# Endogenous Nominal Rigidities and Monetary Policy*

Takeshi Kimura† Takushi Kurozumi‡ Naoko Hara§

First draft: December 26, 2007; this version: January 18, 2008

**Abstract**

Monetary policy analysis with exogenously given nominal rigidities is subject to Lucas' critique, if the degree of them varies over policy regimes as recent empirical studies point out. In a Calvo style sticky price model, we endogenize nominal rigidities and examine its implications for monetary policy. While previous studies stress that the frequency of price adjustment changes with steady state inflation, we focus on how this frequency varies in response to changes in the Taylor rule in the same steady state. We find that a more aggressive policy response to inflation makes firms less likely to reset their prices, resulting in a flat slope of the New Keynesian Phillips curve as observed in the post-1982 U.S. economy and a small variance of shocks to the curve as in the Great Moderation. We also find that an aggressive policy response to inflation can stabilize both inflation and the output gap by exploiting the feedback effect of the policy stance on firms' price setting. Taking into account this effect is thus crucial to the policy conduct. Further, we show that an endogenous inflation weight of the social welfare loss function is critical to policy evaluation, since this weight changes significantly with the frequency of price adjustment.

*JEL classification:* E31; E32; E52

*Keywords:* Monetary policy; Endogenous nominal rigidities; Lucas' critique

*The authors appreciate discussions and comments from Hibiki Ichiue, Eiji Maeda, Kazuo Monma, Etsuro Shioji, Toyoichiro Shirota and seminar participants at the Bank of Japan. Any remaining errors are the sole responsibility of the authors. The views expressed herein are those of the authors and should not be interpreted as those of the Bank of Japan.

†Financial Markets Department, Bank of Japan. E-mail: takeshi.kimura@boj.or.jp

‡Corresponding author. Research and Statistics Department, Bank of Japan, 2-1-1 Nihonbashi Hongokucho, Chuo-ku, Tokyo 103-8660, Japan. Tel.: +81 3 3279 1111; fax: +81 3 5255 6758. E-mail: takushi.kurozumi@boj.or.jp

§Research and Statistics Department, Bank of Japan. E-mail: naoko.hara@boj.or.jp

# 1 Introduction

Nominal rigidities are a crucially important issue for central banks all over the world. In the presence of such rigidities, monetary policy can exert an influence on the real economy and its policy impact depends greatly on the degree of them. Therefore, in order to discuss the desirable policy, a model that accurately describes nominal rigidities present in the actual economy is indispensable.[1] In particular, such a model is required to answer the questions of whether and how the degree of nominal rigidities varies in response to changes in the economic environment. Nevertheless, recent studies put aside these questions by assuming exogenously given nominal rigidities. The most conspicuous example is the now very popular Calvo (1983) style sticky price models. While Rotemberg (1987) and Ball and Mankiw (1994) consider these models as ones reduced from some original models that contain a rigid micro-foundation for nominal rigidities, most recent studies use the Calvo style models themselves for evaluating alternative policies. Clearly, such policy evaluation yields a misleading policy implication, if the frequency of price adjustment assumed in the Calvo style models changes across the policies. In fact, a recent empirical work by Fernández-Villaverde and Rubio-Ramírez (2007) addresses the question of "How structural are structural parameters?" and finds that the frequency of price adjustment varies over the years in the U.S., in particular, it changed after Paul Volcker took up the chairman of the Federal Reserve. This empirical finding indeed suggests that monetary policy analysis with exogenously given nominal rigidities is subject to Lucas' (1976) critique.

In this paper we endogenize nominal rigidities in a Calvo style sticky price model. Specifically, we consider firms which choose the probability of price adjustment so as to maximize their expected profit in the face of fixed costs to set a new price. Our approach for endogenous nominal rigidities is similar to Ball, Mankiw and Romer (1988), Romer (1990), Kiley (2000), Devereux and Yetman (2002) and Levin and Yun (2007). Yet, our analysis differs from theirs

[1]In the Eurosystem's Inflation Persistence Network (IPN), Angeloni et al. (2006) discuss the implications for macroeconomic modeling of IPN empirical studies on firms' price setting behavior.

in the following important way. The previous studies consider that the probability of price adjustment is chosen in response to changes in the monetary policy regime represented by the level of steady state inflation. This implies that the nominal rigidities are constant in the same steady state. By contrast, we assume that firms determine the probability in response to changes in the Taylor (1993) rule's policy responses to inflation and the output gap, which the recent literature, such as Taylor (1999), Clarida, Galí and Gertler (2000) and Lubik and Schorfheide (2004), considers as a more important aspect of the policy regime. Consequently, our approach allows the degree of nominal rigidities to vary even in the same steady state.

With the model, we examine the implications of endogenous nominal rigidities for monetary policy. Our main findings are the following three. First of all, in stark contrast to models with exogenously given nominal rigidities, our model with endogenous nominal rigidities shows that a more aggressive policy response to inflation makes firms less likely to reset their prices, resulting in a flatter slope and a smaller shock coefficient of the New Keynesian Phillips curve. This result is consistent with findings of the recent empirical literature. Taylor (1999), Clarida, Galí and Gertler (2000) and Lubik and Schorfheide (2004) find that the Taylor rule contains a much stronger response to inflation in the post-1982 U.S. economy than in the pre-Volcker one. During the same periods, Fernández-Villaverde and Rubio-Ramírez (2007) and Smets and Wouters (2007) show that firms' probability of price adjustment becomes lower and Lubik and Schorfheide (2004) present a flatter slope and a smaller shock variance of the New Keynesian Phillips curve. The result also offers theoretical support for the good policy hypothesis about the U.S. Great Moderation pointed out by Bernanke (2004). The shock to the New Keynesian Phillips curve, which we call the price shock, generates a trade-off in monetary policymaking bewteen stabilization of inflation and the output gap. Then, a more aggressive policy response to inflation results in a smaller coefficient of this shock and hence lessens the trade-off in policymaking, thereby reducing macroeconomic volatility. Second, an aggressive policy response to inflation can stabilize both inflation and the output gap by exploiting the feedback effect of the policy stance on firms' price setting. This suggests that taking into account this feedback effect is of crucial importance to the conduct of monetary policy. Last but not least, precise endogenous weights of the social welfare loss function are critical to policy evaluation under endogenous nominal rigidities. The weight of inflation variability increases significantly with the probability of no price adjustment, reflecting welfare distortions due to price dispersion. Therefore, policy evaluation with the loss function's weights relative to inflation stabilization as in the previous literature underestimates the welfare losses from inflation variability and hence induces a misleading implication for monetary policy.

What is the intuition for our results? When the central bank adjusts the interest rate more aggressively in response to inflation, each firm's relative price to the general price level becomes more stable. Consequetly, firms are less likely to reset their prices, since such price changes do not pay due to the fixed cost to set a new price. This in turn implies that the central bank's more aggressive policy response to inflation makes firms less likely to reflect current and expected future shocks to their current prices. As a consequence, inflation becomes less responsive to the price shocks, which generate the trade-off between stabilization of inflation and the output gap. Thus, the central bank can stabilize both inflation and the output gap by responding aggressively to inflation. In our model, a second order approximation to the representative household's utility function can be reduced to a weighted sum of variability of inflation and the output gap. The weight of inflation variability then increases with the probability of no price adjustment, since a rise in this probability enlarges welfare distortions due to price dispersion. Hence, the policy evaluation with the relative weight of output gap variability to inflation variability as used in the previous literature underestimates the welfare losses from inflation variability, so that such policy evaluation induces the misleading policy implication that the central bank should not respond to the output gap. The desirable policy enhancing social welfare, however, suggests a mild policy response to the output gap as well as an aggressive policy response to inflation. Therefore, in the presence of endogenous nominal rigidities, the endogenous inflation weight of the social welfare loss function is of crucial importance for policy evaluation.

The remainder of the paper proceeds as follows. Section 2 endogenizes nominal rigidities in a Calvo style sticky price model. Section 3 presents a positive analysis of endogenous nominal rigidities and Section 4 shows a normative analysis. Finally, Section 5 concludes.

# 2 An optimizing model with endogenous nominal rigidities

In this section we endogenize nominal rigidities in a Calvo (1983) style sticky price model, which has been used in the recent monetary policy literature. To this end we take a similar approach to previous studies, such as Ball, Mankiw and Romer (1988), Romer (1990), Kiley (2000), Devereux and Yetman (2002) and Levin and Yun (2007), and assume that firms choose the probability of price adjustment so as to maximize their expected profit in the face of fixed costs to set a new price.

The economy consists of households, firms and a central bank.[2] We describe each in turn.

