Explaining the Exchange Rate Pass-Through in Different Prices

Ehsan U. Choudhri, Hamid Faruqee and Dalia S. Hakura[1]

Carleton University, International Monetary Fund, and International Monetary Fund

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Abstract

This paper examines the performance of a variety of new open economy macroeconomic models in explaining the exchange rate pass-through in a wide range of prices. Quantitative versions of different models are used to derive the dynamic response of various prices to an exchange rate shock. Predicted responses are compared with the evidence based on VAR models to examine how well different models fit the data. The results show that the best-fitting model incorporates a number of features highlighted by different strands of the literature: sticky prices, sticky wages, distribution costs and a combination of local and producer currency pricing.

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E-mail Addresses: ehsan_choudhri@carleton.ca, hfaruqee@imf.org, dhakura@imf.org

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Corresponding author: Dalia Hakura, International Monetary Fund, Room HQ 10-612, 700 19th Street, N.W., Washington, DC 20431. Tel.: 202-623-6721, Fax: 202-623-6343.

1. Introduction

Recently, there has been a revival of interest in understanding how changes in the exchange rate pass through to prices. The pass-through process has been explored within the new open economy macroeconomic framework based on optimizing behavior. One issue that has received much attention is why exchange rate changes have little effect on consumer prices. A number of explanations have emerged to explain this phenomenon.[2] One strand in the literature (Betts and Devereux (1996, 2000), for example) assumes that import prices in each market are temporarily rigid in local currency. This type of nominal rigidity can block the transmission of exchange rate changes to consumer prices in the short run. Another strand in the literature follows the assumption in Obstfeld and Rogoff (1995) that prices are sticky in producer's currency, but considers imports as intermediate goods that need to go through production or distribution processes before they are consumed by households.[3] The production or distribution channels can dampen the effect of exchange rate changes and account for a low pass-through to consumer prices.

The issue of whether price setting is based on local currency pricing (LCP) or producer currency pricing (PCP) has important implications for monetary and exchange rate policy.[4] A promising test for discriminating between the LCP and PCP hypotheses is provided by the evidence on the relationship between the exchange rate and the international prices of traded goods. The two hypotheses imply different degrees of exchange rate pass-through to import and export prices. These differences are especially pronounced in the simple case (typically assumed in theoretical models) where prices are predetermined for one period. In this case, the elasticity of the import price with respect to the exchange rate in the short run equals zero under LCP

[2] See Engel (2002) for a review of these explanations.

[3] McCallum and Nelson (1999) model imports as raw materials in the production process. Burstein, Neves, and Rebelo (2003) emphasize the importance of distribution channels.

[4] Models based on producer currency pricing (PCP) support the traditional case for exchange rate flexibility while models with local currency pricing (LCP) raise doubts about the desirability of flexible exchange rates. The two types of models would imply different optimal monetary policy rules.

and equals one under PCP. These implications of LCP and PCP are reversed for the pass-through to export prices (in home currency).[5] Empirical evidence suggests that the pass-through to import and export prices tends to be somewhere between zero and one and this evidence does not appear to support either model.[6]

The evidence on the pass-through to international prices, however, is not necessarily inconsistent with more general models based on LCP or PCP, which incorporate more realistic price dynamics and richer models of international price discrimination.[7] Under staggered price adjustment, for example, prices of some imported or exported goods would be adjusted in each period and would be able to respond to exchange rate changes. In this case, LCP would imply that the pass-through coefficient is greater than zero in the short run for import prices and less than one for export prices. Also, if the degree of international price discrimination is influenced by the exchange rate, the short-run import (export) price elasticity could be less than one (greater than zero) under PCP.

The compatibility of the generalized versions of LCP and PCP models with the empirical evidence on exchange rate pass-through to various prices has not been adequately investigated. A number of quantitative applications of new open economy macroeconomics (e.g., Chari, Kehoe and McGrattan (2000), Bergin and

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[5] A related test proposed by Obstfeld and Rogoff (2000a) is that the sign of the correlation between the exchange rate (expressed as the price of foreign currency) and the terms of trade is positive under LCP and negative under PCP. They also provide evidence that the terms of trade tend to be negatively correlated with the exchange rate for a large sample of industrial countries, in accordance with the PCP hypothesis.

[6] See Goldberg and Knetter (1997) for a review. They find that the degree of pass-through to international prices over a year is typically around 0.5. See also Campa and Goldberg (2002), who test the simple versions of the LCP and PCP hypotheses for the pass-through to import prices and find that both hypotheses are rejected for most countries in their sample of OECD countries.

[7] Corsetti and Dedola (2002) develop a model where the price elasticity of demand in a market depends on local distribution costs and is thus sensitive to the exchange rate. Faruqee (1995) also discusses a model of international price discrimination based on market-specific costs.

Feenstra (2001), Kollmann (2001)) have examined the performance of LCP models with staggered wage-price setting in explaining certain empirical regularities, but the ability of these models to explain the exchange rate pass-through to various prices remains unexplored.[8] Bergin (2002) evaluates the relative performance of LCP and PCP models in fitting selected macroeconomic data for three countries. His data set, however, includes only one price index (CPI) and thus his tests do not address the question of how well LCP or PCP assumptions explain the behavior of other price indexes, especially import and export prices (or the terms of trade).

This paper explores the ability of different new open economy macroeconomic models to explain the exchange rate pass-through to a broad set of prices that includes key domestic and international prices. For this purpose, the paper develops a general small-economy model that nests LCP and PCP, and can incorporate a number of different specifications of wage-price dynamics along with international price discrimination based on distribution costs. A number of interesting variants of LCP and PCP models can be distinguished as special cases of the general model. The model assumes two differentiated goods, a traded intermediate and a nontraded final consumer good, and one differentiated primary factor, labor. This simple structure gives rise to five price indexes for the home economy: the consumer price index, the producer and export price indexes (based on the home and foreign prices of the home intermediate good), the import price index, and the wage index (based on prices of labor services). A quantitative version of the model is used to derive the dynamic response of the five prices to an exchange rate shock for different variants of the model. Predicted responses are compared with the evidence on the pass-through of exchange rate shocks to examine how well different variants fit the data.

The evidence on the pass-through of exchange rate shocks to different prices is based on impulse response functions derived from VAR models estimated for a sample of major industrial countries. Specifically, for the non-U.S. G-7 countries, we estimate a VAR model that includes the five price indices highlighted in our model. The impulse response functions are then derived from these estimates using a procedure to identify exchange rate shocks, which is based on assumptions that are consistent with the theoretical model. The VAR

[8] McCallum and Nelson (2001) explore the capability of a PCP-based model to explain the correlations between (current and lagged) exchange rate depreciations and price changes, but they focus only on changes in the consumer price index.

evidence suggests that the exchange rate pass-through to consumer prices and wages is low in the short run and near zero in the first quarter. The pass-through to export and import prices is larger but incomplete in the short run, and the first-quarter value ranges from about a fourth for export prices to roughly a half for import prices. Minimizing the distance between the VAR and model responses, we explore versions of the model that best explain the observed behavior of prices in response to an exchange rate shock. Although some versions of both LCP and PCP models can track the paths of domestic prices and wages well, they perform poorly in matching the responses of international prices. Hybrid models that combine LCP and PCP improve the fit, largely by providing a better explanation of the behavior of international prices.

The evidence based on the impulse response analysis of VAR models is presented in Section 2. Section 3 summarizes a general model that combines features highlighted by different approaches and distinguishes a number of models of interest as special cases of the general model. The relative performance of these models in matching the VAR data is discussed in Section 4. Concluding remarks are offered in section 5.

2. Evidence

This section presents evidence on the exchange rate pass-through to different prices for non-US G-7 countries, based on the impulse response functions derived from a VAR model. As our small-economy model is designed for economies with exogenously determined foreign variables, the United States is excluded from our basic sample, although its inclusion would not materially alter the empirical results that are presented. The basic VAR model includes data on seven endogenous and two exogenous variables. The endogenous variables consist of: the interest rate (R), the exchange rate (S), the import price index (P_M), the export price index (P_X), the producer price index (P_Y), the consumer price index (P_C), and the wage rate (W). The exogenous variables are the foreign interest rate (R^*) and the foreign consumer price index (P_C^*).[9]

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[9] As our focus is on predicting the behavior of prices, the basic VAR model does not include an indicator of real economic activity. Our sensitivity analysis shows, however, that adding real output to the basic model does not make much difference to the main results.

The data for all variables are seasonally adjusted quarterly series at annual rates.[10] The sample period ranges from 1979:1 to 2001:3. The interest rates are measured by the three-month treasury bill rate or an equivalent money market rate. The import and export price indexes are expressed in home currency and based on unit values. The exchange rate represents the nominal effective exchange rate (expressed as the price of a currency basket in terms of the home currency) based on trade weights. The series on the foreign interest rate and the foreign price level are constructed using the same trade weights as those in the effective exchange rate. With the exception of interest rates, all series are in logs.

We assume that all series except interest rates are I(1), in accordance with our theoretical model discussed below. Tests of unit roots and stationarity are broadly consistent with this assumption.[11] Cointegration tests do not provide strong evidence that the system is cointegrated.[12] The basic VAR model is thus estimated in the following form:

$$\mathbf{y}_t = \mathbf{c} + A(L)\mathbf{y}_{t-1} + B(L)\mathbf{x}_t + \mathbf{u}_t, \qquad (1)$$

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[10] The data for import and export unit values and the wage rate are from OECD's Analytical Database. Series on the consumer price index and the nominal effective exchange rate are obtained from IMF's Information Notice System. The IMF's International Financial Statistics is the source of all other data.

[11] For price indexes and the exchange rate, the augmented Dickey-Fuller test does not generally reject the null of unit root while the Kwiatkowski-Philips-Schmidt-Shin test mostly rejects the null of stationarity. The results of these tests for the interest rate are mixed and are not in strong conflict with our assumption that this variable is stationary.

