The Systematic Component of Monetary Policy in SVARs: An Agnostic Identification Procedure

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Abstract

In this paper we identify monetary policy shocks in structural vector autoregressions (SVARs) imposing sign and zero restrictions on the systematic component of monetary policy, while leaving the non-policy equations unrestricted. We find that an exogenous increase in the federal funds rate leads to a persistent decline in output and prices. Our results show that the conventional effects of monetary policy shocks do not hinge on exact identification schemes, based on often questionable exclusion restrictions, but are consistent with a large set of SVARs. The analysis is robust to various specifications of the systematic component of monetary policy widely used in the literature.

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1 Introduction

Following Sims (1972, 1980, 1986), researchers have analyzed the effects of monetary policy on output using structural vector autoregressions (SVAR). Most of them have concluded that an increase in the federal funds rate or a decrease in money supply are contractionary, i.e. they have a significant negative effect on output. The set of studies supporting this view includes Bernanke and Blinder (1992), Christiano, Eichenbaum and Evans (1996), Leeper, Sims and Zha (1996), and Bernanke and Mihov (1998).[1] This intuitive result has become the cornerstone rationale behind New Keynesian dynamic stochastic general equilibrium (DSGE) models. Researchers also estimate New Keynesian models matching the model implied dynamic responses to a monetary policy shock with those implied by a SVAR − see Rotemberg and Woodford (1997) and Christiano, Eichenbaum and Evans (2005).

The consensus about the contractionary effects of monetary policy shocks has been challenged by Uhlig (2005), who using an agnostic identification strategy found no evidence to support such view. Uhlig's (2005) critique is that traditional SVARs require a tremendous number of possibly spurious restrictions and the identification of all shocks in the system. Thus, he proposes to only identify monetary policy shocks by imposing sign restrictions on just the impulse response functions of prices and nonborrowed reserves to this shock. These restrictions eliminate the well-known price and liquidity puzzles, while remaining agnostic about the responses of other variables, and in particular output, to the monetary policy shock.[2] Furthermore, this approach does not restrict the response of any variable to the remaining structural shocks. This means that Uhlig (2005) does not identify a single model but a set of models that are coherent with his sign restrictions. In other words, he does not identify the structural parameters but just set identifies them.

In this paper we endorse the agnostic approach, but instead of imposing restrictions on impulse responses functions to a monetary policy shock, we impose them on the monetary policy equation. In particular, we use an agnostic identification scheme to restrict the systematic component of monetary policy. Our approach is inspired by Leeper, Sims and Zha (1996), Leeper and Zha

[1] Leeper, Sims and Zha (1996), Bagliano and Favero (1998), and Christiano, Eichenbaum and Evans (1999), survey this extensive literature.

[2] See Sims (1992) for a description of the price puzzle, and **?** for a description of the liquidity puzzle.

(2003), and Sims and Zha (2006a) line of work that emphasizes the need to specify and estimate behavioral relationships for monetary policy. Policy choices in general, and monetary policy choices in particular, do not evolve independent of economic conditions: *Even the harshest critics of monetary authorities would not maintain that policy decisions are unrelated to the economy* (Leeper, Sims and Zha, 1996). Thus, to isolate exogenous changes in policy, one needs to model how policy reacts to the economy.

Specifically, we restrict the systematic component of monetary policy following three specifications used in the literature. The first specification derives directly from Christiano, Eichenbaum and Evans (1996), and it implies that the federal funds rate responds positively to output and prices. The second specification originates from the widely used Taylor rule and implies that the federal funds rate responds to output growth and inflation. The third specification considers the class of monetary rules described in Leeper, Sims and Zha (1996), Leeper and Zha (2003), and Sims and Zha (2006a,b), in which money and the federal funds rate are the only variables entering the monetary policy equation.

But we extend the existing literature in two ways. First, we impose sign and zero restrictions on the monetary policy equation to identify SVARs with a *reasonable* but loosely specified systematic component of monetary policy. Second, we leave the non-policy equations unrestricted, remaining agnostic about the non-policy structure of the economy and the impulse response function of output to a monetary policy shock. Hence, as Uhlig (2005), we do not identify a single model but a set of models that are coherent with our sign and zero restrictions.

We highlight two results. First, we find that an exogenous increase in the federal funds rate has persistent contractionary effects on output. The decline in real activity, together with the decline in prices, causes a medium-term loosening of the monetary policy stance. Hence, our agnostic identification scheme recovers the consensus on the effects of monetary policy shocks, while addressing Uhlig (2005)'s critique. Second, we show that the identification scheme in Uhlig (2005) violates our restrictions on the systematic component of monetary policy. It follows from Leeper, Sims and Zha (1996), Leeper and Zha (2003), and Sims and Zha (2006a), that Uhlig (2005) does not identify monetary policy shocks.

To further understand the relationship between the identification schemes, we combine the sign restrictions on impulse responses functions in Uhlig (2005) with our restrictions on the systematic component. We find that our restrictions substantially shrink the set of models originally identified by Uhlig (2005), and that excluding models with counterfactual monetary policy equations suffices to generate a negative response of output and recover the consensus. On the contrary, while the restrictions in Uhlig (2005) refine the set of admissible models obtained using our approach, they have a modest impact on inference.

We use the methodology developed by Arias, Rubio-Ramirez and Waggoner (2014) to impose sign and zero restrictions on the structural parameters of the SVAR. We use the results in Rubio-Ramírez, Waggoner and Zha (2010) to impose sign restrictions only. Caldara and Kamps (2012) use the same methodology to identify tax and government spending shocks disciplining the systematic component of fiscal policy.

The structure of the paper is as follows. In Section 2, we describe the SVAR methodology and describe our baseline identification scheme. In Section 3, we describe the results and compare them with Uhlig (2005). In Section 4 we repeat the exercise using alternative specifications of the monetary policy equation. In Section 5, we conclude.

2 Methodology

Let's consider the following SVAR

$$\mathbf{y}_t'\mathbf{A}_0 = \sum_{\ell=1}^{p} \mathbf{y}_{t-\ell}'\mathbf{A}_\ell + \mathbf{c} + \varepsilon_t' \quad \text{for } 1 \leq t \leq T, \tag{1}$$

where $\mathbf{y}_t$ is an $n \times 1$ vector of endogenous variables, ε_t is an $n \times 1$ vector of structural shocks, $\mathbf{A}_\ell$ is an $n \times n$ matrix of structural parameters for $0 \leq \ell \leq p$ with $\mathbf{A}_0$ invertible, $\mathbf{c}$ is a $1 \times n$ vector of parameters, p is the lag length, and T is the sample size. The vector ε_t, conditional on past information and the initial conditions $\mathbf{y}_0, ..., \mathbf{y}_{1-p}$, is Gaussian with mean zero and covariance matrix $\mathbf{I}_n$, the $n \times n$ identity matrix. The model described in equation (1) can be written as

$$\mathbf{y}_t'\mathbf{A}_0 = \mathbf{x}_t'\mathbf{A}_+ + \varepsilon_t' \quad \text{for } 1 \leq t \leq T, \tag{2}$$

where $\mathbf{A}_+' = \begin{bmatrix} \mathbf{A}_1' & \cdots & \mathbf{A}_p' & \mathbf{c}' \end{bmatrix}$ and $\mathbf{x}_t' = \begin{bmatrix} \mathbf{y}_{t-1}' & \cdots & \mathbf{y}_{t-p}' & 1 \end{bmatrix}$ for $1 \leq t \leq T$. The dimension of $\mathbf{A}_+$ is $m \times n$, where $m = np + 1$. We call $\mathbf{A}_0$ and $\mathbf{A}_+$ the structural parameters. The reduced form representation implied by equation (2) is

$$\mathbf{y}_t' = \mathbf{x}_t'\mathbf{B} + \mathbf{u}_t' \quad \text{for } 1 \leq t \leq T,$$

where $\mathbf{B} = \mathbf{A}_+\mathbf{A}_0^{-1}$, $\mathbf{u}_t' = \varepsilon_t'\mathbf{A}_0^{-1}$, and $\mathbb{E}\left[\mathbf{u}_t\mathbf{u}_t'\right] = \mathbf{\Sigma} = \left(\mathbf{A}_0\mathbf{A}_0'\right)^{-1}$. The matrices $\mathbf{B}$ and $\mathbf{\Sigma}$ are the reduced form parameters. Finally, the impulse response functions (IRFs) are as follows.