## 2.1 Households

There is a continuum of infinitely-lived identical households. Each household's preferences over consumption $C_t$ and labor hours $H_t$ are represented by the utility function

$$E\sum_{t=0}^{\infty}\beta^t\left[\frac{C_t^{1-\sigma}}{1-\sigma}\exp(g_t)-\frac{H_t^{1+\eta}}{1+\eta}\right], \tag{1}$$

where $E$ denotes the expectations operator, $\beta \in (0,1)$ is the discount factor, $\sigma > 0$ measures relative risk aversion, $\eta \geq 0$ is the inverse of the Frisch labor supply elasticity and $g_t$ represents a preferences shock. Consumption $C_t = [\int_0^1 C_{j,t}^{(\theta-1)/\theta} dj]^{\theta/(\theta-1)}$ is represented as a composite of differentiated goods produced by firms, $C_{j,t}$, $j \in [0,1]$, with an identical price elasticity of demand $\theta > 1$. Thus, cost-minimizing demand for good $i$ is given by $C_{j,t} = (P_{j,t}/P_t)^{-\theta} C_t$,

[2] As in recent monetary policy studies, we assume that fiscal policy is 'Ricardian', i.e. it appropriately accommodates consequences of monetary policy for the government budget constraint. We thus leave hidden the government budget constraint and fiscal policy.

where the aggregate price index satisfies

$$P_t = \left( \int_0^1 P_{j,t}^{\theta-1} dj \right)^{\frac{1}{\theta-1}}. \tag{2}$$

Each household's budget constraint is given by

$$P_t C_t + B_t = W_t H_t + (1 + i_{t-1}) B_{t-1} + T_t, \tag{3}$$

where $W_t$ denotes the nominal wage, $T_t$ is nominal profit received from firms and $B_t$ denotes the household's holdings of nominal one-period bonds, which earn the nominal interest rate $i_t$ in the subsequent period.

In the presence of complete financial asset markets, a representative household chooses consumption, bond holdings and hours worked so as to maximize the utility function (1) subject to the budget constraint (3). The optimality conditions for the utility maximization then yield

$$C_t^{-\sigma} \exp(g_t) = \beta E_t \left[ C_{t+1}^{-\sigma} \exp(g_{t+1}) \frac{1 + i_t}{1 + \pi_{t+1}} \right], \tag{4}$$

$$\frac{H_t^{\eta}}{C_t^{-\sigma} \exp(g_t)} = \frac{W_t}{P_t}, \tag{5}$$

where $\pi_t = P_t / P_{t-1} - 1$ is the inflation rate and $E_t$ is the expectations operator conditional on information available in period $t$. Log-linearizing (4) and using the market clearing condition $C_{j,t} = Y_{j,t}$ for each good $j \in [0, 1]$, we have households' Euler equation for optimal spending decisions in terms of the output gap $x_t = y_t - y_t^*$

$$x_t = E_t x_{t+1} - \sigma^{-1} \left( i_t - E_t \pi_{t+1} - r_t^* \right). \tag{6}$$

Here, $y_t$ and $y_t^*$ are the log of aggregate output and its flexible-price counterpart that would obtain in the absence of nominal rigidities, $r_t^* = r^* + (g_t - E_t g_{t+1}) - \sigma(y_t^* - E_t y_{t+1}^*)$ denotes the natural rate of interest, and $r^*$ is its steady state value, so that the difference $r_t^* - r^*$ represents a natural interest rate shock. We assume that this shock follows a stationary first order autoregressive process with a persistence parameter $\rho_r \in (-1, 1)$ and a variance of shock innovations $v_r > 0$.

## 2.2 The central bank

As in Taylor (1993), the central bank conducts monetary policy by adjusting the nominal interest rate in response to inflation and the output gap

$$i_t \;=\; r^* + \pi^* + \phi_\pi(\pi_t - \pi^*) + \phi_x x_t, \tag{7}$$

where $\pi^*$ is the central bank's target for the inflation rate, which is assumed to be zero for simplicity, and $\phi_\pi$, $\phi_x$ show non-negative policy responses to inflation and the output gap. For determinacy of equilibrium, we assume throughout the paper that the Taylor principle is satisfied, i.e. $\phi_\pi > 1$.

## 2.3 Firms

We turn next to firms' behavior. There is a continnum of firms $j \in [0,1]$, each of which produces one kind of differentiated goods using the production technology $Y_t = z_t H_t^a$, where $H_t$ is labor input, $a \in (0,1]$ is the labor elasticity of production, and $z_t$ is a productivity shock. This firm sets the price of the good to sell it to households in a monopolistically competitive market.

Firms can reset their prices, paying a fixed cost $F > 0$. This fixed cost to set a new price is based on a recent empirical work by Zbaracki et al. (2004), who find that managerial costs (i.e. information gathering, decision-making, and communication costs) are six times larger than menu costs while customer costs (i.e. communication and negotiation costs) are twenty times larger. We assume as in the recent monetary policy literature that each firm's probability of resetting its price in the subsequent period is independent of this firm's past history of price adjustment. Let $\alpha_j$ denote firm $j$'s probability of no price adjustment in the next period. Then, from Rotemberg (1987) and Walsh (2003), it follows that firm $j$'s profit maximization is equivalent to its minimization of loss in profit, which equals up to the second order approximation the expectations of $L_t(\alpha_j, \alpha)$ given by

$$L_t(\alpha_j, \alpha) = F + \min_{p_{j,t}} E_t \sum_{k=0}^{\infty} (\beta\alpha_j)^k \left(p_{j,t} - p^*_{j,t+k}\right)^2 + \beta(1-\alpha_j) \sum_{k=1}^{\infty} (\beta\alpha_j)^{k-1} E_t L_{t+k}(\alpha_j, \alpha), \tag{8}$$

where $\alpha$ is other firms' probability of no price adjustment, $p_{j,t}$ is the log price of good $j$ set by firm $j$ in period $t$, and $p^*_{j,t}$ denotes the log price of good $j$ that would obtain if the nominal rigidities are absent in period $t$. In the right hand side of (8), the first and second terms reflect, respectively, the fixed cost to set a new price in period $t$ and a loss in profit from keeping the price unchanged after period $t$. The final term represents the sum of losses in profit from setting a new price in some future period and then keeping it unchanged after that period. The desired price $p^*_{j,t}$ is given by

$$p^*_{j,t} = p_t + mc_t + \mu_t = p_t + \gamma x_t + u_t, \tag{9}$$

where $p_t$ is the log of the aggregate price index $P_t$, $mc_t$ is the log-deviation of real marginal cost from its steady state value,[3] and $\mu_t$ represents a price markup shock (i.e. the log-deviation of the price markup from its steady state value) and where the second equality follows from the relationship between real marginal cost and the output gap, $mc_t = \gamma x_t + \tilde{u}_t$ with $\gamma = (\sigma + \eta)/[1 + \theta(1 - a)/a]$,[4] and the definition of a price shock, $u_t = \mu_t + \tilde{u}_t$. This price shock represents not only the price markup shock, $\mu_t$, but also the difference between real marginal cost and the output gap, $\tilde{u}_t = mc_t - \gamma x_t$, which is caused, for instance, by movements in nominal wages that push real wages away from their equilibrium values due to frictions in the labor market as in Erceg, Henderson and Levin (2000). We assume that the price shock $u_t$ follows a stationary first order autoregressive process with a persistence parameter $\rho_u \in (-1, 1)$ and a variance of shock innovations $v_u > 0$.

Each firm's problem has two steps. In the first step, the firm chooses the probability of price adjustment so as to minimize expected loss in profit under optimal staggered price setting. In the second step, given this chosen probability, the firm sets an optimal staggered price. In order to solve this two step problem, we begin with the second step. From the minimization

[3]We can show that in our model the real marginal cost is the same across firms.

[4]This can be derived from the household's optimality condition (5) and the labor market clearing condition $W_t/P_t = a z_t H_t^{a-1}$. See also Walsh (2003, p. 239).

problem in (8), the optimal staggered price setting in period $t$ is given by

$$p^o_{j,t} = (1-\beta\alpha_j)E_t\sum_{k=0}^{\infty}(\beta\alpha_j)^k p^*_{j,t+k} = (1-\beta\alpha_j)E_t\sum_{k=0}^{\infty}(\beta\alpha_j)^k \left(p_{t+k}+\gamma x_{t+k}+u_{t+k}\right), \qquad (10)$$

where the second equality follows from (9). Next, we consider firms' choice of the probability of price adjustment, namely, we endogenize nominal rigidities in our model similarly to Ball, Mankiw and Romer (1988), Romer (1990), Kiley (2000), Devereux and Yetman (2002) and Levin and Yun (2007). The optimality condition for firm $j$'s choice of the probability $\partial EL_t(\alpha_j,\alpha)/\partial\alpha_j = 0$ is given by

$$F + E\sum_{k=0}^{\infty}(\beta\alpha_j)^{k-1}\left[\beta\alpha_j - k(1-\beta\alpha_j)\right]\left(p^o_{j,t}-p^*_{j,t+k}\right)^2 = 0, \qquad (11)$$

where the Envelope Theorem is used to exclude terms reflecting the fact that $p^o_{j,t}$ changes with $\alpha_j$. As shown in Appendix A, substituting (9) and (10) into (11) yields

$$\begin{aligned} F + &\sum_{k=0}^{\infty}(\beta\alpha_j)^{k-1}\left[\beta\alpha_j - k(1-\beta\alpha_j)\right] \\ &\times V\left[\frac{1-\beta\alpha_j}{1-\beta\rho_u\alpha_j}u_t - \sum_{h=1}^{k}\pi_{t+h} - \gamma x_{t+k} - u_{t+k} + l_t(\alpha_j,\alpha)\right] = 0, \end{aligned} \qquad (12)$$

where $V$ is the variance operator and

$$l_t(\alpha_j,\alpha) = \sum_{h=1}^{\infty}(\beta\alpha_j)^h E_t\pi_{t+h} + \gamma(1-\beta\alpha_j)\sum_{h=0}^{\infty}(\beta\alpha_j)^h E_t x_{t+h}.$$

The condition for $\alpha$ to be a Nash equilibrium is that this optimality condition holds at $\alpha_j = \alpha$ for every firm $j$. Then, in such an equilibrium, the aggregate price index (2) yields

$$p_t = (1-\alpha)p^o_{j,t} + \alpha p_{t-1},$$

and hence combining this equation, (9) and (10) leads to the so-called New Keynesian Phillips curve

$$\pi_t = \beta E_t\pi_{t+1} + \frac{\gamma(1-\alpha)(1-\alpha\beta)}{\alpha}x_t + \frac{(1-\alpha)(1-\alpha\beta)}{\alpha}u_t, \qquad (13)$$

which has been widely used in the recent monetary policy literature. This suggests that our model indeed endogenizes nominal rigidities in the canonical model of monetary policy. The equilibrium value of $\alpha$ can be obtained as follows. Given a $\alpha$, we solve the system consisting of households' Euler equation (6), the Taylor rule (7) and the New Keynesain Phillips curve (13) and then substitute the obtained equilibrium processes of inflation and the output gap into the right-hand side of the reduced optimality condition (12) with $\alpha_j = \alpha$. Note that the equilibrium processes are unique because this is ensured by the assumed Taylor principle. We continue this procedure until we find a $\alpha$ that meets (12) with $\alpha_j = \alpha$. In the next section, we examine features of the equilibrium probability of price adjustment.