[12] For each country, the Phillips and Ouliaris (1990) test does not reject the hypothesis that there is no cointegrating relation among non-stationary variables. The Johansen test with the small sample adjustment proposed by Reimers (1992) produces mixed results across countries. A VECM model was estimated in cases where this test indicated non-zero cointegrating relations. Estimation of the VECM model, however, produced very low coefficients on the error correction terms. The impulse response functions over short periods implied by the VECM model were thus similar to those derived from VAR model (1).

where $\mathbf{y}_t = [R_t, \Delta \log S_t, \Delta \log P_{Mt}, \Delta \log P_{Xt}, \Delta \log P_{Yt}, \Delta \log P_{Ct}, \Delta \log W_t]$ is the vector of endogenous variables, $\mathbf{x}_t = [R_t^*, \Delta \log P_{Ct}^*]$ is the vector of exogenous variables, $\mathbf{c}$ is a vector of constants, $A(L)$ and $B(L)$ are matrix polynomials in the lag operator *L*, and $\mathbf{u}_t$ is a vector of residuals. Our main objective is to obtain evidence on how exchange rate shocks affect different prices over time. We thus do not attempt to identify all structural disturbances, but introduce minimal restrictions that are sufficient to identify the dynamic response of each variable to the exchange rate shock. Our identifying restrictions are based on plausible assumptions that are consistent with the theoretical framework. However, we also consider alternative identification schemes and examine the sensitivity of our results to the use of alternative schemes.

In the structural model (underlying the VAR), we identify the equation determining the interest rate with the monetary policy rule and that determining the exchange rate with the uncovered interest parity.[13] The exchange rate shock is viewed as the shock to the interest parity relation.[14] Our basic identification scheme introduces the following restrictions on the structural model: (a) In the interest and exchange rate equations, the coefficients on $\Delta \log P_{Mt}$, $\Delta \log P_{Xt}$, $\Delta \log P_{Yt}$, $\Delta \log P_{Ct}$ and $\Delta \log W_t$ equal zero. (b) In the interest rate equation, the coefficient on $\Delta \log S_t$ equals zero.

[13] We use an interest rate measure (i.e., the treasury bill rate or an equivalent money market rate) that is available for a large number of countries on a comparable basis and is suitable for the interest parity relation. A limitation of this measure, however, is that it does not represent the policy rate that would be appropriate for the monetary policy rule.

[14] Our theoretical model motivates the shock to the interest parity as arising from a stochastic bias in exchange rate expectations as suggested by Devereux and Engel (2002) and Jeanne and Rose (2002). This motivation is appealing as such bias could potentially account for much of the observed short-term volatility in the exchange rate. Our empirical measure does not distinguish this source from other sources of shocks to the parity relation, and is thus only loosely related to the theory. The VAR approach does, however, isolate shocks to the interest parity from other shocks.

Restriction (a) is based on the view that while prices in asset markets are monitored and reported quickly, it takes time to collect and report information on prices in the goods and labor markets.[15] We assume that prices in the goods and labor markets are observed with, at least, a one-period lag, and thus the structural shocks to the interest and exchange rates are not contemporaneously correlated with these prices.[16] As the interest and exchange rates are observed immediately, the coefficients of both $\Delta \log S_t$ (in the interest rate equation) and R_t (in the exchange rate equation) need not equal zero. An estimate of one of these coefficients (given the estimates of the variance-covariance matrix for reduced-form shocks) is sufficient to identify the structural exchange rate shock. Our estimates of the interest rate rule (discussed in section 4.1) indicate that the coefficient of $\Delta \log S_t$ in this relation is small and not significantly different from zero for most countries in our sample. These results are consistent with our restriction (b), which simplifies the identification of the exchange rate shock.[17] Given restrictions (a) and (b), the dynamic response of an endogenous variable to a structural exchange rate shock is simply the orthogonalized impulse response function for the variable in response to a shock to the $\Delta \log S_t$ equation, using a recursive ordering with R_t as the first and $\Delta \log S_t$ as the second variable. Note that the ordering of the remaining variables can be shown not to matter for calculating this impulse response function.

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[15] The assumption that information lags do not allow monetary authorities to respond to prices and output within the period has been used to identify monetary policy shocks (see Sims and Zha (1998) and Kim and Roubini (2000)). Here we also assume similar information delays for exchange market dealers.

[16] This assumption is more appealing for monthly data, but even for quarterly data used in this study, this assumption may not be unreasonable for most prices.

[17] Modifying the identification scheme to allow a non-zero coefficient of $\Delta \log S_t$ (based on our estimates of the interest rate rule) makes little difference to our results. In fact, since the contemporaneous correlation between the reduced-form interest and exchange rate shocks tends to be low, our results would not be affected much even if we used an alternative recursive ordering with $\Delta \log S_t$ as the first and R_t as the second variable.

The VAR model (1) with four lags for both endogenous and exogenous variables was estimated for each country in our sample. Dynamic responses of the five price indexes to an exchange rate shock were then derived from this model using our basic identification scheme. Table 1 summarizes the evidence on the short- and medium-term price effects of an exchange rate shock for non-US G-7 countries. It shows the response of each price index in quarters 1, 4 and 10 to a one-unit exchange rate shock in quarter 1. The response of the terms of trade (which can be readily derived) is also of interest and is shown in this table. The standard errors of the impulse response function were also calculated and are displayed in the table.[18] The table suggests considerable cross-country variation in the response of prices, especially international prices.[19]

To describe common tendencies of the non-US G-7 group, Table 1 also shows the average response for these countries.[20] The average response with 90% confidence bands (from quarter 1 through 10) is illustrated in Figure 1. The figure exhibits marked differences between the behavior of consumer, producer and labor prices

[18] The standard errors for the country responses are computed according to the formula given in Hamilton (1994, p. 339), and are used to construct confidence bands discussed below. A bootstrap procedure based on Runkle (1987) was also used to estimate confidence bands, but it gave similar results.

[19] There is considerable literature on the exchange rate pass-through at the micro level, which finds that the elasticity of prices (and other variables) with respect to the exchange rate varies not only across countries but also across industries (see, for example, Branson and Marston, 1989, Knetter, 1993, and Campa and Goldberg, 2002). Here, however, we focus only on the macro-level effects.

[20] The average response represents a simple average of the responses of the six countries in the group. To calculate the standard error of the average response, we assume that country responses are distributed independently and normally. An alternative approach to capturing common tendencies would be to aggregate national data and estimate VARs for the aggregate data. For our purpose, however, a shortcoming of this approach is that changes in the aggregate effective exchange rate net out within-group bilateral changes in the exchange rates, and thus aggregate data would introduce a bias in the estimates of the exchange rate pass-through.

on the one hand and the export and import prices on the other. The response of the latter set of prices is not only stronger and more hump shaped but also has wider confidence bands. In Section 4, we evaluate the performance of different models in matching the average non-US G-7 response functions illustrated in Figure 1. However, in view of the variation in price responses across countries, our sensitivity analysis also explores how different models fit the data for individual countries.

3. Model

This section discusses a general version of the model, which combines features highlighted by different approaches. Major variants of the LCP and PCP models are identified at the end of the section as special cases of the general model. The relative performance of these variants is evaluated in the next section. In discussing the model, we focus on the relations for the home economy, which is assumed to be small. Analogous relations are assumed for the foreign economy with an asterisk denoting foreign variables (foreign nominal values are expressed in foreign currency).

3.1 Technology

Assume two types of products, a nontraded final (consumer) good and a traded intermediate good and one primary factor, labor. Both types of products and labor represent a continuum of differentiated varieties in the unit interval. Let $C_t(c)$ and $Y_t(y)$ denote amounts of consumer and intermediate goods varieties, indexed by $c,\ y \in [0, 1]$. The two goods are produced by the following technology:

$$C_t(c) = A_C Q_t(c)^{\gamma} N_{Ct}(c)^{1-\gamma}, \qquad Y_t(y) = A_Y Z_t(y)^{\alpha} N_{Yt}(y)^{1-\alpha}, \tag{2}$$

where $Q_t(c)$ and $Z_t(y)$ are composite intermediate inputs (including both home and foreign varieties) while $N_{Ct}(c)$ and $N_{Yt}(y)$ are bundles of differentiated labor services. Traded intermediate goods are combined with nontraded labor services to produce both the consumption and intermediate goods. The intermediate-good technology allows for a Leontief type input-output structure suggested by Basu (1995).

The intermediate input bundles for the consumer and intermediate goods are defined as:

$$Q_t = [\nu^{1/\sigma} Q_{Mt}^{\ 1-1/\sigma} + (1-\nu)^{1/\sigma} Q_{Ht}^{\ 1-1/\sigma}]^{\sigma/(\sigma-1)},\ Z_t = [\nu^{1/\sigma} Z_{Mt}^{\ 1-1/\sigma} + (1-\nu)^{1/\sigma} Z_{Ht}^{\ 1-1/\sigma}]^{\sigma/(\sigma-1)}, \tag{3}$$

$$Q_{Mt} = [\int_0^1 Y_{QMt}(y^*)^{1-1/\varepsilon} dy^*]^{\varepsilon/(\varepsilon-1)}, \qquad Z_{Mt} = [\int_0^1 Y_{ZMt}(y^*)^{1-1/\varepsilon} dy^*]^{\varepsilon/(\varepsilon-1)}, \tag{4}$$

$$Q_{Ht} = [\int_0^1 Y_{QHt}(y)^{1-1/\varepsilon} dy]^{\varepsilon/(\varepsilon-1)}, \qquad Z_{Ht} = [\int_0^1 Y_{ZHt}(y)^{1-1/\varepsilon} dy]^{\varepsilon/(\varepsilon-1)}, \tag{5}$$

where $Y_{QHt}(y)$ and $Y_{ZHt}(y)$ denote the amounts of a home variety used in the production of the consumption and intermediate goods while $Y_{QMt}(y^*)$ and $Y_{ZMt}(y^*)$ denote the corresponding amounts of an imported foreign variety, indexed by $y^* \in [0,1]$. The elasticity of substitution between domestic and foreign bundles of the intermediate good, σ, is allowed to be different than the elasticity between varieties within each bundle, ε. Each home variety is supplied to both final and intermediate demand at home and abroad, so that its output equals $Y_t(y) = Y_{QHt}(y) + Y_{ZHt}(y) + Y^*_{QMt}(y) + Y^*_{ZMt}(y)$.

We assume that imported varieties need to go through distribution channels before use in the production of the intermediate and final goods, and the distribution process requires local labor services. Assume a Leontief technology for distribution and suppose that the distribution of one unit of the imported variety y^* requires δ units of the labor service bundle, $N_{Mt}(y^*)$, so that

$$N_{Mt}(y^*) = \delta[Y_{QMt}(y^*) + Y_{ZMt}(y^*)]. \tag{6}$$

This formulation adds trade costs based on local distribution services and provides a basis for international price discrimination as in Corsetti and Dedola (2002).[21]

Labor service bundles in the three activities are defined as

$$N_{Ct} = [\int_0^1 L_{Ct}(l)^{1-1/\varepsilon} dl]^{\varepsilon/(\varepsilon-1)}, N_{Yt} = [\int_0^1 L_{Yt}(l)^{1-1/\varepsilon} dl]^{\varepsilon/(\varepsilon-1)}, N_{Mt} = [\int_0^1 L_{Mt}(l)^{1-1/\varepsilon} dl]^{\varepsilon/(\varepsilon-1)}, \tag{7}$$

where $L_{Ct}(l)$, $L_{Yt}(l)$ and $L_{Mt}(l)$ represent amounts of a household's labor service, indexed by $l \in [0,1]$, used in the production of the final and intermediate goods and the distribution of imports. The elasticity of substitution between varieties of labor services is also assumed, for simplicity, to equal ε.

