Journal of International Money and Finance 68 (2016) 21–49

Contents lists available at ScienceDirect

Journal of International Money and Finance

journal homepage: www.elsevier.com/locate/jimf

Oil price shocks and their transmission mechanism in an oil-exporting economy: A VAR analysis informed by a DSGE model

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A R T I C L E   I N F O

Article history:
Available online 6 June 2016

Keywords:
Oil price shock
Structural VAR
Sign restrictions
Two-country DSGE model
Canada

A B S T R A C T

This paper examines the macroeconomic effects of oil price shocks and the oil shock transmission mechanism in an oil-exporting country, Canada. We use a structural VAR with sign restrictions that comes from a two-country dynamic stochastic general equilibrium (DSGE) model to jointly identify oil price, domestic supply and U.S. and domestic monetary policy shocks. This identification strategy not only controls for reverse causality from the Canadian and U.S. macroeconomic conditions to the real oil prices, but more importantly, it also allows for contemporaneous interactions between the Canadian and U.S. variables. We find that oil shocks have a stimulative effect on Canadian aggregate demand, appreciate the Canadian dollar, improve the terms of trade and reduce real wages. Foreign disturbances, including innovations in oil prices and the U.S. interest rate, have a significant influence on Canadian economic activities. Our counterfactual analysis indicates that the reaction of the U.S. interest rate as an indirect transmission channel for oil price shocks plays a moderate role in explaining the real exchange rate and inflation, but has negligible impacts on the Canadian output and interest rate.

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http://dx.doi.org/10.1016/j.jimonfin.2016.05.004
0261-5606/

1. Introduction

One important empirical characteristic of oil prices is that increases in oil prices have been associated with a contemporaneous increase in the consumer price index (CPI) and federal funds rates. This inflationary nature of oil price shocks is of obvious interest to central banks with inflation targets. While much attention has focused on the implication of oil price shocks for domestic output, inflation and monetary policy in oil-importing economies, especially the U.S., the situation is vastly different for those countries that both consume and export oil. In light of the contributions of Bernanke et al. (1997, 2004), Leduc and Sill (2004), Carlstrom and Fuerst (2006), Kilian (2008) and others, it seems safe to speak of a consensus on the pattern of the U.S. economy's response to an oil price shock. Nonetheless, empirical evidence on the economic consequences of oil price shocks and their transmission mechanism in an oil-exporting country such as Canada is subject to numerous debates.[1] One of the difficulties encountered is the inability to correctly identify underlying shocks and single out the contributions of transmission channels in an open economy setup.

A large volume of literature identifies oil price shocks using the Cholesky factorization, where oil prices are allowed to influence all the other macroeconomic variables contemporaneously but where shocks to other variables have no immediate impact on the prices (see Blanchard and Galí, 2007; Burbidge and Harrison, 1984 and Leduc and Sill, 2004). In similar fashion, Kormilitsina (2011) and Pieschacón (2009) identify oil price shocks by imposing strict exogeneity of oil prices. These identification assumptions will clearly be incorrect if economic developments in the country of consideration affect the world oil price contemporaneously. Yet, it is inappropriate to consider the real price of oil as an exogenous variable because it equals the dollar price of oil dividing by an endogenous variable, the GDP deflator. Intuitively, because the U.S. dollar is the sole pricing and settlement currency in oil transactions, the fluctuating value of the dollar, which is affected by U.S. monetary policy, plays an important role in exacerbating run-ups and precipitous falls in world oil prices. Therefore, an identification approach that allows for simultaneity between prices of oil and the U.S. funds rate has the potential to generate more credible results. Another strand of literature on the macroeconomic impact of oil price shocks on the Canadian economy includes Burbidge and Harrison (1984), Mork et al. (1994), Cologni and Manera (2008) and others. All these studies assume Canada as a closed-economy, focusing in particular on the response of real economy growth and consumer price inflation to oil price shocks. None of these papers, however, provides a quantitative assessment of the economic consequences of oil price shocks on a comprehensive set of Canadian aggregate variables nor explores the importance of international transmission channels of oil price shocks.

In contrast with these papers, our empirical methodology builds on a VAR framework with sign restrictions to evaluate the effects of oil prices on Canadian economic activities. We apply this identification scheme in an open-economy setup to jointly identify the oil price, domestic supply and U.S. and domestic monetary policy shocks with mutually exclusive sign restrictions on each shock. We also include the U.S. interest rate, the bilateral real exchange rate between the U.S. and Canada and U.S. output to capture the most important transmission channels through which oil prices may affect Canadian economic activities indirectly. This approach not only controls for reverse causality from the Canadian and U.S. macroeconomic conditions to the real oil prices, but more importantly, it also allows for contemporaneous interactions between the Canadian and U.S. variables. Specifically, we derive a set of theoretically coherent information from a two-country dynamic stochastic general equilibrium (DSGE) framework augmented with an oil sector to select impulse response functions in the estimated

[1] Burbidge and Harrison (1984) estimate a closed-economy VAR for Canada. They find that oil price shocks have negative impact on Canadian industrial production. Mork et al. (1994) report a statistically significant negative correlation between oil price increases and GDP growth for the U.S., Canada, France, Germany and Japan over the period 1967 through 1994. Based on more recent data for 1980:1–2003:3; however, Cologni and Manera (2008) find that oil price shocks have an insignificant stimulative impact on the Canadian GDP. The relationship between oil prices and the value of the Canadian dollar is also a topic of debate. Amano and van Norden (1995) report a negative relationship between energy prices and the Canadian dollar. That is, higher real energy prices lead to a depreciation of the Canadian dollar. In later work, however, Issa et al. (2008) find that such a relationship broke down in the early 1990s.

VAR. The way of implementing sign restictions is to use an acceptance sampling scheme where draws that jointly satisfy all the restrictions are kept.

The empirical analysis yields several insights. First, we find that oil price shocks have a stimulative impact on Canadian aggregate demand. Canada's output rises following a positive oil price shock, while U.S. output falls. The oil price shock generates significant hump-shaped responses of inflation and of domestic and U.S. interest rates. The comovement of domestic inflation and output after an oil price shock exhibits the key features of an aggregate demand shock. As would be expected, a positive oil price shock leads to a significant appreciation of Canadian dollars and a fall in the real wage. Second, oil price shocks make an important contribution to the forecast variance of domestic variables. Similar findings can be found in Blanchard and Galí (2007) for the U.S. and in Pieschacón (2009) for Mexico and Norway. Third, we find that U.S. interest rate disturbances account for a significant portion of the forecast variation in the Canadian macro variables. This finding is in line with quantitative evidence from reduced-form VAR and the calibrated DSGE models for Canada (see, for example, Cushman and Zha, 1997[2]; Mendoza, 1991; Schmitt-Grohé, 1998).

The robustness of our identification strategy is confirmed by examining our strategy against a couple of alternative specifications. We examine whether the identification strategy matters for our results by deriving the impulse responses from a typical Cholesky factorization. We investigate the sensitivity of our results to the alternative specifications of macro variable systems.

The most important finding from our empirical analysis is that we decompose the effects of an oil price shock into direct and indirect components and provide rough estimates of the contribution of endogenous U.S. monetary policy responses. In this counterfactual experiment, we simply do not allow the U.S. fund rate to respond to an oil price shock on impact, in the manner of Bernanke et al. (1997). That is, we shut off the U.S. monetary policy responses that would otherwise be implied by the empirical model after an oil shock. The difference between the total effect of an oil price shock on the domestic variables and the effect when the U.S. policy response is shut down is then interpreted as a measure of the contribution of the endogenous foreign policy responses. We find that the reaction of U.S. interest rate as an indirect transmission channel for oil price shocks plays at most a moderate role in explaining the bilateral real exchange rate and the Canadian inflation, but has negligible impacts on the Canadian output and interest rate.

The rest of the paper is organized as follows. Section 2 reviews the stylized facts of oil prices and Canadian economic activities for the period 1980:Q1–2011:Q3. Section 3 provides a description of the estimation methodology of the empirical model. Section 4 empirically identifies the effects of real oil price shocks, Canadian and U.S. monetary shocks, and the contribution of foreign disturbances on Canadian macroeconomic activity. Section 5 checks the robustness of the empirical results and the identification strategy. Section 6 quantifies the contribution of endogenous U.S. monetary policy and the contribution of international transmission in response to oil price shocks. Section 7 concludes.

2. Stylized facts of oil prices

In what follows, we present some stylized facts regarding the nature of the relationship between the oil prices and major U.S. and Canadian macroeconomic variables for the period 1980:Q1–2011:Q3.[3] These empirical facts are also used to derive sign restrictions for the structural VAR model. We estimate the dynamic correlations between the real price of oil and the aggregate variables of interest. We measure the degree of comovement of world oil prices with the cycle by the correlation coefficient $\rho(j)$, where $j \in \{0, \pm1, \pm2, \pm3, \pm4\}$. Information regarding whether the contemporaneous correlation coefficient, $\rho(0)$, is positive, zero or negative can indicate whether oil prices are procyclical, acyclical

[2] Cushman and Zha (1997) propose a block exogenous assumption for Canada and therefore assume the foreign block simply to follow a recursive ordering structure. Without identifying each of the foreign shocks, they conclude that foreign factors, including exports, imports, foreign output, prices, interest rate and commodity prices are the most important driver of the Canadian business cycle. More than 74% of output fluctuation is accounted for by the foreign block.

[3] See Appendix A for a more detailed description of the data.

Table 1
Dynamic correlations.

	$j=-4$	$j=-3$	$j=-2$	$j=-1$	$j=0$	$j=1$	$j=2$	$j=3$	$j=4$
(A) $\rho(P_{oil,t}, x_{t+j})$									
CPI	–0.21	–0.16	–0.09	0.04	0.25	0.46	0.51	0.42	0.27
CPI_{us}	–0.28	–0.16	–0.06	0.06	0.31	0.50	0.63	0.62	0.49
Y_{can}	0.24	0.31	0.37	0.39	0.23	0.09	–0.05	–0.17	–0.27
Y_{us}	0.18	0.19	0.24	0.23	0.09	–0.17	–0.31	–0.41	–0.42
R_{can}	0.23	0.18	0.16	0.17	0.25	0.12	–0.01	–0.13	–0.26
R_{us}	0.08	0.17	0.28	0.39	0.46	0.36	0.23	0.08	–0.15
CA$/US$	0.13	–0.01	–0.15	–0.24	–0.37	–0.36	–0.29	–0.20	–0.05
Real Wage	0.23	0.07	–0.06	–0.25	–0.44	–0.34	–0.30	–0.20	–0.07
(B) $corr(R_{can,t}, x_{t+j})$									
R_{us}	0.13	0.38	0.58	0.70	0.81	0.72	0.56	0.37	0.17
π_{can}	–0.11	0.00	0.14	0.23	0.32	0.31	0.27	0.26	0.11

Note: The cross correlations based on the series detrended using the HP _lter with the smoothing parameter equal to 1600.

or countercyclical, respectively.[4] Moreover, the cross-correlation coefficient $\rho(j)$ provides information about whether the cycle of oil prices is leading, is synchronous, or is lagging the cycle of the reference variables as $|\rho(j)|$ reaches a maximum for a negative, zero or positive j, respectively.

Table 1 shows the degree of cyclical correlations between the oil price and a comprehensive set of quarterly Canadian aggregate time series by the correlation coefficient $\rho(j)$.[5] Several key features are evident in Table 1. First, the inflationary nature of oil prices is apparent. Oil prices are positively contemporaneously correlated with CPI, and lead CPI by two quarters. Second, the oil prices are procyclical and lag the Canadian GDP by one quarter, as indicated by the HP filter, while they lag U.S. cycles by two quarters. Third, there are systematic movements of nominal interest rates in relation to oil prices. Oil prices are positively contemporaneously correlated with both the Canadian and U.S. short-term interest rates, suggesting that the central bank may simultaneously react to oil price shocks due to their inflationary nature. Moreover, the contemporaneous correlation of oil prices is strongly negative with the bilateral Canada–U.S. exchange rate (CA$/US$), suggesting that a sharp increase in oil prices boosts the value of the Canadian dollar against its U.S. counterpart. Finally, oil prices are negatively and strongly contemporaneously correlated with the Canadian real wages as indicated in the last row of Panel A in Table 1.

Aside from the relationship between oil and macro-variables, Panel B reports the lead–lag relationship between the Canadian short-run interest rate and the U.S. interest rate, as well as Canadian inflation. First, the Canadian interest rates are highly synchronized with the cycle of U.S. interest rates, which suggests, to some extent, the convergency of Canadian monetary policy with U.S. macroeconomic policy. Second, the short-run interest rate has a significant contemporaneous comovement with CPI inflation, which indicates that as an explicit inflation targeter, the Canadian monetary authority typically raises/lowers the short-term interest rate when inflation appears to be above/below target. However, the correlations between inflation and future interest rates are negative ($corr(\pi_t, R_{t+4}) = -0.11$), which is in line with the conventional wisdom that interest rates and inflation tend to be inversely related.

[4] Following Fiorito and Kollintzas (1994), we say that the series is strongly contemporaneously correlated, weakly contemporaneously correlated, and contemporaneously uncorrelated with the cycle based on $0.23 \le |\rho(0)| < 1$, $0.1 \le |\rho(0)| < 0.23$, $0 \le |\rho(0)| < 0.1$, respectively. Note that Fiorito and Kollintzas (1994) provide more details on how to determine the cutoff points of 0.1 and 0.23.

[5] Table 1 reports the cross correlations based on the Hodrick–Prescott (HP) filter with a smoothing parameter of 1600 for quarterly data, at lags and leads of one, two, three and four quarters.

3. Estimation of the empirical model: identification of structural shocks

In the following section, we use a VAR model to provide more structural evidence on the macroeconomic effects of underlying shocks for Canada. In the VAR specification, we use the following variables: Canadian output, real world oil prices, Canadian CPI inflation, the bilateral Canada–U.S. real exchange rate, real hourly wages, Canadian and U.S. short-term nominal interest rates and U.S. output.

