a larger portfolio response if the initial portfolio already contains a large share of domestic assets. If we think instead of balance sheet operations in Q_t as the policy instrument, the foregoing says that these are much less effective at changing interest rates if the initial portfolio already contains a large share of domestic government bonds.

Equilibrium System of Equations We now solve for the complete equilibrium system of equations determining the economy's consumption and portfolio choices and its interest rate and exchange rate dynamics, given set of policy variables μ_t and Q_t. We will use this system of equations in Section 3.2 to analyze the effects of sterilized foreign exchange intervention.

Our economy does not fluctuate around a steady state because its state variables, the shock processes and wealth a_t, follow geometric Brownian motion processes. The following analysis therefore characterizes the economy's behavior by computing the equilibrium for constant baseline values of the state variables, denoted by a bar above the respective variable.[14] This allows us to isolate the effects of government policies on equilibrium consumption and portfolio choices, both of which can be expressed as multiples of wealth.[15] The behavior of interest rates and exchange rates is characterized by computing their drift and diffusion coefficients.

To compute the equilibrium set of equations, we begin with the observation that consumption has to satisfy two equilibrium conditions. The first is the cash constraint (12), and the second the consumption optimality condition (27). The latter in turn links the evolution of consumption and assets, and therefore needs to be analyzed in conjunction with equation (24).

First, by Itô's Law, (12) can be stochastically differentiated as

$$dc_t = \alpha_t dm_t + m_t d\alpha_t + dm_t d\alpha_t \ . \tag{31}$$

Again by Itô's Law, real money balances evolve as

$$\begin{aligned} dm_t \ &= \ m_t \left[\mu_t - \varepsilon_t + (\sigma_{E,t})^2 + \left(\sigma^g_{E,t}\right)^2 - \sigma_M \sigma_{E,t} - \sigma^g_{M,t}\sigma^g_{E,t}\right] dt \\ &\quad + m_t \left[\sigma_M - \sigma_{E,t}\right] dB_t + m_t \left[\sigma^g_{M,t} - \sigma^g_{E,t}\right] dW_t \ . \end{aligned} \tag{32}$$

[14] The calibration of these values is discussed in Section 3.1.

[15] Recall that condition (18) ensures that household wealth will be continuous at the time of implementation of a new policy.

We substitute (2), (12) and (32) into (31) to obtain the evolution of consumption:

$$\begin{aligned} & \frac{dc_t}{c_t - y} \\ = \; & \left[\mu_t - \varepsilon_t + \nu + (\sigma_{E,t})^2 + \left(\sigma^g_{E,t}\right)^2 - \sigma_M \sigma_{E,t} - \sigma^g_{M,t}\sigma^g_{E,t} + \sigma_\alpha \sigma_M - \sigma_\alpha \sigma_{E,t}\right] dt \\ & + \left[\sigma_M - \sigma_{E,t} + \sigma_\alpha\right] dB_t + \left[\sigma^g_{M,t} - \sigma^g_{E,t}\right] dW_t \; . \end{aligned} \tag{33}$$

Similarly, we stochastically differentiate the consumption optimality condition (27) and substitute (24) and (2). After simplifying, we obtain:

$$\begin{aligned} & \frac{dc_t}{c_t - y} \\ = \; & \left[\left(r - \frac{\beta}{(1 + (i^q_t/\alpha_t))}\right) + \left(\frac{i^q_t}{\alpha_t + i^q_t}\left(\nu - (\sigma_\alpha)^2\right)\right) - \gamma \Im (n^m_t + n^q_t - 1)^2\right] dt \\ & + \left[\sigma_r + \frac{i^q_t}{\alpha_t + i^q_t}\sigma_\alpha\right] dB_t - \sigma^g_g dW_t + \left[\frac{i^q_t}{\alpha_t + i^q_t}\left(\nu dt + \sigma_\alpha dB_t\right)\right] \frac{dc_t}{c_t - y} \; . \end{aligned} \tag{34}$$

We substitute (33) into (34) and separately equate the terms multiplying dt, dB_t and dW_t, while taking account of equation (23) determining fiscally induced exchange rate volatility. This results in the following six equations:

$$\begin{aligned} & \mu_t + \nu - \varepsilon_t + (\sigma_{E,t})^2 + \left(\sigma^g_{E,t}\right)^2 - \sigma_M \sigma_{E,t} - \sigma^g_{M,t}\sigma^g_{E,t} + \sigma_\alpha \sigma_M - \sigma_\alpha \sigma_{E,t} \\ = \; & \left(r - \frac{\beta}{(1 + (i^q_t/\bar{\alpha}))}\right) + \left(\frac{i^q_t}{\bar{\alpha} + i^q_t}\left(\nu + \sigma_\alpha \sigma_M - \sigma_\alpha \sigma_{E,t}\right)\right) - \gamma \Im (n_t - 1)^2 \quad , \end{aligned} \tag{35}$$

$$\sigma_M + \sigma_\alpha - \sigma_r - \sigma_{E,t} = \frac{i^q_t}{\bar{\alpha} + i^q_t}\sigma_\alpha \;\; \text{(3 equations)}, \tag{36}$$

$$\sigma^g_{M,t} - \sigma^g_{E,t} + \sigma^g_g = 0 \quad , \tag{37}$$

$$\sigma^g_{E,t} = \frac{\sigma^g_g}{n_t} \quad , \tag{38}$$

where we have used the notation $n_t = n^m_t + n^q_t$. In addition we have the household optimality conditions

$$\bar{\alpha}\bar{M} = E_t(c_t - y) \quad , \tag{39}$$

$$c_t = y + \frac{\beta \bar{a}}{(1 + (i_t^q/\bar{\alpha}))} \quad , \tag{40}$$

$$n_t = \frac{i_t^q - r - \varepsilon_t + (\sigma_{E,t})^2 + \left(\sigma_{E,t}^g\right)^2 + (\sigma_r)^2 + (\sigma_r \sigma_{E,t}) + 2\gamma\mathfrak{I}}{\left(\sigma_{E,t}^g\right)^2 + 2\gamma\mathfrak{I}} \quad , \tag{41}$$