3.2 Firm Behavior

[21] We assume that a Leontief-type distribution process is needed only for moving intermediate goods across borders. For simplicity, we do not require such a process for converting intermediates into the consumption good.

Each firm sets a price for its variety and meets the demand at that price. We first discuss the behavior of firms producing the intermediate good. These firms are able to price discriminate across home and foreign markets and can choose different prices for domestic sales and exports. Denote the prices of variety *y* in the domestic and foreign markets by $P_{Yt}(y)$ and $P_{Et}(y)$. The producer and export price indexes, P_{Yt} and P_{Et}, are defined as the cost-minimizing prices of Q_{Ht} (Z_{Ht}) and Q^*_{Mt} (Z^*_{Mt}), so that $P_{Yt} = [\int_0^1 P_{Yt}(y)^{1-\varepsilon}\, dy]^{1/(1-\varepsilon)}$ and $P_{Et} = [\int_0^1 P_{Et}(y)^{1-\varepsilon}\, dy]^{1/(1-\varepsilon)}$. Then using (5), the foreign counterparts of (4), and the distribution assumption for the foreign country, we can derive the (intermediate and final) demand for a variety in the home and foreign markets as

$$Y^d_{Ht}(y) = (Z_{Ht} + Q_{Ht})(P_{Yt}(y)/P_{Yt})^{-\varepsilon}, \qquad Y^{d*}_{Mt}(y) = (Z^*_{Mt} + Q^*_{Mt})[(P_{Et}(y) + \delta S_t W^*_t)/P_{Et}]^{-\varepsilon}, \tag{8}$$

where S_t is the exchange rate and W^*_t is the foreign wage index.

We assume staggered price setting based on a model suggested by Calvo (1983).[22] At each point in time, the probability that a firm will change its price is constant and equal to $1-\pi$. We use the letter *X* to distinguish prices of varieties set at different dates. For firms that set a new price at *t*, let X_{Yt} represent the home price and X_{Et} the export price in home currency. The export price in foreign currency is denoted by X^*_{Mt} ($= X_{Et}/S_t$). We initially consider a hybrid case where some firms use PCP while others use LCP. Assume that the proportion of firms using PCP to set a new price at each point in time is constant and equal to ϕ.

Let superscripts P and L denote prices set under PCP and LCP. Given the demand functions (8), the firms using PCP (LCP), choose values of X^P_{Yt} (X^L_{Yt}) and X^P_{Et} (X^{*L}_{Mt}) to maximize the present discounted value of profits. The solution to this profit-maximization problem can be expressed as

$$X^P_{Yt} = X^L_{Yt} = E_t \frac{\varepsilon \sum_{\tau=t}^{\infty} DR_{t,\tau}\pi^{\tau-t}\Omega_{Y\tau}MC_{Y\tau}}{(\varepsilon-1)\sum_{\tau=t}^{\infty} DR_{t,\tau}\pi^{\tau-t}\Omega_{Y\tau}}, \tag{9}$$

[22] The Calvo staggered pricing generates the same price dynamics as pricing based on quadratic adjustment costs. The choice of the Calvo formulation is convenient, however, since it can be readily modified to obtain staggered pricing based on Taylor (1980), which we also explore.

$$X_{Et}^{P} = E_t \frac{\varepsilon \sum_{\tau=t}^{\infty} DR_{t,\tau} \pi^{\tau-t} \Omega_{E\tau} MC_{Y\tau} (1 + \chi_{\tau}^{*} / \varepsilon)}{(\varepsilon - 1) \sum_{\tau=t}^{\infty} DR_{t,\tau} \pi^{\tau-t} \Omega_{E\tau}}, \tag{10}$$

$$X_{Mt}^{*L} = E_t \frac{\varepsilon \sum_{\tau=t}^{\infty} DR_{t,\tau} \pi^{\tau-t} \Omega_{M\tau}^{*} MC_{Y\tau} (1 + \chi_{\tau}^{*} / \varepsilon) / S_{\tau}}{(\varepsilon - 1) \sum_{\tau=t}^{\infty} DR_{t,\tau} \pi^{\tau-t} \Omega_{M\tau}^{*}}, \tag{11}$$

where $\Omega_{Y\tau} \equiv (Z_{H\tau} + Q_{H\tau}) P_{Y\tau}^{\varepsilon}$, $\Omega_{E\tau} \equiv (Z_{M\tau}^{*} + Q_{M\tau}^{*}) P_{E\tau}^{\varepsilon} (X_{Et}^{P} / S_{\tau} + \delta^{*} W_{\tau}^{*})^{1-\varepsilon}$,

$\Omega_{Mt}^{*} \equiv (Z_{M\tau}^{*} + Q_{M\tau}^{*}) P_{E\tau}^{\varepsilon} (X_{Mt}^{*} + \delta^{*} W_{\tau}^{*})^{1-\varepsilon}$, $\chi_{\tau}^{*} \equiv \delta^{*} S_{\tau} W_{\tau}^{*} / MC_{Y\tau}$, $DR_{t,\tau}$ is the stochastic discount rate based on household preferences, and MC_{Yt} represents the marginal cost. Note that the effect of the distribution cost operates via the ratio, χ_{τ}^{*}, which increases in S_{τ}. Thus, in the presence of distribution costs ($\delta^{*} > 0$), there would be a positive exchange rate pass-through to export prices even under PCP.

For the consumer good, let X_{Ct} denote the price for firms that set a new price at *t*. The profit-maximizing value of X_{Ct} can be similarly derived as

$$X_{Ct} = E_t \frac{\varepsilon \sum_{\tau=t}^{\infty} DR_{t,\tau} \pi^{\tau-t} C_{\tau} P_{C\tau}^{\varepsilon} MC_{C\tau}}{(\varepsilon - 1) \sum_{\tau=t}^{\infty} DR_{t,\tau} \pi^{\tau-t} C_{\tau} P_{C\tau}^{\varepsilon}}, \tag{12}$$

where $P_{C\tau}$ is the consumer price index (defined as the cost-minimizing price of C_{τ}).

In the presence of staggered price setting, the consumer, producer, export and import price indexes can be expressed as

$$P_{Ct} = [(1-\pi) \sum_{\tau=t}^{-\infty} \pi^{t-\tau} X_{C\tau}^{1-\varepsilon}]^{1/(1-\varepsilon)}, \qquad P_{Yt} = [(1-\pi) \sum_{\tau=t}^{-\infty} \pi^{t-\tau} X_{Y\tau}^{1-\varepsilon}]^{1/(1-\varepsilon)}, \tag{13}$$

$$P_{Et} = [(1-\pi) \sum_{\tau=t}^{-\infty} \pi^{t-\tau} \{\phi (X_{E\tau}^{P})^{1-\varepsilon} + (1-\phi)(S_t X_{M\tau}^{*L})^{1-\varepsilon}\}]^{1/(1-\varepsilon)}, \tag{14}$$

$$P_{Mt} = [(1-\pi) \sum_{\tau=t}^{-\infty} \pi^{t-\tau} \{\phi^{*} (S_t X_{E\tau}^{*P})^{1-\varepsilon} + (1-\phi^{*})(X_{M\tau}^{L})^{1-\varepsilon}\}]^{1/(1-\varepsilon)}, \tag{15}$$

where $X_{Yt} = X_{Yt}^{P} = X_{Yt}^{L}$, $P_{Mt} = S_t P_{Et}^{*}$, while $X_{E\tau}^{*P}$ and $X_{M\tau}^{L}$ are foreign counterparts of $X_{E\tau}^{P}$ and $X_{M\tau}^{*L}$.

3.3 Household Behavior, Asset Markets

Each household is a monopolistically competitive supplier of a labor service and a shareholder in profits of all home firms. Households set the wage rate and meet the demand for their service at the predetermined wage rate. The expected lifetime utility of a household is assumed to be

$$E_t \sum_{\tau=t}^{\infty} \beta^{\tau-t} [\frac{1}{1-\rho} C_{\tau}(l)^{1-\rho} - \frac{1}{1+\mu} L_{\tau}(l)^{1+\mu}], \tag{16}$$

where $C_\tau(l)$ and $L_\tau(l)$ are the household's consumption basket and labor supply, and β is the discount rate. The consumption basket for each household is given by $C_t = [\int_0^1 C_t(c)^{1-1/\varepsilon} dc]^{\varepsilon/(\varepsilon-1)}$.

There are two bonds: home bonds denominated in home currency and foreign bonds denominated in foreign currency. For simplicity, we assume that domestic markets are complete and only foreign bonds are used for international transactions. To allow a role for noise traders, we adopt the setup suggested by Devereux and Engel (2002), and assume that all international transactions by the home country are undertaken by foreign exchange dealers on behalf of households. The budget constraint of a household is

$$P_{Ct}C_t(l) + B_{H,t+1}(l) = W_t(l)L_t(l) + \Pi_t(l) + TR_t(l) + (1 + R_{t-1})B_{Ht}(l) , \tag{17}$$

where $W_t(l)$ is the household's wage rate, $B_{Ht}(l)$ is the holding of the home bond, R_{t-1} is the interest rate on a loan in period *t – 1* paid out at the beginning of period *t*, $TR_t(l)$ are transfers from the foreign exchange dealers and $\Pi_t(l)$ is the household's share of profits from monopolistically competitive firms producing the final and intermediate goods. The demand for a variety of labor service can be derived from (7) as

$$L_t^d(l) = (N_{Ct} + N_{Yt} + N_{Mt})(W_t(l)/W_t)^{-\varepsilon} , \tag{18}$$

where $W_t = [\int_0^1 W_t(l)^{1-\varepsilon} \, dl]^{1/(1-\varepsilon)}$ is the wage index, and represents the cost–minimizing price of labor service bundles, N_{Ct}, N_{Yt} and N_{Mt} .