We apply the first-difference to the natural logarithm of each variable with the exception of the short-term interest rates and inflation rates.[6]

The VAR model is estimated for the sample period 1980:Q1–2011:Q3 with four lags.[7] The real oil prices, domestic output and inflation are included as the focus of our interest. The remaining variables in the model are added to capture the most important transmission channels through which oil prices may affect economic activity indirectly, in part by incorporating changes in domestic monetary policies and U.S. monetary policies. These channels include a variety of demand and supply-side effects of oil prices operating via exchange rates, financial variables and the international trade in goods.

Consider a structural VAR of the form

$$A_0 Y_t = A(L)Y_{t-1} + \varepsilon_t, \quad \varepsilon_t \sim N(0, I_m), \tag{1}$$

where Y_t is an $m \times 1$ vector of endogenous variables, A_0 is an invertible contemporaneous impact matrix, $A(L)$ denotes a polynomial coefficient matrices of the form $A(L) = \sum_{s=1}^{p} A_s L^s$, L is the lag operator and ε_t is a vector of structural shocks, which are mutually independent.

[6] Our a-theoretical VAR model can be thought of as an unrestricted state-space form solution of our two-country DGSE model augmented with an oil sector. The sign restrictions for our VAR model come from our DGSE model. To compare the DSGE model to the VAR model, we use the same data set. In our model economy, some variables are growing in steady state because there is a stochastic trend in the DSGE model. It simply comes from the unit root in the technology process given as follows:

$$lnA_t = \gamma + lnA_{t-1} + \epsilon_{At}$$

Thus, solving the model involves using stationary transformations of variables with unit roots they are rendered stationary according to the following formula: $\hat{X}_t = (X_t/A_t)$. (Among the literature using the first differenced macro data to validate the prediction of DSGE models, see Adolfson et al., 2007; Chang et al., 2002; Smets and Wouters, 2007). The growth rate of a variable with unit roots, say growth rate of output,

$$g_{y,t} = Y_t Y_{t-1} = \frac{Y_t/A_t}{Y_t/A_t}\frac{A_t}{A_{t-1}} = \frac{\hat{Y}_t}{\hat{Y}_{t-1}}\frac{A_t}{A_{t-1}}$$

and when we take logarithms both sides,

$$ln(g_{y,t}) = \gamma + ln(\hat{Y}_t) - ln(\hat{Y}_{t-1}) + \epsilon_{A,t}$$

Following Chang et al. (2002), the impulse response function of variables with/without unit roots, X_t can be calculated using the cumulative summation of impulse responses of the growth rate of variable X, $g_{X,t}$. Under such circumstances, the technology shock will have a permanent impact on the real variables, while transitory shocks such as monetary shocks, oil price shocks, and preference shocks, only have transitory effects on the real variables. It is worth noting that for a permanent shock, impulse responses of X_t and $\hat{X}_t$ are different. For a transitory shock, however, impulse responses of X_t and $\hat{X}_t$ are identical. That is, for a transitory shock in our DSGE model, such as an oil price shock or a monetary shock, we will get identical impulse responses of X_t no matter whether we calculate the cumulative summation of impulse responses of the growth rate of X_t or simply report the detrended $\hat{X}_t$. Therefore, in order to be consistent with the variables defined in our DSGE model, we calculate the impulse responses of variables with unit roots by cumulatively summing the impulse responses of the growth rate of those variables.

[7] The selection of lags is based on AIC criteria. Also, this specification is flexible enough to match the autocorrelogram of year-on-year inflation and the output at a quarterly frequency.

In identifying the shocks in Canada, we employ a structural VAR approach with sign restrictions.[8] We use this identification strategy for two reasons. First, this strategy employs a set of theoretically coherent information to select impulse response functions from the complete set of orthogonal alternatives obtained from rotations of the contemporaneous impact matrices, rather than relying solely on reduced-form equations and traditional zero restrictions. Note that the most common approach to identifying oil price shocks is the Cholesky factorization, where oil prices are allowed to influence all the other macroeconomic variables contemporaneously but where shocks to other variables have no immediate impact on the prices (see Blanchard and Galí, 2007; Burbidge and Harrison, 1984 and Leduc and Sill, 2004). These identification assumptions will clearly be incorrect if economic developments in the country of consideration affect the world oil price contemporaneously. To overcome the shortcomings of traditional zero restrictions, we use an alternative identification strategy with sign restrictions on impulse response functions to identify the oil price shocks by allowing for reverse causality from the Canadian and U.S. macroeconomic conditions to the real oil prices. Second, non-recursive identification structures outperform the Cholesky approach in addressing the empirical anomalies in an open economy setup, such as the "exchange rate puzzle" and the "price puzzle", when financial variables are included. Cushman and Zha (1997) show that as the monetary authority in a small open economy is likely to respond quickly to the foreign variables, the Cholesky approach fails to allow for these features. Without imposing such stringent restrictions, sign restrictions on the VAR model allows better identification of contemporaneous interactions between Canadian and U.S. variables in that there is no need to assume that certain variables affect others only with a lag. Thus monetary policy shocks in a small open economy can be correctly identified in the absence of empirical puzzles.

Despite the fact that our VAR model has eight variables, we will not have a complete decomposition of a reduced-form shock into all of its structural components, but instead identify only four shocks: oil price shocks, domestic supply shocks, domestic monetary shocks and U.S. monetary shocks. Since the effects of oil price, U.S. monetary policy and domestic monetary policy shocks on Canadian economy are the most important ingredients of this paper,[9] we jointly identify these three shocks with mutually exclusive sign restrictions on each shock. In addition, we also identify the domestic supply shock jointly. Because a positive oil price shock is likely to be confused with a negative domestic supply shock, the inclusion of the domestic supply shock should help to more effectively isolate the oil price shock. Following Peersman (2005), we assume that an oil price shock has the largest contemporaneous impact on oil prices so as to discriminate a domestic supply shock from an oil price shock. Since identifying these shocks of interest is sufficient for the purpose of this paper, we do not impose restrictions on other shocks.

Table 2 summarizes our identification restrictions.[10] The restrictions we use to identify the shocks come from a dynamic general equilibrium model that encompasses an open economy New-Keynesian model augmented with an oil sector. We use a subset of the model's predictions and, as in Canova and De Nicoló (2002),[11] we focus only on qualitative (sign) restrictions, as opposed to quantitative (magnitude) restrictions, to identify shocks. Since we calculate the impulse responses of a macro variable by cumulatively summing the impulse responses of the growth rate of that variable, our sign restrictions are actually imposed on the cumulative sum of the impulse responses of the first differenced variables in order to back out the actual responses of level variables.

[8] A discussion of the technicalities of the identification procedure can be found in Appendix B. For a detailed description of the implementation of sign restrictions, we refer to Canova and De Nicoló (2002).

[9] Similarly, Uhlig (2005) and Canova et al. (2007) employ sign restrictions to identify only a single shock or a subset of shocks and leave the rest of the shocks unidentified.

[10] In our structure VAR model, we do not impose any sign restrictions on the domestic output responses to an oil price shock, instead letting the data determine the sign of these responses. In terms of the U.S. GDP responses to an oil price shock, we are not completely trying to match the empirical model to the DSGE model and the sign restrictions only apply on impact.

[11] Similarly, Peersman (2005) and Baumeister and Peersman (2008) derive the sign conditions from a standard aggregate demand and supply scheme. Canova and De Nicoló (2002) and Canova et al. (2007) derive sign restrictions from DSGE models to identify structural shocks in the data.

Table 2
Sign restrictions.

	R_{us}	P_{oil}	Y_{can}	π	*Real Wage*	R_{can}	*CA$ = US$*	Y_{us}
Oil price shock	≥ 0	≥0		≥0		≥0		≤0
U.S. monetary shock	≥0					≥0	≥0	≤0
Canada monetary shock			≤0	≤0		≥0	≤0	
Canada supply shock			≥0	≤0		≤0	≥0	

Note: A "≥" (or "≤") indicates that the impulse response of the variable in VAR is restricted to be non-negative (non-positive) for 3 quarters after a shock. A blank entry indicates that no restriction is imposed on the response.

We briefly sketch the features of the model and describe the restrictions it implies on the responses of the variables to shocks.[12] The model economy is composed of two countries, an oil-exporting home country and an oil-importing foreign country. Oil is used as an input in production and also as part of the consumption bundle.[13] Oil transactions are assumed to be invoiced in the foreign currency, which generates an asymmetry, whereby domestic firms bear more exchange rate risk than foreign firms when facing oil price shocks. That is, the production cost of a domestic firm depends not only on world oil prices but also its bilateral exchange rate. Moreover, the foreign economy is unaffected by economic activities in the home country, while it does influence the home country via trade (including oil and non-oil trade) and complete financial markets. To allow the model to deliver realistic responses to monetary policy, we include three types of nominal rigidity, as wages, domestic goods prices and imported goods prices are all set using a Calvo-style structure. Taylor rules capture the fact that home and foreign monetary authorities endogenously react to oil price shocks due to their inflationary nature.

The model-implied restrictions we consider are robust, in the sense that they hold for variations in the parameters within some reasonable range. These restrictions are also generally consistent with empirical cross-correlations between variables calculated in the empirical section. Consider a positive innovation of the oil price. On the one hand, for Canada, a sharp rise in oil prices boosts the bilateral exchange rate and real income gains, while on the other hand, the strong Canadian dollar dampens exports, and the higher interest rates deter the aggregate demand and tend to reduce output. As the two forces counter each other, the sign of responses largely depends on the parameter values. So we do not impose any sign restriction on the output responses to an oil price shock, instead letting the data determine the sign of this response. We assume that the oil price shocks must not decrease CPI inflation or the nominal interest rate. The domestic and foreign monetary policy shocks have distinct effects on real domestic activities. We assume that after a contractionary domestic monetary policy shock, the response of output and inflation are not positive, and the tightening monetary policy appreciates the domestic currency against its U.S. counterpart. We do not impose sign restrictions on the world oil prices, U.S. interest rates or U.S. output because these variables are assumed to be exogenous to a monetary policy shock originating from the Canadian economy. After an unexpected rise in the U.S. interest rate, we assume that the response of U.S. output is not positive and that the Canadian dollar depreciates against U.S. dollar on impact. According to the uncovered interest rate parity condition and the empirical cross-correlation between the Canadian and U.S. interest rates, we expect a non-negative impact on the domestic interest rate. Furthermore, given the fact that world crude oil prices are denominated in U.S. dollars, there is no immediate increase in the oil price.

Since the restrictions in Table 2 hold for several horizons, we are free to choose how many periods to restrict for identification purposes. In general, the smaller is the number of restricted responses, the larger is the number of draws satisfying them, which, however, implies a weaker link between the DSGE model and the empirical analysis. As the number of restricted responses increases, we tighten up the empirical analysis to the model more firmly, but the number of draws satisfying the restric-

[12] Appendix C briefly sketches the features of a new open economy macroeconomics (NOEM) model which produces the identifying restrictions we use in the paper.
[13] Note that we introduce oil usage directly in the production function as in Carlstrom and Fuerst (2006) but unlike Leduc and Sill (2004), who tie oil use to capacity utilization.

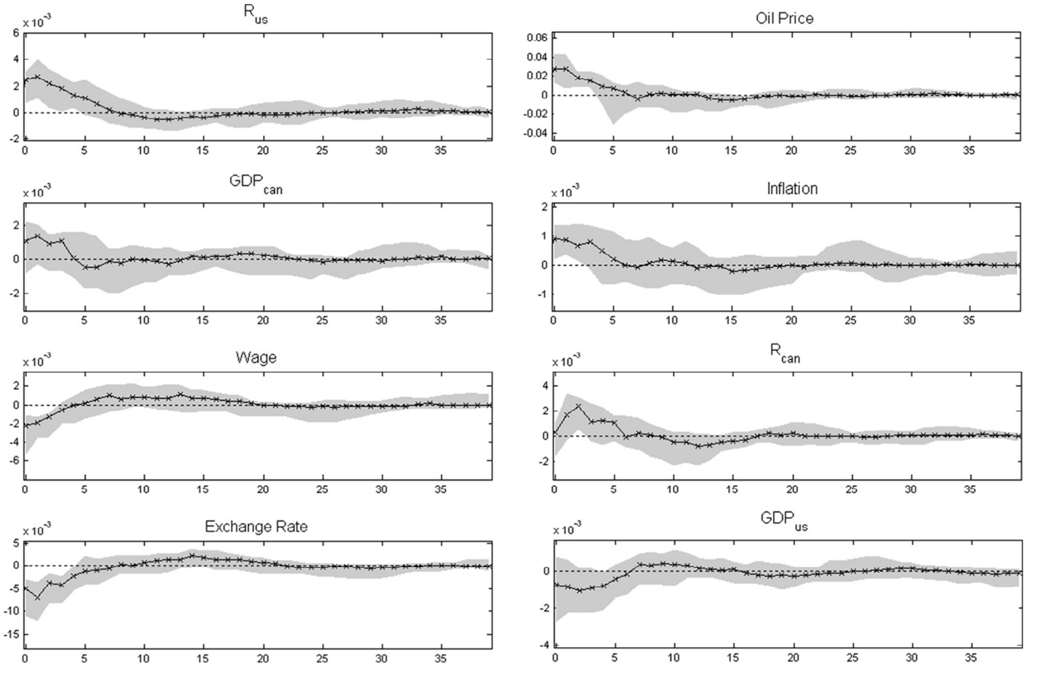

Fig. 1. Dynamic responses to a positive oil price shock. The shaded area represents the 70% error band.

tions may drop dramatically. We choose the time period over which the prior sign restrictions are binding up to three quarters, since this choice seems to accommodate both concerns.

4. Effects of underlying structural shocks

In this section, using the sign restrictions derived from our DSGE model, we identify the effects of real oil price shocks, Canadian and U.S. monetary shocks, and the contribution of foreign disturbances on Canadian macroeconomic variables.