where

$$n_t = \frac{\bar{M} + Q_t}{E_t} \quad . \tag{42}$$

This set of 10 equilibrium equations (35) - (42) determines the 10 endogenous variables ε_t, $\sigma_{E,t} = [\sigma_{E,t}^M \ \sigma_{E,t}^\alpha \ \sigma_{E,t}^r]$, $\sigma_{E,t}^g$, $\sigma_{M,t}^g$, n_t, i_t^q, c_t and E_t, given policy variables μ_t and Q_t. It needs to be established on a case-by-case basis, for specific calibrations of the economy, that this system has a unique solution. We have found unique solutions for all calibrations we considered. In that case all endogenous variables including n_t can be written uniquely in terms of the exogenous policy and shock processes. This verifies the regularity conditions posited earlier for $\varepsilon_t, \sigma_{E,t}, \sigma_{E,t}^g, \tau_t$ and $\sigma_{T,t}$. It also verifies, in Appendix II, that our conjectured value function and resulting policy functions for n_t^m and n_t^q solve the Hamilton-Jacobi-Bellman equation.

3 Policy Implications

3.1 Calibration and Estimation

To analyze the properties of the model we now turn to a calibrated example for Mexico, a small open economy with a substantial outstanding stock of domestic currency denominated government liabilities. We use this calibration to explore the behavior of portfolio choices, consumption and depreciation/inflation, under different assumptions about government balance sheet operations and therefore interest rates.

We use quarterly data[16] from the first quarter of 1996 through the second quarter of 2004

[16] The two data sources are International Financial Statistics (IFS) and Banco de Mexico. The data series for dr_t^b is the US treasury bill rate divided by one period ahead US CPI inflation.

(34 observations), to calibrate a baseline economy and to estimate the drifts and variance-covariance matrix of the first three of the economy's four shock processes, dM_t, $d\alpha_t$ and dr_t^b. The fourth shock process, exogenous government spending dG_t, cannot be estimated directly for two reasons. First, dG_t is not modeled as a geometric Brownian motion, but instead as an Itô process that relates spending to aggregate wealth a_t, for which there is no easily identifiable counterpart in the data.[17] Second, our theoretical concept of government spending excludes both a drift or positive mean spending, and spending volatility that induces an endogenous tax response instead of an exchange rate response. A meaningful decomposition of actual government spending along the lines of our model is beyond the scope of this paper.[18] Instead we calibrate σ_g^g based on an assumption about the fraction of money volatility caused by government spending. We then perform sensitivity analysis for a range of other plausible values for σ_g^g.

Benchmark Calibration We begin by calibrating the parameters $\beta = 0.04$, $y = 1$, and $\gamma = 0.0001$. Next we assume that, on average, the fraction of consumption financed by income from financial assets equals 2%, in other words $\overline{((c-y)/c)} = 0.02$. We can use this relationship to recover average normalized real consumption, and in combination with data for real base money we can then compute $\bar{\alpha} = 0.688$. Given the sample average nominal exchange rate $\bar{E} = 9.35$, we also obtain a baseline value for nominal money $\bar{M} = 0.277$. To recover a baseline value for $\bar{Q}$ we set $\overline{i^q} = 0.095$, its average over the second half of the sample period, when Mexican default risk premia had declined from their previously high levels. Then we recover $\bar{a}$ from (27), $\overline{n^m}$ from (12), and on the basis of the foregoing we find that $\bar{n} = 0.241$ based on Mexican debt and base money data.[19] This implies a value for $\overline{n^q}$,

Domestic absorption is used in place of c_t.

[17] Below we construct a model consistent sample average of aggregate wealth $\bar{a}$, but not its time series.

[18] This is closely related to the problem of distinguishing fiscally dominant and monetary dominant policy regimes in the data, see Canzoneri, Cumby and Diba (2004).

[19] If the real annual financial returns on Mexican government debt are multiplied by 0.241^{-1}, the resulting figure equals roughly 2% of annual consumption, in line with our earlier assumption about the fraction of consumption financed by financial asset income.

and we obtain $\bar{Q} = 1.0311$.

Estimation of Shock Processes Note that the three B_t shock processes can be rewritten, using Itô's Law, as:

$$d\log M_t = \left[\mu_t - \frac{1}{2}\left(\sigma_M\right)^2 - \frac{1}{2}\left(\sigma^g_{M,t}\right)^2\right]dt + \sigma_M dB_t + \sigma^g_{M,t} dW_t \quad , \tag{43}$$

$$d\log \alpha_t = \left[\nu - \frac{1}{2}\left(\sigma_\alpha\right)^2\right]dt + \sigma_\alpha dB_t \ , \tag{44}$$

$$dr^b_t = rdt + \sigma_r dB_t \ . \tag{45}$$

The model-consistent variance-covariance matrix between these shocks is

$$\Sigma = \begin{bmatrix} \left(\sigma_M\right)^2 + \left(\sigma^g_{M,t}\right)^2 & \sigma_M\sigma_\alpha & \sigma_M\sigma_r \\ \sigma_M\sigma_\alpha & \left(\sigma_\alpha\right)^2 & \sigma_\alpha\sigma_r \\ \sigma_M\sigma_r & \sigma_\alpha\sigma_r & \left(\sigma_r\right)^2 \end{bmatrix} \ . \tag{46}$$