Definition 1. *Let $(\mathbf{A}_0, \mathbf{A}_+)$ be any value of structural parameters, the IRF of the i-th variable to the j-th structural shock at finite horizon h corresponds to the element in row i and column j of the matrix*

$$\mathbf{L}_h\left(\mathbf{A}_0, \mathbf{A}_+\right) = \left(\mathbf{A}_0^{-1}\mathbf{J}'\mathbf{F}^h\mathbf{J}\right)', \textit{ where } \mathbf{F} = \begin{bmatrix} \mathbf{A}_1\mathbf{A}_0^{-1} & \mathbf{I}_n & \cdots & \mathbf{0} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{A}_{p-1}\mathbf{A}_0^{-1} & \mathbf{0} & \cdots & \mathbf{I}_n \\ \mathbf{A}_p\mathbf{A}_0^{-1} & \mathbf{0} & \cdots & \mathbf{0} \end{bmatrix} \textit{ and } \mathbf{J} = \begin{bmatrix} \mathbf{I}_n \\ \mathbf{0} \\ \vdots \\ \mathbf{0} \end{bmatrix}.$$

Papers in the literature that are concerned about set identification of structural parameters typically impose sign and/or zero restrictions on either $\mathbf{A_0}$ or the IRFs. The identification approach we propose in this paper combines sign and zero restrictions on both $\mathbf{A_0}$ and the IRFs. We use restrictions on $\mathbf{A_0}$ to discipline the systematic component of monetary policy while restrictions on the IRFs to restrict the dynamics of the structural shocks.

Our methodology is based on Rubio-Ramírez, Waggoner and Zha (2010) and Arias, Rubio-Ramirez and Waggoner (2014). For details, we refer the reader to the mentioned papers, but we can summarize the characterization to the restrictions as follows. Let us assume that we want to impose restrictions on some elements of $\mathbf{A_0}$ and on some IRFs at different horizons. It is convenient to stack $\mathbf{A_0}$ and the IRFs for all the relevant horizons into a single matrix of dimension $k \times n$, which we denote by $f(\mathbf{A}_0, \mathbf{A}_+)$. For example, if we impose restrictions at horizons zero and one, then

$$f(\mathbf{A}_0, \mathbf{A}_+) = \begin{bmatrix} \mathbf{A_0} \\ \mathbf{L}_0(\mathbf{A}_0, \mathbf{A}_+) \\ \mathbf{L}_1(\mathbf{A}_0, \mathbf{A}_+) \end{bmatrix}, \text{ where } k = 3n \text{ in this case.}$$

We represent the sign restrictions on $f(\mathbf{A}_0, \mathbf{A}_+)$ used to identify structural shock j by a selection matrix $\mathbf{S}_j$, where the number of columns in $\mathbf{S}_j$ is equal to k and $1 \leq j \leq n$. Thus, $(\mathbf{A}_0, \mathbf{A}_+)$ are values of structural parameters such that the sign restrictions on structural shock j hold if and only if $\mathbf{S}_j f(\mathbf{A}_0, \mathbf{A}_+) \mathbf{e}_j > 0$, where $\mathbf{e}_j$ denotes the j-th column of $\mathbf{I}_n$ (the identity matrix of dimension $n \times n$). Similarly, we represent the zero restrictions on $f(\mathbf{A}_0, \mathbf{A}_+)$ used to identify structural shock j by selection matrices $\mathbf{Z}_j$, where the number of columns in $\mathbf{Z}_j$ is also equal to k. Thus, $(\mathbf{A}_0, \mathbf{A}_+)$ are values of structural parameters such that the zero restrictions on structural shock j hold if and only if $\mathbf{Z}_j f(\mathbf{A}_0, \mathbf{A}_+) \mathbf{e}_j = 0$. When we only impose sign restrictions, we draw from the posterior distribution of the structural parameters using algorithms in Rubio-Ramírez, Waggoner and Zha (2010). When we impose sign and zero restrictions, we draw using algorithms in Arias, Rubio-Ramirez and Waggoner (2014).

To highlight the implications of our identification scheme, we choose a widely used specification of the reduced-form VAR model. In particular, we make our results comparable to Uhlig (2005), and we use Bayesian methods to estimate the same reduced form model as Uhlig (2005) on his dataset, which spans U.S. monthly data from 1965:I to 2003:XII, using his priors. Given that the priors, the reduced form model and the data has been extensively discussed by Uhlig (2005), for our purposes it suffices to mention that the VAR specification includes output (real GDP), y_t, the GDP deflator, p_t, an index of commodity prices, $p_{c,t}$, total reserves, tr_t, nonborrowed reserves, nbr_t, and the federal funds rate, r_t. We take the natural logarithm of all variables except for the federal funds rate. Without loss of generality, throughout the paper we discuss identification schemes assuming that variables follow the order of listing above. This vector of endogenous variables is standard in the literature and has been used, among others, by Christiano, Eichenbaum and Evans (1996) and Bernanke and Mihov (1998). The VAR specification includes twelve lags ($p = 12$) and does not include any deterministic term.[3]

2.1 Sign Restrictions on IRFs

Agnostic identification schemes are commonly associated with imposing sign restrictions on IRFs. A seminal paper in this literature is Uhlig (2005). This paper asks what are the effects of monetary policy shocks on output. In order to identify monetary policy shocks, he imposes the following restrictions.

Restrictions 1. *A monetary policy shock leads to a negative response of the GDP deflator, commodity prices, and nonborrowed reserves, and to a positive response of the federal funds rate, all at horizons* $t = 0, \ldots, 5$.

Restrictions 1 rule out the price puzzle –a positive response of the price level following a monetary contraction– and the liquidity puzzle, a positive response of monetary aggregates. Uhlig (2005) motivates those restrictions as ruling out implausible behaviors of prices and reserves, so that the set of admissible SVARs does not include models that we would anyway rule out as not interesting from a theoretical perspective. Restrictions 1 imply non-linear restrictions on $(\mathbf{A_0}, \mathbf{A}_+)$. But the crucial features of the identification described by Restrictions 1 are that (i) it remains agnostic about the response of output after an increase in the federal funds rate and (ii) it only identifies monetary policy shocks. This implies that Restrictions 1 do not identify the structural parameters but only set identifies them, allowing a set of models –and not a single model– to be compatible with the restrictions.

Without loss of generality, if we let the monetary policy shock to be the first structural shock,

[3]We repeat the analysis using an updated version of the dataset running until 2007, and a version with quarterly data. Results reported in the following Sections are robust to the use of these dataset and are available upon request.

we characterize Restrictions 1 with the matrices described below.[4]

$$f(\mathbf{A}_0, \mathbf{A}_+) = \begin{bmatrix} \mathbf{L}_0(\mathbf{A}_0, \mathbf{A}_+) \\ \vdots \\ \mathbf{L}_5(\mathbf{A}_0, \mathbf{A}_+) \end{bmatrix}, \ \mathbf{S}_1 = \begin{bmatrix} \mathbf{S}_{10} & \mathbf{0}_{m,n} & \cdots & \mathbf{0}_{m,n} \\ \mathbf{0}_{m,n} & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & \mathbf{0}_{m,n} \\ \mathbf{0}_{m,n} & \cdots & \mathbf{0}_{m,n} & \mathbf{S}_{15} \end{bmatrix}, \text{ and}$$

$$\mathbf{S}_{1t} = \begin{bmatrix} 0 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \text{ for } t = 0, \ldots, 5, \text{ where } m = 6 \text{ and } n = 4.$$

We plot in Figure 1 the IRFs to an exogenous monetary policy tightening identified imposing Restrictions 1. Throughout the paper, we normalize the size of the shock to be equal to one standard deviation. All results are based on 10,000 draws from the posterior distribution of the structural parameters. The shadowed area shows the 68% confidence bands and the solid lines shows the median IRFs. This figure replicates Figure 6 in Uhlig (2005). Panel (A) shows that the median response of output is positive. In addition, in the short run there is evidence that the 68% confidence bands do not contain zero. Panels (B) and (C) show the response of the GDP deflator and the commodity price index, respectively, which are restricted to be negative for six months to exclude the price puzzle. Panels (D) and (E) show the response of total reserves and nonborrowed reserves, both of which are negative in the short run. The reduction in nonborrowed reserves is more significant because the response of this variable is restricted to be negative for six months to exclude the liquidity puzzle. Finally, Panel (F) shows the response of the federal funds rate, which is restricted to be positive for the first six months, and it become negative 18 months after the shock.

Hence, consistent with Uhlig (2005), the main result of Figure 1 is the lack of support for the contractionary effects on output of an exogenous increase in the federal funds rate. This result presents a challenge to the consensus according to which output decreases in response to a monetary

[4] In the paper, it will always be the case that the monetary policy shock will be the first structural shock.