Households choose the consumption path and the wage rate to maximize expected lifetime utility (16) subject to their budget constraints (17) and the demand constraint (18). The optimal consumption choice implies the Euler condition (with $C_t^{-\rho}(l) = C_t^{-\rho}$ under complete domestic markets):

$$E_t \beta \frac{P_{Ct}C_t^{\rho}}{P_{C,t+1}C_{t+1}^{\rho}} = \frac{1}{1 + R_t} . \tag{19}$$

The household stochastic discount rate is given by

$$DR_{t,\tau} = \beta^{\tau-t} \frac{P_{Ct}C_t^{\rho}}{P_{C\tau}C_\tau^{\rho}} , \tag{20}$$

The wage rate for a labor service is also set in a staggered fashion based on the Calvo model. Let X_{Wt} denote the wage rate for households who set a new wage rate at *t*. Assume that the probability that a household will change the wage rate at a point in time is also equal to $1-\pi$. We can then derive the optimal value of X_{Wt} as

$$X_{Wt} = E_t \frac{\varepsilon \sum_{\tau=t}^{\infty} DR_{t,\tau} \pi^{\tau-t} (N_{C\tau} + N_{Y\tau} + N_{Mt}) W_\tau^{\varepsilon} L_\tau^{\mu}}{(\varepsilon - 1) \sum_{\tau=t}^{\infty} DR_{t,\tau} \pi^{\tau-t} (N_{C\tau} + N_{Y\tau} + N_{Mt}) W_\tau^{\varepsilon} P_{C\tau}^{-1} C_\tau^{-\rho}} . \tag{21}$$

Under staggered wage setting, the wage index equals

$$W_t = [(1-\pi) \sum_{\tau=t}^{-\infty} \pi^{t-\tau} X_{W\tau}^{1-\varepsilon}]^{1/(1-\varepsilon)} . \tag{22}$$

The home monetary authority uses an interest rate rule to set the domestic interest rate. Foreign exchange dealers maximize the excess returns from purchasing a foreign bond and free entry drives these returns to zero, so that

$$E_t^f [DR_{t,t+1}(1+R_t^*) S_{t+1} - S_t] = 0 , \tag{23}$$

where E_t^f denotes the expectations of the foreign exchange dealers. As suggested by the noise-trader model, we assume that there is a stochastic bias in the expectations of foreign exchange dealers, which gives rise to a shock to the interest parity relation. Under the simplifying assumption that the expected discount rate is the same for foreign exchange dealers and households (i.e., $E_t^f DR_{t,t+1} = E_t DR_{t,t+1}$), the shock simply represents a stochastic bias in the expected value of the next period exchange rate. Since we use a log-linearized version of the interest parity relation in the quantitative application of the model, we define the shock as

$$u_t = \log(E_t^f S_{t+1} / E_t S_{t+1}) . \tag{24}$$

3.4 Variations

We explore a number of variants of the general model, which are suggested by the literature or represent an interesting combination of features. Table 2 lists these variants and summarizes their features. Models 1-3 assume LCP ($\phi = 0$). Model 1 follows Chari, Kehoe, and McGrattan (2000) and others in combining LCP with staggered goods prices and flexible wage rates. Distribution costs are absent in this model ($\delta = \delta^* = 0$). Model 2 assumes that both goods prices and wages are determined in a staggered fashion as in Kollmann (2001). Although distribution costs have been incorporated only in the PCP models, Model 3 adds these costs to LCP (with sticky wages and prices) to facilitate comparison with the PCP based models. Models 4-6 are suggested by the literature assuming PCP ($\phi = 1$). Model 4 represents the basic version similar to

Obstfeld and Rogoff (2000a), which assumes sticky wages, flexible goods prices and no distribution costs. Model 5 follows Corsetti and Dedola (2002) in adding distribution costs to a flexible-price model. Model 6 also incorporates PCP based sticky goods prices. Note that although models 4 and 5 are associated with the PCP approach, the currency of price setting for these flexible-price models does not really matter under our informational assumption that the exchange rate is known before the price is determined. Finally, Models 7 and 8 represent hybrid models that allow both LCP and PCP (i.e., $0 \leq \phi \leq 1$). Only goods prices are sticky in Model 7, while both wages and prices are sticky in Model 8. Distribution costs are included in both models.

4. Performance of Different Models

In this section, we examine the relative performance of different models (listed in Table 2) in explaining the evidence on the pass-through of exchange rate shocks to different prices. For each model, we obtain an approximate solution based on relations linearized around a deterministic steady state with zero net foreign assets.[23] Some parameters of the model can be readily estimated from the data, but there are a number of parameters for which no clear-cut empirical measures are available. For such parameters, we chose values similar to those used by other quantitative models if there is a not much disagreement in the literature. In cases where there is no consensus, we start with a reasonable common value for all models but later search for values that would provide the best fit for each model (according to a criterion discussed below). A number of

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[23] For these models, a steady state is not well defined. It is possible, however, to modify these models to induce stationarity in equilibrium dynamics without significantly altering the short run dynamics. As a concrete example, we explored the following variation based on Benigno (2001), and Schmitt-Grohe and Uribe (2003). Letting nfa_t denote net foreign assets as a proportion of GDP, we modified (the linearized version of) the interest parity relation in our model as $R_t = R_t^* + E_t \log S_{t+1} - \log S_t - \Gamma nfa_t + u_t$. We verified that very small positive values of parameter Γ (e.g., Γ = .001) bring about slow convergence to a steady state (with zero net foreign assets), but keep the price dynamics over the first 10 quarters virtually the same as the basic model.

stochastic shocks can be added to linearized relations in our model. However, since we are concerned mainly with the impulse response analysis for the exchange rate shock, we focus only on this shock.

4.1 Parameter Values

Parameters in the linearized versions of different models can be expressed as functions of a basic set of parameters. This set can be divided into three groups: (1) structural parameters appearing in the specification of preferences, technology and the wage-price adjustment mechanism, (2) policy-determined parameters in the interest rate rule, and (3) steady-state values of certain variables. Values chosen for parameters in each group are shown in Table 3. Only initial values are shown for parameters whose values were later varied across models. Values of foreign parameters (when needed) were set equal to the values of the corresponding home parameters.

The values for the structural parameters are chosen as follows. The discount rate (β) is set equal to its usual quarterly value of 0.99 (which implies that the real rate of interest in the steady state equals 0.04 at an annualized rate). For the coefficient of relative risk aversion (ρ), we chose a value of 4.0, which is not too different from the values used in a number of recent quantitative models. However, as larger and smaller values of this coefficient have been suggested in the literature, we let its value vary from 0.5 to 10.0 in our sensitivity analysis. There is even less agreement on the appropriate value for the elasticity of labor supply ($1/\mu$). We initially choose a value of 2.0 for this elasticity ($\mu = 0.5$) for all models, but later allow the elasticity to vary between zero and infinity. We set both the elasticity of substitution between varieties of different bundles (ε) and the elasticity of substitution between home and foreign bundles of goods (σ) equal to 5.0. This value is within the range of estimates suggested by recent studies (see Obstfeld and Rogoff (2000b) for a review). However, we later allow σ to differ from ε and consider a wide range from 1.5 to 12.5 for this parameter. Finally, we set the probability of changing prices in the Calvo model ($1-\pi$) equal to its typically-assumed value of 0.25.

We estimated an interest rate rule for non-US G-7 countries. Our basic version of the rule ignores the possible influence of economic activity and assumes the following form:

$$R_t = \varphi_0 + \varphi_1 R_{t-1} + \varphi_2 E_t \Delta \log P_{Ct} + \varphi_3 \Delta \log S_t + v_t \,, \qquad (25)$$

where v_t is a monetary policy shock. Policymakers target the expected inflation rate under our assumption that they do not observe current consumer prices. Instrumental variables were used to estimate the effect of the expected inflation rate in the policy rule.[24] We also used the SUR method to allow for the possibility of contemporaneous correlation between policy shocks across countries. Estimates of φ_1 and φ_2 were positive and significant for all non-US G-7 countries. Estimates of φ_3, however were close to zero for all countries and insignificant in most cases. We set the value of this parameter equal to zero. The values of φ_1 and φ_2 were set equal to the simple averages of their estimates for the non-US G-7 countries.

To solve different models, we also need steady state values of the following variables and their foreign counterparts: the shares of intermediate inputs in total revenue for the traded and non-traded goods sectors, θ_{ZY} and θ_{QC}, and the share of imports in total costs of intermediates, $\widetilde{\theta}_M$. The available data report the share of imports valued at international rather than domestic (distribution-cost inclusive) prices. However, letting θ_M denote the import share at international prices, we can solve for $\widetilde{\theta}_M$ as a function of θ_M and χ (the ratio of home distribution cost to foreign marginal cost). Also note that the technology parameters, α and γ, represent shares of intermediates in total costs, which can be calculated using estimates of the revenue shares (θ_{ZY} and θ_{QC}) and the markup implied by the elasticity, ε. We used the available input-output data for our non-US G-7 sample to estimate steady state values of θ_{ZY}, θ_{QC} and θ_M.[25] We do not have a good estimate of χ. The

[24] After replacing $E_t \Delta \log P_{Ct}$ by $\Delta \log P_{Ct}$ in (25), this equation was estimated using 4 lagged values of $\Delta \log P_{Ct}$, $\Delta \log P_{Yt}$, $\Delta \log P_{Mt}$, $\Delta \log P_{Et}$, $\Delta \log W_t$ and $\Delta \log S_t$ as instruments for $\Delta \log P_{Ct}$.

[25] The data for each country were first averaged over the years for which they were available in the sample period to obtain country measures. Simple averages of these measures were then used to estimate the parameters.

evidence on distribution costs suggests an upper bound of about 1.0 for this parameter.[26] We initially assume that χ equals 0.5 in the steady state, but later allow it to vary between zero and one. Estimates of θ_{ZY}, θ_{QC}, θ_{MZ}, χ and ε were then used to derive the values of α, γ and $\widetilde{\theta}_M$.

Finally, we assume the following stochastic process for the exchange rate shock:

$$u_t = \psi u_{t-1} + \xi_t , \tag{26}$$

where ξ_t is white noise. We scale the shock ξ_t and choose the value of ψ to make the short- and medium-term response of the exchange rate (expressed as log deviations from the steady- state value) predicted by each model closely match the response generated by the VAR analysis.[27] Note that the values of ξ and ψ chosen by this criterion differ across models.

4.2 Basic Results

We first examine the performance of each model for parameter values given in Table 3. We use a loss function to measure the overall fit of a model to the VAR data. The loss function sums the squared deviations of the model responses of the five variables from the VAR responses over 10 quarters. For models 1-8, Table 4 shows the total loss as well as components of the loss associated with each of the five variables. Figures 2-4 show how well different models track the VAR responses of the five basic variables and the terms of trade.[28]

[26] Burstein, Neves, and Rebelo (2003) suggest that distribution costs are large and account for roughly 40 % of the consumer price in the US. The ratio of distribution to marginal costs implied by this estimate would depend on the markup, and this ratio would equal one under our assumed mark-up of 0.25 (implied by $\varepsilon = 5.0$). Their estimates include distribution costs for both domestic and imported goods and would represent an upper limit on distribution costs specific to imports.