# 3 A positive analysis of endogenous nominal rigidities

In this section we do a positive analysis of the endogenous nominal rigidities introduced above. In particular, we first examine how the degree of nominal rigidities varies with the monetary policy regime represented by the Taylor rule's policy responses. We then investigate how the economy responds to the natural interest rate and price shocks under endogenous nominal rigidities.

## 3.1 Calibration of model parameters

To that end we need a realistic calibration of the parameters of our model. Our calibration for the quarterly model with annualized inflation and interest rates is summarised in Table 1. As in line with the literature, we set the discount factor $\beta = 0.99$, the inverse of labor supply elasticity $\eta = 1/0.15$ (Ball and Romer, 1990),[5] the price elasticity of demand $\theta = 7.88$ (Rotemberg and Woodford, 1997), and the labor elasticity of production $a = 0.7$. The other parameter values are set based on the estimates of Lubik and Schorfheide (2004): the risk aversion $\sigma = 1.86$; the persistence parameter and the innovation variance of natural interest rate shocks $\rho_r = 0.83$, $v_r = (0.18\,\sigma)^2$; and those of price shocks $\rho_u = 0.85$, $v_u = (0.64\,\gamma)^2$, where $\gamma = (\sigma + \eta)/[1 + \theta(1 - a)/a]$. Finally, we set each firm's fixed cost to set a new price $F = 3.22$ in a similar way

[5] Pencavel (1986) and Card (1994) survey the empirical literature on intertemporal labor supply and conclude that the estimates of the Frisch labor supply elasticity based on micro data are at most about 0.2.

to Devereux and Yetman (2002). Lubik and Schorfheide (2004) show that the estimated slope of the New Keynesain Phillips curve (13) is 0.58. Then, the parameter values specified above generate $\alpha = 0.585$ from the equation $\gamma(1-\alpha)(1-\alpha\beta)/\alpha = 0.58$. We choose the fixed cost $F$ so that the optimality condition (12) with $\alpha_j = \alpha$ holds at $\alpha = 0.585$ when the policy responses of the Taylor rule (7) are set by Taylor's (1993) estimates of $\phi_\pi = 1.5$ and $\phi_x = 0.5$.[6]

### 3.2 How do nominal rigidities vary with monetary policy stances?

We first examine features of endogenous nominal rigidities in response to changes in the Taylor rule's policy response to inflation. The upper figure of Figure 1 shows how an increase in the policy response to inflation from $\phi_\pi = 1.1$ to $\phi_\pi = 3$ with an increment of 0.1 alters the equilibrium probability of no price adjustment $\alpha$ in the cases of the policy response to the output gap $\phi_x = 0, 0.5, 1$. In this figure we can see that in each case of the policy response to the output gap, the probability $\alpha$ becomes higher as the policy response to inflation $\phi_\pi$ increases. That is, in the face of the central bank's more aggressive policy response to inflation, firms are less likely to reset their prices. Also, when the policy response to inflation is close to one, the probability $\alpha$ increases substantially, but once this policy response becomes high enough, the increase in the probability is diminishing.

What is the intuition for this result? If the general price level is unstable, (9) implies that the desired price $p^*_{j,t}$ is also unstable. Then, firms are likely to reset their prices even with paying the fixed cost to set a new optimal price. On the contrary, when the general price level becomes more stable as a consequence of the central bank's more aggressive policy response to inflation, the desired price becomes more stable and hence the price adjustment is less likely to pay due to the fixed cost. Consequently, firms are less likely to reset their prices.

We next investigate how the degree of nominal rigidities varies with the Taylor rule's policy response to the output gap. The lower figure of Figure 1 shows how an increase in the policy

[6] As the model requires, the choice of the fixed cost $F$ is based on the quarterly data, but not the annualized one, generated by the system of households' Euler equation (6), the Taylor rule (7) and the New Keynesain Phillips curve (13).

response to the output gap from $\phi_x = 0$ to $\phi_x = 1$ with an increment of 0.1 alters the equilibrium probability of no price adjustment $\alpha$ in the cases of the policy response to inflation $\phi_\pi = 1.1, 1.5, 3$. In this figure we can see that in each case of the policy response to inflation, the probability $\alpha$ becomes lower as the policy response to the output gap $\phi_x$ increases. That is, in the face of the central bank's more aggressive policy response to the output gap, firms are more likely to reset their prices. This feature is more apparent when the policy response to inflation is closer to one, but once this policy response is high enough, the decrease in the probability $\alpha$ is slight. The intuition for this result is that the central bank's more aggressive policy response to the output gap makes inflation more volatile, since there is a trade-off in monetary policymaking between stabilization of inflation and the output gap. Therefore, from the same argument as above, firms are more likely to reset their prices.

These features of endogenous nominal rigidities in response to changes in the Taylor rule's policy responses are consistent with findings of the recent empirical literature. As pointed out by Taylor (1999), Clarida, Galí and Gertler (2000) and Lubik and Schorfheide (2004), the Taylor rule's policy response to inflation becomes much stronger in the post-1982 period than in the pre-Volcker period, due to the change in monetary policy regimes after Paul Volcker took up the chairman of the Federal Reserve. During the same periods, Fernández-Villaverde and Rubio-Ramírez (2007) and Smets and Wouters (2007) show that firms' probability of no price adjustment becomes higher. These facts are consistently explained by our model with endogenous nominal rigidities, as shown in the upper figure of Figure 1. Also, Lubik and Schorfheide (2004) show that the slope of the New Keynesian Phillips curve (13) becomes flatter during these periods. This fact can also be accountable by our model. Figure 2 shows that the central bank's more aggressive policy response to inflation leads to a flatter slope of New Keynesian Phillips curve (13). This figure also shows that when the policy response to inflation is strong enough, the slope changes little for a realistic range of the policy response to the output gap, e.g. $0 \leq \phi_x \leq 0.5$.

### 3.3 How do the economy's responses to shocks change?

Figure 3 shows how the impulse responses to the natural interest rate shock differ between the cases of exogenously given nominal rigidities and endogenous ones. In this figure, we add a one standard deviation of the innovations to the natural interest rate shock in period one. Figure 3.a considers the case in which the Taylor rule's policy response to inflation increases from $\phi_\pi = 1.5$ to $\phi_\pi = 3$ keeping the policy response to the output gap fixed at $\phi_x = 0.5$. We can see in this figure that while inflation and nominal interest rates are less responsive to the natural interest rate shock under endogenous nominal rigidities than under exogenously given ones, the output gap is more responsive. On the contrary, when we consider the case in which the policy response to the output gap increases from $\phi_x = 0.5$ to $\phi_x = 1$ keeping the policy response to inflation fixed at $\phi_\pi = 1.5$, Figure 3.b shows that inflation and nominal interest rates are more responsive but the output gap is less responsive. This is because when nominal rigidities are endogenous, the central bank's more aggressive policy response to inflation (the output gap) results in a flatter (steeper) slope of the New Keynesian Phillips curve (13), and thereby inflation shows a weaker (stronger) response to the natural interes rate shock than when nominal rigidities are exogenously given, but the output gap has a stronger (weaker) response. Thus, when the New Keynesian Phillips curve contains a flatter slope as a consequence of a more aggressive policy response to inflation relative to the output gap, the natural interest rate shocks are accommodated by the quantity adjustment rather than by the price adjustment.