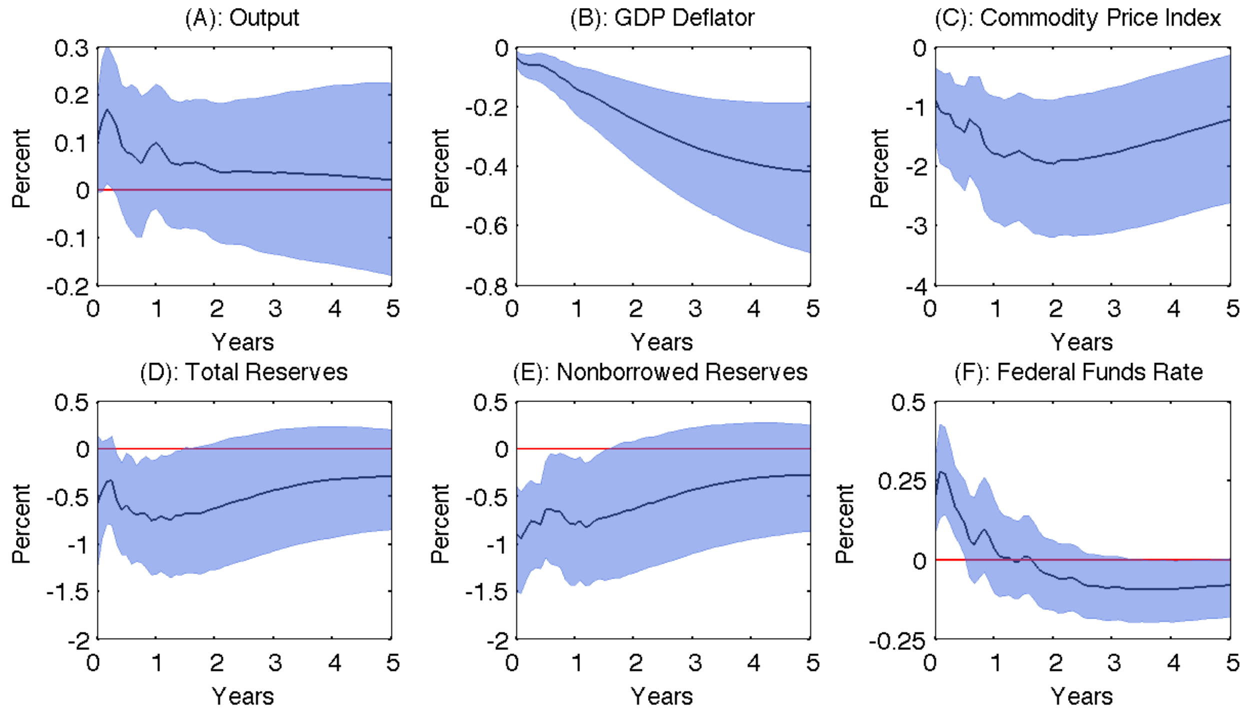

Figure 1: IRFs to a Monetary Policy Shock Identified Using Restrictions 1

policy tightening. Replicating Uhlig (2005) is important because in the next section we show that, despite their appeal, Restrictions 1 imply a counterfactual systematic component of the monetary policy and therefore do not identify monetary policy shocks.

2.2 Systematic Component of Monetary Policy

The identification of monetary policy shocks either requires or implies the specification of how policy usually reacts to economic conditions. Leeper, Sims and Zha (1996), Leeper and Zha (2003), and Sims and Zha (2006a) emphasize the need to specify and estimate the behavioral relationship for policy. As discussed in the previous section, Uhlig (2005) deviates from this paradigm. But we argue that the implied systematic component provides a useful way to check whether the set of identified models is a sensible one.

In both cases, we need to characterize the systematic component. To this end, it is important to note that labeling a structural shock in the SVAR as the monetary policy shock is equivalent to specifying the same equation as the monetary policy equation. Thus, the first equation of the SVAR,

$$\mathbf{y}_t'\mathbf{a}_{0,1} = \sum_{\ell=1}^{p} \mathbf{y}_{t-\ell}'\mathbf{a}_{\ell,1} + \varepsilon_{1t} \quad \text{for } 1 \leq t \leq T, \tag{3}$$

is the monetary policy equation, where ε_{1t} denotes the first entry of ε_t, $\mathbf{a}_{\ell,1}$ denotes the first column of $\mathbf{A}_\ell$ for $0 \leq \ell \leq p$, and $a_{\ell,ij}$ denotes the (i, j) entry of $\mathbf{A}_\ell$. Consequently, $\sum_{\ell=1}^{p} \mathbf{y}_{t-\ell}'\mathbf{a}_{\ell,1}$ describes the systematic component of monetary policy.

When analyzing the systematic component of monetary policy we borrow from the literature. In the paper we consider three specifications of the monetary policy equations. The benchmark specification, discussed in this section, is motivated by Christiano, Eichenbaum and Evans (1996). The second and third specifications, discussed in Section 4, are motivated by Taylor (1993, 1999) the former, and Leeper, Sims and Zha (1996), Leeper and Zha (2003), Sims and Zha (2006a), and Sims and Zha (2006b) the latter. Even though each of these approaches characterizes the systematic component of monetary policy in a particular way, they deliver similar results.

The monetary policy equation implied Christiano, Eichenbaum and Evans (1996) makes two important identification assumptions about the systematic component of monetary policy. They are summarized as follows

Restrictions 2. *The federal funds rate is the monetary policy instrument and it only reacts contemporaneously to output and prices.*

Restrictions 2 comprise of two parts. First, the fact that the federal funds rate is the policy instrument is supported by empirical and anecdotal evidence. Except for a short period between October 1979 and October 1982, in which the Federal Reserved explicitly targeted nonborrowed reserves, monetary policy in the U.S. since 1965 can be characterized by a direct or indirect interest rate targeting regime.[5] Sims and Zha (2006b) also provide support for this view since they find that a regime with the federal funds rate as the policy instrument was in place in most of their sample running from 1959 to 2003. Even so, they also suggest that one should be careful applying the Taylor formalism to interpret specific historical periods: For example, as in Bernanke and Blinder

[5]See Bernanke and Blinder (1992) and Chappell Jr, McGregor and Vermilyea (2005).

(1992), they find that policy behavior was better characterized by nonborrowed reserves targeting in the first three years of Volcker's tenure as Chairman of the Fed, October 1979 and October 1982, as well as in the first years of Burns' tenure as Chairman of the Fed in the early 1970s. Having these exceptions in mind, one could conclude that the Fed has used the federal funds rate as its monetary policy instrument almost continuously since 1965, although the federal funds rate is formally the Fed policy instrument since 1997.

Second, the federal funds rate does not react to changes in reserve aggregates. Bernanke and Blinder (1992) and Christiano, Eichenbaum and Evans (1996) include reserve aggregates because in the mid-1990s these aggregates were viewed as alternative instruments to characterize the conduct of monetary policy. But also in these papers, when the federal funds rate is the monetary instrument, reserves aggregates do not enter the monetary equation.

Next we impose qualitative restrictions on the response of the federal funds rate to economic conditions, which we summarize as follows.

Restrictions 3. *The contemporaneous reaction of the federal funds rate to output and prices is nonnegative.*

Restrictions 3 are implicitly included in the Federal Reserve Act according to which the objectives of monetary policy are maximum employment, stable prices, and moderate long-term interest rates. From a more general perspective they are a reflection of the modern conduct of monetary policy whereby the new monetary policy rules are not so mechanical as at the beginning of 20th century, but rather they are based on the grounds of achieving certain economic goals such as full employment and price stability as mentioned above, see Woodford (2003).

We see the set of behavioral policy equations consistent with Restrictions 2 and 3 as the largest set describing the historical conduct of US monetary policy towards fulfilling these objectives. Importantly, we stress that Restrictions 2 and 3 are sign restrictions on the behavior of the monetary policy equation but they are not equilibrium outcomes.

It is also the case that, contrary to Christiano, Eichenbaum and Evans (1996), we leave the remaining equations unrestricted, hence we only identify monetary policy shocks. But an important feature of the identification described by Restrictions 2 and 3 is that it remains agnostic about the response of output to an increase in the federal funds rate. These two features imply that, as in Uhlig (2005), Restrictions 2 and 3 do not identify the structural parameters but only set identify them, allowing a set of models –and not a single model– to be compatible with the restrictions.

If we only concentrate on the contemporaneous coefficients, we can rewrite equation (3) as

$$r_t = \psi_y y_t + \psi_p p_t + \psi_{p_c} p_{c,t} + \psi_{tr} tr_t + \psi_{nbr} nbr_t + a_{0,61}^{-1} \varepsilon_{1,t} \tag{4}$$

where $\psi_y = a_{0,61}^{-1} a_{0,11}$, $\psi_p = a_{0,61}^{-1} a_{0,21}$, $\psi_{p_c} = a_{0,61}^{-1} a_{0,31}$, $\psi_{tr} = a_{0,61}^{-1} a_{0,41}$, and $\psi_{nbr} = a_{0,61}^{-1} a_{0,51}$. Equipped with this representation of the monetary policy equation, we describe Restrictions 2 and 3 as follows.