We want to use the maximum-likelihood estimates of this matrix to separately identify, including their signs, the nine diffusion processes σ_M, σ_α and σ_r.[20] The difficulty is of course that the tenth component of this matrix, $\left(\sigma^g_{M,t}\right)^2$, is not separately identified. We therefore make the additional assumption $\left(\sigma^g_{M,t}\right)^2 = 3\left(\sigma_M\right)^2$. This says that monetary policy pursues a tight target path for inflation with little exogenous random variability in money growth σ_M, and with the accommodation of fiscal shocks being the main source of observed variability in money growth. We impose the further identifying restrictions that the real interest rate is completely exogenous ($\sigma^M_r = \sigma^\alpha_r = 0$), and that the money supply responds instantaneously to velocity shocks but not vice versa ($\sigma^M_\alpha = 0$). Finally the estimated diffusions, from (43) and (44), can be used to recover the drift processes μ and ν, while r can be estimated directly. We obtain the following results: $\mu = 0.0772$, $\nu = -0.0178$, $r = 0.0229$, $\sigma^M_M = 0.0159$, $\sigma^\alpha_M = -0.0009$, $\sigma^r_M = 0.0026$, $\sigma^\alpha_\alpha = 0.0294$, $\sigma^r_\alpha = -0.0059$, $\sigma^r_r = -0.0186$ and $\sigma^g_{M,t} = 0.0276$.

[20] Identifying the shock processes requires estimating continuous-time diffusion processes from a discrete sample. Aït-Sahalia (2002) shows that this can be quite complex in general settings, but Campbell, Lo and MacKinlay (1997, Ch. 9) show that geometric Brownian motion processes can be estimated in a straightforward fashion by maximum likelihood.

Exogenous Fiscal Volatility To calibrate the key parameter σ_g^g consistently with the model, we solve the calibrated baseline economy (35) - (42) taking $\sigma_{M,t}^g$ to be exogenous (see above) and solve for σ_g^g endogenously. We obtain $\sigma_g^g = 0.0045$. Our sensitivity analysis will allow for higher and lower σ_g^g to demonstrate the key importance of this parameter in creating imperfect asset substitutability and scope for balance sheet operations. To do so we flip the system (35) - (42), holding σ_g^g constant at the chosen value, and solving for $\sigma_{M,t}^g$. This amounts to creating counterfactual economies in which the variance of money growth is higher or lower than in the baseline economy in order to accommodate different fiscal spending volatility.

3.2 Monetary Policy

The two monetary policy variables are (μ_t, Q_t) or alternatively (μ_t, i_t^q). We will make no assumptions about the inflation target, and instead simply hold μ_t constant at its estimated value for Mexico. The main subject of this paper is interest rate policy, or alternatively balance sheet operations. We show the effects of a sterilized foreign exchange intervention in Figure 2. In each panel of this figure, we decompose that intervention into its two components, an unsterilized foreign exchange intervention and a subsequent domestic open market operation (OMO). The left half of each panel shows the effect of a doubling of the nominal money supply through an unsterilized foreign exchange purchase, a purchase of foreign bonds h in exchange for money M. The right half of each panel shows how the economy reacts if this expansion of the money supply is reversed through a domestic open market sale, a sale of domestic currency bonds Q against money M. These two operations combined leave the money supply M constant while changing the currency composition of private portfolios.

The unsterilized foreign exchange purchase is highly inflationary, causing a doubling of the exchange rate and price level. This reduces the real value of domestic bonds and therefore the overall share of domestic assets in agents' portfolios. This is reflected in both

an equilibrium reduction in mean return and in an equilibrium increase in portfolio risk. First, the interest rate drops by around 0.15%. Second, because the government's reduced domestic liabilities provide a smaller cushion against fiscal shocks, exchange rate volatility and therefore portfolio risk doubles to 0.4% in annual interest equivalent terms. The cost to the government of higher exchange rate volatility outweighs the interest savings, so that taxes have to rise. Note that consumption is barely affected by the change in interest rates, principally because in our calibration based on Mexican data velocity is extremely high. This may not be true for other countries, in which case a lower interest rate would stimulate consumption significantly.

The open market operation completely sterilizes the foreign exchange intervention, so that the exchange rate depreciation is reversed. But variables do not return to their baseline values. Most importantly, while real money balances are nearly unchanged after sterilization, the real quantity of outstanding domestic liabilities has increased significantly, thereby increasing interest rates, lowering exchange rate volatility, and lowering the required tax rate to balance the government budget. Sterilized intervention therefore has significant real effects, and with a lower velocity those effects would also include significantly lower consumption.

The bottom left panel of Figure 2 shows the domestic interest rate in our economy. The broken line represents the uncovered interest parity relation of equation (29). Domestic currency assets display a currency risk discount. The fact that in many developing countries one often observes an overall risk premium is due to either borrowing risk premia that are larger and that start to apply at lower levels of domestic asset portfolio shares than we have allowed for here, or to Peso-problem type premia of the kind emphasized by Obstfeld (1987).

The following Figures 3-5 illustrate these effects over a broader range of sterilized interventions. This time we show the domestic asset share n_t in % along the horizontal axis. To facilitate comparison, we allow n_t to vary between 7% and 30% irrespective of the volatility of government spending. Figure 3 shows the baseline case. The first panel plots

the relationship between n_t and the stock of domestic currency denominated government securities Q_t. Issuing more nominal debt increases the real debt stock given that full sterilization keeps the nominal money stock constant, which keeps the nominal exchange rate nearly constant. As the domestic debt share rises from 7% to 30%, the equilibrium interest rate i_t^q rises by around 0.30% and fiscally induced exchange rate volatility $\sigma_{E,t}^g$ falls from 0.5% in annual interest rate equivalent terms to near zero. This lowers overall exchange rate volatility by the same amount, because exchange rate volatility originating from the three non-fiscal shocks is nearly constant. From around a 25% debt share onwards, further expansions of the nominal debt stock have quite modest effects on interest rates and exchange rate volatility. This implies that our baseline economy, whose debt share n_t is fairly high at just below 25%, features a nominal interest rate within only about 10 basis points of uncovered interest parity. At such levels, balance sheet operations would have fairly small effects on interest rates. Note that a higher interest rate also has a secondary effect on mean depreciation ε_t, but this is minor compared to the effect of the nominal anchor μ_t. Finally, as we saw above, a higher debt stock allows the government to lower the mean tax rate, because the negative effect of higher interest rates on the budget is more than offset by the positive effect of less volatile exchange rates.