As for the price shock, Figure 4 shows how the impulse responses to this shock differ between the cases of exogenously given nominal rigidities and endogenous ones. Similarly to above, we add a one standard deviation of the innovations to the price shock in period one. In Figure 4.a, where the policy response to inflation increases from $\phi_\pi = 1.5$ to $\phi_\pi = 3$ keeping the policy response to the output gap fixed at $\phi_x = 0.5$, we can see that inflation, the output gap and the nominal interest rate all show weaker responses to the price shock when nominal rigidities are endogenous than when they are exogenously given. By contrast, Figure 4.b illustrates that these three variables show stronger responses when the policy response to the output gap increases from $\phi_x = 0.5$ to $\phi_x = 1$ keeping the policy response to inflation fixed at $\phi_\pi = 1.5$. The intuition for this result is as follows. As a consequence of a more aggressive policy response to inflation relative to the output gap, firms are less likely to reset their prices and hence less likely to reflect current and expected future shocks to their current prices. Therefore, inflation is less responsive to the price shock of the New Keynesian Phillips curve (13). In other words, the coefficient of the price shock, $(1-\alpha)(1-\alpha\beta)/\alpha$, becomes smaller, as shown in Figure 5. The price shock generates a trade-off in monetary policymaking between stabilization of inflation and the output gap, so that the decrease in the price shock coefficient lessens the trade-off in policymaking and hence yields weaker impulse responses of inflation, the output gap and the nominal interest rate. This decrease is empirically supported by Lubik and Schorfheide (2004), who show that the standard deviation of disturbances to the New Keynesian Phillips curve is reduced almost by half in the post-1982 periods compared to in the pre-Volcker periods. More importantly, the decrease in the coefficient of price shocks offers theoretical support for the good policy hypothesis about the U.S. Great Moderation pointed out by Bernanke (2004). That is, small shocks during the Great Moderation are not by good luck but are thanks to the good monetary policy under the chairmanship of Paul Volcker and Alan Greenspan. Figure 6.b shows that a more aggressive policy response to inflation reduces variances of inflation and the output gap under endogenous nominal rigidities. The strong policy stance toward price stability taken by Volcker and Greenspan alters firms' price setting behavior and thereby lessens the trade-off in policymaking between stabilization of inflation and the output gap, resulting in low macroeconomic volatility.

From these results of the positive analysis, we can see that the model with endogenous nominal rigidities provides a realistic framework for monetary policy analysis.

# 4 A normative analysis of endogenous nominal rigidities

We have examined features of endogenous nominal rigidities in response to changes in the Taylor rule and have shown that our model with endogenous nominal rigidities accounts for the empirical evidence in the post-1982 U.S. economy and the Great Moderation.

In this section we do a normative policy analysis, namely, we investigate implications of endogenous nominal rigidities for monetary policy. We first examine how variability of inflation and the output gap changes with the Taylor rule's policy responses. Figure 6 considers the situation in which the policy response to inflation increases from $\phi_\pi = 1.1$ to $\phi_\pi = 3$ with an increment of 0.1 keeping its policy response to the output gap fixed at each value of $\phi_x = 0, 0.5, 1$. In the case of exogenously given nominal rigidities, we set firms' probability of no price adjustment by the benchmark value of $\alpha = 0.585$. Then, as shown in Figure 6.a, when the policy response to inflation becomes more aggressive, it reduces inflation variability but increases output gap variability under each policy response to the output gap. By contrast, in the case of endogenous nominal rigidities, Figure 6.b shows that a more aggressive policy response to inflation lowers both the inflation and output gap variability.

What is the intuition for this difference between the cases of exogenously given nominal rigidities and endogenous ones? The price shock generates the trade-off in monetary policymaking bewteen the stabilization of inflation and the output gap and hence results in the trade-off between variability of inflation and the output gap if nominal rigidities are exogenously given. When the rigidities are endogenous, however, a more aggressive policy response to inflation alters firms' price setting behavior and thereby lessens the trade-off in policymaking, as noted before. Consequently, variability of both inflation and the output gap reduces.

Figure 7 presents the situation in which the Taylor rule's policy response to the output gap increases from $\phi_x = 0$ to $\phi_x = 1$ with an increment of 0.1 keeping its policy response to inflation fixed at each value of $\phi_\pi = 1.1, 1.5, 3$. In the case of exogenously given nominal rigidities, again, Figure 7.a shows the trade-off between variability of inflation and the output gap stemming from the trade-off in policymaking between stabilization of these two variables. A similar result holds in the case of endogenous nominal rigidities, as shown in Figure 7.b. When the policy response to inflation is close to one, a more aggressive policy response to the output gap reduces output gap variability slightly but increases inflation variability substantially. Once the policy response to inflation is strong enough, inflation variability increases slightly and output gap variability decreases for a more aggressive policy response to the output gap. This is because, as shown in Figure 1.b, when the policy response to inflation is close to one, a more aggressive policy response to the output gap decreases the equilibrium probability of no price adjustment $\alpha$ greatly, but once the policy response to inflation is strong enough, the decrease in $\alpha$ is slight.

These results suggest that in the conduct of monetary policy, the cental bank should take into account the feedback effect of its policy stance on firms' price setting. By exploiting this feedback effect, the central bank's aggressive adjustment of the interest rate in response to inflation can reduce variability of both inflation and the output gap. Also, with a sufficiently strong policy response to inflation, the bank can lower the output gap variability by responding aggressively to the output gap at the cost of a slight increase in inflation variability.

We turn next to policy evaluation in terms of social welfare. As shown by Woodford (2003), the maximization of the representative household's utility function is equivalent up to the second order approximation to the minimization of a social welfare loss function of the form

$$\frac{\alpha\theta}{(1-\alpha)(1-\alpha\beta)}V(\pi_t) + \gamma V(x_t) = \frac{\alpha\theta}{(1-\alpha)(1-\alpha\beta)}\left[V(\pi_t) + \frac{\gamma(1-\alpha)(1-\alpha\beta)}{\alpha\theta}V(x_t)\right]. \quad (14)$$

One point of our paper is that the weight of inflation variability of this social welfare loss fucntion depends on nominal rigidities, i.e. the equilibrium probability of no price adjustment $\alpha$. This is because a higher equilibrium probability of no price adjustment enlarges welfare distortions due to price dispersion. In order to clarify this paper's point that the policy evaluation with the relative weight of output gap variability as used in the previous literature induces a misleading policy implication, we also consider a loss function of the form

$$V(\pi_t) + \frac{\gamma(1-\alpha)(1-\alpha\beta)}{\alpha\theta}V(x_t). \quad (15)$$

From Figure 6.b and 7.b, the reader may guess that the desirable Taylor rule reducing losses measured by (15) and enhancing social welfare (14) has aggressive policy responses to both inflation and the output gap. However, Figure 8.a shows that the desirable Taylor rule reducing the losses (15) has an aggressive policy response to inflation but no response to the output gap. This is because when the policy response to inflation is strong enough, the relative weight of output gap variability in (15) is very small, as shown in Figure 9.a. Thus, the policy evaluation with such a small relative weight of output gap variability suggests that the central bank should not repond to the output gap. Yet, this policy suggestion is misleading. Indeed, as shown in Figure 8.b, the desirable Taylor rule enhancing social welfare (14) has a mild policy response to the output gap as well as an aggressive policy response to inflation. In this figure, we can see that no policy response to the output gap is worse than the relatively large response of $\phi_x = 1$ when the policy response to inflation is sufficiently large. Why does the policy evaluation with the relative weight of output gap variability induce the misleading policy implication? The key point is that the weight of inflation variability in the social welfare loss function (14) increases substantially with the equilibrium probability of no price adjustment as shown in Figure 9.b. As a consequence, the policy evaluation with the relative output gap weight heavily underestimates the welfare losses from inflation variability. Therefore, the endogenous inflation weight of the social welfare loss function is critical to policy evaluation under endogenous nominal rigidities.

## 5 Concluding remarks

In this paper we have endogenized nominal rigidities in a Calvo style sticky price model, which has been a canonical model in the recent monetary policy literature, and have examined its implications for monetary policy. Specifically, our model with endogenous nominal rigidities assumes that firms choose the probability of price adjustment so as to maximize their expected profit in the face of fixed costs to set a new price and in response to changes in the monetary policy regime represented by the Taylor rule's policy responses to inflation and the output gap. This is in stark contrast with previous studies which stress that the probability of price adjustment change with steady state inflation. We have shown that when the policy response to inflation becomes more aggressive, firms are less likely to reset their prices, resulting in a flat slope of the New Keynesian Phillips curve as observed in the post-1982 U.S. economy and a small variance of price shocks to the curve as in the Great Moderation. We have also shown that an aggressive policy response to inflation can stabilize both inflation and the output gap by exploiting the feedback effect of the policy stance on firms' price setting. This suggests that in the conduct of monetary policy, the central bank should take into account this feedback effect. Further, we have shown that the endogenous weight of inflation variability in the social welfare loss function is critical to policy evaluation under endogenous nominal rigidities, since this weight increases substantially with the probability of no price adjustment, reflecting welfare distortions due to price dispersion. This implies that the policy evaluation with the relative weight of output gap variability as used in the previous literature induces a misleading policy implication because of its underestimate of the welfare losses from inflation variability.

In monetary policy analysis, uncertainty about inflation dynamics is one of the most crucial issues. Angeloni, Coenen and Smets (2003) and Kimura and Kurozumi (2007), for instance, address the question of how the central bank should conduct monetary policy under such uncertaity.[7] In these studies, however, nominal rigidities are assumed to be exogenously given, so that there is no feedback effect of monetary policy on firms' price setting. Therefore, the previous studies are subject to Lucas' (1976) critique. The same argument can hold true with other issues in monetary policy analysis. Our paper then suggests that the consideration of endogenous nominal rigidities may change the monetary policy implications obtained in the previous literature.

This paper has investigated only the features of endogenous nominal rigidities in response to changes in the monetary policy regime. Our model with endogenous nominal rigidities can also be used for the analysis of how firms alter their price setting behavior in response to changes in the economic environment facing them. For instance, another paper of ours, Kimura, Kurozumi and Hara (2007), explains why and how the traditional Phillips curve in Japan became flat in the past decade. Like this excercise, our model with endogenous nominal rigidities can be applied for various issues in macroeconomics.