Remark 1. *Restrictions 2 imply that $\psi_{tr} = \psi_{nbr} = 0$, while Restrictions 3 imply that $\psi_y, \psi_p, \psi_{p_c} \geq 0$.*

Let s_{10}, the number of sign restrictions at horizon 0, be equal to 5, s_{1+} –the number of sign restrictions at horizon greater than 1– equal to 1, and z_{10}, the number of zero restrictions at horizon zero, be equal to 2. If we let the monetary policy shock be the first structural shock, then Restrictions 2 and 3 and the normalization on the federal funds rates impose restrictions on $(\mathbf{A}_0, \mathbf{A}_+)$ and they are characterized using the following matrices.

$$f(\mathbf{A}_0, \mathbf{A}_+) = \begin{bmatrix} \mathbf{A}_0 \\ \mathbf{L}_0(\mathbf{A}_0, \mathbf{A}_+) \\ \vdots \\ \mathbf{L}_5(\mathbf{A}_0, \mathbf{A}_+) \end{bmatrix}, \ \mathbf{S}_1 = \begin{bmatrix} \mathbf{S}_{10} & \mathbf{0}_{s_{10},n} & \dots & \mathbf{0}_{s_{10},n} \\ \mathbf{0}_{s_{1+},2n} & \mathbf{S}_{11} & \mathbf{0}_{s_{1+},n} & \dots \\ \vdots & \mathbf{0}_{m,n} & \ddots & \vdots \\ \mathbf{0}_{s_{1+},2n} & \vdots & \dots & \mathbf{S}_{15} \end{bmatrix},$$

$$\mathbf{Z}_1 = \begin{bmatrix} \mathbf{Z}_{10} & \mathbf{0}_{z_{10},5n} \end{bmatrix}, \mathbf{S}_{10} = \begin{bmatrix} -1 & 0 & 0 & 0 & 0 & 0 & \mathbf{0}_{1,n} \\ 0 & -1 & 0 & 0 & 0 & 0 & \vdots \\ 0 & 0 & -1 & 0 & 0 & 0 & \vdots \\ 0 & 0 & 0 & 0 & 0 & 1 & \mathbf{0}_{1,n} \\ \mathbf{0}_{s,1} & \dots & \dots & \dots & \dots & \mathbf{0}_{s,1} & \mathbf{S} \end{bmatrix}, \mathbf{S} \equiv \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}',$$

$$\mathbf{S}_{1t} = \mathbf{S} \text{ for } t = 1, \dots, 5, \text{ and } \mathbf{Z}_{10} = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}.$$

We impose two normalizations. First, when we impose restrictions 2 and 3 only, we normalize the sign of the shock by assuming that the federal funds rate response remains positive for six months.[6] Second, when we impose restrictions 3, we also restrict $a_{0,61} > 0$ in order to satisfy the regularity conditions for $f(\mathbf{A}_0, \mathbf{A}_+)$ specified in Arias, Rubio-Ramirez and Waggoner (2014).

In Section 3 we also present results for the identification of monetary policy shocks that jointly imposes Restrictions 1, 2, and 3 on $(\mathbf{A}_0, \mathbf{A}_+)$. To characterize this identification scheme, we set $s_{10} = 7$, $s_{1+} = 1$, $z_{10} = 4$, and matrix $\mathbf{S}$ to

$$\mathbf{S} = \begin{bmatrix} 0 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

in the above introduced set of matrices.

[6] We choose six months as our baseline because there is ample evidence of short-run smoothing of policy rates (**?**). Results are robust to imposing this normalization for one and three months. We also apply this normalization to the policy rules considered in Section 4

3 Results

In this section we characterize the implied systematic component of monetary policy in Uhlig (2005) and highlight that it is very counterfactual. We then present results for our agnostic identification scheme based on Restrictions 2 and 3.

3.1 Systematic Component of Monetary Policy and Uhlig (2005)

We now describe the systematic component of monetary policy consistent with the monetary policy shocks identified in Uhlig (2005). By construction, the set of models satisfying Restrictions 1 implies $\psi_{tr} \neq 0$ and $\psi_{nbr} \neq 0$, and hence violates Restrictions 2. As explained in Arias, Rubio-Ramirez and Waggoner (2014), unless we draw the structural parameters conditioning on the zero restrictions, the set of identified models satisfying such zero restrictions has measure zero. That is, the monetary policy equations implied by Uhlig (2005) contain three monetary instruments.

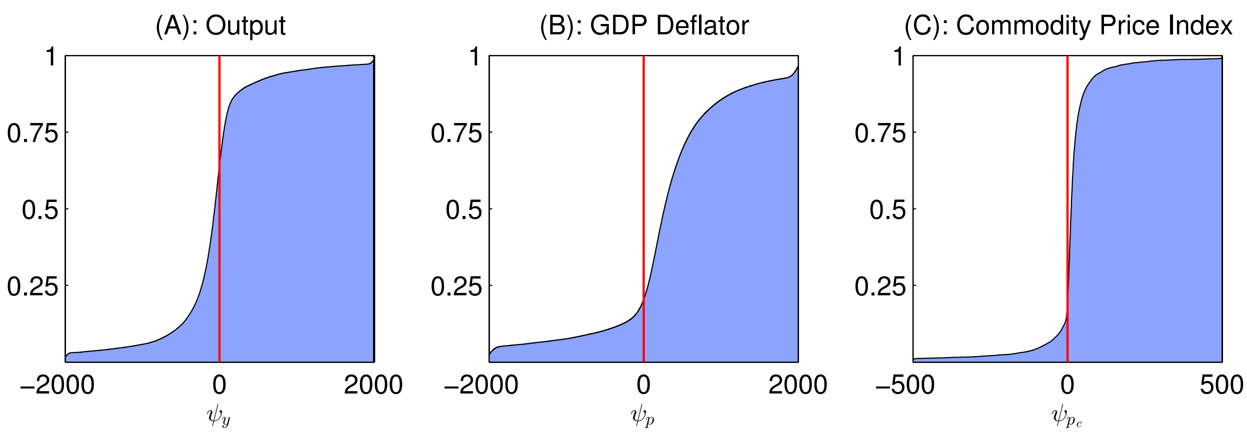

Figure 2: Systematic Component of Monetary Policy Implied by Uhlig (2005)

More importantly, we show in Figure 2 that Restrictions 1 also imply coefficients on output (ψ_y) and prices (ψ_p and ψ_{p_c}) that violate Restrictions 3. Panels (A), (B), and (C) show the cumulative density functions (CDFs) of the coefficients ψ_y, ψ_p, and ψ_{p_c}. The y-axis indicates the value of the CDFs and the x-axis indicates the support of this distribution. Restrictions 1 lead to a significant probability mass on negative values that imply a monetary tightening in response to a decrease in either prices or output.

This exercise shows that Uhlig's (2005) identification scheme implies a counterfactual systematic component of monetary policy, that violates both Restrictions 2 and 3. Following Leeper, Sims and Zha (1996), Leeper and Zha (2003), and Sims and Zha (2006a), a corollary to our findings is that the shocks identified by Restrictions 1 are not monetary policy shocks, because the identification does not appropriately control for the endogenous response of monetary policy to economic activity.

3.2 Restricting the Systematic Component of Monetary Policy

We now present results derived imposing Restrictions 2 and 3 on the monetary policy equation. We first combine those restrictions with Uhlig (2005) sign restrictions, and then apply them in isolation. The normalization associated to the federal funds rate response is always present but only plays a role when we apply Restrictions 2 and 3 in isolation since they are implicit in Restrictions 1. This is also the case in Section 4.

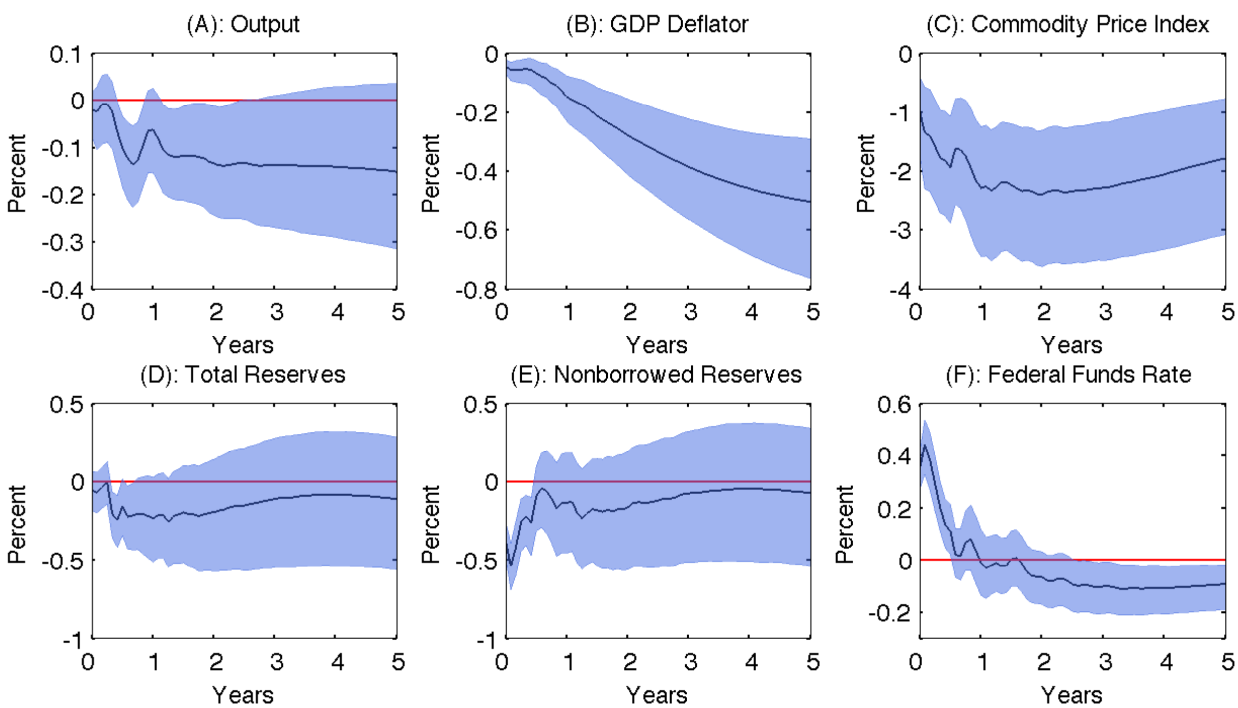

Figure 3: IRFs to a Monetary Policy Shock Identified Using Restrictions 1, 2, and 3