[27] Specifically, the ξ shock is scaled to have the predicted response of the exchange rate equal to 1.0 at quarter 1 (as in the impulse response analysis). The value of ψ is then chosen to make the response approximately equal to 0.63 at quarter 10 (which represents the average quarter-10 response for the non-US G-7 countries).

[28] There has been much interest in the literature in explaining the behavior of the real exchange rate. In our analysis, however, the response of the nominal exchange rate is closely matched with the VAR response for

(continued)

The 90% confidence region for each VAR response is also shown (as shaded area) in these figures to explore whether the differences between the model and VAR responses are statistically significant.

The relative performance of LCP based models is illustrated in Figure 2. The basic LCP versions assume no distribution costs and are represented by Model 1 with flexible and Model 2 with sticky wages. Both models run into problems matching the VAR data. For consumer and producer prices as well as wages, the responses predicted by the two models exceed the VAR responses over all periods. The model responses for wages, in fact, lie much above the 90% band after quarter 3. For international prices, moreover, the model predictions deviate considerably from the VAR estimates, and are well outside the 90% region over the first 3 quarters.

Distribution costs have not received much attention in the LCP models, but it is interesting to see how the introduction of such costs would affect their performance. Model 3 that incorporates distribution costs does, in fact, improve the fit substantially. The overall loss for Model 3 decreases by over 20% compared to Model 2. The improvement, however, results largely from better tracking of wages and domestic prices. Indeed, Model 3's predictions for import and export prices (and the terms of trade), are not much different from those of Models 1 and 2. Distribution costs thus have little influence on the exchange rate pass through to international prices.[29] Interestingly, these costs do dampen the response of wages and domestic prices. The essential reason for this result is that imports and labor used in distribution are complements under the assumption of Leontief technology for distribution. The decrease in demand for imports induced by an increase in the exchange rate decreases the demand for distribution labor and reduces the pressure on wage rates. The diminished response of labor costs also leads to a lower exchange rate pass-through to producer and consumer prices.

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each model (by the choice of ξ and ψ) and the foreign CPI is exogenous (because of the small-country assumption). A model's performance in matching the (CPI-based) real exchange rate would thus essentially reflect its ability to track the CPI.

[29] This effect is weak under staggered prices because only a fraction of the total number of firms set a new price in each period, and the new price depends on expected future changes as well as current changes in the exchange rate.

Figure 3 illustrates the performance of Models 4-6, which are associated with the PCP approach. Model 4 represents the basic version with sticky wages, flexible prices, and no distribution costs. This model performs poorly in matching the data for most prices. The addition of distribution costs in Model 5, however, brings about a considerable improvement in the fit (although this model's predicted values for consumer, producer and import prices over the first few quarters are still much above the 90% bands). Both Models 4 and 5 differ sharply from the LCP models in matching international prices: they do a poorer job of tracking import prices, but provide a better fit for export prices and the terms of trade.[30] Model 6 adds sticky prices with PCP. This feature improves the fit of consumer and producer prices, but worsens that of export prices. In terms of the overall fit, Model 6's performance is slightly better than Model 5, but not as good as the best-performing LCP Model 3.

We next examine the performance of sticky-price hybrid models that allow both LCP and PCP. For these models, ϕ can vary between zero (pure LCP) and one (pure PCP). We search over this range to choose the best-fitting (loss-minimizing) value. Figure 4 illustrates the performances of the two hybrid models: Model 7 with flexible and Model 8 with sticky wages. Distribution costs are included in both models. These models provide a much better fit than the pure LCP and PCP models. A key source of improvement for the hybrid models is that initial responses of import and export prices (which lie between the responses predicted by the pure LCP and PCP models) are closer to the VAR responses. The hybrid model responses, moreover, are not significantly different from the VAR responses (at the 90% level) for all variables and almost all periods. Note,

[30] Obstfeld and Rogoff (2000a) have drawn attention to tests based on the terms of trade behavior for discriminating between the LCP and PCP hypotheses. Our results for the terms of trade, however, are not conclusive. Although the PCP models correctly predict the sign of the initial impact on the terms of trade, and match the terms of trade series somewhat better than the LCP models, predictions of both types of models diverge significantly from the VAR response over the first few periods. As our results indicate, moreover, the relative performance of the PCP and LCP models for matching export price series is different from that for import price series. These differences do not show up in tests based only on the terms of trade series.

however, that even the hybrid models do not fare well in explaining the degree of persistence and the hump-shaped pattern of most price series. This problem in matching the dynamics of price series is especially noticeable for import prices.

Interestingly, the optimal value of ϕ is equal to 0.45 for Model 7 and 0.46 for Model 8. This result suggests an almost equal weight for LCP and PCP firms. Also, the sticky-wage version performs somewhat better than the flexible-wage version. Thus the basic analysis indicates that the best-fitting model includes all features highlighted by different approaches in the literature: sticky prices, sticky wages, distribution costs, and a combination of LCP and PCP.

4.3 Sensitivity Analysis

We undertook an extensive sensitivity analysis to examine the robustness of our results to a number of variations. We first explored whether the relative performance of different models is sensitive to the procedure used to estimate the VAR responses. Our basic identification scheme assumes that prices affect the interest and exchange rates with a lag because of information delays. An alternative view assumes instead that the exchange rate and monetary policy shocks affect domestic prices and wages with a lag, and these variables may be observed by policymakers (and exchange market dealers) contemporaneously. We used a recursive procedure based on this view to identify the exchange rate shock and estimate price responses to this shock.[31] As another variation, we also estimated price responses from a larger VAR model that included domestic output as an additional variable. These variations, however, did not alter our key results. Model 3 continued to perform the best among Models 1-3 while Model 6 remained the best performer among Models 4-6. As before, Model 3 outperformed Model 6, and hybrid Models 7 and 8 further improved the fit.

Our loss function gives equal weights to deviations of model responses from the VAR responses for all five price indexes. The standard errors for the VAR responses differ considerably across the five variables and it can be argued that the loss function should take these differences into account. Thus we also used a weighted

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[31] This procedure estimated orthogonalized impulse response functions using a recursive ordering with exchange rate as the fifth variable (after consumer prices, producer prices, the wage rate, and the interest rate, but before import and export prices).

loss function, in which the weight assigned to the sum of squared deviations for a variable is inversely related to the variance of the (orthogonalized) shock to that variable.[32] As shocks to import and export prices tend to have larger variances than shocks to other prices, the weighted loss function penalizes a model less for poorer prediction of international prices. The use of the weighted loss function did not affect the rankings of different models. The differences in their performance were, in fact, more pronounced. For example, Models 3 outperformed Models 1-2 and Model 6 outperformed Models 4-5 by substantial margins. The performance of hybrid models, moreover, was much better than that of the pure models.[33]

As discussed above, there is considerable disagreement about the values of ρ, μ and σ. We also do not have a good estimate of χ. We thus also explore variations in the values of these parameters.[34] We assume that $\rho \in [0.5, 10.0]$, $\mu \in [0, \infty]$, $\sigma \in [1.5, 12.5]$ and $\chi \in [0, 1.0]$. For each model, we search over these intervals to find the values of ρ, μ, σ, and χ, which minimize the loss ($\chi = 0$ for Models 1, 2 and 4, which do not include distribution costs). For the hybrid models, we also determine the optimized value of ϕ. Table 5 reports the losses for Models 1-8 resulting from the search procedure. For each model, the table also shows the loss-minimizing values of ρ, μ, σ, and where relevant, those of χ and ϕ. Relaxation of parameter

[32] For variable j, let SSD_j denote the sum of squared deviations of model responses from the VAR responses over 10 quarters. The weighted loss function is defined as $L = \sum_j SSD_j / \text{var}_j$, where var_j is the variance of the orthogonalized shock to variable j, and depends on the ordering of the variable in the Choleski decomposition. We initially used the ordering given in VAR (1), but later experimented with alternative orderings. The relative ranking of models did not depend much on how the variables were ordered.

[33] The weighted loss function favored the LCP assumption more in that the optimal value of ϕ in models 7 and 8 fell to less than one third in this case.

[34] We also considered small variations in the value of π in the Calvo staggered price model, but these variations did not have much affect on the results. The results were also not very sensitive to the use of the Taylor instead of the Calvo model (with a similar average fixed-price interval).

constraints provides a potential for an improvement in the fit and all models show a reduction in the total loss (compare Tables 4 and 5). The loss-minimizing parameter values vary from one model to another. One key change in the relative performance of the models is that Model 5 with flexible prices and distribution costs now outperforms all pure models.[35] Note, however, that this improvement in the performance of Model 5 involves the choice of extreme values for ρ, μ, and χ, and a near-extreme value for σ. The hybrid models, however, continue to dominate pure models. Interestingly, the loss-minimizing value of ϕ remains close to one half, suggesting an equally important role for LCP and PCP. The search for loss-minimizing parameters did not much affect the pattern of model responses, and even the hybrid models continued to have difficulties in matching the hump-shaped dynamics of most prices, especially import prices.

The above hybrid models assume that the mix of local- and producer-currency firms is the same at home and abroad (i.e., $\phi = \phi^*$). We also explored the asymmetric case which removes this constraint and searches for separate best-fitting values for ϕ and ϕ^*. The asymmetric case improved the fit of the hybrid models by allowing them greater flexibility in matching import and export prices. The value of ϕ in this case was 0.58 while that of ϕ^* was 0.43. These results suggest a marginally weaker role for LCP in explaining the response of export prices, but a slightly stronger role for explaining the import price response.

Our results so far are based on matching the average responses for the non-US G-7 group. To explore the role of inter-country differences, we also examined how well different models perform in matching the VAR responses for individual countries in the non-US G-7 group. To facilitate comparisons with our basic results, we summarize the results of this exercise using the same procedure as that underlying our basic results.[36] We found considerable cross-country variation in the overall loss associated with each model. The relative performance of different models, however, was similar across countries with the following notable

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[35] Also, Models 1 and 2 without distribution costs perform almost as well as Model 3 with these costs. Distribution costs thus do not make much difference to the LCP models if ρ, μ and σ are allowed to vary.