[7]See Levin and Moessner (2005) for an overview of this literature.

# Appendix

## A Derivation of (12)

To derive (12), it suffices to show that

$$p^o_{j,t} - p^*_{j,t+k} = \frac{1-\beta\alpha_j}{1-\beta\rho_u\alpha_j}u_t - \sum_{h=1}^{k}\pi_{t+h} - \gamma x_{t+k} - u_{t+k} + l_t(\alpha_j,\alpha). \tag{16}$$

Substituting (9) into (10) yields

$$\begin{aligned} p^o_{j,t} &= (1-\beta\alpha_j)E_t\sum_{k=0}^{\infty}(\beta\alpha_j)^k p^*_{j,t+k} \\ &= (1-\beta\alpha_j)E_t\sum_{k=0}^{\infty}(\beta\alpha_j)^k(p_{t+k}+\gamma x_{t+k}+u_{t+k}) \\ &= (1-\beta\alpha_j)\sum_{k=0}^{\infty}(\beta\alpha_j)^k E_t p_{t+k} + \gamma(1-\beta\alpha_j)\sum_{k=0}^{\infty}(\beta\alpha_j)^k E_t x_{t+k} + \frac{1-\beta\alpha_j}{1-\beta\rho_u\alpha_j}u_t. \end{aligned}$$

Then, this can be reduced to

$$p^o_{j,t} = p_t + \frac{1-\beta\alpha_j}{1-\beta\rho_u\alpha_j}u_t + l_t(\alpha_j,\alpha), \tag{17}$$

since we have

$$\begin{aligned} \sum_{k=0}^{\infty}(\beta\alpha_j)^k E_t p_{t+k} &= \sum_{k=0}^{\infty}(\beta\alpha_j)^k\left(\sum_{h=1}^{k}E_t\pi_{t+h}+p_t\right) \\ &= \sum_{k=0}^{\infty}(\beta\alpha_j)^k\sum_{h=1}^{k}E_t\pi_{t+h} + p_t\sum_{k=0}^{\infty}(\beta\alpha_j)^k \\ &= \frac{1}{1-\beta\alpha_j}\sum_{k=1}^{\infty}(\beta\alpha_j)^k E_t\pi_{t+k} + \frac{1}{1-\beta\alpha_j}p_t. \end{aligned}$$

Finally, using (9) and (17), we have (16).

## References


[1] Angeloni, Ignazio, Luc Aucremanne, Michael Ehrmann, Jordi Galí, Andrew T. Levin, and Frank Smets. 2006. "New Evidence on Inflation Persistence and Price Stickiness in the Euro Area: Implicaitons for Macro Modeling." *Journal of European Economic Association*, 4: 562-574.

[2] Angeloni, Ignazio, Günter Coenen, and Frank Smets. 2003. "Persistence, the Transmission Mechanism and Robust Monetary Policy." *Scottish Journal of Political Economy*, 50: 527-549.

[3] Ball, Laurence, N. Gregory Mankiw, and David Romer. 1988. "The New Keynesian Economics and the Output-Inflation Trade-off." *Brookings Papers on Economic Activity* 1: 1-65.

[4] Ball, Laurence and N. Gregory Mankiw. 1994. "A Sticky-Price Manifesto." *Carnegie-Rochester Conference Series on Public Policy* 41: 127-151.

[5] Ball, Laurence and David Romer. 1990. "Real Rigidities and the Non-Neutrality of Money." *Review of Economic Studies* 57: 183-203.

[6] Bernanke, Ben S. 2004. "The Great Moderation." Speech at the meetings of the Eastern Economic Association, Washington, DC, Febrary 20.

[7] Calvo, Guillermo A. 1983. "Staggered Prices in a Utility-Maximizing Framework." *Journal of Monetary Economics*, 12: 383-398.

[8] Card, David. 1994. "Intertemporal Labor Supply: An Assessment." In *Advances in Econometrics Sixth World Congress*, Vol. 2, eds. Christopher A. Sims, 51-78. Cambridge, U.K.: Cambridge University Press.

[9] Clarida, Richard, Jordi Galí, and Mark Gertler. 2000. "Monetary Policy Rules and Macroeconomic Stability: Evidence and Some Theory." *Quarterly Journal of Economics*, 115: 147-180.

[10] Devereux, Michael B. and James Yetman. 2002. "Menu Costs and the Long-Run Output-Inflation Trade-off." *Economics Letters*, 76: 95-100.

[11] Erceg, Christopher J., Dale W. Henderson, and Andrew T. Levin. 2000. "Optimal Monetary Policy with Staggered Wage and Price Contracts." *Journal of Monetary Economics*, 46: 281-313.

[12] Fernández-Villaverde, Jesús and Juan F. Rubio-Ramirez. 2007. "How Structural Are Structural Parameters?" NBER Working Paper, 13166.

[13] Kiley, Michael T. 2000. "Endogenous Price Stickiness and Business Cycle Persistence." *Journal of Money, Credit, and Banking*, 32: 28-53.

[14] Kimura, Takeshi and Takushi Kurozumi. 2007. "Optimal Monetary Policy in a Micro-Founded Model with Parameter Uncertainty." *Journal of Economic Dynamics and Control*, 31: 399-431.

[15] Kimura, Takeshi, Takushi Kurozumi, and Naoko Hara. 2007. "What Happened to the Phillips Curve in Japan? A Perspective of Endogenous Nominal Rigidities." Mimeo, Bank of Japan.

[16] Levin, Andrew T. and Richhild Moessner. 2005. "Inflation Persistence and Monetary Policy Design: An Overview." European Central Bank Working Paper 539.

[17] Levin, Andrew T. and Tack Yun. 2007. "Reconsidering the Natural Rate Hypothesis in a New Keynesian Framework." *Journal of Monetary Economics*, 54: 1344-1365.

[18] Lubik, Thomas A. and Frank Schorfheide. 2004. "Testing for Indeterminacy: An Application to U.S. Monetary Policy." *American Economic Review*, 94: 190-217.

[19] Lucas, Robert E., Jr. 1976. "Econometric Policy Evaluation: A Critique." *Carnegie Rochester Conference Series on Public Policy*, 1: 19-46.

[20] Pencavel, John. 1986. "Labor Supply of Men: A Survey." In *Handbook of Labor Economics*, vol. 1, eds. Orley C. Ashenfelter and Richard Layard, 3-102. Amsterdam: North-Holland.

[21] Romer, David. 1990. "Staggered Price Setting with Endogenous Frequency of Adjustment." *Economics Letters*, 32: 205-210.

[22] Rotemberg, Julio J. 1987. "The New Keynesian Microfoundations." In *NBER Macroeconomics Annual 1987*, ed. Stanley Fischer, 69-104. Cambridge, MA: MIT Press.

[23] Rotemberg, Julio J. and Michael Woodford. 1997. "An Optimization-Based Econometric Framework for the Evaluation of Monetary Policy." In *NBER Macroeconomics Annual 1997*, eds. Ben S. Bernanke and Julio J. Rotemberg, 297-346. Cambridge, MA: MIT Press.

[24] Smets, Frank and Rafael Wouters. 2007. "Shocks and Frictions in US Business Cycles: A Bayesian DSGE Approach." *American Economic Review*, 97: 586-606

[25] Taylor, John B. 1993. "Discretion Versus Policy Rules in Practice." *Carnegie-Rochester Conference Series on Public Policy* 39: 195-214.

[26] Taylor, John B. 1999. "A Historical Analysis of Monetary Policy Rules." In *Monetary Policy Rules*, ed. John B. Taylor, 319-341. Chicago: University of Chicago Press.

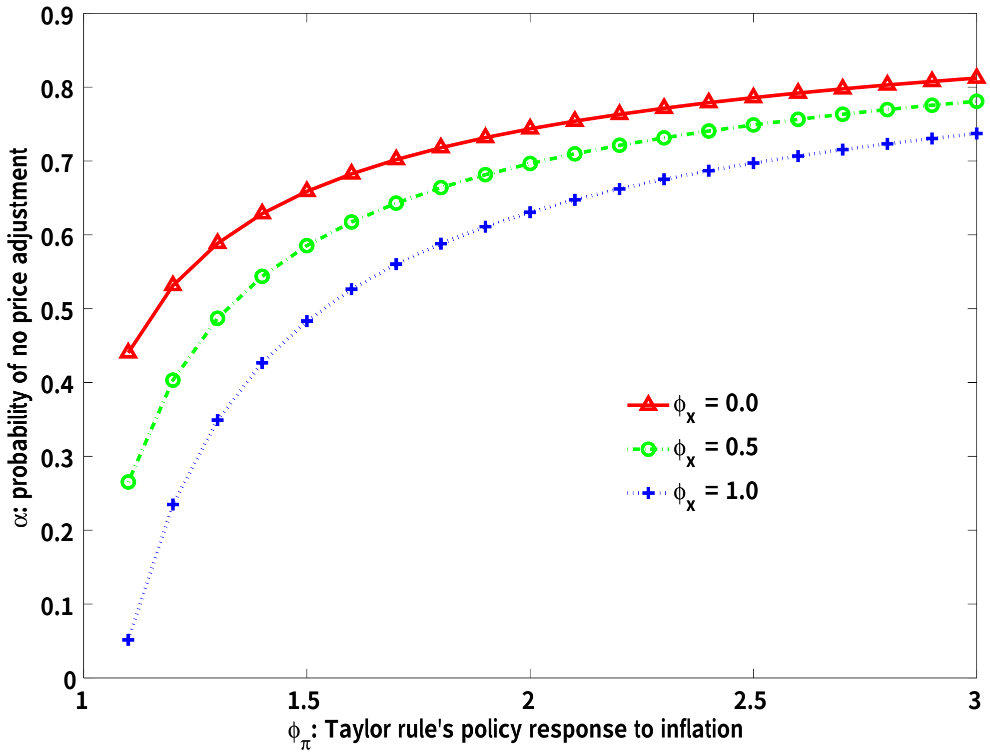
[27] Walsh, Carl E. 2003. *Monetary Theory and Policy, Second Edition*, Cambridge, MA: MIT Press.