It is now also clear that the effect of a given contraction of the money supply depends on the market through which that contraction is implemented. The effects on interest rates are larger if domestic rather than foreign bonds are sold to households, because under domestic open market operations the portfolio share n_t expands not just due to a drop in the exchange rate but also due to an expansion of the domestic nominal bond stock. This requires an even lower interest rate to establish portfolio balance.

Figures 4 and 5 show how these results depend on the volatility of exogenous fiscal shocks, leaving all other model parameters unchanged. In Figure 4 we see that, when the fiscal shock diffusion σ_g^g is reduced by a factor of four to 0.0011, balance sheet operations over the same range of Q as those reported in Figure 3 have almost no effect on interest rates

and exchange rate volatility, while we see in Figure 5 that raising σ_g^g by a factor of four to 0.018 increases the range over which balance sheet operations have very significant effects.

Figure 4 suggests why empirical studies of sterilized intervention may have found little evidence for their effect in industrialized countries. In such countries the fiscal situation is generally much more robust, and fiscal dominance is much less of a problem. Even if there was fiscal dominance, the ability of such countries to issue substantial amounts of domestic currency denominated debt means that the induced exchange rate volatility would be comparatively low. On the other hand, developing countries face the opposite scenario. As shown by Catão and Terrones (2005), they face serious fiscal dominance problems. And the well-known work of Eichengreen and Hausmann (2005) documents that they have much more difficulty issuing substantial stocks of domestic currency debt (for reasons that are not modeled in this paper). In such countries sterilized intervention would be a second tool of monetary policy that gives the government autonomy to set nominal interest rates independently of the inflation target.[21]

4 Conclusion

We have studied a general equilibrium monetary portfolio choice model of a small open economy. The model emphasizes the importance of fiscal policy for the number and effectiveness of the instruments available to monetary policy, specifically for its ability to affect prices and allocations through balance sheet operations such as sterilized intervention. Conventional theoretical results concerning the ineffectiveness of sterilized intervention depend on the assumption of full lump-sum redistribution of stochastic seigniorage income and the complete absence of exogenous fiscal spending shocks. When this assumption is relaxed, government balance sheet operations in domestic and foreign currency bonds

[21] Of course, such government liability dollarization is otherwise not necessarily a blessing. Mishkin (2000) and Mishkin and Savastano (2001) discuss several problems that it creates for the conduct of monetary policy.

become an effective second tool of monetary policy. They change domestic interest rates, the mean and variance of exchange rate depreciation and inflation, and household consumption and portfolio choices.

In this economy uncovered interest parity fails to hold and is replaced by a general equilibrium portfolio balance equation. Sizeable currency risk discounts are obtained when a government's nominal liabilities are small and when the volatility of its fiscal shocks is high. Borrowing risk premia are possible when a government issues large amounts of nominal liabilities, but our paper has not focused on that aspect. It has however provided the analytical apparatus for doing so.

We are very hopeful that this paper can open up a fruitful area for future research. Together with Obstfeld (2004), who has recently reversed his earlier negative verdict on the usefulness of such models, we believe that the time may have come for a new generation of general equilibrium portfolio balance models. Some of today's pressing policy problems, such as international portfolio valuation effects, require such an approach. An extension of the current paper to a two-country model is the subject of ongoing work by the authors.

Appendix I Returns on Assets

The return on real money balances is derived using Itô's law to differentiate M_t/E_t holding M_t constant:

$$\begin{aligned} m_t dr_t^m &= M_t d\left(\frac{1}{E_t}\right) = \\ &\frac{-M_t}{E_t^2} E_t \left[\varepsilon_t dt + \sigma_{E,t} dB_t + \sigma_{E,t}^g dW_t\right] + \frac{1}{2}\frac{2M_t}{E_t^3} E_t^2 \left[(\sigma_{E,t})^2 + (\sigma_{E,t}^g)^2\right] dt \quad , \end{aligned}$$

which yields the return

$$dr_t^m = \left(-\varepsilon_t + (\sigma_{E,t})^2 + (\sigma_{E,t}^g)^2\right) dt - \sigma_{E,t} dB_t - \sigma_{E,t}^g dW_t \quad . \tag{A.1}$$

The real return on the domestic bond is given by its nominal interest rate i_t^q, minus the change in the international value of domestic money as in (A.1). We have

$$dr_t^q = \left(i_t^q - \varepsilon_t + (\sigma_{E,t})^2 + (\sigma_{E,t}^g)^2\right) dt - \sigma_{E,t} dB_t - \sigma_{E,t}^g dW_t \quad . \tag{A.2}$$

The real return on international bonds is exogenous and given by (3), which is repeated here for completeness.