4.1. Effects of an oil price shock

Fig. 1 displays the impulse responses for a horizon of up to 40 quarters after a one-standard-deviation shock to the real oil prices. The solid line denotes the posterior mean impulse response and the shaded area defines the 16th and 85th percentile confidence bands.[14]

As Canada is a net oil exporter, an oil price shock can be thought of as a positive shock to the terms of trade, which would in general lead to an expansion of the domestic economy and generate real income gains. It is not surprising that the domestic output runs up following an oil shock, while the U.S. output responds negatively to the same shock. A sharp rise in the real oil price is associated with a statistically significant appreciation of the Canadian dollar against its U.S. counterpart and a significant increase in CPI inflation. The monetary authority in Canada and the U.S. endogenously react to a positive oil

[14] The confidence bands are computed by a Bayesian method. Bayesian estimation proceeds by taking many draws from the posterior distribution of the VAR coefficients $B(L)$ which belongs to the Normal-Wishart family as well as many draws on Givens matrix $Q(\theta)$, where θs come from a uniform distribution on $[0,\pi]$. Since the sample distribution of impulse responses may not be normal, the bands are not necessarily centered around the means of response. The detailed discussion of our Bayesian method can be found in Appendix B.

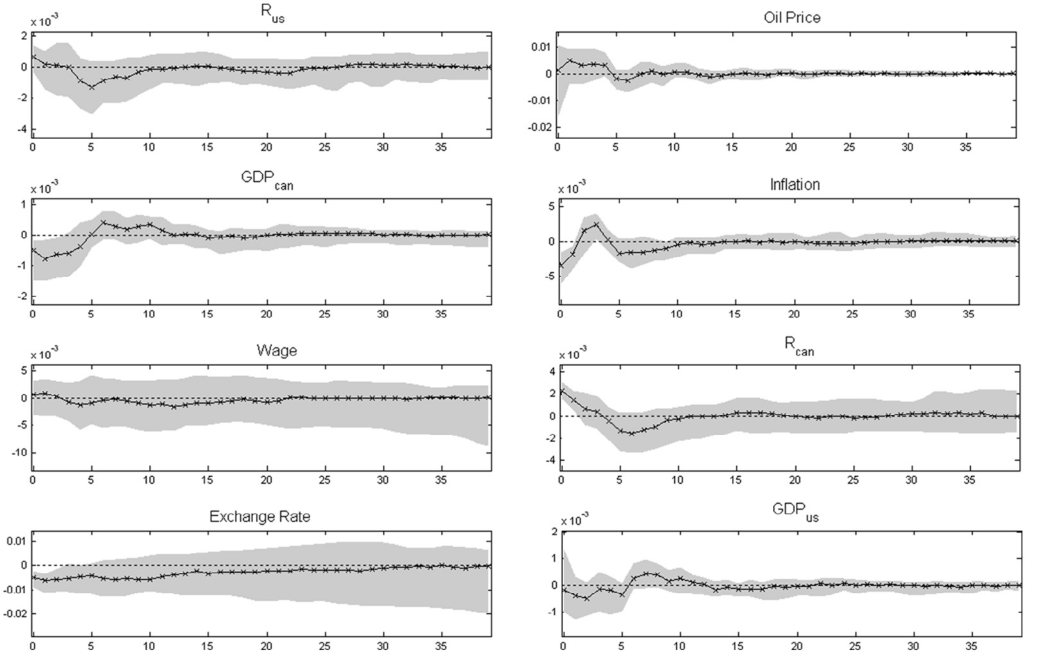

Fig. 2. Dynamic responses to a contractionary domestic monetary policy shock. The shaded area represents the 70% error band.

price shock due to its inflationary effect. Additionally, the real hourly wage rate falls significantly and gradually returns to its pre-shock level after four quarters. Similar finding about real wages can be found in Rotemberg and Woodford (1996) for the U.S.

4.2. *Effects of domestic monetary policy shocks*

To check on whether our identification strategy is successful in jointly identifying oil price shocks, monetary policy shocks and technology shocks, we now examine the identified Canadian and U.S. monetary policy shocks.[15] Fig. 2 displays the impulse responses to a domestic tightening monetary policy shock. The unexpected contractionary monetary policy shock is accompanied by an immediate and significant appreciation of the Canadian dollar that lasts about two years – the exchange rate effect. The inflation rate first drops by a small (but statistically significant) amount and remains below the steady state for about three quarters – the price effect. Output shows a statistically significant but relative small decline for about four quarters. The real hourly wage responds gradually and positively, though the response is insignificant. It is not surprising that in case of U.S. fund rates and U.S. output, the reactions of these variables to Canadian monetary disturbances are neither statistically significant nor large. In addition, the monetary policy shock is quite persistent, generating pronounced hump-shaped responses from all of the domestic variables in the system. Our results are consistent with traditional theoretical predictions that a tightening monetary policy shock has recessionary consequences.

4.3. *Effects of U.S. monetary policy shocks*

We now consider the effects of U.S. contractionary monetary policy shocks on the Canadian economy in Fig. 3. As the U.S. funds rate increases, the Canadian dollar depreciates strongly and significantly

[15] To conserve space, the impulse responses to a Canadian supply shock are not reported here.

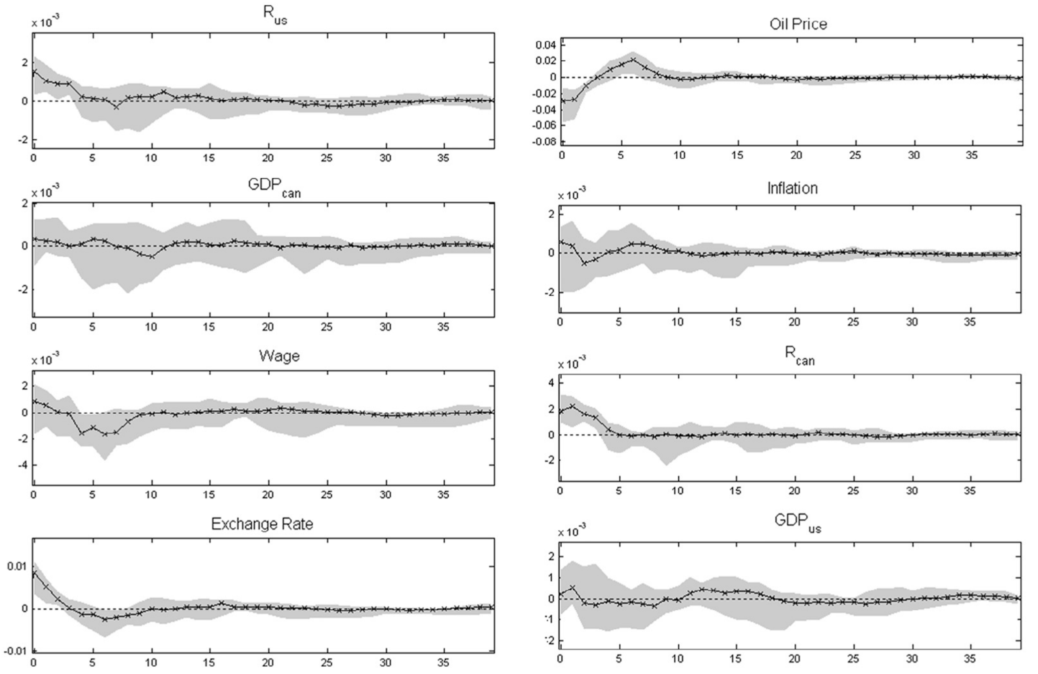

Fig. 3. Dynamic responses to a contractionary U.S. monetary policy shock. The shaded area represents the 70% error band.

relative to the U.S. dollar on impact, but the depreciation is short-lived, as the real exchange rate shows evidence of overshooting. This finding agrees with Cushman and Zha (1997) for Canada and with Kim and Roubini (2000) for G7 countries including Canada. The devaluation of the Canadian dollar is associated with an inflationary effect as the domestic inflation rates tend to increase significantly after the domestic depreciation. However, we also observe that the domestic monetary authority responds strongly to the U.S. rate increases with an interest rate hike, which exerts downward pressure on domestic inflation. As these two forces counter each other, the responses of the CPI inflation rates are statistically insignificant (except for a significant positive response in the second quarter). As the higher interest rate dampens aggregate demand, domestic output falls persistently and significantly before returning to its pre-shock level. A positive innovation in U.S. fund rates has a significant negative impact on real oil prices.

4.4. The contribution of foreign disturbances on Canadian macro variables

To assess the role of underlying structural shocks in fluctuations of macroeconomic variables, we calculate the forecast error variance decomposition (FEVD) based on the VAR model. Table 3 shows the contribution of the structural shocks to the variation in real exchange rates, the domestic interest rate, CPI inflation and domestic output, at several horizons $t = 1, 4, 8, 12, 20$. Since we leave some individual shocks unidentified, the label “other shocks” in Table 3 refers to the decomposition from a subset of unidentified individual shocks and the identified Canadian supply shock combined.

The results of the variance decomposition exercise show the shocks originating abroad play an important role in explaining the fluctuations in Canadian macroeconomic variables. First, the oil price shock has an important contribution to the forecast variance of domestic variables. For instance, the oil shock has significant contribution to the variance of the bilateral Canada–U.S. real exchange, CPI inflation and real output on impact, accounting for 18.19, 25.77 and 21.07 percent of the total variance, respectively. In the case of the domestic interest rate, the contribution peaks during the fourth

Table 3
Forecast error variance decomposition: the VAR model.

Quarter ahead	R_{us} shock	P_{oil} shock	R_{can} shock	Other shocks
Real exchange rate				
1	47.40	18.19	11.55	22.86
4	36.68	24.47	12.82	26.03
8	35.08	19.14	13.96	31.82
12	35.02	17.90	14.11	32.97
20	30.42	17.15	20.65	31.78
Domestic interest rate				
1	24.06	2.59	38.56	34.79
4	38.59	19.62	33.86	7.93
8	33.00	16.46	23.92	26.62
12	34.67	14.69	23.01	27.63
20	33.53	14.45	21.83	30.19
CPI inflation				
1	4.83	25.77	42.54	26.86
4	18.27	23.26	40.61	17.86
8	23.95	18.29	35.21	22.55
12	22.22	15.90	32.91	28.97
20	22.07	12.89	27.30	37.74
Real GDP				
1	1.58	21.07	27.39	49.96
4	3.45	9.96	29.04	57.55
8	8.86	7.03	24.40	59.71
12	9.69	6.61	22.39	61.31
20	16.15	5.41	18.90	59.54

quarter after an oil price shock, accounting for 19.62 percent. Interestingly, an oil shock contributes to a large share of the domestic interest rate fluctuation in longer horizons rather than on impact. This fact might indicate that the changes in oil prices gradually pass-through to the core inflation, which is the target of the Canadian monetary authority. Second, the impact of fluctuation in U.S. fund rates on the Canadian economy is significant. In all cases, by the 20th quarter, U.S. monetary policy shock still explains a large amount of the variance of the Canadian macroeconomic variables. A similar finding can be found in Cushman and Zha (1997). Third, domestic monetary policy disturbances are also an important source of fluctuations in the domestic economic activities. In the case of Canadian output, the contribution of a domestic monetary policy shock peaks in the fourth quarter, accounting for around 29.04 percent of the total output variance, while the impact on output decreases over longer horizons. This finding agrees with the results in Bernanke and Mihov (1998) and Sims and Zha (2006) for the U.S. and in Cushman and Zha (1997) for Canada. Finally, the oil shock together with U.S. and Canadian monetary policy shocks is the primary source of fluctuations in the Canadian economy, especially in the short run. This observation is consistent with the fact that Canada as a small open economy is mainly subject to demand shocks instead of supply shocks.

5. Robustness of identification strategy

In this section, the robustness of the baseline results is examined against a couple of alternative specifications. We examine whether the identification strategy matters for our results by deriving the impulse responses from a typical Cholesky factorization. We also investigate the sensitivity of our results to the alternative specifications of macro variable systems.[16]

[16] In Appendix D we provide further evidence of robustness. Appendix D-1 provides simulation evidence that the sign restrictions are consistent with the predictions of the model. Appendix D-2 shows that, relative to the standard VAR model, shocks obtained from the sign restrictions VAR model are more consistent with actual changes in world oil prices. We also estimate the VAR model with linearly detrended data. The corresponding estimation results are largely in line with our paper's results. See Appenidx D-3 for these results.

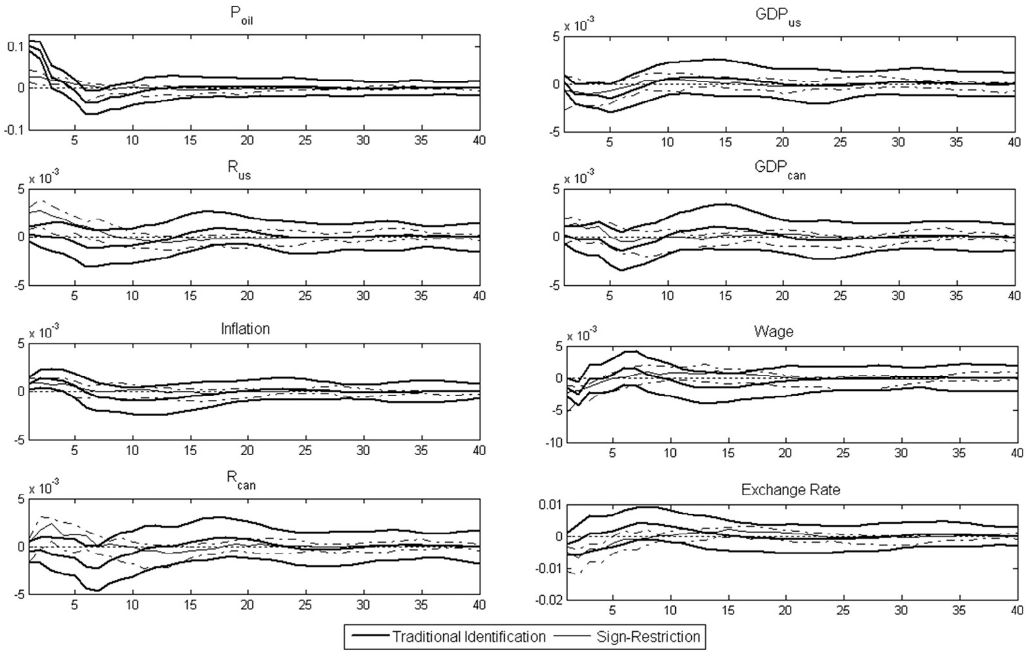

Fig. 4. Note: The thick line refers to the responses to an oil price shock under the traditional identification strategy; the thin line to the responses to an oil price shock under the sign-restriction strategy. The dashed lines cover 70% confidence interval.