[28] Woodford, Michael. 2003. *Interest and Prices. Foundations of a Theory of Monetary Policy*. Princeton: Princeton University Press.

[29] Zbaracki, Mark J., Mark Ritson, Daniel Levy, Shantanu Dutta, and Mark Bergen. 2004. "Managerial and Customer Costs of Price Adjustment: Direct Evidence from Industrial Markets." *Review of Economics and Statistics*, 86: 514-533.

Table 1: Baseline calibration for the model

| | | |
|---|---|---|
| $\beta$ | discount factor | 0.99 |
| $\sigma$ | relative risk aversion | 1.86 |
| $\eta$ | inverse of labor supply elasticity | 1/0.15 |
| $\theta$ | price elasticity of demand | 7.88 |
| $a$ | labor elasticity of production | 0.7 |
| $\rho_r$ | persistence parameter of natural interest rate shocks | 0.83 |
| $v_r$ | variance of innovations to natural interest rate shocks | $(0.18\,\sigma)^2$ |
| $\rho_u$ | persistence parameter of price shocks | 0.85 |
| $v_u$ | variance of innovations to price shocks | $(0.64\,\gamma)^2$ |
| $F$ | fixed cost to set a new price | 3.22 |



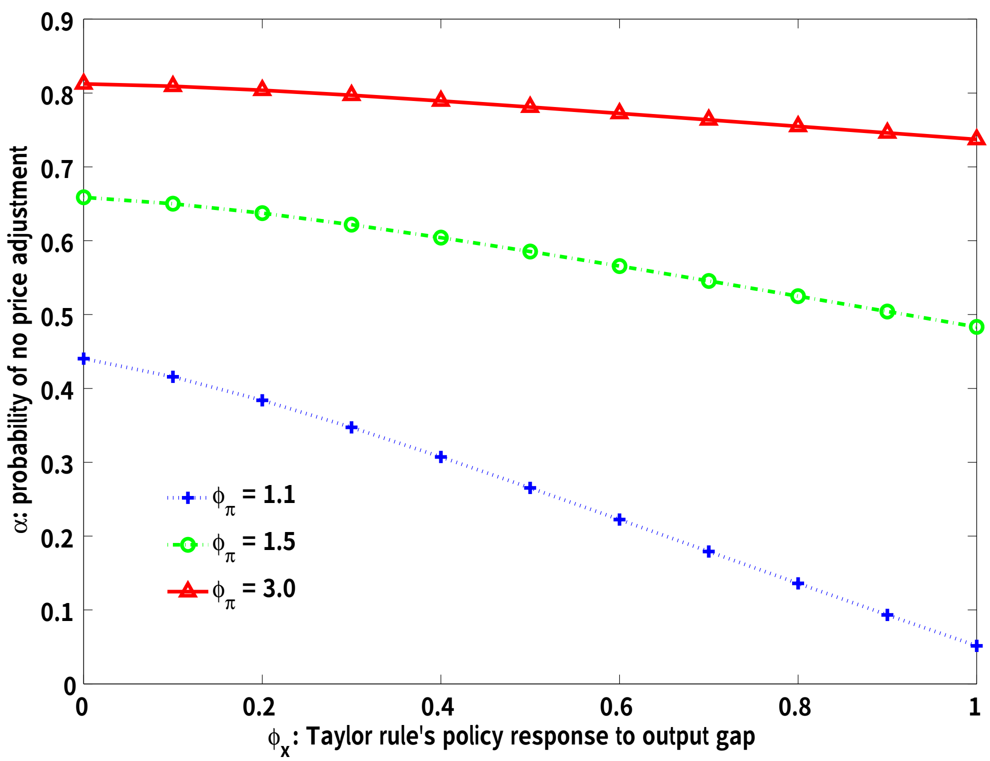




Figure 1: Taylor rule's policy responses and endogenous nominal rigidities.

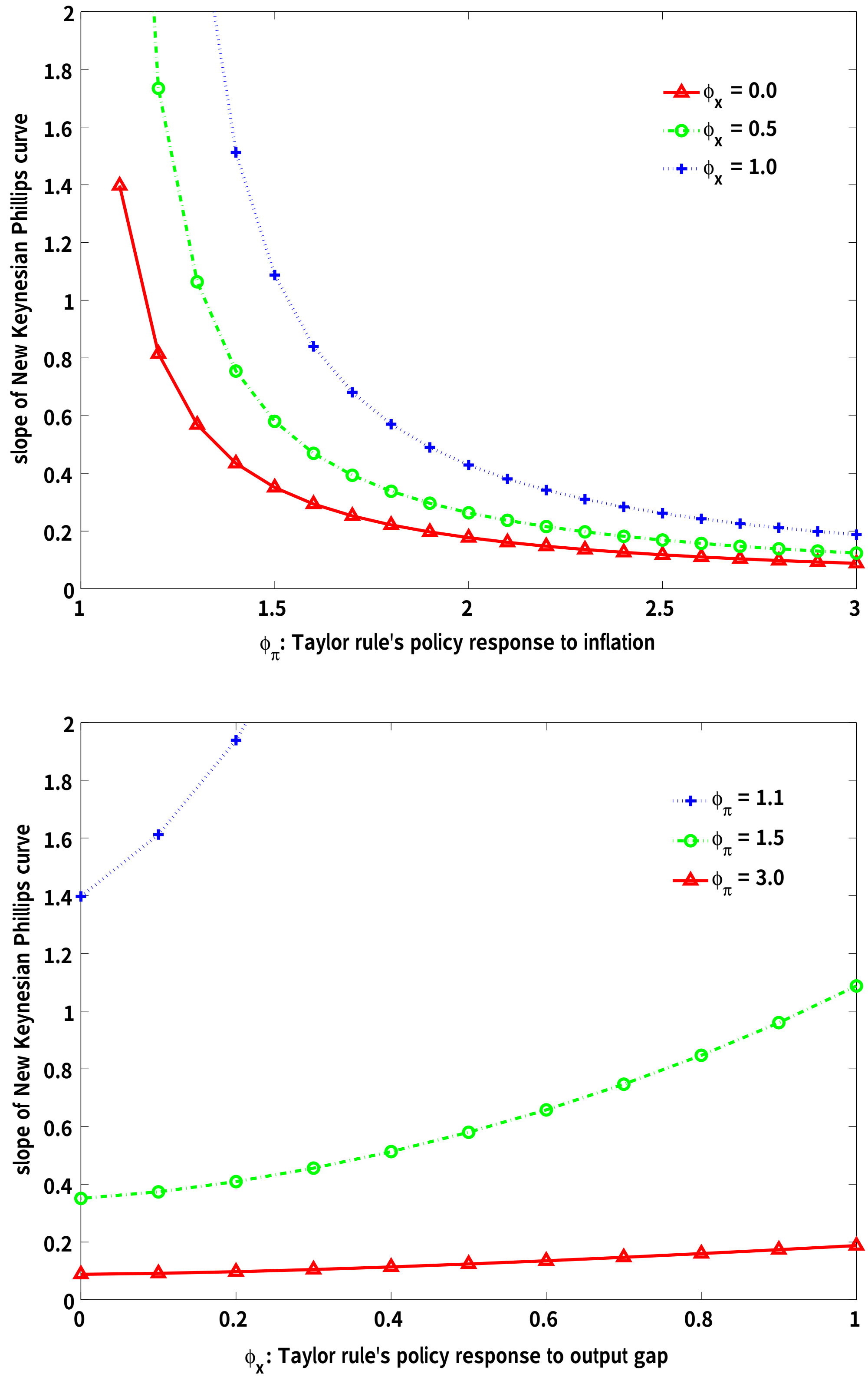



Figure 2: Taylor rule's policy responses and the slope of New Keynesian Phillips curve.