[36] That is, the model responses are based on fixed parameter values, the VAR responses use the basic identification scheme, and the loss function assigns the same weight to each price.

exceptions.[37] For Italy, the flexible-price Models 4 and 5 outscored all other models.[38] For Germany and Japan, moreover, the best-performing PCP model (Model 6 for Germany and Model 5 for Japan) provided a better fit than the best-performing LCP model (Model 3 for both countries). The hybrid models, however, produced the lowest loss for all countries except Italy. The optimal value of ϕ varied from one country to another. It was greater than 0.5 for Italy, Germany and Japan (where the PCP models worked better), but smaller than 0.5 for the remaining countries.

5. Conclusions

New open economy macroeconomic models provide an appealing framework for examining the exchange rate pass-through to different prices. There is considerable controversy, however, about what features are needed to explain the exchange rate pass-through. Although a number of explanations have been proposed, there has been little work in assessing the ability of different models to explain the dynamic responses of a broad range of prices to an exchange rate shock. To explore this question, this paper examines the performance of a variety of models that are suggested by different approaches or represent an interesting combination of features highlighted in the literature. The fit of each model is evaluated by comparing responses predicted by each model with the evidence for non-US G-7 countries, based on impulse response analysis of a VAR model.

Our basic results are based on matching model responses with the average VAR responses for the non-US G-7 group. These results indicate that models based on LCP are able to predict the responses of domestic (consumer and producer) prices and wages well provided that these models are extended to include distribution costs for imports. A LCP model with distribution costs, in fact, provides a better overall fit to the VAR data than a comparable PCP model. Both LCP and PCP models, however, have problems matching the responses of import and export prices. Interestingly, a hybrid model that gives roughly equal weights to LCP and PCP firms

[37] The country VAR responses also had larger standard errors, making it difficult to discriminate between different models on the basis of statistical tests.

[38] The response of the producer price index is much higher in Italy than other countries (see Table 1). This feature favors the flexible-price models, which imply a high pass-through to this index.

provides a significantly improved tracking of international price responses. Sticky-wage versions perform marginally better than flexible-wage versions. Thus the best-fitting model not only assumes sticky goods prices with a mixture of LCP and PCP, but also incorporates sticky wages and distribution costs for imports.

The paper undertakes an extensive sensitivity analysis to examine the robustness of the results to a number of variations. These variations include different procedures for estimating price responses to an exchange rate shock, a wide range of values for certain parameters, changes in the criterion used to evaluate the fit of a model, and matching responses of individual non-US G-7 countries instead of average group responses. The relative performance of different models is not affected much in most variations. The key result that hybrid models provide a better fit than the pure LCP or PCP models turns out to be very robust and survives all variations. Even the best-performing hybrid models, however, have problems in matching the degree of persistence and the hump-shaped pattern of most price series, especially the import price series. Explaining these features of the price dynamics would be an important topic for future research.

There is a growing literature that uses the new open economy macroeconomic framework to determine the optimal monetary policy behavior. A number of papers have demonstrated that that the form of the optimal monetary policy rule is sensitive to the modeling of the exchange rate pass-through.[39] The findings of this paper suggest that it would be useful to allow for both LCP and PCP in understanding the optimal conduct of monetary policy.

[39] See, for example, Devereux and Engel (2001), and Smets and Wouters (2002).

Table 1. The Response of Different Prices to an Exchange Rate Shock: Non-US G7 Countries

Response at Quarter\	Canada	France	Germany	Italy	Japan	U.K.	Average
Consumer Prices (CPI)							
1	-0.02	0.00	0.15	0.02	-0.01	0.02	0.02
	(0.02)	(0.07)	(0.07)	(0.01)	(0.01)	(0.09)	(0.01)
4	0.08	0.10	0.20	0.14	0.04	0.10	0.11
	(0.10)	(0.35)	(0.12)	(0.06)	(0.03)	(0.44)	(0.06)
10	0.20	0.09	0.36	0.26	0.09	0.11	0.19
	(0.19)	(0.35)	(0.18)	(0.15)	(0.06)	(0.56)	(0.07)
Producer Prices (PPI)							
1	0.03	-0.09	0.02	0.10	0.02	0.01	0.01
	(0.03)	(0.05)	(0.04)	(0.02)	(0.02)	(0.01)	(0.01)
4	0.22	-0.14	0.17	0.34	0.13	0.06	0.13
	(0.14)	(0.27)	(0.09)	(0.15)	(0.05)	(0.05)	(0.06)
10	0.28	-0.07	0.16	0.33	0.12	0.05	0.15
	(0.37)	(0.37)	(0.12)	(0.32)	(0.10)	(0.06)	(0.11)
Wage rate (W)							
1	0.00	0.14	0.12	-0.02	0.00	-0.03	0.04
	(0.03)	(0.03)	(0.16)	(0.02)	(0.01)	(0.02)	(0.03)
4	0.01	0.10	-0.14	0.07	0.03	-0.01	0.01
	(0.11)	(0.13)	(0.26)	(0.11)	(0.03)	(0.07)	(0.06)
10	0.08	0.19	-0.01	0.27	-0.02	-0.02	0.08
	(0.19)	(0.22)	(0.24)	(0.22)	(0.06)	(0.14)	(0.08)
Import prices (PM)							
1	0.34	0.32	0.39	0.50	0.80	0.37	0.45
	(0.06)	(0.09)	(0.13)	(0.09)	(0.14)	(0.06)	(0.04)
4	0.51	0.68	0.77	0.70	1.34	0.40	0.73
	(0.18)	(0.41)	(0.35)	(0.51)	(0.42)	(0.23)	(0.15)
10	-0.18	0.18	0.27	0.13	0.79	0.16	0.22
	(0.28)	(0.65)	(0.46)	(0.98)	(0.82)	(0.32)	(0.26)
Export prices (PX)							
1	0.23	0.30	0.03	0.29	0.50	0.17	0.25
	(0.05)	(0.05)	(0.09)	(0.06)	(0.10)	(0.04)	(0.03)
4	0.30	0.39	0.16	0.59	0.50	0.23	0.36
	(1.42)	(0.23)	(0.26)	(0.24)	(0.21)	(0.19)	(0.09)
10	0.19	0.24	0.06	0.25	0.44	0.07	0.21
	(0.40)	(0.47)	(0.30)	(0.48)	(0.34)	(0.33)	(0.16)
Terms of trade (TOT)							
1	-0.11	-0.03	-0.36	-0.21	-0.30	-0.20	-0.20
	(0.05)	(0.10)	(0.14)	(0.07)	(0.06)	(0.05)	(0.03)
4	-0.21	-0.28	-0.61	-0.11	-0.84	-0.17	-0.37
	(0.15)	(0.32)	(0.30)	(0.31)	(0.27)	(0.15)	(0.11)
10	0.37	0.06	-0.21	0.12	-0.35	-0.09	-0.02
	(0.31)	(0.36)	(0.42)	(0.53)	(0.53)	(0.13)	(0.17)

Notes: Standard errors are in parentheses.

Table 2. Comparison of Different Models

Model	Pricing Practice	Goods Prices	Wage Rate	Distribution Costs?	Related Models
Model 1	LCP	Sticky	Flexible	No	Chari, Kehoe and McGrattan (2000)
Model 2	LCP	Sticky	Sticky	No	Kollmann (2001)
Model 3	LCP	Sticky	Sticky	Yes	
Model 4	n.a.	Flexible	Sticky	No	Obstfeld and Rogoff (2000a)
Model 5	n.a.	Flexible	Sticky	Yes	Corsetti and Dedola (2002)
Model 6	PCP	Sticky	Sticky	Yes	
Model 7	mixed	Sticky	Flexible	Yes	
Model 8	mixed	Sticky	Sticky	Yes	

Note: Under flexible goods prices, the currency of price setting does not matter.

Table 3. Parameter Values

Parameter	
1. Structural Parameters	
Discount Rate (β)	0.99
Coefficient of Relative Risk Aversion (ρ)	4.00
Elasticity of Labor Supply ($1/\mu$)	2.00
Substitution Elasticity Between Varieties (ε)	5.00
Substitution Elasticity Between Home and Foreign Goods (σ)	5.00
Probability of Changing Prices ($1-\pi$)	0.25
2. Interest Rate Rule	
Coefficient of Lagged Interest Rate (φ_1)	0.85
Coefficient of the Expected Inflation Rate (φ_2)	0.17
Coefficient of the Exchange Rate Change (φ_3)	0.00
3. Steady State Values	
Revenue Share of Intermediates, Traded Goods (θ_{ZY})	0.64
Revenue Share of Intermediates, Non-Traded Goods (θ_{QC})	0.35
Import Share at International Prices (θ_M)	0.13
Distribution to Marginal Cost Ratio (χ)	0.50

Table 4. Relative Performance of Different Models: Fixed Parameter Values

	Components of the Loss Due to:					Total Loss
	CPI	PPI	W	PM	PX	
Model 1	0.04	0.07	0.25	0.58	0.48	1.42
Model 2	0.02	0.06	0.19	0.57	0.46	1.30
Model 3	0.00	0.01	0.03	0.54	0.44	1.02
Model 4	0.37	0.66	0.41	1.05	0.12	2.61
Model 5	0.09	0.26	0.11	0.88	0.04	1.37
Model 6	0.00	0.02	0.06	0.92	0.23	1.24
Model 7	0.00	0.02	0.07	0.40	0.06	0.54
Model 8	0.00	0.01	0.04	0.40	0.06	0.51

Notes: In Models 7 and 8 the optimized values
of ø are 0.45 and 0.45 respectively.

Table 5. Relative Performance of Different Models: Optimized Parameter Values

	Loss-Minimizing Values				Components of Loss Due to:					Total Loss
	ρ	μ	σ	χ	CPI	PPI	W	PM	PX	
Model 1	0.5	1	2	0	0.013	0.007	0.006	0.56	0.407	0.993
Model 2	4	0	6	0	0.026	0.007	0.003	0.56	0.396	0.992
Model 3	0.5	1	6	0.5	0.018	0.007	0.006	0.529	0.424	0.984
Model 4	1	0	2	0	0.044	0.217	0.016	1.094	0.043	1.413
Model 5	0.5	0	2	1	0.017	0.058	0.003	0.66	0.044	0.783
Model 6	10	1	10	1	0.007	0.004	0.015	0.801	0.235	1.062
Model 7	4	2	7	1	0.014	0.005	0.01	0.336	0.06	0.425
Model 8	9	1	5	1	0.019	0.006	0.004	0.332	0.064	0.425

Notes: The value of χ is fixed at zero for Models 1, 2 and 4. The optimal values of ø
are 0.48 and 0.47 for Models 7 and 8 respectively.