To check for the robustness of our empirical results, we compare them with the impulse responses obtained from the VAR with the traditional zero restrictions. In this recursive identification procedure, we place the oil prices at the top of the ordering so as to allow oil prices to influence all other macroeconomic variables contemporaneously but allow other structural shocks to affect the oil prices only with a lag. Fig. 4 displays the impulse responses to an oil price shock. The shaded area represents the two-standard-deviation confidence intervals, obtained using a Monte Carlo procedure.

The most controversial response to an oil shock are those of interest rates because the impulse responses are quite different across the two identification strategies. Under the traditional Cholesky decomposition, both U.S. and Canadian interest rates fall persistently in the wake of oil shocks. This finding indicates that the contemporaneous correlations between the oil price and interest rates are negative while a host of empirical studies suggest otherwise. As the U.S. dollar is the sole pricing and settlement currency for oil, the fluctuating value of the dollar, which is determined by the U.S. monetary policy, plays an important role in exacerbating the run-up and precipitous fall in world oil prices. Therefore, the traditional zero restrictions that other variables have no immediate impact on the oil prices may be misspecified.

It is worth noting that a potential problem associated with the conventional approach is that the responses of oil prices to an oil shock are much higher than those derived from the VAR with sign restrictions. This finding might indicate that part of the oil shock identified by the conventional approach is picked up by other shocks when sign restrictions are applied.

Another dimension worth examining for robustness is the choice of variables included. We check three alternative specifications of VAR models. In the alternative eight-variable system, the real wage rates are replaced by the terms of trade. In the seven-variable system, the U.S. output is removed from the VAR model. In the nine-variable system, the U.S. CPI inflation is included in the data. All the estimated results from the alternative models confirm the findings in our baseline eight-variable VAR model and are not reported to conserve space.

6. Consequences of an oil price shock when monetary policy variables remain fixed

In this section, we decompose the effects of an oil price shock into direct and indirect components and provide rough estimates of the contribution of endogenous U.S. monetary policy responses. In this counterfactual experiment, we simply do not allow the U.S. fund rate to respond to an oil price shock on impact, in the manner of Bernanke et al. (1997).[17] That is, we shut off the U.S. monetary policy responses that would otherwise be implied by the empirical model after an oil shock.[18] In this case, U.S. monetary policy is not allowed to respond to an oil price shock that affects the domestic economy through international transmission channels. The difference between the total effect of an oil price shock on the domestic variables and the effect when the U.S. policy response is shut down is then interpreted as a measure of the contribution of the endogenous foreign policy responses.[19]

In Fig. 5, the crossed line provides estimates of the benchmark model and the circled line presents the impulse response functions for an increase of one standard deviation in the price of oil. The gap between two marked lines can be interpreted as the indirect contribution of endogenous reaction of U.S. monetary policy. The results indicate that in the absence of an endogenous reaction of U.S. monetary policy after an oil price shock, U.S. output would have increased as one would anticipate. It is because the milder responsive fund rates in the U.S. lead to a larger effect on the expected inflation and thus a larger decline in the real rate of interest, which has a stimulating impact on investment and output. This is essentialy consistent with Carlstrom and Fuerst's (2006) conclusion for the U.S. The counterfactual experiment, however, implies that an endogenous reaction of U.S. policy rate accounts for a small proportion of the variation in domestic economic activity. Quantitatively, the cumulative effects on domestic output are small over a long horizon. For the dynamic behavior of the domestic inflation and real exchange rate, the differences between resultant impulse response functions are moderate on impact, which suggests that the counterfactual simulation attributes part of an inflationary effect and an appreciation of Canadian dollar that follows an oil shock to the endogenous responses of U.S. monetary policy. Finally, the domestic interest rate would increase more mildly under the counterfactual scenario, but the differences seem minor, given the confidence bands around the impulse responses. However, it is worth noting that a U.S. monetary policy shock does have considerable direct impacts on nominal oil prices. As shown in Fig. 5, a positive innovation in U.S. fund rates has a significant negative impact on real oil prices. This is because as the U.S. dollar is the sole pricing and settlement currency in oil transaction, the fluctuating value of the dollar, which is determined by the U.S. monetary policy, plays an important role in determining the fluctuation in the world oil prices.

7. Conclusion

Empirical analysis of the impact of oil prices and their transmission mechanism in small open economies has been subject to numerous debates. One of the difficulties encountered is the inability to correctly identify and single out the contributions of structural shocks in a small economy. The present paper tries to contribute to this research agenda by using a structural VAR with sign restrictions derived from

[17] Sims and Zha (2006) and Bernanke et al. (1997) employ similar approaches to investigate the contribution of endogenous monetary policy changes in a VAR context. They shut down the policy response by setting the policy instrument as its baseline value throughout the simulation.

[18] In this counterfactual experiment, we simply isolate the impacts of oil prices on U.S. interest rates while U.S. interest rates are responding to other variables. Therefore, we observe U.S. interest rate increases slightly on impact because past variables in the system have impacts on U.S. interest rate.

[19] We also consider another counterfactual experiment. In the second experiment, we keep both domestic and foreign monetary policy responses constant throughout the counterfactual simulation. This scenario is intended to eliminate the resulting domestic and foreign policy component of an oil price shock, leaving only the direct effect of the oil price shocks on the economy. Similar to the first experiment, the difference between the effect when only the U.S. policy response is turned off and the effect when both domestic and foreign policies are turned off is then interpreted as a measure of the contribution of the systematic domestic policy response to an oil price shock. It turns out that the contribution of the endogenous domestic policy responses is negligible and not reported for this reason. We also examined keeping U.S. interest rate counterfactually constant to all variables. Those results are similar to our counterfactual results and not reported for this reason.

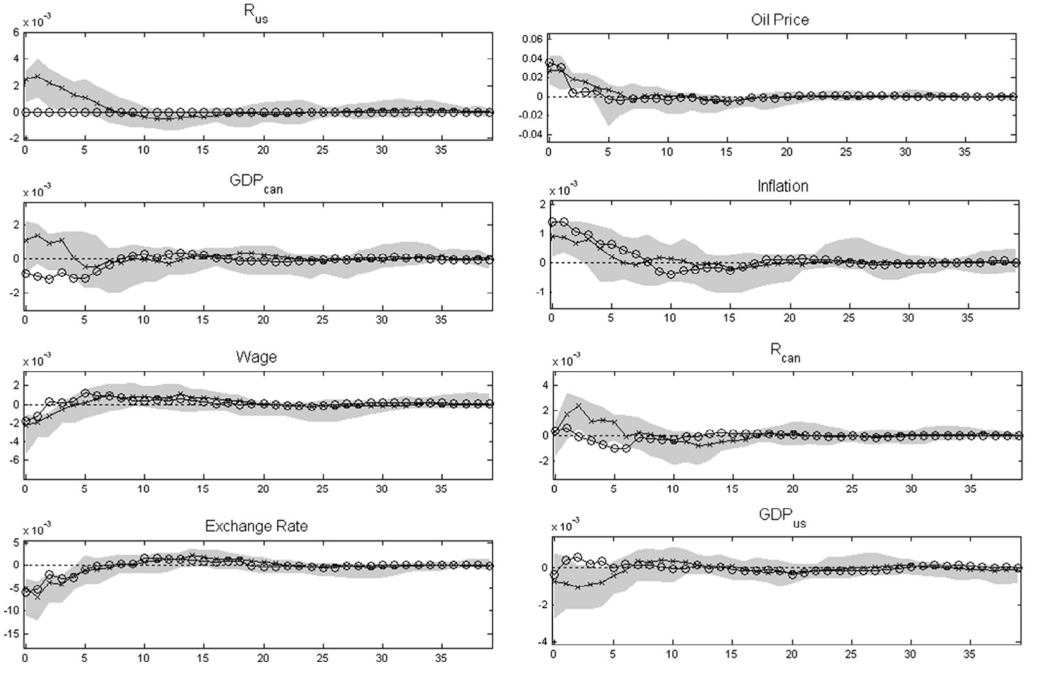

Fig. 5. Counterfactual Experiment: R_{us} does not respond to an oil price shock.
Note: Dynamic responses to a positive oil price shock under counterfactual scenarios. The cross line refers to the benchmark model; the circled line to the scenario where R_{us} is kept counterfactually constant.

a NOEM model with an oil sector to jointly identify oil price, domestic supply and foreign and domestic monetary policy shocks and examine the roles of transmission channels of oil shocks in an open-economy setup.

Our identification scheme appears to be successful in identifying oil price and monetary policy shocks by imposing theoretically coherent information to select impulse response functions. The effects of each structural shock on macroeconomic variables are consistent with the predictions of a broad set of theoretical models. Based on data for 1980:Q1–2011:Q3, we find that oil shocks have a stimulative effect on Canadian aggregate demand, appreciate the Canadian dollar, improve the terms of trade and reduce real wages. Note also that foreign disturbances, including innovations in oil prices and the U.S. interest rate, have a significant influence on Canadian economic activities.

Our counterfactual experiment indicates that the reaction of U.S. interest rate as an indirect transmission channel for oil price shocks plays at most a moderate role in explaining the bilateral real exchange rate and the Canadian inflation, but has negligibe impacts on the Canadian output and interest rate. This finding sugests that the indirect effects of oil shocks on macroeconomic performance through the systematic responses of U.S. monetary policy may not act as a significant transmission channel in determining macroeconomic fluctuations in oil-producing countries.

Acknowledgments

Keqiang Hou thanks the Chinese Social Science and Humanities Research Council, Ministry of Education of China (No. 12YJC790057) for funding this research. Appreciation is also extended to the anonymous reviewer for making very helpful suggestions.

Appendix A. Data description

The common period covered by all series is 1980:Q1–2011:Q3. Some series at monthly frequencies are converted to quarterly by simple averaging. We take the natural logarithm of each variable with the exception of the short-term interest rates and inflation rates. The Canadian data for this project are obtained from CANSIM. Series numbers are indicated in brackets and correspond to CANSIM database numbers.

- Output is measured by real GDP per capita [V1992067], denoted as Y_{can}
- The CPI inflation rate is measured by changes in consumer price index [V41690973], denoted as π_{can}
- The average nominal wage is measured by average hourly labor earnings (wage and salary [V500266]/total working hours [V2348296])
- Short-term interest rate is measured by the rate on Canadian three-month treasury bills [V122484], denoted as R_{can}
- The terms of trade is measured by the ratio of exports deflator [V1997750] to the imports deflator [V1997753]
- The series in per capita terms are obtained by dividing by the Canadian civilian population aged 15 and over [V2062810]

The U.S. data are taken from the Database at the Federal Reserve Bank of St. Louis with the series numbers in brackets. The world oil prices come from IMF Primary Commodity Prices database available at http://www.imf.org.external/np/res/commod/externaldata.csv.

- Foreign output is measured by real U.S. GDP per capita [GDPC1] divided by the U.S. civilian noninstitutional population aged 16 and over [CNP16OV], denoted as Y_{us}
- The foreign inflation rate is measured by changes in consumer price index for all urban consumers [CPIAUCSL], denoted as π_{us}
- The foreign interest rate is measured by the rate on U.S. three-month treasury bills [TB3MS], denoted as R_{us}
- The real exchange rate is measured by average Canadian dollars per unit of U.S. dollar [EXCAUS]
- The world oil price is measured by simple average of three spot prices of crude oil (Dated Brent, West Texas Intermediate, and the Dubai Fateh), US$ per barrel [POILAPSP], denoted as P_{oil}

Appendix B. Implementation of sign restrictions

In the following, we briefly describe the technical features of VAR identification with sign restrictions based on Canova and De Nicoló (2002).

Consider a reduced form VAR representation, which is associated with the structural model in equation (1), is given by

$$Y_t = B(L)Y_{t-1} + e_t, \quad e_t \sim N(0, \Sigma), \tag{B-1}$$

where $B(L) = A_0^{-1}A(L)$ and $e_t = A_0^{-1}\varepsilon_t = V\varepsilon_t$ is the vector of one-step ahead prediction error with variance–covariance matrix $\Sigma = E[e_t e_t'] = VE[\varepsilon_t \varepsilon_t']V' = VV'$. Without imposing further restrictions the decomposition of Σ is not unique. The multiplicity of these decompositions comes from the fact that for any orthogonal matrix Q satisfying $QQ' = I$, $\Sigma = VQQ'V'$ produces another admissible decomposition.