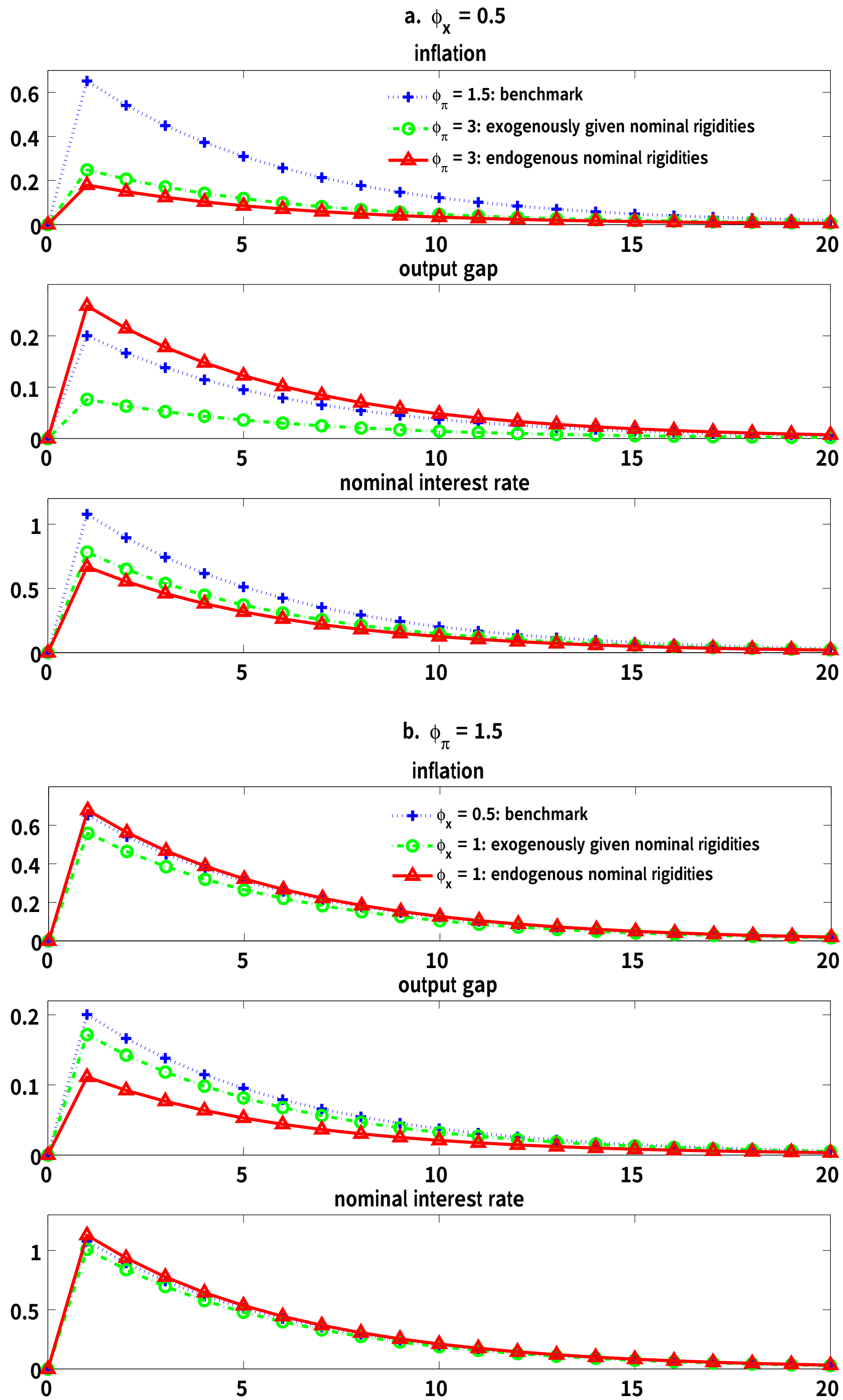



Figure 3: Impulse responses to natural interest rate shocks.

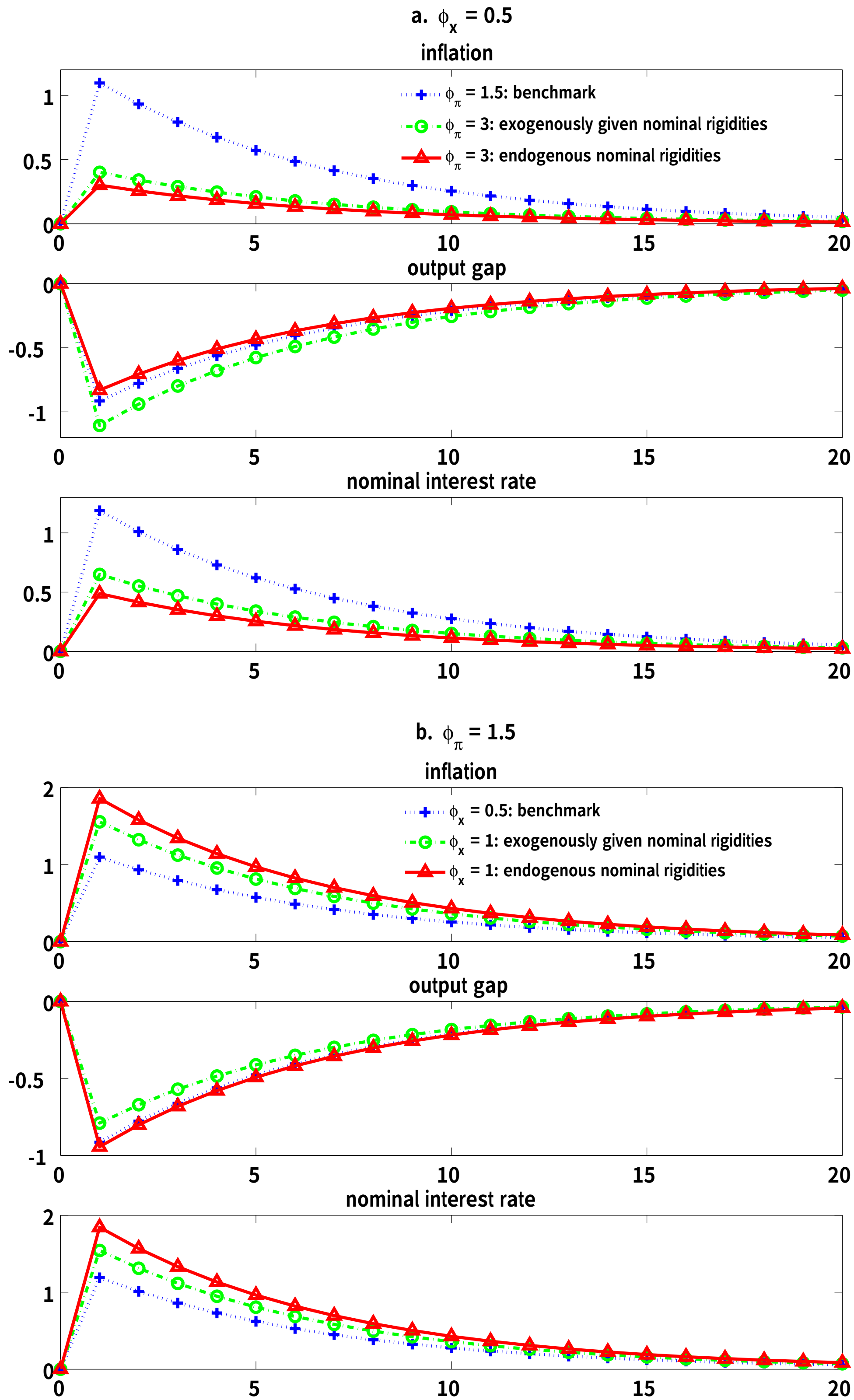



Figure 4: Impulse responses to price shocks.