We plot in Figure 3 the IRFs to a monetary policy shock identified imposing jointly Restrictions

1, 2, and 3. Importantly, as for Uhlig (2005), this identification scheme remains silent about the effects of output to a monetary policy shock. We emphasize two results. First, the output response is negative and it builds up over time. Second, the contour of the fed funds rate is similar to Uhlig (2005), positive up to one year, and negative thereafter. But contrary to Uhlig (2005), we can rationalize this path with the systematic component of monetary policy, as the drop in the federal funds rate is the endogenous response of policy to the decline in real activity and prices.

Finally, we plot in Figure 4 the IRFs to a monetary shock identified imposing only Restrictions 2 and 3. Dropping Restrictions 1 has little effects on the our main finding: output drops following monetary tightening and, together with a drop in prices, leads to a long-run loosening of the policy stance. Panel (B) shows that dropping restrictions on prices leads to the emergence of the price puzzle, although of quantitatively modest size.

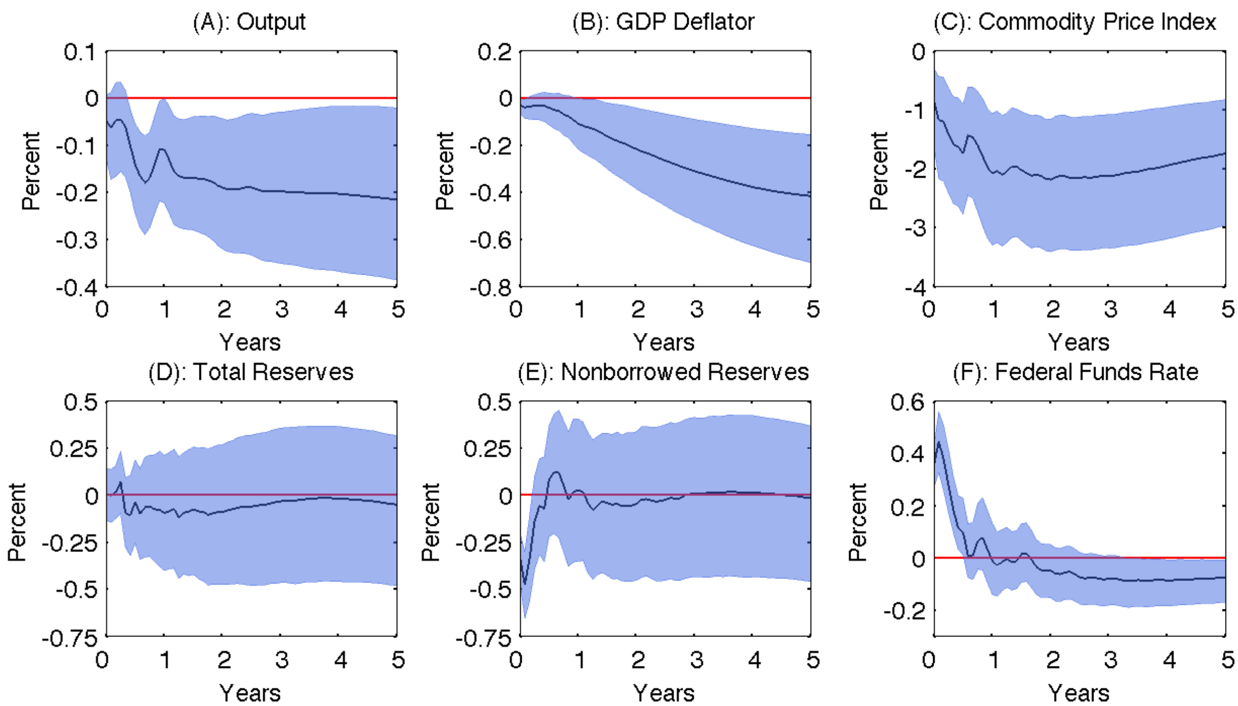

Figure 4: IRFs to a Monetary Policy Shock Identified Using Restrictions 2 and 3

All told, three messages emerge from this section. First, one key ingredient is missing from Uhlig (2005) identification scheme. This ingredient is not, as discussed in Uhlig (2005), a dogmatic zero restriction on the output response to a monetary policy shock, but the imposition of some discipline in the systematic component of monetary policy. Second, an agnostic identification scheme that restricts the systematic behavior of monetary policy is consistent with the consensus over the effects of monetary policy on output. Third, once the systematic behavior of monetary policy is restricted, imposing additional sign restrictions on IRFs as motivated by Uhlig (2005) helps refining the set of admissible models, but is not crucial for the results.

4 Alternative Systematic Components of Monetary Policy

In this section we consider two alternative specifications of the monetary policy equation. The first specification is a Taylor rule motivated by Taylor (1993, 1999) and the second is a money rule motivated by Leeper, Sims and Zha (1996), Leeper and Zha (2003), Sims and Zha (2006a), and Sims and Zha (2006b). Each of these specifications have received wide attention in the empirical monetary literature and provide alternative descriptions of the systematic component.

4.1 Taylor Rule

In the specification of the monetary policy equation studied in Section 2, the federal funds rate responds to output and price levels. But researchers, especially those working with DSGE models, often consider Taylor-type monetary policy equations where the funds rate responds to output growth and inflation instead. Inspired by the Taylor rule, we model the systematic component of monetary policy using the following sets of restrictions.

Restrictions 4. *The federal funds rate is the monetary policy instrument and it only reacts contemporaneously to output growth and inflation.*

Restrictions 5. *The contemporaneous reaction of the federal funds rate to output growth and inflation is nonnegative.*

We specify a Taylor rule in the growth rate of output and not in the output gap as common in the DSGE literature because our reduced form specification does not include potential output.

However, results are qualitatively similar for a specification that includes output instead of its growth rate.

As in Section 2, we identify the behavior of the monetary policy equation leaving the remaining equations unrestricted. Hence, we only identify monetary policy shocks and we remain agnostic about the response of output after an increase in the federal funds rate. Thus, we only set identify the structural parameters.

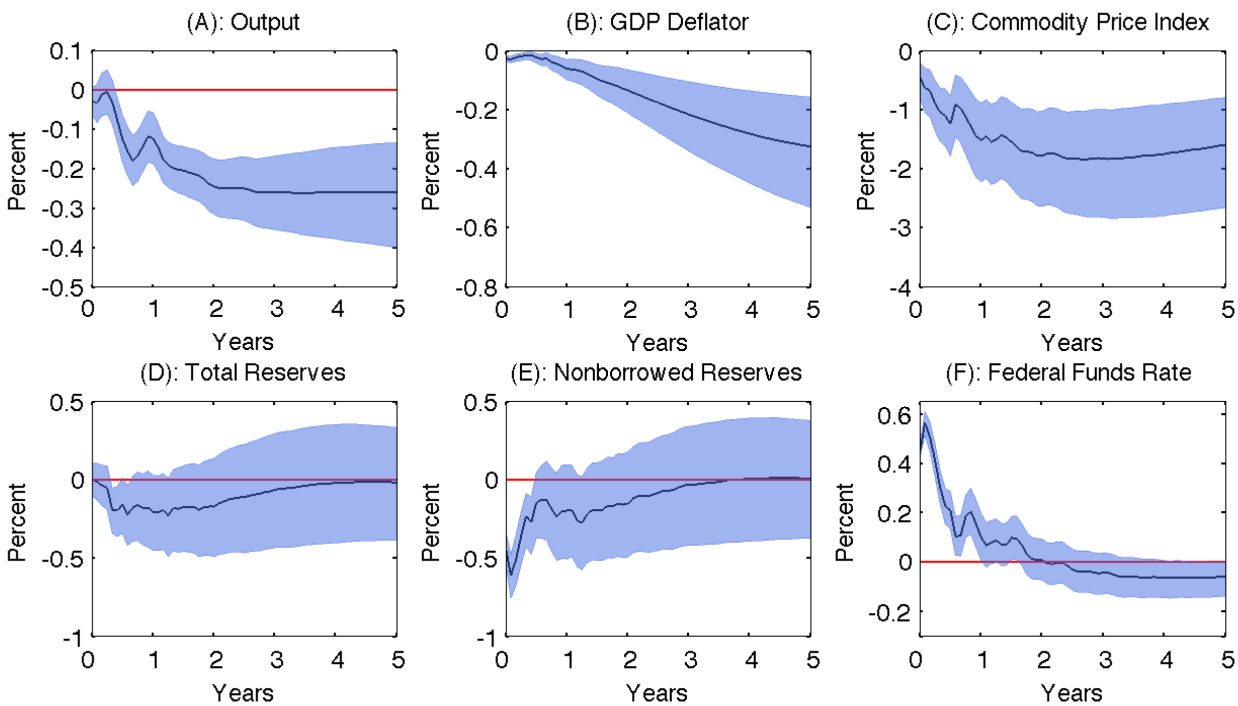

Figure 5: IRFs to a Monetary Policy Shock Identified Using Restrictions 1, 4, and 5