In order to trace out all possible impulse response functions to the orthogonal structural shocks, we transform equation (B-1) into a vector moving average representation (see Canova and De Nicoló, 2002 and Uhlig, 2005)

$$Y_t = C(L)e_t = C(L)V\varepsilon_t \tag{B-2}$$

$$C(L) = I_m + C_1L + C_2L^2 + \ldots = \left[I_m - B_1L - B_2L^2 - \ldots - B_pL^p\right]^{-1} \tag{B-3}$$

where $C_i = J'M^iJ, i = 0, 1, 2, \ldots \infty$ and J and M are given by

$$J_{mp,m} = \begin{bmatrix} I_m \\ 0_m \\ 0_m \\ \vdots \\ 0_m \end{bmatrix}, \quad M_{mp,mp} = \begin{bmatrix} B_1 & B_2 & \ldots & B_{p-1} & B_p \\ I_m & 0_m & \ldots & 0_m & 0_m \\ 0_m & I_m & \ldots & 0_m & 0_m \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0_m & 0_m & \ldots & I_m & 0_m \end{bmatrix}$$

The term C_iV denotes the corresponding VAR impulse responses to a structural shock in ε_t.[20] Now consider a $m \times m$ Givens matrix $Q_{pq}(\theta)$ of the form

$$Q_{pq}(\theta) = \begin{bmatrix} 1 & 0 & \ldots & \ldots & \ldots & \ldots & 0 \\ 0 & \ddots & \ldots & \ldots & \ldots & \ldots & 0 \\ \vdots & \vdots & \cos\theta & \ldots & \sin\theta & \vdots & \vdots \\ \vdots & \vdots & \vdots & 1 & \vdots & \vdots & \vdots \\ \vdots & \vdots & \sin\theta & \ldots & \cos\theta & \vdots & \vdots \\ 0 & \ldots & \ldots & \ldots & \ldots & \ddots & 0 \\ 0 & \ldots & \ldots & \ldots & \ldots & 0 & 1 \end{bmatrix}$$

where $\theta \in [0, \pi]$, the subscript (p, q) indicates the rows p and q which are rotated by the angle θ and $I_k = Q_{pq}(\theta)Q_{pq}(\theta)'$ for all θ. We then have that

$$Q(\theta) = Q_{12}(\theta_{12})Q_{13}(\theta_{13})\ldots Q_{1m}(\theta_{1m})Q_{23}(\theta_{23})\ldots Q_{2m}(\theta_{2m})\ldots Q_{m-1,m}(\theta_{m-1,m}) \tag{B-4}$$

is also an orthogonal matrix such that $\Sigma = VQ(\theta)Q(\theta)'V'$ and $e_t = VQ(\theta)Q(\theta)'\varepsilon_t = \tilde{V}\tilde{\varepsilon}_t{}'$.[21] The vector $\tilde{\varepsilon}_t$ is the new set of rotated orthogonal shocks, which has the same covariance matrix as ε_t but which has a different impact upon Y_t through its impact matrix $C_iA_0^{-1}Q(\theta)$. The empirical distribution for the impulse responses are derived in a Bayesian framework. Bayesian estimation proceeds by taking many draws from the posterior distribution of the VAR coefficients $B(L)$ which belongs to the Normal-Wishart family as well as many draws on Givens matrix $Q(\theta)$. Specifically, in a m variable system, according to equation (B-4), $Q(\theta)$ depends upon $\frac{m(m-1)}{2}$ bivariate rotation matrices $Q_{pq}(\theta)$ with $\theta = \theta_1, \ldots, \theta_{\frac{m(m-1)}{2}}$. As shown in Uhlig (2005) and Canova and De Nicoló (2002), all possible rotations can be produced by drawing θ from a uniform distribution on $[0,\pi]$. For each draw, we calculate the corresponding impulse responses and check whether the sign restrictions are satisfied. In this way, all possible impulse response functions can be traced out by varying the angle $\theta \in [0,\pi]$ and only those $Q(\theta)$s that generate impulse responses that comply with the sign restrictions will be retained.

Appendix C. The model economy

This appendix briefly sketches the features of a new open economy macroeconomy (NOEM) model which produces the identifying restrictions we use in the paper.

[20] Consider a temporary shock to the k^{th} component of ε_t such that ε_t^k equals unity. Then the response of $Y_{t+i} = C_iV\varepsilon_t^k$, for $i = 1, 2, 3, \ldots$, which is just the k^{th} column of C_i. Thus, the columns of C_i give us the impulse responses of each endogenous variable, at time $t+j$, to shocks administered at time t.

[21] Simply define $\tilde{V} = VQ(\theta)$ and $\tilde{\varepsilon}_t = \varepsilon_t'Q(\theta)$.

C-1. Household sector

The economy is populated by a continuum of households indexed by $j \in [0, 1]$. The preference of the household j is defined over consumption of final goods and leisure:

$$E_0 \sum_{t=0}^{\infty} \beta^t \left\{ \log(C_t(j) - hC_{t-1}) - \frac{N_t(j)^{1+\sigma_L}}{1+\sigma_L} \right\} \tag{C-1}$$

where E_0 denotes the mathematical expectation condition on date $t = 0$ information, $C_t(j)$ is total consumption, and $N_t(j)$ is the amount of type j labor provided by the household j. Parameter σ_L is the inverse elasticity of work effort with respect to the real wage. Preferences display the external habit formation in consumption governed by $h \in [0, 1]$ and C_{t-1} is the past aggregate consumption. The final good consumption, $C_t(j)$ is given by,

$$C_t(j) = \left[\gamma^{\frac{1}{\epsilon}} (O_{c,t}(j))^{\frac{\epsilon-1}{\epsilon}} + (1-\gamma)^{\frac{1}{\epsilon}} (Z_t(j))^{\frac{\epsilon-1}{\epsilon}} \right]^{\frac{\epsilon}{\epsilon-1}} \tag{C-2}$$

where parameter ϵ is the elasticity of substitution between oil and non-oil consumption, and γ denotes the oil share in the total consumption bundle. $O_{c,t}(j)$ represents oil consumption, and $Z_t(j)$ is a composite non-oil consumption index of imported and domestically produced goods defined as:

$$Z_t(j) = \omega^{-\omega} (1-\omega)^{(\omega-1)} C_{F,t}(j)^{\omega} C_{H,t}(j)^{1-\omega} \tag{C-3}$$

where $\omega \in [0, 1]$ is the import ratio measuring the degree of openness. The demand for oil and non-oil consumption are given by

$$Z_t(j) = (1-\gamma) \left(\frac{P_{Z,t}}{P_t} \right)^{-\epsilon} C_t(j), \quad O_{c,t}(j) = \gamma \left(\frac{P_{o,t}}{P_t} \right)^{-\epsilon} C_t(j) \tag{C-4}$$

where $P_{o,t}$ and $P_{Z,t}$ are the price of oil and the core consumption deflator, respectively. Analogously, the demand functions for home and foreign non-oil goods are given by,

$$C_{H,t}(j) = (1-\omega) \left(\frac{P_{H,t}}{P_{Z,t}} \right)^{-1} Z_t(j), \quad C_{F,t}(j) = \omega \left(\frac{P_{F,t}}{P_{Z,t}} \right)^{-1} Z_t(j) \tag{C-5}$$

where $P_{H,t}$ and $P_{F,t}$ are the prices of the home produced and imported goods, respectively. Thus, the consumption-based price index, P_t, and the non-fuel consumption price index is given by

$$P_t = \left[\gamma P_{o,t}^{1-\epsilon} + (1-\gamma) P_{Z,t}^{1-\epsilon} \right]^{\frac{1}{1-\epsilon}}, \quad P_{Z,t} = P_{F,t}^{\omega} P_{H,t}^{1-\omega} \tag{C-6}$$

The household j holds one-period internationally traded contingent claims at the end of period t, receives payments of his labor income and dividends from the domestic firms, importers and oil producers. Hence, his budget constraint at time t is given by,

$$\sum_{s^{t+1}} \mathcal{Q}_{t,t+1} B_{t+1}(j) + P_t C_t(j) = B_t(j) + W_t(j) N_t(j) + \Pi_t(j) - \Xi_t(j) \tag{C-7}$$

where $W_t(j)$ is the nominal wage set by household j, $\Pi_t(j)$ is the profits that household j is entitled to, and $\Xi_t(j)$ is the fix cost for oil extraction. $\mathcal{Q}_{t,t+1}$ is the stochastic discount rate on nominal payoffs, and $B_{t+1}(j)$ is the nominal payoff on a portfolio held at the end of period t. The complete international financial markets implies that there exists a complete set of state-contingent claims. When utility is separable between consumption and leisure, complete financial markets ensure consumption is equaled across households.

C-1.1. Consumption decisions

We first consider the first order conditions for choosing consumption and state-contingent security holding.

$$\Lambda_t(j) = \frac{1}{C_t(j) - hC_{t-1}} \tag{C-8}$$

$$E_t(Q_{t,t+1}) = E_t\left[\beta \frac{P_t}{P_{t+1}} \frac{\Lambda_{t+1}(j)}{\Lambda_t(j)}\right] \tag{C-9}$$

where $\Lambda_t(j)$ is the Lagrange multiplier associated with the household j's budget constraint and $E_t(Q_{t,t+1}) = (1+i_t)^{-1}$ is the nominal return on a state-contingent security maturing in t + 1 and i_t denotes the nominal interest rate. Since we are assuming the existence of a complete set of state-contingent claims, consumption is equalized across households. Therefore, in what follows, we can omit index j from consumption.

$$E_t\left[\beta \frac{P_t}{P_{t+1}}\left(\frac{C_t - hC_{t-1}}{C_{t+1} - hC_t}\right)\right] = \frac{1}{1+i_t} \tag{C-10}$$

C.1.2. Wage setting

Each household j is a monopolistic supplier of a differentiated labor service. Assuming there is a set of perfectly competitive labor service assemblers that hire labor from each household and bundle it into an aggregate labor service unit, N_t is then used by the domestic goods producer and oil producer. The labor service unit is defined as:

$$N_t = \left(\int_0^1 N_t(j)^{\frac{\varepsilon_L - 1}{\varepsilon_L}} dj\right)^{\frac{\varepsilon_L}{\varepsilon_L - 1}} \tag{C-11}$$

where ϵ_L measures the wage elasticity of demand among differentiated labor services. The labor service assembler maximizes its profits in the labor market by solving

$$\max W_t N_t - \int W_t(j) N_t(j) dj \tag{C-12}$$

where $N_t(j)$ is the labor supply of household j, $W_t(j)$ is the wage rate set by the household, and W_t is the aggregate wage index defined below. From the above maximization problems, individual households face a downward sloping demand function:

$$N_t(j) = \left(\frac{W_t(j)}{W_t}\right)^{-\epsilon_L} N_t \tag{C-13}$$

where the aggregate wage index, W_t, can be defined as,

$$W_t = \left(\int_0^1 W_t(j)^{1-\epsilon_L} dj\right)^{\frac{1}{1-\epsilon_L}} \tag{C-14}$$

Following Erceg et al. (2000) where the wage setting is subject to a nominal rigidity in a discrete time version of Calvo (1983), we assume that each household can reoptimize its wage in a given period with a constant probability $(1 - \phi_w)$, which is independent of other households and of the time elapsed since last adjustment. Thus, the law of large number implies that only a $(1 - \phi_w)$ fraction of households are able to re-optimize their nominal wage each period while the other fraction ϕ_w cannot. For those who are not allowed to re-optimize their nominal wage in the current period, we assume that their nominal wages remain constant during the interval between re-optimizations, and that they must supply any quantity of labor service demanded at the wage that they have decided on. Thus, a constant elasticity of substitution (CES) aggregate wage index evolves according to the difference equation:

$$W_t = \left(\phi_w W_{t-1}^{1-\epsilon_L} + (1-\phi_w) W_t^{T^{1-\epsilon_L}}\right)^{\frac{1}{1-\epsilon_L}} \tag{C-15}$$

If instead re-optimization is possible in the current period, a household j will set the target wage, $W_t^T(j)$ to maximize

$$\max E_{t-1}\left\{\sum_{k=0}^{\infty}(\beta\phi_w)^k\left[\Lambda_{t+k}N_{t,t+k}(j)\frac{W_t^T(j)}{P_{t+k}} - \frac{1}{1+\sigma_L}N_{t,t+k}(j)^{1+\sigma_L}\right]\right\} \tag{C-16}$$

subject to the labor demand (C-13). Note that E_{t-1} denotes the mathematical expectation condition on date $t-1$ information, which implies that wage setting occurs prior to the realization of any aggregate disturbance at time t (see Rotemberg and Woodford, 1996) and $N_{t,t+k}(j)$ stands for the labor supply of household j in period $t+k$ if the last wage re-optimization occurs in t. The variable Λ_{t+k} denotes the household's marginal utility of consumption at date $t+k$. The solution of the above problem satisfies the following first-order condition:

$$E_{t-1}\left\{\sum_{k=0}^{\infty}(\beta\phi_w)^k\left[\Lambda_{t+k}N_{t,t+k}(j)\frac{W_t^T(j)}{P_{t+k}} - \frac{\epsilon_L}{\epsilon_L - 1}N_{t,t+k}(j)^{1+\sigma_L}\right]\right\} = 0 \tag{C-17}$$

Equation (C-17) indicates that the household j will set its optimal wage so that the present discounted value of marginal disutility from working equals that of marginal utility of real wage income measured by $\Lambda_{t+k}, \forall k \geq 0$.

C-2. Inflation, the real price of oil, the real exchange rate and terms of trade

In this section, we start by defining the real price of oil expressed in terms of final consumption goods as $P_{o,t}^r \equiv \frac{P_{o,t}}{P_t}$. Using equation (C-6), the relative price of non-oil goods can be written as

$$P_{Z,t}P_t = \left(\frac{1-\gamma P_{o,t}^{r\ 1-\epsilon}}{1-\gamma}\right)^{\frac{1}{1-\epsilon}} \tag{C-18}$$

Taking logs and the first difference, we arrive at an identity linking headline inflation, core inflation and the change in the real price of oil,

$$\pi_t = \pi_{z,t} + \frac{\gamma}{1-\gamma}\left(p_{o,t}^r - p_{o,t-1}^r\right) \tag{C-19}$$

where $p_{o,t}^r$ is the log of the real price of oil.