Figure 1. Price Responses to an Exchange Rate Shock
(average impulse-responses for non-U.S. G-7)

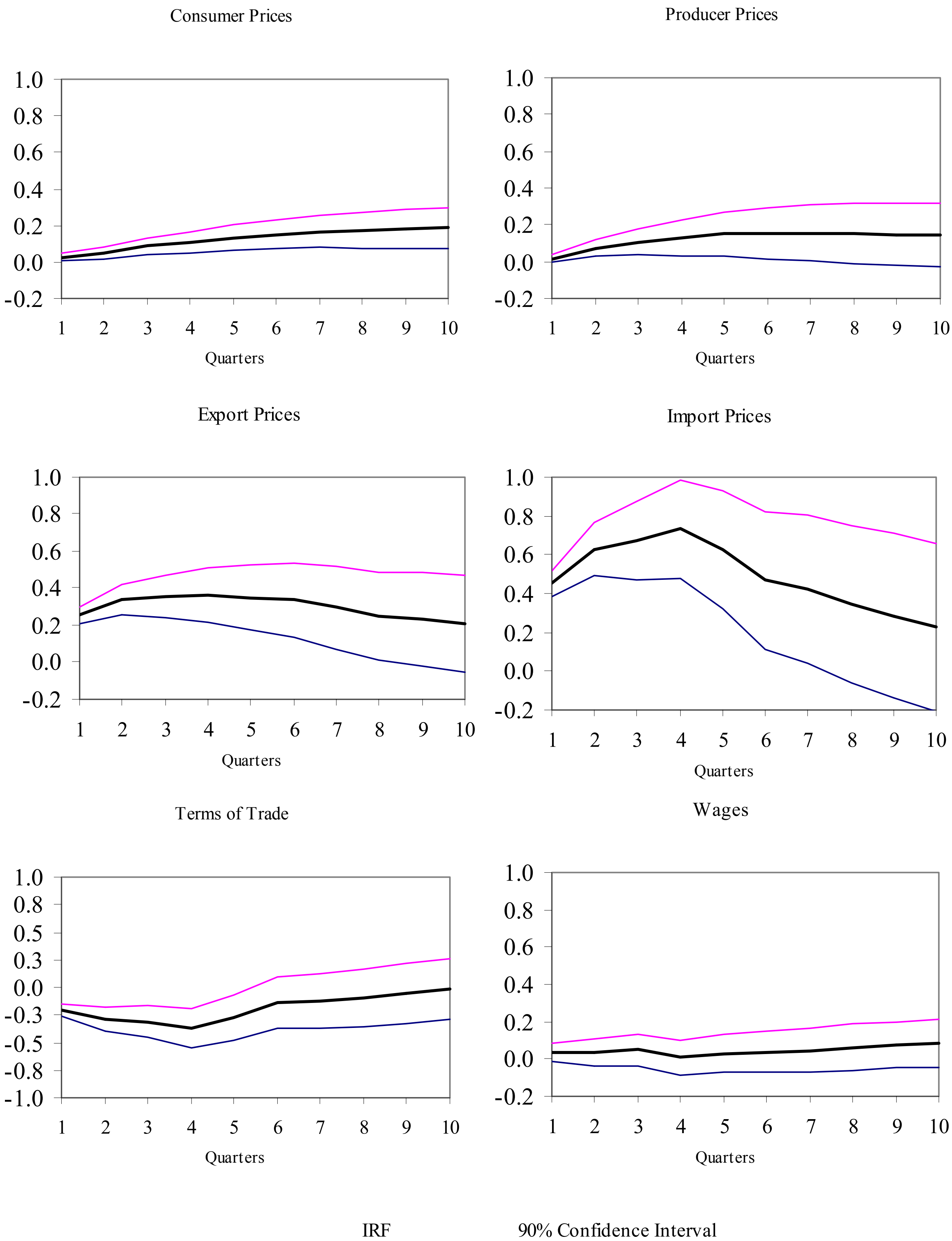


Figure 2. Performance of Models 1, 2 and 3 with Fixed Parameter Values

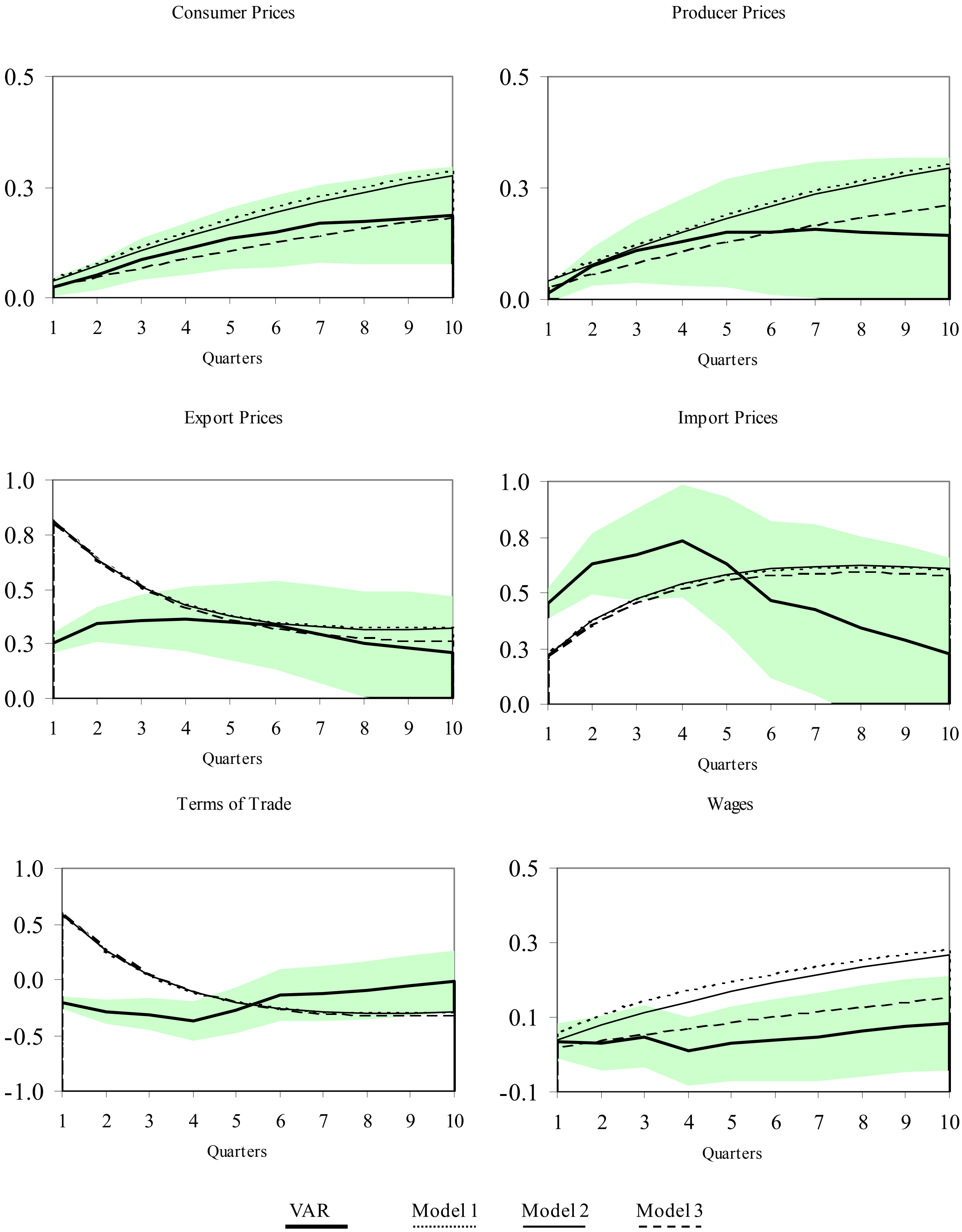


Figure 3. Performance of Models 4, 5 and 6 with Fixed Parameter Values

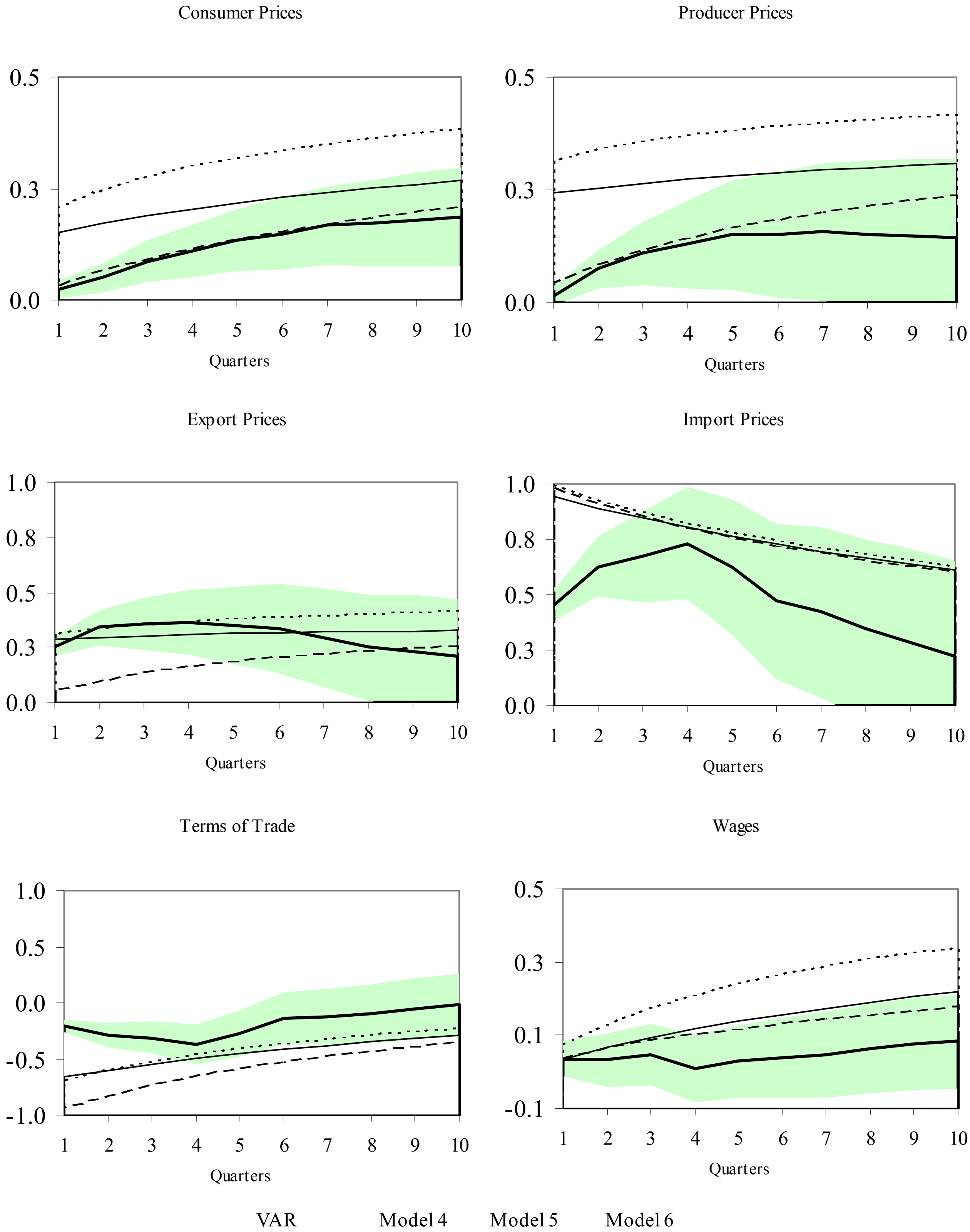
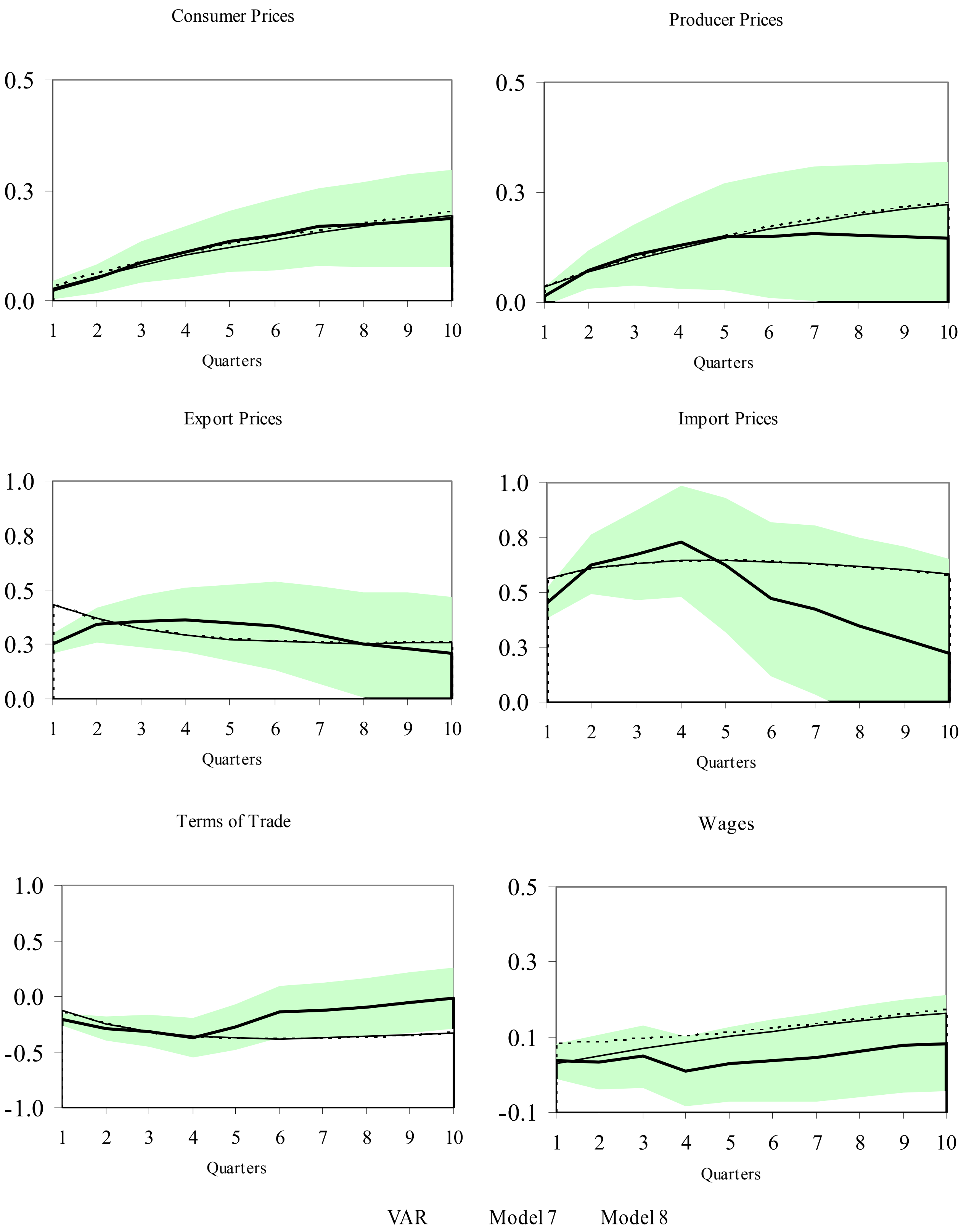


Figure 4. Performance of Models 7 and 8 with Fixed Parameter Values



References

Benigno, Pierpaolo, 2001, "Price Stability with Imperfect Financial Integration," mimeo.

Basu, Susanto, 1995, "Intermediate Goods and Business Cycles: Implications for Productivity and Welfare," *American Economic Review*, Vol. 85, pp. 512-531.

Bergin, Paul R., 2002, "Putting the "New Open Economy Macroeconomics" to a Test," mimeo, January.

_____, and Robert C. Feenstra, 2001, "Pricing-to-Market, Staggered Contracts, and Real Exchange Rate Persistence," *Journal of International Economics*, Vol. 54, pp. 333-359.

Betts, Caroline, and Michael B. Devereux, 1996, "The Exchange Rate in a Model of Pricing-to-Market," *European Economic Review*, Vol.40, pp. 1007-1021.

_____, 2000, "Exchange Rate Dynamics in a Model of Pricing-to-Market," *Journal of International Economics*, Vol.50, pp. 215-244.

Branson, William H., and Richard C. Marston, 1989, "Price and Output Adjustment in Japanese Manufacturing," NBER Working Paper No. 2878.

Burstein, Ariel T., Joao C. Neves and Sergio Rebelo, 2003, "Distribution Costs and Real Exchange Rate Dynamics During Exchange-Rate-Based Stabilizations," *Journal of Monetary Economics*, Vol. 50, pp. 1189-1214.

Calvo, Guillermo, A., 1983, "Staggered Prices in a Utility-Maximizing Framework," *Journal of Monetary Economics*, Vol. 12, pp. 383-98.

Campa, Jose Manuel, and Linda S. Goldberg, 2002, "Exchange Rate Pass-Through into Import Prices: A Macro or Micro Phenomenon?" mimeo, April.

Chari, V. V., Patrick J. Kehoe and Ellen R. McGrattan, 2000 "Can Sticky Price Models Generate Volatile and Persistent Real Exchange Rates?" NBER Working Paper No. 7869.

Corsetti, Giancarlo, and Luca Dedola, 2002, "Macroeconomics of International Price Discrimination," mimeo March.

Devereux, Michael B., and Charles Engel, 2001, "Monetary Policy in the Open Economy Revisited: Price Setting and Exchange Rate Flexibility," mimeo.

________, 2002, "Exchange Rate Pass-Through, Exchange Rate Volatility, and Exchange Rate Disconnect," *Journal of Monetary Economics*, Vol. 49, pp. 913-940

Engel, Charles, 2002, "The Responsiveness of Consumer Prices to Exchange Rates and the Implications for Exchange Rate Policy: A Survey of a Few Recent New-Open-Economy Models," NBER Working Paper No. 8725.