Since the federal funds rate is the policy instrument, and if we concentrate on the contemporaneous coefficients, we rewrite equation (3) as

$$r_t = \psi_y \Delta y_t + \psi_p \pi_t + \psi_{p_c} \pi_{c,t} + \psi_{tr} tr_t + \psi_{nbr} nbr_t + a_{0,61}^{-1} \varepsilon_{1,t}, \qquad (5)$$

where Δy_t is the monthly output growth, π_t is the monthly inflation rate of the GDP deflator, $\pi_{c,t}$ is the monthly inflation rate of the index of commodity prices, $\psi_y = a_{0,61}^{-1} a_{0,11}$, $\psi_p = a_{0,61}^{-1} a_{0,21}$, $\psi_{p_c} = a_{0,61}^{-1} a_{0,31}$, $\psi_{tr} = a_{0,61}^{-1} a_{0,41}$, and $\psi_{nbr} = a_{0,61}^{-1} a_{0,51}$. Equipped with this representation of the monetary policy equation, we describe Restrictions 4 and 5 as follows.

Remark 2. *Restrictions 4 imply that* $\psi_{tr} = \psi_{nbr} = -a_{0,11}+a_{1,11} = -a_{0,21}+a_{1,21} = -a_{0,31}+a_{1,31} = 0$*, while Restrictions 5 imply that* $\psi_y, \psi_p, \psi_{p_c} \geq 0$*.*

Restrictions 4 and 5 map into restrictions on both $\mathbf{A}_0$ and $\mathbf{A}_+$ because we restrict growth rates for output and prices placing constrains on the coefficients of lagged output and price levels. In fact, restrictions $-a_{0,11} + a_{1,11} = -a_{0,21} + a_{1,21} = -a_{0,31} + a_{1,31} = 0$ equate the coefficients on current and lagged output and price levels to obtain growth rates.

Let $s_{10} = 5$, $s_{1+} = 1$, and $z_{10} = 4$. If we let the monetary policy shock be the first structural shock, then we summarize Restrictions 4, and 5 in the following matrices

$$f(\mathbf{A}_0, \mathbf{A}_+) = \begin{bmatrix} \mathbf{A}_0 \\ \mathbf{A}_1 \\ \mathbf{L}_0(\mathbf{A}_0, \mathbf{A}_+) \\ \vdots \\ \mathbf{L}_5(\mathbf{A}_0, \mathbf{A}_+) \end{bmatrix}, \mathbf{S}_1 = \begin{bmatrix} \mathbf{S}_{10} & \mathbf{0}_{s_{10},n} & \dots & \mathbf{0}_{s_{10},n} \\ \mathbf{0}_{s_{1+},2n} & \mathbf{S}_{11} & \mathbf{0}_{s_{1+},n} & \dots \\ \vdots & \mathbf{0}_{m,n} & \ddots & \vdots \\ \mathbf{0}_{s_{1+},2n} & \vdots & \dots & \mathbf{S}_{15} \end{bmatrix},$$

$$\mathbf{Z}_1 = \begin{bmatrix} \mathbf{Z}_{10} \\ \mathbf{0}_{z_{10},6n} \end{bmatrix}', \mathbf{S}_{10} = \begin{bmatrix} -1 & 0 & 0 & 0 & 0 & 0 & \mathbf{0}_{1,2n} \\ 0 & -1 & 0 & 0 & 0 & 0 & \vdots \\ 0 & 0 & -1 & 0 & 0 & 0 & \vdots \\ 0 & 0 & 0 & 0 & 0 & 1 & \mathbf{0}_{1,2n} \\ \mathbf{0}_{s,1} & \dots & \dots & \dots & \dots & \mathbf{0}_{s,1} & \mathbf{S} \end{bmatrix}, \mathbf{S} = \begin{bmatrix} \mathbf{0}'_{1,n} \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}'$$

$$\mathbf{S}_{1t} = \mathbf{S} \text{ for } t = 1, \ldots, 5, \text{ and } \mathbf{Z}_{10} = \begin{bmatrix} -1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}.$$

As in Section 3, we also present results for the identification of monetary policy shocks that jointly imposes Restrictions 1, 4, and 5. To characterize this identification scheme, we set $s_{10} = 7$, $s_{1+} = 4$, $z_{10} = 4$, and matrix $\mathbf{S}$ to

$$\mathbf{S} = \begin{bmatrix} \mathbf{0}_{1,n} & 0 & -1 & 0 & 0 & 0 & 0 \\ \vdots & 0 & 0 & -1 & 0 & 0 & 0 \\ \vdots & 0 & 0 & 0 & 0 & -1 & 0 \\ \mathbf{0}_{1,n} & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

We plot in Figure 5 the IRFs to a monetary policy shock identified imposing Restrictions 1, 4, and 5. Qualitatively, the results are similar to those obtained using Restrictions 1, 2, and 3: output declines after a negative monetary policy shock, and monetary policy loosens its stance in the long run. But all the IRFs, in particular the output response, are more precisely estimated reinforcing the message that a negative monetary policy shocks is contractionary once the systematic component of monetary policy is taking into account.

We plot in Figure 6 the IRFs to a monetary policy shock identified imposing only Restrictions 4 and 5, together with the sign normalization on the response of the federal funds rate. Dropping Restrictions 1 leads to the emergence of the price puzzle. Nevertheless, the response of output to the monetary tightening is negative and persistent. The response of the other variables is also similar to Figure 5.

The analysis confirms the robustness of our findings.This alternative agnostic identification scheme that restricts the systematic behavior of monetary policy is consistent with the consensus

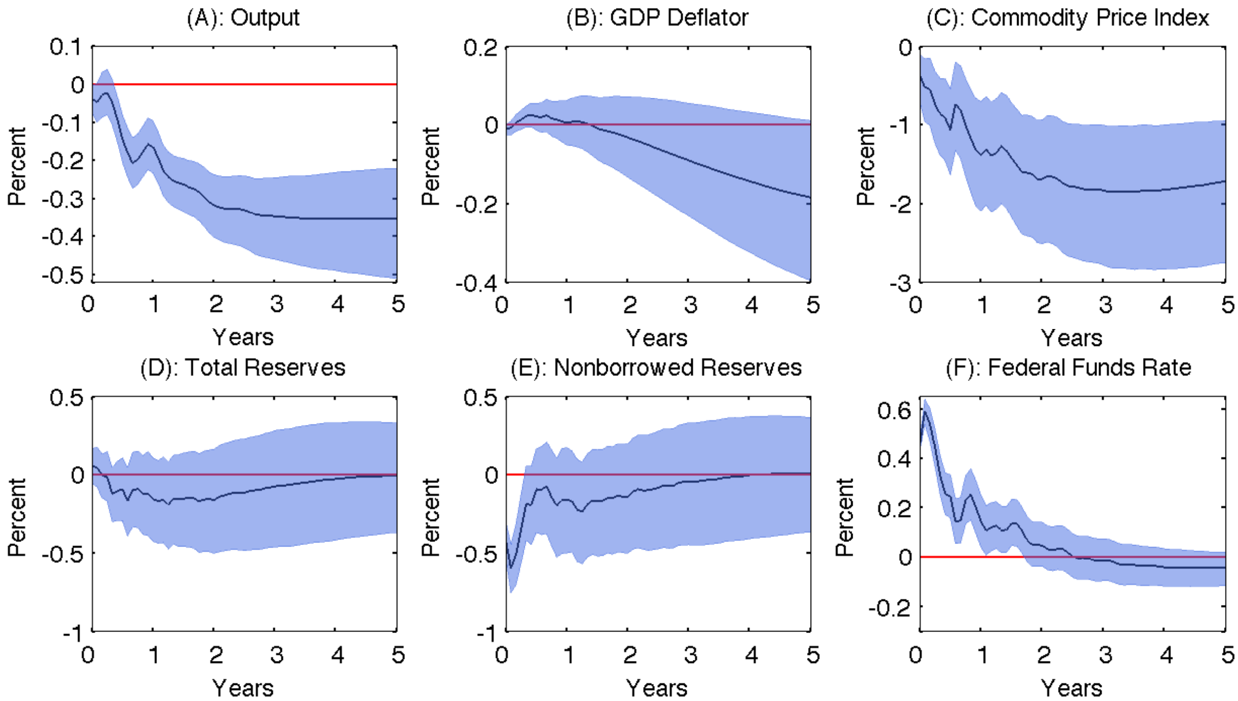

Figure 6: IRFs to a Monetary Policy Shock Identified Using Restrictions 4 and 5

over the effects of monetary policy on output. Imposing additional sign restrictions on IRFs as motivated by Uhlig (2005) helps refining the set of admissible models that are consistent with the systematic component of monetary policy, but is not crucial for the results.