Next, we define the bilateral real exchange rate as $Q_t \equiv \frac{e_t P_t^*}{P_t}$, the ratio of the two countries' CPIs, both expressed in the domestic currency. The terms of trade (TOT) of non-oil goods is defined as $S_{H,t} \equiv \frac{P_{F,t}}{P_{H,t}}$, i.e. the price of foreign goods per unit of home good. Note that an increase in $S_{H,t}$ is equivalent to an increase in competitiveness for the domestic economy. Equation (C-6) can be rewritten as

$$\frac{P_{H,t}}{P_{Z,t}} = S_{H,t}{}^{-\omega} \tag{C-20}$$

Taking logs and the first difference, we derive a relationship between the core inflation, domestic inflation and the terms of trade as follows,

$$\pi_{Z,t} = \pi_{H,t} + \omega(s_{H,t} - s_{H,t-1}) \tag{C-21}$$

C-3. International risk sharing and uncovered interest parity

Under the assumption of complete international financial markets, the expected nominal return from state contingent claims in the domestic currency must be equal to the expected domestic-currency return from the foreign state contingent claims. A first order condition analogous to (C-9) must also hold for the household j in the foreign economy.

$$E_t(\mathcal{Q}_{t,t+1}) = E_t\left[\frac{\beta P_t^*}{P_{t+1}^*}\frac{e_t}{e_{t+1}}\frac{\Lambda_{t+1}^*(j)}{\Lambda_t^*(j)}\right] \tag{C-22}$$

where $\Lambda_t^*(j)$ denotes the foreign household j's marginal utility of consumption at date t.

Combining (C-9) and (C-22), together with the real exchange rate definition, it follows that

$$\Lambda_t = \vartheta\Lambda_t^* Q_t \tag{C-23}$$

for all t and where ϑ is a constant which depends on initial conditions about relative net asset positions.

The assumption of a complete international financial market recovers another relationship, the uncovered interest parity (UIP) condition. If we equate the nominal returns (in terms of domestic currency) of a state contingent security in a foreign currency $e_t(1+i_t^*)^{-1} = E_t(\mathcal{Q}_{t,t+1}e_{t+1})$ to that of the same state contingent security in domestic currency, $(1+i_t)^{-1} = E_t\mathcal{Q}_{t,t+1}$, we obtain

$$E_t\left[\mathcal{Q}_{t,t+1}\left((1+i_t)-(1+i_t^*)\frac{e_{t+1}}{e_t}\right)\right] = 0 \tag{C-24}$$

C-4. Domestic production

C-4.1. Aggregation of domestic goods

The domestic good aggregator, Y_t is the bundle of differentiated goods which is supplied to domestic and foreign consumers. The Dixit–Stiglitz aggregator is

$$Y_t = \left(\int_0^1 Y_t(i)^{\frac{\epsilon_H-1}{\epsilon_H}}di\right)^{\frac{\epsilon_H}{\epsilon_H-1}} \tag{C-25}$$

where $Y_t(i)$ represents the quantity of a differentiated good i. The optimal allocation of expenditure across differentiated goods implies a downward-sloping demand function for a good i,

$$Y_t(i) = \left(\frac{P_{H,t}(i)}{P_{H,t}}\right)^{-\epsilon_H} Y_t \tag{C-26}$$

where $P_{H,t}(i)$ denotes the price of good $Y_t(i)$ and ϵ_H measures the price elasticity of demand among differentiated goods. $P_{H,t}$ denote the price index of composite domestic goods given by

$$P_{H,t} = \left(\int_0^1 P_{H,t}(i)^{1-\epsilon_H}di\right)^{\frac{1}{1-\epsilon_H}} \tag{C-27}$$

C-4.2. Intermediate producers

In the domestic goods market, there is a continuum of monopolistic competitive firms producing differentiated goods indexed by $i \in [0, 1]$ with a CES production function

$$Y_t(i) = A_t\left[(1-\alpha)^{\frac{1}{\epsilon_m}} N_{m,t}(i)^{\frac{\epsilon_m-1}{\epsilon_m}} + \alpha O_{m,t}(i)^{\frac{\epsilon_m-1}{\epsilon_m}}\right]^{\frac{\epsilon_m}{\epsilon_m-1}} \tag{C-28}$$

where $N_{m,t}(i)$ is the labor input, and $O_{m,t}(i)$ is oil used in production. A_t is a domestic technology shock. The level of technology is common to all firms. Parameter ϵ_m defines the elasticity of substitution between labor and oil in production. Note that for the sake of simplicity, this elasticity is constrained to be the same as for households.

A producer i solves its maximization problem in two stages. In the first stage, taking the price of both inputs as given, the producer chooses the cost minimizing quantities of labor and oil to solve the following static cost minimization problem:

$$\min_{N_{m,t}(i),O_{m,t}(i)} W_t N_{m,t}(i) + P_{o,t} O_{m,t}(i)$$

subject to (C-28). This cost minimization implies that firm i's nominal marginal cost $MC_t(i)$ is given by:

$$MC_t(i)^{\epsilon_m} = \frac{W_t^{\epsilon_m}}{(1-\alpha)(Y_t(i)/N_{m,t}(i))} = \frac{P_{o,t}^{\epsilon_m}}{\alpha(Y_t(i)/O_{m,t}(i))} \tag{C-29}$$

Letting $MC_t^r(i) \equiv (MC_t(i)/P_{H,t})$ denotes firm i's real marginal cost, we have

$$MC_t^r(i) = A_t^{-1}\left[(1-\alpha)W_t^{r\,1-\epsilon_m} + \alpha P_{o,t}^{r\;1-\epsilon_m}\right]^{\frac{1}{1-\epsilon_m}} S_{H,t}^{\omega}\left(\frac{1-\gamma P_{o,t}^{r\;1-\epsilon}}{1-\gamma}\right)^{\frac{-1}{1-\epsilon}} \tag{C-30}$$

where $W_t^r \equiv \frac{W_t}{P_t}$. Notice that the real marginal cost depends not only on the real prices of inputs but also on the terms of trade of non-oil goods and that all these factors are common to all firms.

These domestic firms are assumed to set prices in a Calvo-staggered fashion. Analogously to the case of households, a fraction $(1 - \phi_h)$ of firms selected randomly, set new prices optimally each period, while the remaining fraction ϕ_h of firms keep their price unchanged. The CES aggregate price index consequently evolves according to

$$P_{H,t} = \left[(1-\phi_h)P_{H,t}^{T\;1-\epsilon_H} + \phi_h P_{H,t-1}^{1-\epsilon_H}\right]^{\frac{1}{1-\epsilon_H}} \tag{C-31}$$

Since firms are not allowed to re-optimize on their prices every period, the optimal price determination becomes an inherently dynamic problem. In the second stage, the domestic good producer i chooses its target price $P_{H,t}^T(i)$ so as to maximize the present value of its real profits:

$$\max E_{t-1}\left\{\sum_{k=0}^{\infty}(\beta\phi_h)^k \frac{\Lambda_{t+k}}{\Lambda_t} Y_{t,t+k}(i)\left[\frac{P_{H,t}^T(i)}{P_{H,t+k}} - MC_{t,t+k}^r\right]\right\} \tag{C-32}$$

subject to the demand function (C-26). $Y_{t,t+k}(i)$ denotes the sales of good i in period $t+k$, if the most recent price adjustment came into effect in period t. The term $\beta^k \frac{\Lambda_{t+k}}{\Lambda_t}$ represents the appropriate discount factor for future profits between date t and $t+k$, and $\phi_h{}^k$ stands for the probability that prices will not be re-optimized for k period. The solution to above maximization problem is given by

$$E_{t-1}\left\{\sum_{k=0}^{\infty}(\beta\phi_h)^k \frac{\Lambda_{t+k}}{\Lambda_t} Y_{t,t+k}(i)\left[\frac{P_{H,t}^T(i)}{P_{H,t+k}} - \frac{\epsilon_H}{\epsilon_H-1} MC_{t,t+k}^r\right]\right\} = 0 \tag{C-33}$$

Note that if domestic good prices are flexible, i.e. if $\phi_h = 0$, a representative firm chooses the price for its differentiated product as a constant markup over the nominal marginal cost $P^T_{H,t} = \frac{\epsilon_H}{\epsilon_H - 1} P_{H,t} MC^r_t$.

C-5. Domestic importers

Following Monacelli (2005) we assume that endogenous deviation from purchasing power parity (PPP) in the short term arises due to the existence of monopolistically competitive importers. Although the law of one price holds at the wholesale level for the differentiated foreign goods, importers sell these goods to domestic consumers and charge a mark-up over their cost, which results in a wedge between domestic and import prices of foreign goods in the short run. We define the law of one price gap as

$$\Psi_t = \frac{e_t P^*_{F,t}}{P_{F,t}} \tag{C-34}$$

Combining (C-34), (C-18) and (C-20) yields the following equation linking LOP gap, the real price of oil, the terms of trade and the real exchange rate:

$$\Psi_t = Q_t \left(\frac{1 - \gamma^* P^{r*\,1-\epsilon}_{o,t}}{1 - \gamma^*} \right)^{\frac{1}{1-\epsilon}} \left(\frac{1 - \gamma P^{r\;1-\epsilon}_{o,t}}{1 - \gamma} \right)^{\frac{-1}{1-\epsilon}} S^{\omega-1}_{H,t} \tag{C-35}$$

Similar to domestic producers, importers operate under Calvo-style pricing structure, with $1 - \phi_f$ importers setting the target prices, $P^T_{F,t}$ optimally each period. The CES aggregate price index consequently evolves according to the relation

$$P_{F,t} = \left[(1 - \phi_f) P^{T\;1-\epsilon_F}_{F,t} + \phi_f P^{1-\epsilon_F}_{F,t-1} \right]^{\frac{1}{1-\epsilon_F}} \tag{C-36}$$

and retailers setting prices in period t face a demand curve

$$C_{F,t}(i) = \left(\frac{P^T_{F,t}(i)}{P_{F,t}} \right)^{-\epsilon_F} C_{F,t} \tag{C-37}$$

Thus, a particular importer i maximizes the present value of its retail profits:

$$\max E_t \left\{ \sum_{k=0}^{\infty} (\beta\phi_f)^k \frac{\Lambda_{t+k}}{\Lambda_t} C_{F,t+k}(i) \left[\frac{P^T_{F,t}(i)}{P_{F,t+k}} - \Psi_{t+k} \right] \right\} \tag{C-38}$$

subject to the demand function (C-37). The firm's optimization problem implies the first order condition:

$$E_t \left\{ \sum_{k=0}^{\infty} (\beta\phi_f)^k \frac{\Lambda_{t+k}}{\Lambda_t} C_{F,t+k}(i) \left[\frac{P^T_{F,t}(i)}{P_{F,t+k}} - \frac{\epsilon_F}{\epsilon_F - 1} \Psi_{t+k} \right] \right\} = 0 \tag{C-39}$$

C-6. Oil producing firms

We now discuss the features of oil production in the model economy. Since a small oil exporting country is a price-taker with little bargaining power in the international oil market, we assume world oil prices are determined exogenously. In addition, we assume that the domestic economy is populated by identical local oil producers who, taking the world oil price as given, extract oil to satisfy the domestic and foreign demand. A representative oil producer pays a fix cost to maintain its oil well and produce oil according to the following decreasing returns to scale technology that uses labor as input

$$O_t = A_t N_{o,t}^{\alpha_o} \bar{X}^{1-\alpha_o} \tag{C-40}$$

where $N_{o,t}$ is the labor used in the oil sector, and $\bar{X}$ denotes the other factor input (i.e. oil well) which is constant in the short run. Parameter $\alpha_o \in (0, 1)$ is the share of labor in oil production.

Taking oil prices and wages as given, the firm chooses labor demand in order to maximize profits:

$$\max_{N_{o,t}} P_{o,t} O_t - W_t N_{o,t} - \Xi_t \tag{C-41}$$

subject to (C-40). Variable Ξ_t denotes the fixed cost for oil extraction. The first order condition with respect to $N_{o,t}$ requires equating the marginal product of labor to the real wage in terms of oil.

$$W_t^r P_{o,t}^r = \alpha_o A_t N_{o,t}^{\alpha_o - 1} \bar{X}^{1-\alpha_o} \tag{C-42}$$

Oil market clearing condition requires that

$$O_t = O_{c,t} + O_{m,t} + O_{x,t} \tag{C-43}$$

where $O_{x,t}$ is the oil export to the foreign economy. Thus, the sum of the home oil production equals the sum of home and foreign oil consumption.

C-7. Monetary policy

We assume the monetary policy follows a Taylor-type rule in the following form:

$$\log\left(\frac{r_t}{r}\right) = \rho_r \log\left(\frac{r_{t-1}}{r}\right) + (1-\rho_r)\left(\phi_1 \log\left(\frac{\pi_{Z,t}}{\pi_Z}\right) + \phi_2 \log\left(\frac{y_t}{y}\right)\right) + \varepsilon_{R,t} \tag{C-44}$$

where r, π_Z, y are the steady-state values of r_t, $\pi_{Z,t}$, y_t. The parameter ρ_r is the degree of interest rate smoothing, which reflects the central bank's preference for interest rate stability[22]; ϕ_1 and ϕ_2 are the relative weights measuring central bank's response to log-deviation of core inflation and output from their steady-state values, respectively; and $\varepsilon_{R,t}$ denotes an iid monetary policy shock.

C-8. The foreign economy

The foreign economy is assumed to be an oil importer whose oil demand is satisfied by the oil-exporting economy. We assume that the foreign economy is unaffected by economic activities in the small open economy, but influences the latter via trade (including fuel and non-fuel trade) and capital flows in the financial market. For simplicity, behavioral similarity is assumed between domestic and foreign household and producers. Domestic and foreign economies, however, can differ in price-setting and monetary policy. We arrive at a similar set of optimality conditions describing the dynamic behaviors of the foreign economy with all variables taking a superscript ($\star$) and parameters properly substituted. Note that with the domestic economy being small relative to the foreign economy, foreign non-oil consumption approximately comprises only foreign-produced goods such that $Z^* = C_F^*$ and $P_Z^* = P_F^*$. To capture the systematic reaction to inflationary pressures in the wake of oil price shocks, we assume that the monetary authority in the foreign economy adjusts its nominal interest rate in response to deviations of the foreign inflation and output gap, analogously to (C-44).