$$dr_t^b = r dt + \sigma_r dB_t \quad . \tag{A.3}$$

Appendix II The Value Function

This Appendix verifies the conjectured value function $V(a_t, t) = e^{-\beta t} J(a_t, t) = e^{-\beta t} x[\ln(a_t) + \ln(X(t;\chi_t))]$ and derives closed form expressions for x and $X(t;\chi_t)$. Substitute the conjecture, the optimality condition (16) and (17), and the government policy rules (21), (22) and (23) into the Bellman equation (14). Then cancel terms to get

$$\begin{aligned} & \beta x \ln(a_t) + \beta x \ln(X(t;\chi_t)) - x\frac{\dot{X}(t;\chi_t)}{X(t;\chi_t)} \\ = \; & \ln(a_t) - \ln(x) - \ln(1 + (i_t^q/\alpha_t)) - 1/(1 + (i_t^q/\alpha_t)) \\ & + x\left[r - \gamma\Im\left(n_t^m + n_t^q - 1\right)^2\right] \\ & - \frac{x}{2}\left[(\sigma_r)^2 + \left(\sigma_g^g\right)^2\right] \quad , \end{aligned}$$

where $\dot{X}(t;\chi_t) = \partial X(t;\chi_t)/\partial t$. Equating terms on $\ln(a_t)$ yields

$$x = \beta^{-1} \ . \tag{B.1}$$

This implies the first-order conditions (28) and (27) shown in the paper. We are left with a differential equation in $X(t;\chi_t)$ as follows:

$$\begin{aligned} \frac{\dot{X}(t;\chi_t)}{X(t;\chi_t)} &= \beta \ln(X(t;\chi_t)) - \beta \ln(\beta) + \beta \ln(1 + (i_t^q/\alpha_t)) + \beta/\left(1 + (i_t^q/\alpha_t)\right) \\ &\quad -r + \frac{1}{2}\left((\sigma_r)^2 + \left(\sigma_g^g\right)^2\right) + \gamma\mathfrak{I}\left(n_t^m + n_t^q - 1\right)^2 \quad . \end{aligned} \tag{B.2}$$

The equilibrium set of equations determining the evolution of the economy is presented in the text as (35) - (42). We verify on a case-by-case basis that this system has unique bounded solutions for, among others, n_t. This means that all terms on the right-hand side of (B.2) are, or can be expressed uniquely in terms of, exogenous policy or shock variables χ_t, as conjectured at the outset. Furthermore,

$$\frac{\partial \dot{X}(t;\chi_t)}{X(t;\chi_t)}|_{\dot{X}(t;\chi_t)=0} = \beta > 0 \ . \tag{B.3}$$

This implies that $X(t;\chi_t)$ is saddle path stable for any given χ_t, and is therefore uniquely determined for each t and χ_t.

Our approach has followed Duffie's (1996, chapter 9) discussion of optimal portfolio and consumption choice in that we have focused mainly on necessary conditions. This is because the existence of well-behaved solutions in a continuous-time setting is typically hard to prove in general terms. We have adopted the alternative approach of conjecturing a solution and then verifying it, and have found that our conjecture $V(a_t,t)$ does solve the Hamilton-Jacobi-Bellman equation and is therefore a logical candidate for the value function. In the process of doing so we have also solved for the associated feedback controls (n_t^{q*}, n_t^{m*}) and wealth process a_t^*. We now verify that $V(a_t,t)$ and (n_t^{q*}, n_t^{m*}) are indeed optimal.

Note first that our solutions solve the problem

$$\sup_{n_t^m, n_t^q} \left\{\ln(\alpha_t n_t^m a_t - y) + DJ(a_t,t)\right\} = 0 \quad , \tag{B.4}$$

where

$$DJ(a_t,t) = J_a(a_t,t)F(a_t,n_t^m,n_t^q) + \frac{1}{2}J_{aa}(a_t,t)\left[H(a_t,n_t^m,n_t^q)\right]^2 - \beta J(a_t,t) + \dot{J}(a_t,t) \quad . \tag{B.5}$$

The functions $F(.,.,.)$ and $H(.,.,.)$ are derived from the equilibrium evolution of wealth a_t given the conjectured form of the value function $V(a_t,t)$ and given the associated feedback controls (n_t^{q*}, n_t^{m*}). Let $\sigma_a = [\sigma_r \quad \left(-\sigma_g^g\right)]$ and $Z_t = [B_t \;\; W_t]'$. Then we have

$$da_t = F(a_t,n_t^m,n_t^q)dt + H(a_t,n_t^m,n_t^q)dZ_t \quad ,$$

where

$$\begin{aligned} F(a_t,n_t^m,n_t^q) &= ra_t + y - \alpha_t n_t^m a_t \quad , \\ H(a_t,n_t^m,n_t^q) &= a_t\sigma_a \quad , \end{aligned}$$

and where in line with our previous notation $\left[H(a_t,n_t^m,n_t^q)\right]^2 = a_t^2\left[(\sigma_r)^2 + \left(\sigma_g^g\right)^2\right]$.

Now let (n_t^q, n_t^m) be an arbitrary admissible control for initial wealth a_0 and let a_t be the associated wealth process. By Itô's formula, the stochastic integral for the evolution of the quantity $e^{-\beta t}J(a_t,t)$ can be written as

$$\begin{aligned} e^{-\beta t}J(a_t,t) &= J(a_0,0) + \int_0^t e^{-\beta s}DJ(a_s,s)ds + \int_0^t e^{-\beta s}\psi_s dB_s \quad , \\ \text{where} \quad \psi_t &= J_a(a_t,t)H(a_t,n_t^m,n_t^q) \quad . \end{aligned} \tag{B.6}$$

We proceed to take limits and expectations of this equation. We show first that $\mathbb{E}_0\left(\int_0^t e^{-\beta s}\psi_s dB_s\right) = 0$. To do so we need to demonstrate that $\int_0^t e^{-\beta s}\psi_s dB_s$ is a martingale, which requires that $e^{-\beta s}\psi_s$ satisfies $\mathbb{E}_0\left[\int_0^t \left(e^{-\beta s}\psi_s\right)^2 ds\right] < \infty \;,\; t > 0$. In our case, we have simply that $\psi_t = \sigma_a/\beta$. The condition is therefore satisfied, and we have that

$$\begin{aligned} \lim_{t\to\infty}\mathbb{E}_0\left\{e^{-\beta t}J(a_t,t)\right\} &= \lim_{t\to\infty}\mathbb{E}_0\left\{J(a_0,0) + \int_0^t e^{-\beta s}DJ(a_s,s)ds\right\} \\ &= J(a_0,0) + \int_0^\infty e^{-\beta s}DJ(a_s,s)ds \; . \end{aligned} \tag{B.6'}$$