4.2 Money Rule

Finally, the last specification of the monetary policy equation that we consider follows the money rules postulated in Leeper, Sims and Zha (1996), Leeper and Zha (2003), and Sims and Zha (2006a,b). In these rules, only the federal funds rate and money enter the monetary policy equation. To model this rule, following Sims and Zha (2006b) we replace total reserves and nonborrowed reserves by money as measured by M2.[7] Except for the use of money instead of reserves, the reduced form model is identical to the one we describe in Section 2.

We first replicate Uhlig (2005) main findings using the new reduced form specification in order to

[7]We use monthly data on M2 Money Stock (M2SL) from the H.6 Money Stock Measures of the Board of Governors of the Federal Reserve System downloaded from the Federal Reserve Bank of Saint Louis.

show that his results are not a consequence of using reserves instead of money. To implement Uhlig's (2005) agnostic identification scheme, we replace the sign restrictions on nonborrowed reserves by sign restrictions on money. Hence, we characterize the agnostic identification scheme by the following Restrictions.

Restrictions 6. *A monetary policy shock leads to a negative response of the GDP deflator, commodity prices, and money, and to a positive response of the federal funds rate, all at horizons* $t = 0, \ldots, 5$.

As it was the case with Restrictions 1, Restrictions 6 rule out the price and the liquidity puzzles and imply non-linear restrictions on $(\mathbf{A_0}, \mathbf{A_+})$. But the crucial important feature of the identification described by Restrictions 6 is that it remains agnostic about the response of output after an increase in the federal funds rate and only identifies monetary policy shocks. Hence, Restrictions 6 do not identify the structural parameters but only set identify them, allowing a set of models to be compatible with the restrictions.

We omit the description of the function $f(\mathbf{A}_0, \mathbf{A}_+)$ and the selection matrix $\mathbf{S_1}$ necessary to implement Restrictions 6, because this follows trivially from the ones described in Section 2. We plot in Figure 7 the resulting IRFs. As in Uhlig (2005)'s specification with reserves instead of money, an increase in federal funds rate leads to an increase in output. The output response becomes negative after about six months, but zero is always included in the 68% credible set. Therefore, there is no evidence that a negative monetary policy shocks are contractionary when Restrictions 6 are used to identify monetary policy shocks: Uhlig (2005)'s results survive the swap of reserves for M2.

Next, we specify the identification assumptions consistent with the money rule as follows.

Restrictions 7. *The federal funds rate is the monetary policy instrument and it only reacts contemporaneously to money.*

Restrictions 8. *The contemporaneous reaction of the federal funds rate to money is nonnegative.*

Here again, we identify the behavior of the monetary policy equation leaving the remaining equations unrestricted. Therefore, we only identify monetary policy shocks and we remain agnostic

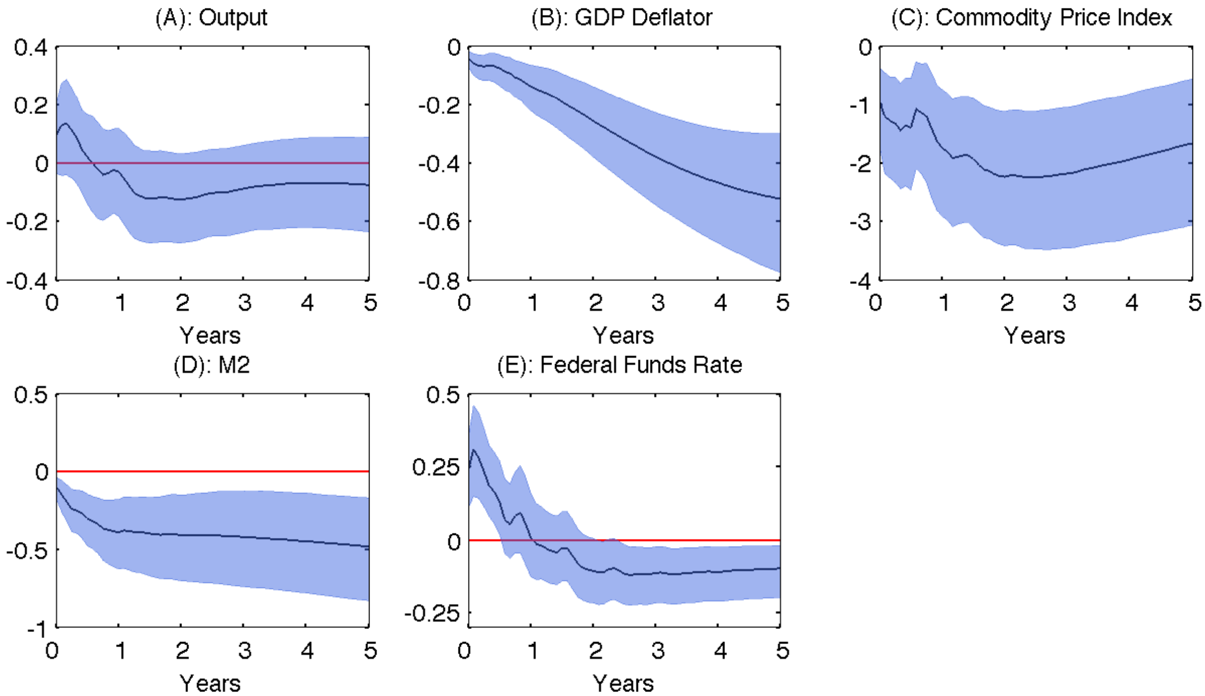

Figure 7: IRFs to a Monetary Policy Shock Identified Using Restrictions 6

about the response of output after an increase in the federal funds rate. As in the previous exercises, we do not identify the structural parameters but only set identify them.

We rewrite the monetary policy equation, concentrating on the contemporaneous coefficients, as

$$r_t = \psi_y y_t + \psi_p p_t + \psi_{p_c} p_{c,t} + \psi_m m_t + a_{0,61}^{-1} \varepsilon_{1,t}, \tag{6}$$

where $\psi_y = a_{0,61}^{-1} a_{0,11}$, $\psi_p = a_{0,61}^{-1} a_{0,21}$, $\psi_{p_c} = a_{0,61}^{-1} a_{0,31}$, and $\psi_m = a_{0,61}^{-1} a_{0,41}$. Equipped with this representation of the monetary policy equation, we summarize Restrictions 7 and 8 as follows.

Remark 3. *Restrictions 7 imply that* $\psi_y = \psi_p = \psi_{p_c} = 0$*, while Restrictions 8 imply that* $\psi_m \geq 0$.

Note also that under Restrictions 7, the monetary equation (6) becomes

$$r_t = \psi_m m_t + a_{0,61}^{-1} \varepsilon_{1,t}. \tag{7}$$

This equation has three possible interpretations. The first, which is consistent with how we specify equation (7), is that the federal funds rate responds to changes in the money stock. The second interpretation is that money supply adjusts to changes in the federal funds rate. This interpretation is consistent with Sims and Zha (2006b)'s view on how monetary policy was conducted between 1979 and 1982. A third interpretation is simply that both the federal funds rate and money respond to Feds actions, and both indicators are important in describing the effects of monetary policy on the economy (Belongia and Ireland, 2014). But inference is consistent with those three different interpretations, which only imply different normalizations in Restrictions 8.