C-9. Exogenous processes

There are eight structural shock processes in the model economy, including an oil price shock, domestic technology shock, domestic and foreign monetary policy shocks. We can describe the stochastic process of these shocks with log-linearized form by the univariate representation:

[22] See, for example, Clarida et al. (2001).

$$\xi_t = \rho_{\xi,t}\xi_{t-1} + \varepsilon_{\xi,t}, \quad \varepsilon_{\xi,t} \sim N\left(0, \sigma_\xi^2\right) \tag{C-45}$$

where $\xi_t = \left\{P_{ot}^{r^*}, \ln(A_t), \xi_{Rt}, \xi_{R^*t}\right\}$.

C-10. Calibration

The model parameters are calibrated using the corresponding data statistics. Table C4 summarizes the calibrated parameters. Parameters specific to the oil sector are set as follows. The share of labor in the production of oil α_o is assigned a value of 8% so that the labor input in the oil sector is about 2% of the Canadian total labor force. Following Blanchard and Galí (2007), we calibrate γ^* and α^* as the share of oil in U.S. consumption and the share of oil in U.S. output to 1.5% and 3%, respectively. The parameter determining the share of oil in Canadian non-oil output is fixed at 5%, consistent with the calibration in Macklem et al. (2001) who calculate the share parameters in production from Canadian 1996 input–output tables. Assuming economic structure of Canada is similar to that of the U.S., we calibrate the share of oil in the Canadian consumption bundle γ to 3%.

We calibrate the model so that the share of foreign goods in the Canadian consumption basket, ω is fixed at 40% to match the average import-to-GDP ratio observed in the data, while we set the share of foreign goods in the U.S. consumption basket ω^* to ensure that the real exchange rate at steady state is equal to unity, which implies that the law of one price holds in the long-term. We assume a low elasticity of substitution of oil in the consumption bundles as well as in the production function. The prior means of ϵ and ϵ_m are both equal to 0.18, which is in line with the estimates obtained by Rotemberg and Woodford (1996) who used data on twenty two-digit U.S. manufacturing sectors. Kilian (2008) also used a similar degree of substitutability between oil and other factors in production. Finally, the discount factor β is set to 0.99, which implies an annual real interest rate of 4%.

Table C4
The calibrated parameters.

Parameters	Description	Values
β	Discount factor	0.99
α_o	Share of labor in the production of oil	0.08
γ	Share of oil in Canada consumption	0.03
γ^*	Share of oil in U.S. consumption	0.015
α	Share of oil in Canada non-oil output	0.05
α^*	Share of oil in U.S. non-oil output	0.03
ω	Share of imported goods in Canada non-oil consumption	0.40
ϵ	Elasticity of substitution between oil and non-oil consumption	0.18
ϵ_m	Elasticity of substitution between oil and labor input	0.18
h	External habit formation in consumption	0.5
σ_L	Inverse elasticity of work effort with respect to wages	1
σ_L^*	Foreign inverse elasticity of work effort with respect to wages	1
ϵ_H	Elasticity of substitution between differentiated domestic goods	8
ϵ_F	Elasticity of substitution between differentiated imported goods	8
ϵ_L	Elasticity of substitution between differentiated labor	8
ϵ_L^*	Foreign elasticity of substitution between differentiated labor	8
ϵ_F^*	Foreign elasticity of substitution between differentiated goods	8
ϕ_H	Calvo-adjustment parameter for price setting in domestic goods	0.65
ϕ_F	Calvo-adjustment parameter for price setting in imported goods	0.65
ϕ_W	Calvo-adjustment parameter for wage setting	0.65
ϕ_H^*	Calvo-adjustment parameter for price setting in U.S.	0.5
ϕ_W^*	Calvo-adjustment parameter for wage setting in U.S.	0.5
ϕ_1	Domestic monetary policy parameter associated with inflation	1.8
ϕ_2	Domestic monetary policy parameter associated with output	0.65
ϕ_1^*	U.S. monetary policy parameter associated with inflation	1.8
ϕ_2^*	U.S. monetary policy parameter associated with output	0.65
ρ_A	Persistence of A_t shock	0.9
ρ_O	Persistence of P_{ot} shock	0.6
ρ_R	Persistence of R_t shock	0.6
ρ_{A^*}	Persistence of R_t^* shock	0.6

We set the parameters describing the domestic monetary policy rule, ϕ_1 and ϕ_2 to the values commonly associated with the Taylor rule. The interest rate smoothing parameter ρ_R is set to 0.6. We choose identical calibration for parameters of the foreign policy rule. The value for the price and wage stickiness parameters are chosen based on evidence on the average frequency of price changes. For Canada, we set 0.65 to the Calvo-adjustment parameter for price setting, which corresponds to an approximate three-quarter contract length as reported in Ambler et al. (2003). The stickiness of wages is set at the same level. For the U.S., we use information reported by Bils and Klenow (2004)[23] to set the Calvo probability parameter ϕ_H^* to 0.5. The stickiness of U.S. wages is set at the same level. The calibrated values for the preference parameters are chosen as follows. The habit parameter h equals 0.5, and the inverse elasticity of labor supply σ_L and σ_L^* are both assumed to be centered at 1. We set the elasticity of substitution between different types of labor ϵ_L and ϵ_L^* to be around 8, which translates into a wage markup equal to 15%, which is consistent with the findings in the micro-econometric studies by Griffin (1996) as based on U.S. data. A number of studies for the U.S. have reported quite a large range for the value of the elasticity of substitution between differentiated goods, ϵ_F^*. The mean of ϵ_F^* is set to 8, which implies a steady state markup of price over marginal cost equal to 15%. We use identical calibration for ϵ_H and ϵ_F. The persistence parameter of the exogenous domestic supply process ρ_A is assumed to be equal to 0.9, while the persistence parameters of other $AR(1)$ processes are set to 0.6.

Appendix D. Further evidence of robustness

D-1. Impulse responses: DSGE versus VAR

To validate our sign restrictions, we compare the impulse–response functions implied by our estimated DSGE model with those obtained from the structural VAR in Fig. D6.[24] The circled line refers to impulse responses generated by the theoretical model, shown as percentage deviations from the steady state; the crossed line refers to VAR-based impulse responses and the shaded area represents the 70% error band.

We calibrate the size of oil shocks in the DSGE model to match its counterpart in the VAR model. Overall, the estimated model is successful in replicating the impulse responses obtained from the VAR, with all variables exhibiting their expected qualitative behaviors. In particular, the estimated model performs quite well in matching the responses of output. As Canada is a net oil exporter, positive oil price shocks lead to an expansion of aggregate demand due to the boost in oil incomes. The model generates a positive response of domestic output after a positive innovation in the price of oil, at approximately 0.15 percent above the steady state, as predicted by the VAR. With oil price changes being passed through to its oil component, the CPI inflation rises on impact, which exerts an upward pressure on the policy rate. Thus, CPI inflation and interest rates rise after an oil shock. In both cases, the model-based responses are qualitatively similar to their VAR-based counterpart in terms of the sign of the responses and dynamic persistence. However, the model underpredicts the magnitude of the response of inflation.

The real wage rate falls in response to the oil price shock. The model predicts that the negative response of the wage rate to an oil price shock is 0.2 percent, which fits the empirical impulse responses quite well. Intuitively, this occurs as a result of the sluggish adjustment of nominal wage and the boosted price level owing to oil price shocks. Although in the medium term the difference becomes more substantial, the response of the real wage in the theoretical model is still within the 70% error band of the empirical impulse response. The model generates a negative and persistent response of the real exchange rate to an increase in oil prices, which implies that increases in oil prices appreci-

[23] Bils and Klenow (2004) document that an average of 26% of U.S. sectoral prices change every 3.3 months which implies a Calvo probability parameter of $\phi_H^* = 0.5$.

[24] To enable a comparison between the DSGE model and the structural VAR, we employ the sign identification strategy to jointly identify the structural shocks in oil prices, domestic supply, and U.S. and Canadian interest rates in our VAR system. This identification strategy uses theoretically coherent information to select impulse response functions from the complete set of orthogonal alternatives obtained from rotations of the contemporaneous impact matrices.

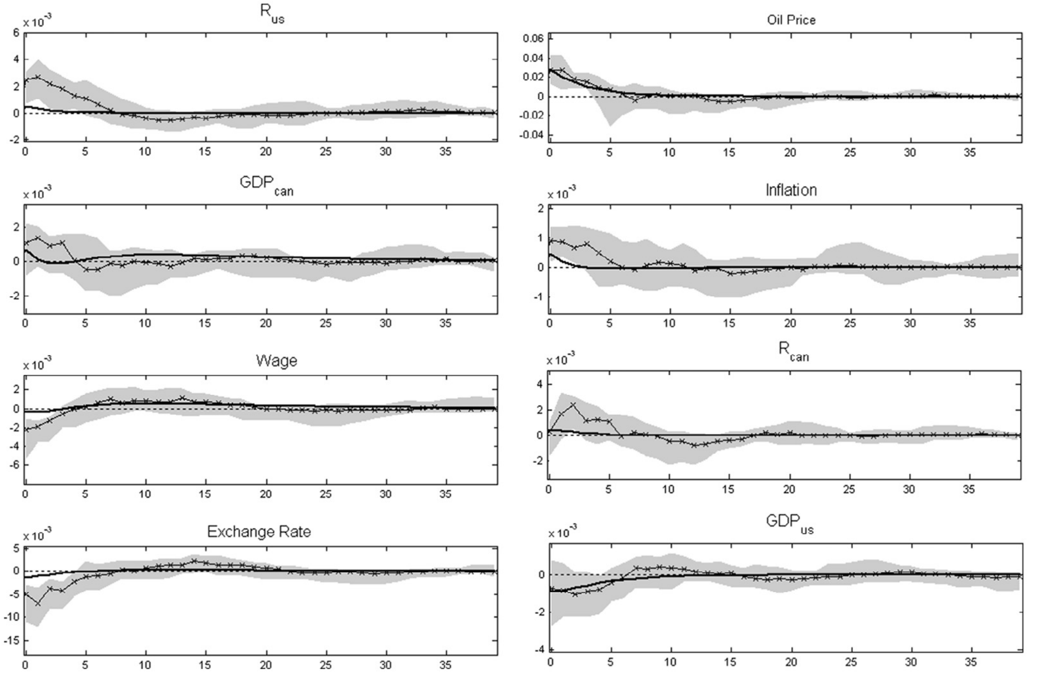

Fig. D6. Impulse response to an oil price shock: VAR vs. model.
Note: Dynamic responses to a positive oil price shock. The shaded area represents the 70% error band. The solid line refers to the responses from the DSGE model. The line with crossed markers represents the responses from the VAR model.

ate Canadian dollars. The response predicted by the model, however, is smaller in magnitude than its VAR-based counterpart.

D-2. Comparison between realized shocks

In Fig. D7 we plot the realizations of the oil shocks for both the VAR with sign restrictions and the standard VAR. Apparently, the realized oil shocks are different over the sample. We find the shocks obtained from the sign restrictions VAR are consistent with the data. For example, during 2005–2010, the world oil prices underwent the significant run-up, precipitous fall and then a quick rebound. The shocks from the sign restrictions VAR can largely capture this dynamic behavior of the world oil prices during this turmoil period. In contrast, the realized shocks in the standard VAR behave like an i.i.d. shock during the same period of the time. This is because the shocks identified with the standard approach mix the oil shocks with other information that the model assumes away. The standard recursive identification approach identifies oil price shocks by imposing strict exogeneity of oil prices and does not allow contemporaneous impacts on the prices oil prices. These identification assumptions will clearly be incorrect if economic developments in the country of consideration affect the world oil price contemporaneously. Therefore, our non-recursive identification structures equipped with a set of theoretically coherent information outperform the Cholesky approach in this regard.

D-3. Impulse responses to oil price and monetary shocks using linearly detrended data

We also estimated the VAR model with linearly detrended data. The estimation results are largely in line with our previous results and these results (as shown in Fig. D8, D9 and D10) are provided as further robustness evidence.

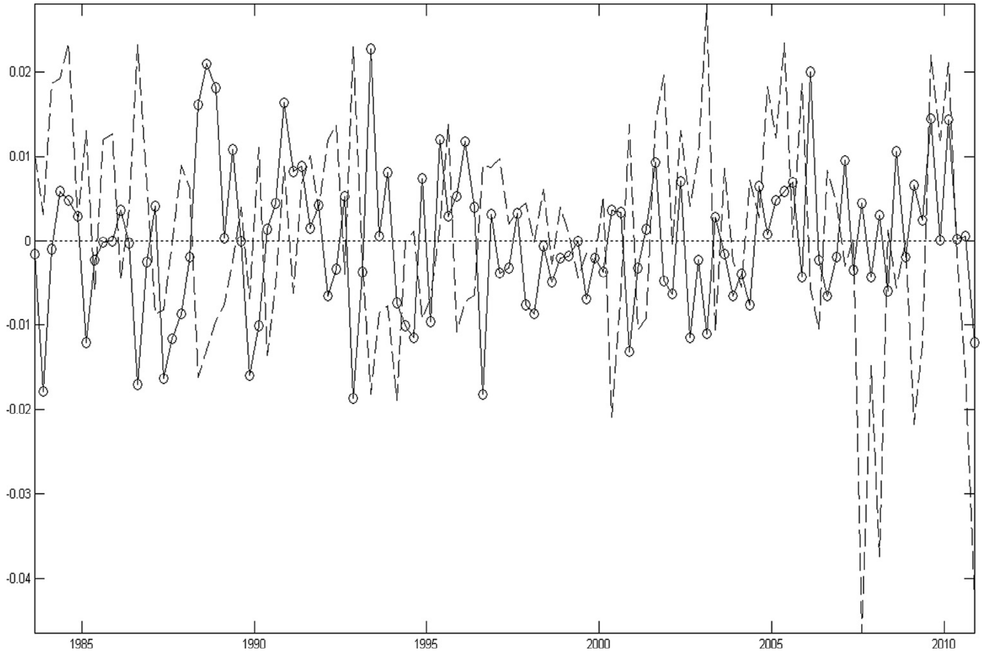

Fig. D7. Realized oil price shocks (1983–2011).
Note: The realized oil price shocks (1983–2011). The dashed line refers to the realized oil shocks obtained from the model with sign restrictions. The line with "o" markers represents the shocks from the model with a traditional identification strategy.