The transversality condition (15) can easily be verified because both wealth a_t and the term $X(t;\chi_t)$ at most grow at an exponential rate. The left-hand side of (B.6') is therefore zero. Because the chosen control is arbitrary, (B.4) implies that

$$-DJ(a_t,t) \geqq \ln(\alpha_t n_t^m a_t - y) \quad ,$$

and therefore

$$J(a_0,0) \geqq \int_0^\infty e^{-\beta s} \ln(\alpha_s n_s^m a_s - y) ds \quad . \tag{B.7}$$

On the other hand, when we do the same calculation for our feedback controls (n_t^{q*}, n_t^{m*}) we arrive at (B.7) but with $\geqq$ replaced by an equality sign:

$$J(a_0,0) = \int_0^\infty e^{-\beta s} \ln(\alpha_s n_s^{m*} a_s^* - y) ds \quad . \tag{B.8}$$

We therefore conclude that $J(a_0,0)$ dominates the value obtained from any other admissible control process, and that the controls (n_t^{q*}, n_t^{m*}) are indeed optimal.

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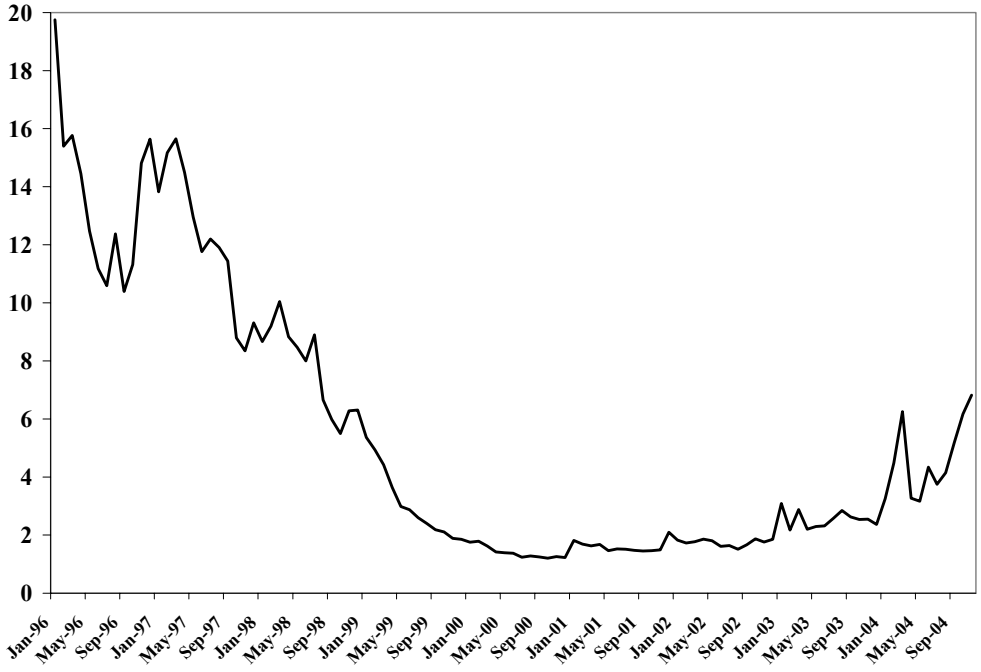


Figure 1: Foreign Holdings of Mexican Peso Denominated Government Securities - % of Total (Source: Banco de Mexico)