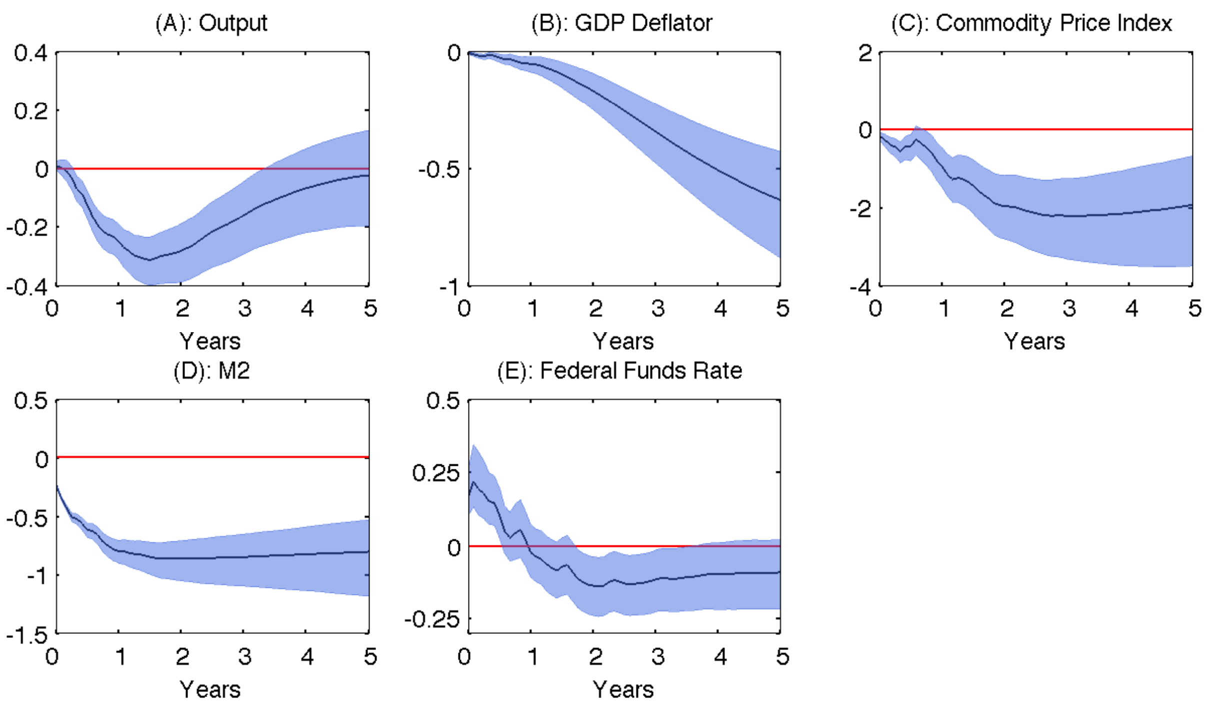

Figure 8: IRFs to a Monetary Policy Shock Identified Using Restrictions 6, 7, and 8

In its current form, Restrictions 8 state that shocks that raise the money stock lead the Federal Reserve to increase the federal funds rate. An alternative interpretation is that a monetary policy shock leads to a simultaneous increase in the federal funds rate and a reduction in money supply.

These restrictions are implemented by defining the function $f(\mathbf{A}_0, \mathbf{A}_+)$, and the matrices $\mathbf{S}_1$, and $\mathbf{Z}_1$, as described below

$$
f\left(\mathbf{A}_0,\mathbf{A}_+\right)=\begin{bmatrix}\mathbf{A}_0\\ \mathbf{L}_0\left(\mathbf{A}_0,\mathbf{A}_+\right)\\ \vdots\\ \mathbf{L}_5\left(\mathbf{A}_0,\mathbf{A}_+\right)\end{bmatrix},\ \mathbf{S}_1=\begin{bmatrix}\mathbf{S}_{10} & \mathbf{0}_{s_{10},n} & \dots & \mathbf{0}_{s_{10},n}\\ \mathbf{0}_{s_{1+},2n} & \mathbf{S}_{11} & \mathbf{0}_{s_{1+},n} & \dots\\ \vdots & \mathbf{0}_{m,n} & \ddots & \vdots\\ \mathbf{0}_{s_{1+},2n} & \vdots & \dots & \mathbf{S}_{15}\end{bmatrix},\ \mathbf{Z}_1=\begin{bmatrix}\mathbf{Z}_{10}\\ \mathbf{0}_{z_{10},5n}\end{bmatrix}',
$$

$$
\mathbf{S}_{10}=\begin{bmatrix}0 & 0 & 0 & -1 & 0 & \mathbf{0}_{1,n}\\ 0 & 0 & 0 & 0 & 1 & \mathbf{0}_{1,n}\\ \mathbf{0}_{s,1} & \dots & \dots & \dots & \mathbf{0}_{s,1} & \mathbf{S}\end{bmatrix},\ \mathbf{S}=\begin{bmatrix}0 & -1 & 0 & 0 & 0\\ 0 & 0 & -1 & 0 & 0\\ 0 & 0 & 0 & -1 & 0\\ 0 & 0 & 0 & 0 & 1\end{bmatrix},
$$

$$
\mathbf{S}_{1t}=\mathbf{S}\text{ for }t=1,\dots,5,\text{ and }\mathbf{Z}_{10}=\begin{bmatrix}1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0\end{bmatrix}.
$$

We plot in Figure 8 the IRFs to a monetary policy tightening consistent with Restrictions 6, 7, and 8. Qualitatively, impulse responses are similar to those plotted in Figure 3. The response of output is more hump-shaped than in the baseline, with output returning to its pre-shock level within five years. Also the response of the federal funds rate rate is hump-shaped, with the stance tightening but still accomodative five after years. As for the Taylor rule specification, the output response is more precisely estimated than in the baseline, in line with the evidence that M2 has has additional predictive power on output compared to the federal funds rate (Belongia and Ireland, 2014).

We plot in Figure 9 the IRFs identified imposing only Restrictions 7 and 8. The response of output remains negative and becomes more persistant, as it is still below its pre-shock level after five years. But the path for the federal funds rate is consistent with a tighter stance of monetary policy than in Figure 8: the initial increase is about 20 basis points higher and it remains positive for around 18 months, staying at zero thereafter. The response of the GDP deflator shows a more pronounced price puzzle than in Figure 6.

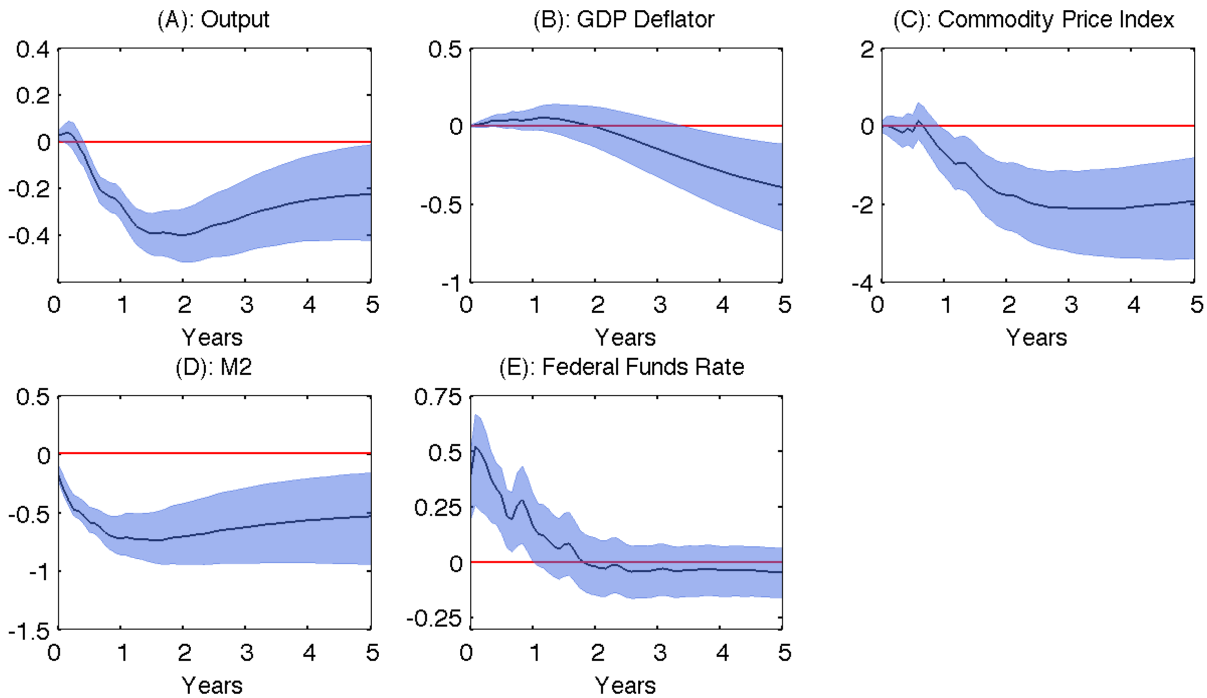

Figure 9: IRFs to a Monetary Policy Shock Identified Using Restrictions 7 and 8

Overall, the evidence presented in this section confirms the results in Section 3: output declines after a contractionary monetary policy shock in SVARs identified imposing some discipline on the systematic component of monetary policy.

5 Conclusion

The agnostic identification of monetary policy shocks imposing sign restrictions on IRFs proposed by Uhlig (2005) finds that increases in the federal funds rate are not contractionary. We re-examine this issue and we show that the identification scheme in Uhlig (2005) implies a counterfactual characterization of the systematic component of monetary policy. We design an agnostic identification scheme that imposes sign and zero restrictions on the systematic component of monetary policy and find that an increase in the federal funds rate leads to a persistent decline in output and prices.

Overall, our results suggest that while set identification is appealing because inference is not based on very specific, and often questionable, exclusion restrictions, it is subject to the danger of including implausible models. Our suggestion is to impose restrictions on objects that can be easily evaluated, in our application the systematic component of monetary policy. The issue of how to specify agnostic restrictions in SVARs is not limited to the identification of monetary policy, and the approach described in this paper can be applied to a variety of identification problems.

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