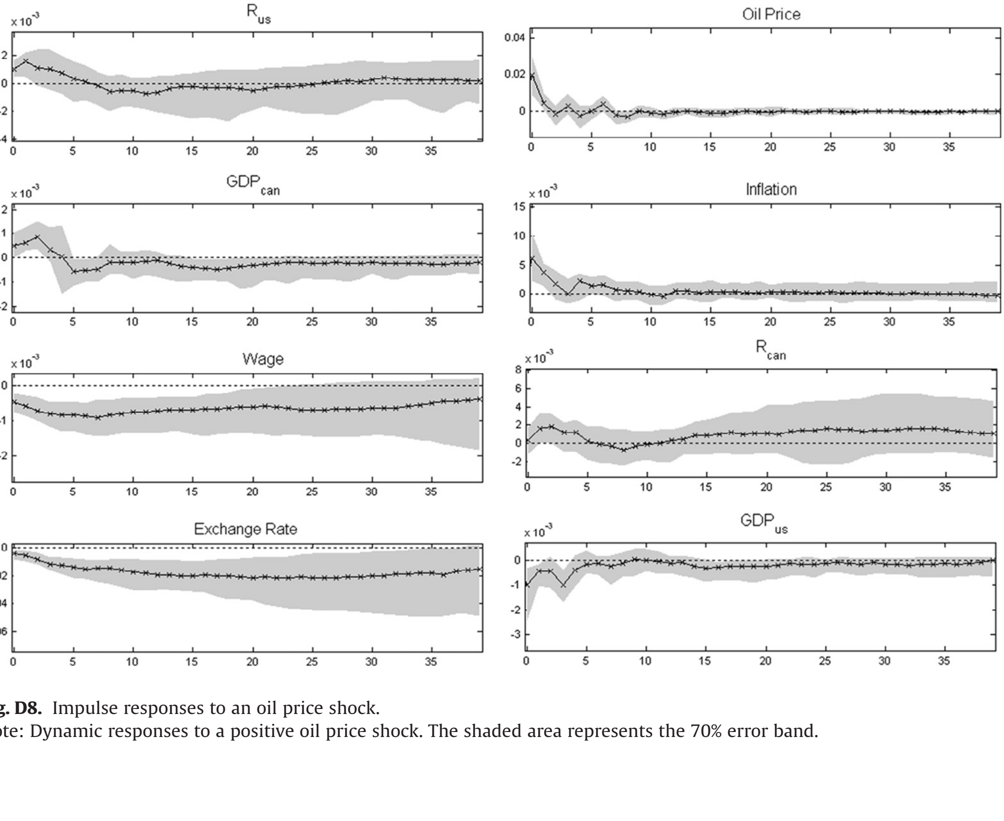

Fig. D8. Impulse responses to an oil price shock.
Note: Dynamic responses to a positive oil price shock. The shaded area represents the 70% error band.

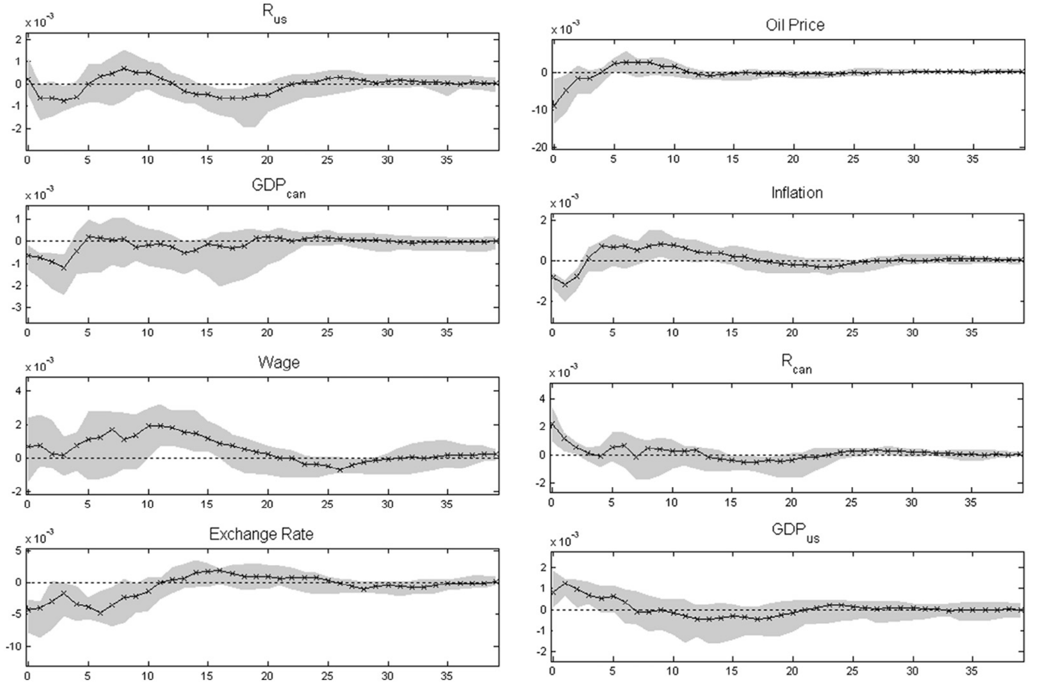

Fig. D9. Impulse responses to a domestic monetary policy shock.
Note: Dynamic responses to a positive domestic monetary policy shock. The shaded area represents the 70% error band.

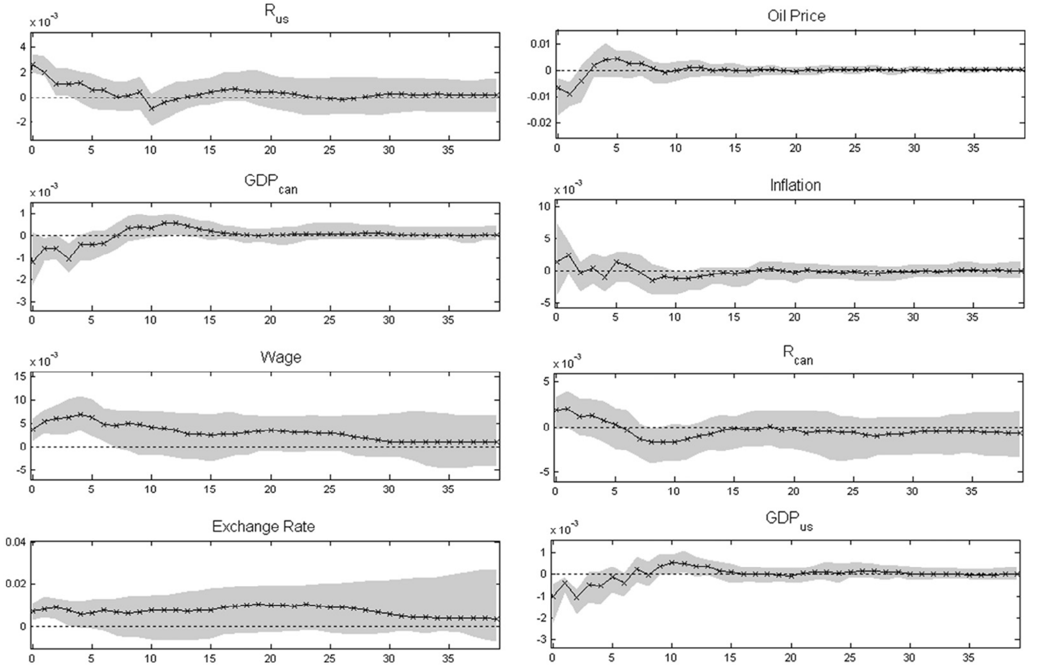

Fig. D10. Impulse responses to a U.S. monetary policy shock.
Note: Dynamic responses to a positive U.S. monetary policy shock. The shaded area represents the 70% error band.

References

Adolfson, M., Laséen, S., Lindé, J., Villani, M., 2007. Bayesian estimation of an open economy DSGE model with incomplete pass-through. J. Int. Econ. 72, 481–511.
Amano, R., van Norden, S., 1995. Terms of trade and real exchange rates: the Canadian evidence. J. Int. Money. Finance 14 (1), 83–104.
Ambler, S., Dib, A., Rebei, N., 2003. Nominal rigidities and exchange rate pass-through in a structural model of a small open economy. Bank of Canada Working Paper 2003–2029.
Baumeister, C., Peersman, G., 2008. Time-varying effects of oil supply shocks on the US economy. Working Papers of Faculty of Economics and Business Administration, Ghent University, Belgium 08/515, Ghent University, Faculty of Economics and Business Administration.
Bernanke, B.S., Mihov, I., 1998. Measuring monetary policy. Q. J. Econ. 113 (3), 869–902.
Bernanke, B.S., Gertler, M., Watson, H., 1997. Systematic monetary policy and the effects of oil price shocks. Brookings Pap. Econ. Act. 1, 91–142.
Bernanke, B.S., Gertler, M., Watson, H., 2004. Reply: oil shocks and aggregate macroeconomic behavior: the role of monetary policy. J. Money Credit Bank. 36 (2), 287–291.
Bils, M., Klenow, P.J., 2004. Some evidence on the importance of sticky prices. J. Polit. Econ. 112, 947–985.
Blanchard, O.J., Galí, J., 2007. The macroeconomic effects of oil shocks: why are the 2000s so different from the 1970s? NBER Working Paper 13368.
Burbidge, J., Harrison, A., 1984. Testing for the effects of oil-price rises using vector autoregression. Int. Econ. Rev. (Philadelphia) 25 (2), 459–484.
Calvo, G.A., 1983. Staggered prices in a utility-maximizing framework. J. Monet. Econ. 12, 383–398.
Canova, F., De Nicoló, G., 2002. Monetary disturbances matter for business fluctuations in the G-7. J. Monet. Econ. 49 (6), 1131–1159.
Canova, F., Gambetti, L., Pappa, E., 2007. The structural dynamics of output growth and inflation: some international evidence. Econ. J. (London) 117 (519), C167–C191.
Carlstrom, C.T., Fuerst, T.S., 2006. Oil prices, monetary policy, and counterfactual experiments. J. Money Credit Bank. 38 (7), 1945–1958.
Chang, Y., Gomes, J.F., Schorfheide, F., 2002. Learning-by-doing as a propagation mechanism. Am. Econ. Rev. 92 (5), 1498–1920.
Clarida, R., Galí, J., Gertler, M., 2001. Optimal monetary policy in an open versus closed economies: an integrated approach. Am. Econ. Rev. 91 (2), 248–252.
Cologni, A., Manera, M., 2008. Oil prices, inflation and interest rates in a structural cointegrated VAR model for the G-7 countries. Energy Econ. 30, 856–888.
Cushman, D.O., Zha, T., 1997. Identifying monetary policy in a small open economy under flexible exchange rates. J. Monet. Econ. 39 (3), 433–448.
Erceg, C.J., Henderson, D.W., Levin, A.T., 2000. Optimal monetary policy with staggered wage and price contracts. J. Monet. Econ. 46 (2), 281–313.
Fiorito, R., Kollintzas, T., 1994. The stylized facts of business cycles in the G7 from a real business cycles perspective. Eur. Econ. Rev. 38, 235–269.
Griffin, P., 1996. Input demand elasticities for heterogeneous labor: firm-level estimates and an investigation into the effects of aggregation. South. Econ. J. 62, 889–901.
Issa, R., Lafrance, R., Murray, J., 2008. The turning black tide: energy prices and the Canadian dollar. Can. J. Econ. 41 (3), 737–759.
Kilian, L., 2008. The economic effects of energy price shocks. J. Econ. Lit. 46 (4), 871–909.
Kim, S., Roubini, N., 2000. Exchange rate anomalies in the industrial countries: a solution with a structural VAR approach. J. Monet. Econ. 45 (3), 561–586.
Kormilitsina, A., 2011. Oil price shocks and the optimality of monetary policy. Rev. Econ. Dyn. 14 (1), 199–223.
Leduc, S., Sill, K., 2004. A quantitative analysis of oil-price shocks, systematic monetary policy, and economic downturns. J. Monet. Econ. 51 (4), 781–808.
Macklem, T., Osakwe, P., Pioro, H., Schembri, L., 2001. The economic consequences of alternative exchange rate and monetary policy regimes in Canada. Bank of Canada Working Paper.
Mendoza, E.G., 1991. Real business cycle in a small open economy. Am. Econ. Rev. 81, 797–818.
Monacelli, T., 2005. Monetary policy in a low pass-through environment. J. Money Credit Bank. 37 (6), 1047–1066.
Mork, K.A., Olsen, O., Mysen, H.T., 1994. Macroeconomic responses to oil price increases and decreases in seven OECD countries. Energy J. 15, 19–35.
Peersman, G., 2005. What caused the early millennium slowdown? Evidence based on vector autoregressions. J. Appl. Econ. (Chichester Engl.) 20 (2), 185–207.
Pieschacón, A., 2009. Oil booms and their impact through fiscal policy. SSRN Elect. J.
Rotemberg, J.J., Woodford, M., 1996. Imperfect competition and the effects of energy price increases on economic activity. J. Money Credit Bank. 28 (4), 549–577.
Schmitt-Grohé, S., 1998. The international transmission of economic fluctuations: effects of U.S. business cycle on the Canadian economy. J. Int. Econ. 44, 257–287.
Sims, C.A., Zha, T., 2006. Does monetary policy generate recessions? Macroeconom. Dynam. 10 (02), 231–272.
Smets, F., Wouters, R., 2007. Shocks and frictions in US business cycles: a Bayesian DSGE approach. Am. Econ. Rev. 97 (3), 586–606.
Uhlig, H., 2005. What are the effects of monetary policy on output? Results from an agnostic identification procedure. J. Monet. Econ. 52 (2), 381–419.