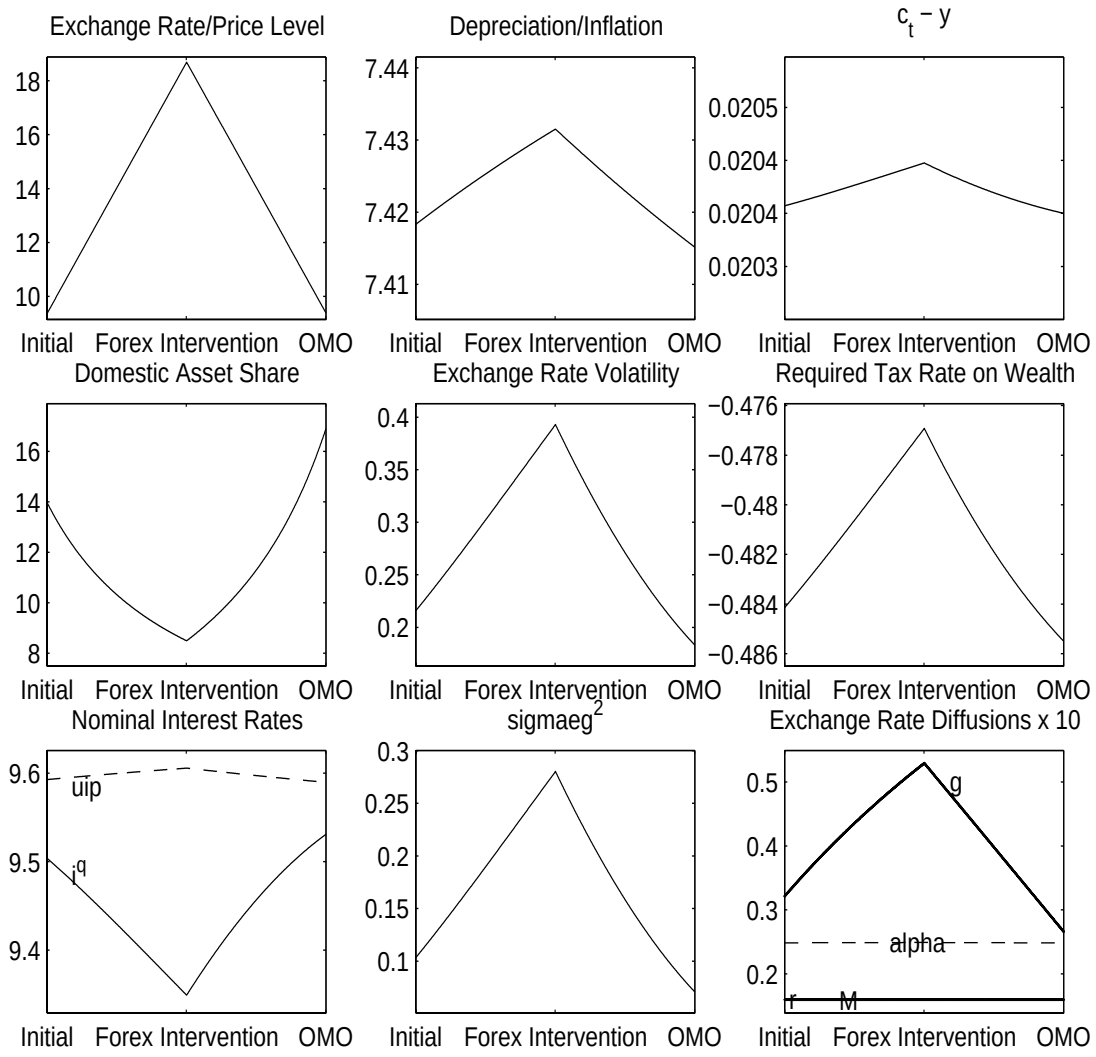


Figure 2: Unsterilized Foreign Exchange Purchase and Open Market Sale

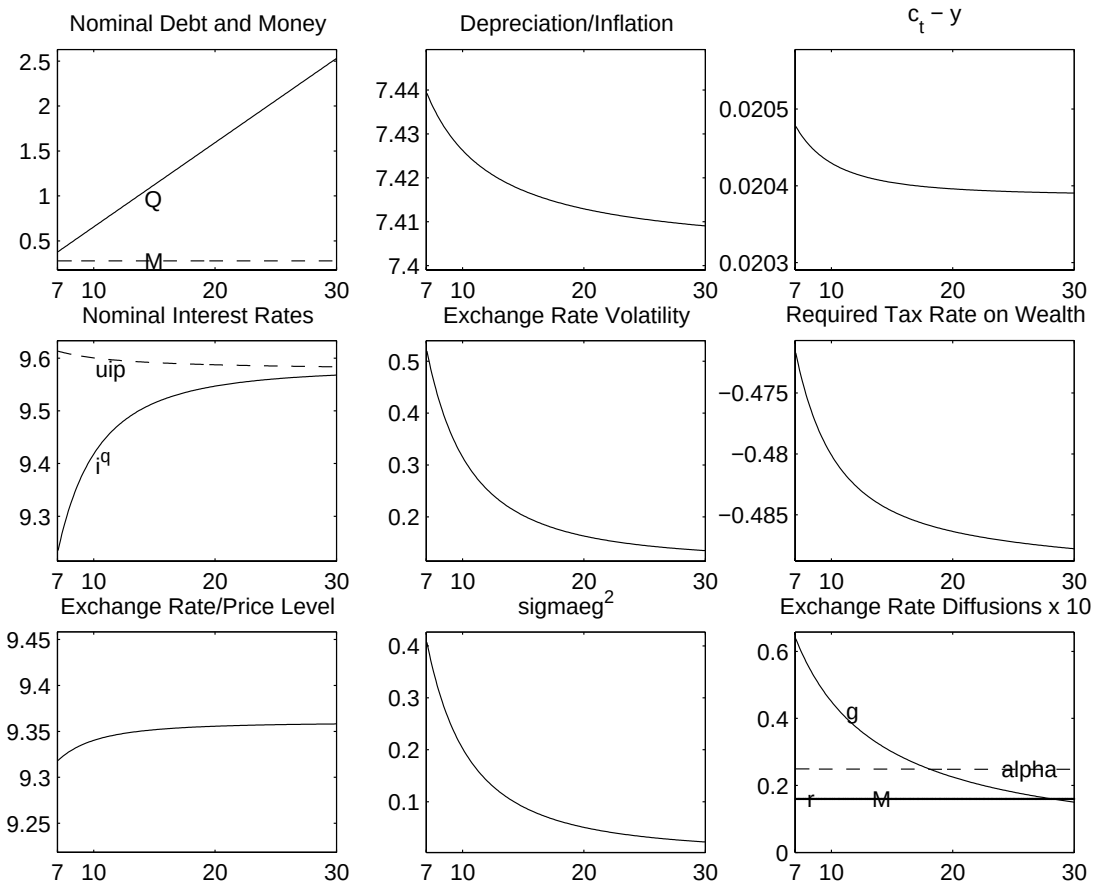


Figure 3: Sterilized Foreign Exchange Intervention - Baseline Case