Faruqee, Hamid, 1995, "Pricing to Market and the Real Exchange Rate," *IMF Staff Papers*, Vol. 42, No. 4, pp. 855-881.

Goldberg, Pinelopi, and Michael Knetter, 1997, "Goods Prices and Exchange Rates: What Have We Learned?" *Journal of Economic Literature*, Vol.35, pp.1243-92.

Hamilton, James D., 1994, *Time Series Analysis*, (Princeton: Princeton University Press)

Jeanne, Olivier, and Andrew K. Rose, 2002, "Noise Trading and Exchange Rate Regimes," *Quarterly Journal of Economics*, Vol. 117, pp. 537-69.

Kim, Soyoung and Nouriel Roubini, 2000, "Exchange Rate Anomalies in the Industrial Countries: A Solution with a Structural VAR Approach," *Journal of Monetary Economics*, Vol. 45, pp. 561-586.

Knetter, Michael M., 1993, "International Comparisons of Price-to-Market Behavior," *American Economic Review*, Vol.83, pp.473-486.

Kollmann, Robert, 2001, "The Exchange Rate in a Dynamic-Optimizing Business Cycle Model With Nominal Rigidities: A Quantitative Investigation," *Journal of International Economics*, Vol. 55, pp.243-262.

McCallum, Bennett T. and Edward Nelson, 1999, "Nominal Income Targeting in an Open-Economy Optimizing Model," *Journal of Monetary Economics*, Vol. 43, pp.553-578.

________, 2001, "Monetary Policy for an Open economy: An Alternative Framework with Optimizing Agents and Sticky Prices," mimeo.

Phillips, P. C. B. and S. Ouliaris, 1990, "Asymptotic Properties of Residual Based Tests for Cointegration," *Econometrica*, Vol. 58, pp. 165-93.

Obstfeld, Maurice, and Kenneth Rogoff, 1995, "Exchange Rate Dynamics Redux," *Journal of Political Economy*, Vol.103, pp. 624-660.

______, 2000a, " New Directions for Stochastic Open Economy Models," *Journal of International Economics*, Vol. 50, pp.117-153.

______, 2000b, "The Six Major Puzzles in International Macroeconomics: Is There a Common Cause?" NBER Working Paper No. 7777.

Reimers, H.-E., 1992, "Comparisons of Tests for Multivariate Cointegration," *Statistical Papers*, Vol. 33, pp. 335-359.

Runkle, David, 1987, "Vector Autoregressions and Reality," *Journal of Business and Economic Statistics*, Vol. 5, pp. 437-42.

Sims, Christopher A. and Tao A. Zha, 1998, "Does Monetary Policy Generate Recessions?" Federal Reserve Bank of Atlanta Working Paper 98–12.

Smets, Frank, and Raf Wouters, 2002, "Openness, Imperfect Exchange Rate Pass-Through and Monetary Policy," *Journal of Monetary Economics*, Vol. 49, pp. 947-81.

Taylor, John B., 1980, "Aggregate Dynamics and Staggered Contracts," *Journal of Political Economy*, Vol. 88, pp. 1-22.

Schmitt-Grohe, Stephanie, and Martin Uribe, 2003, "Closing Small Open Economy Models," *Journal of International Economics*, Vol. 61, pp. 163-185.