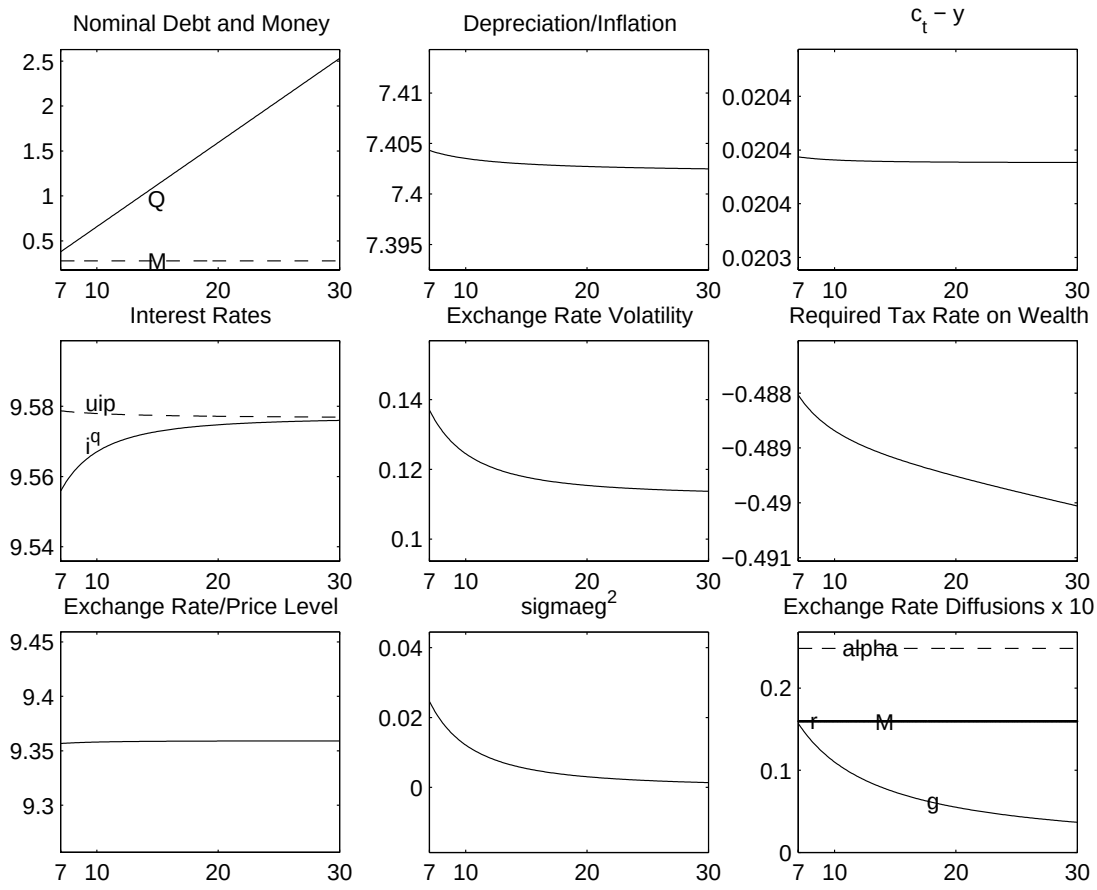


Figure 4: Sterilized Foreign Exchange Intervention - Low Volatility of Fiscal Shocks

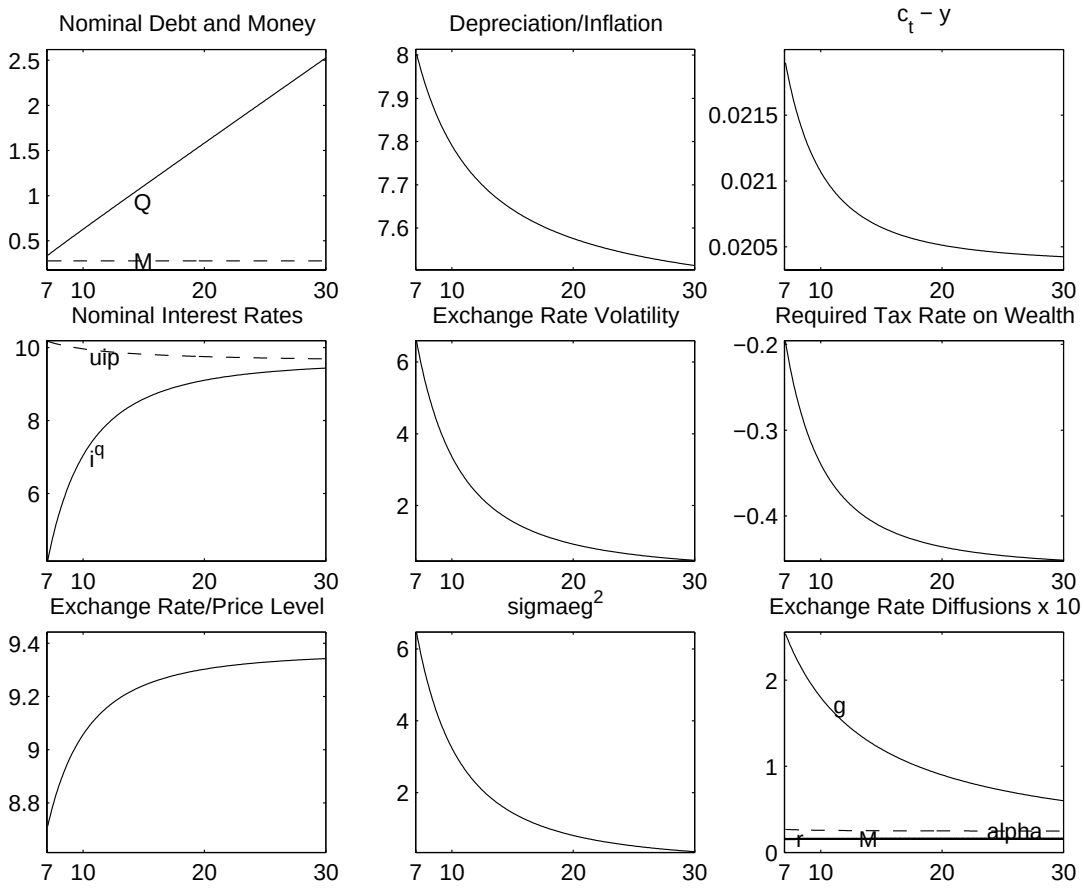


Figure 5: Sterilized Foreign Exchange Intervention - High Volatility of Fiscal Shocks