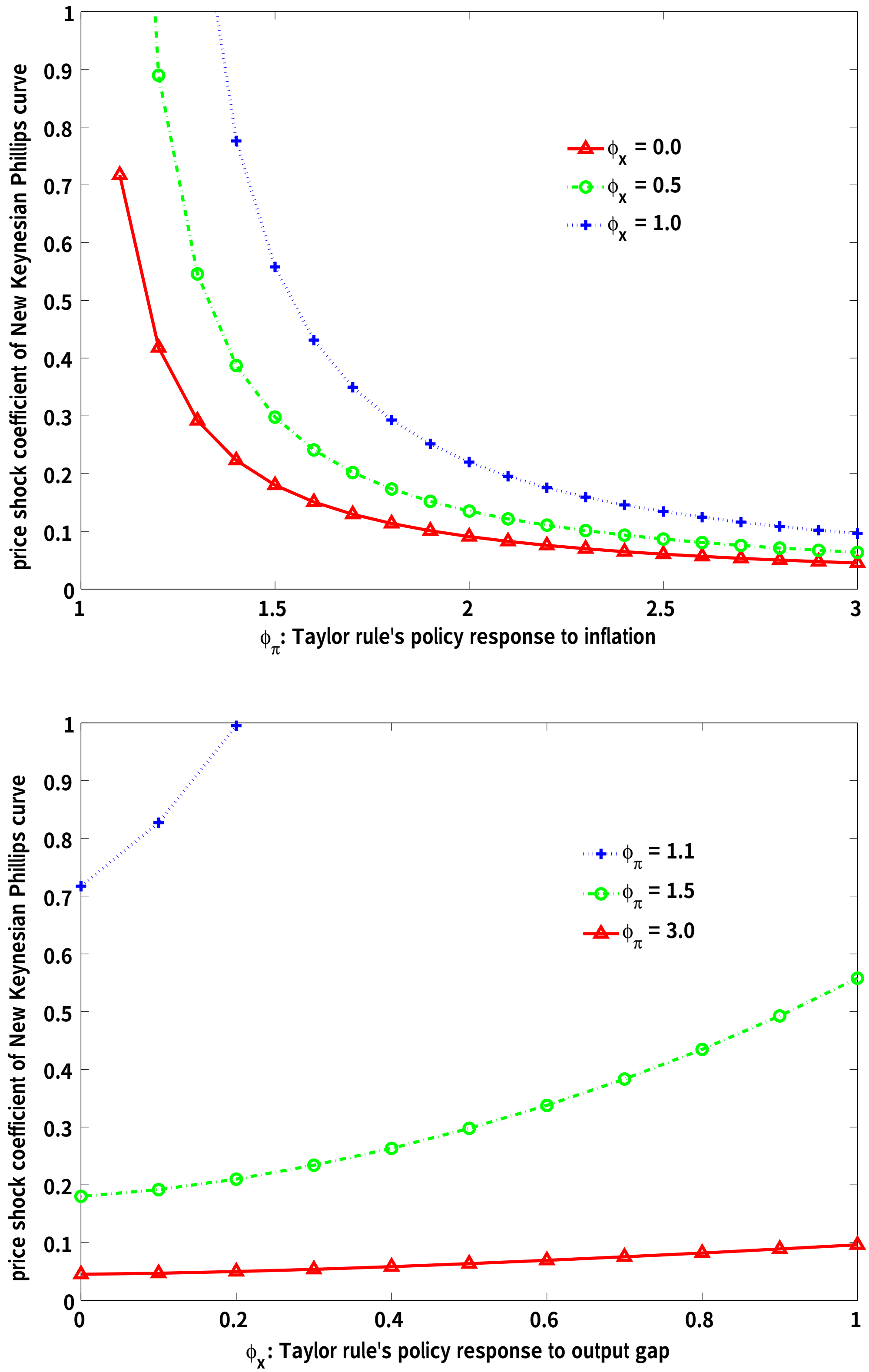



Figure 5: Taylor rule's policy responses and the price shock coefficient of New Keynesian Phillips curve.

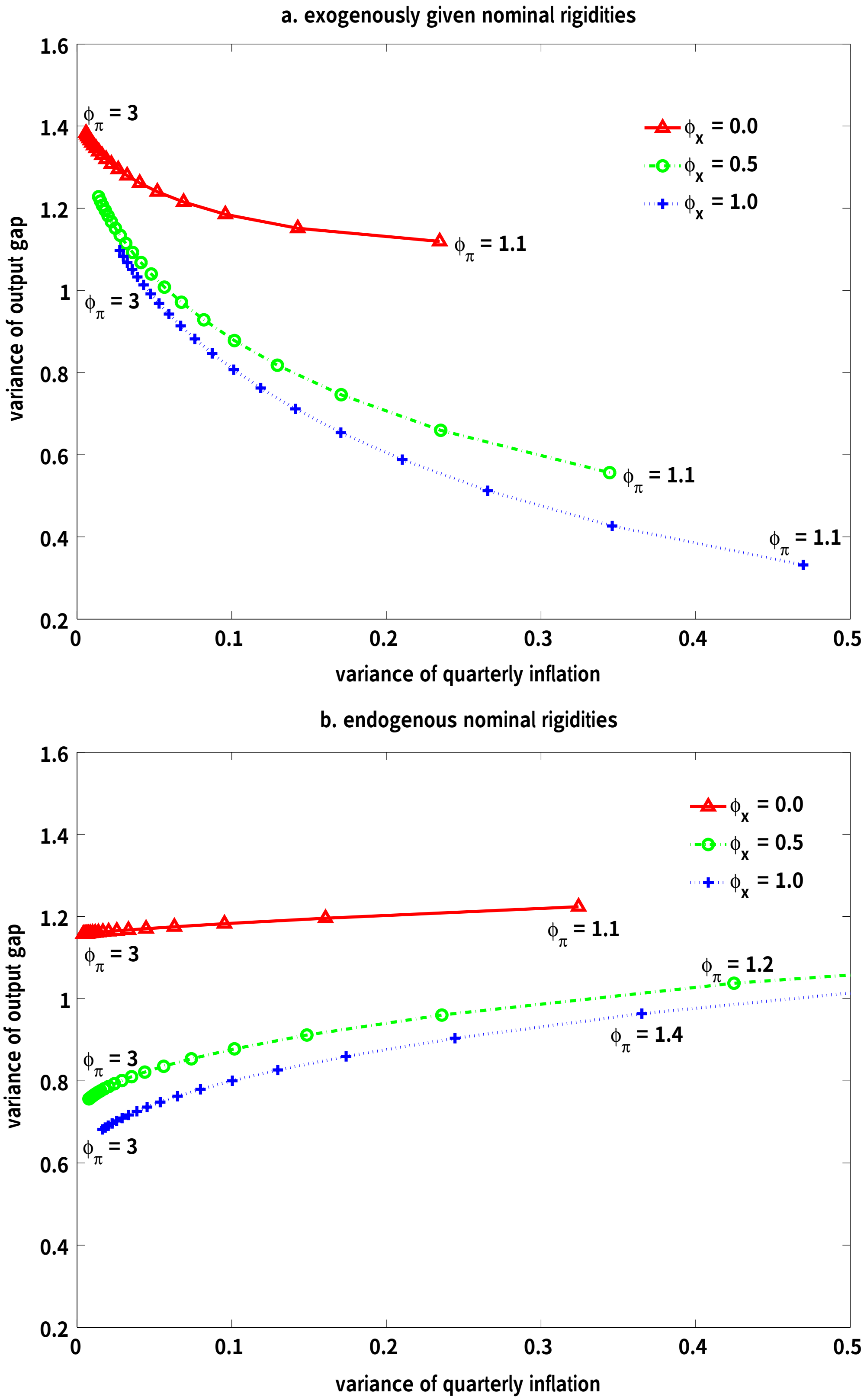



Figure 6: Macroeconomic volatility and Taylor rule's policy response to inflation.

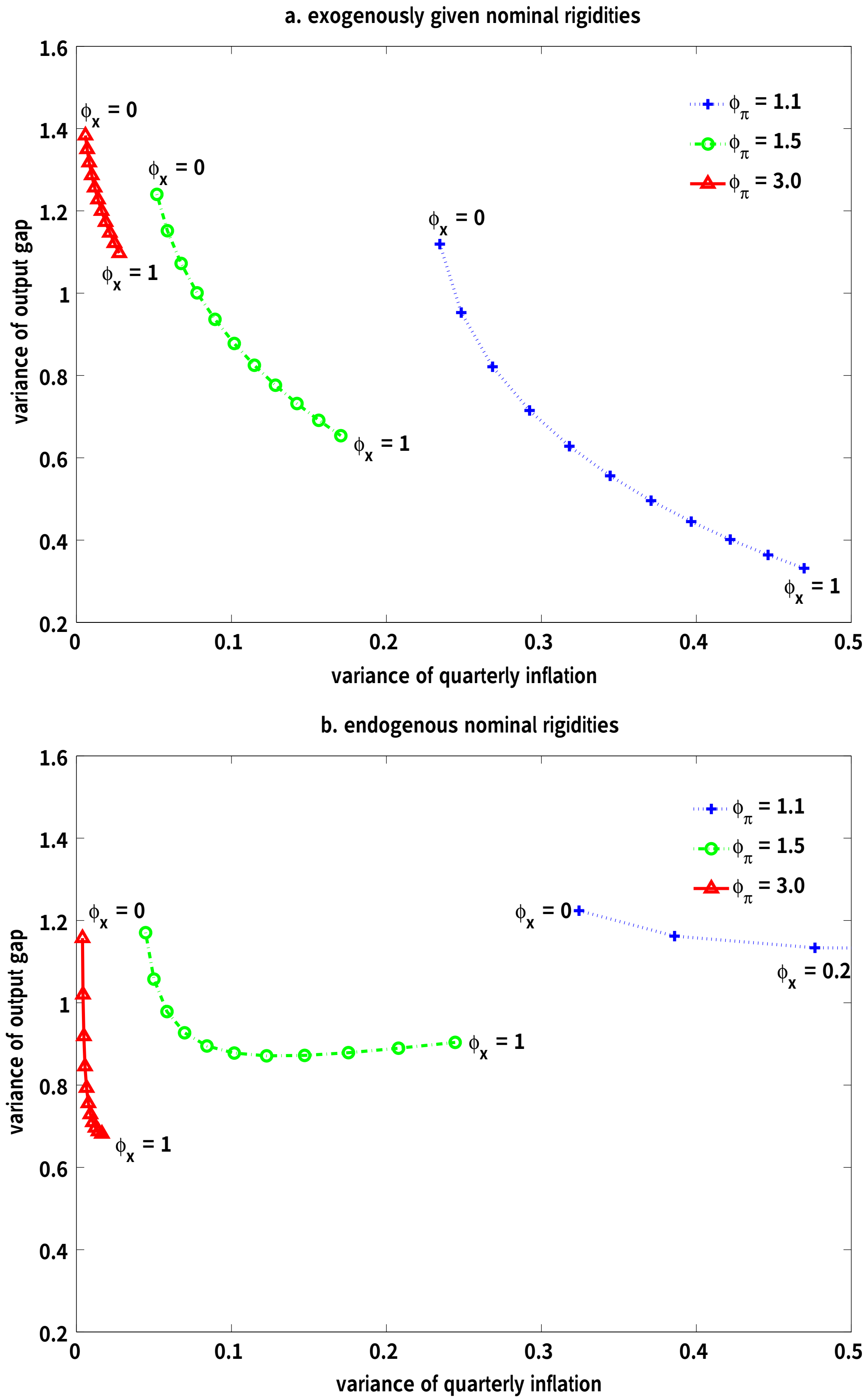
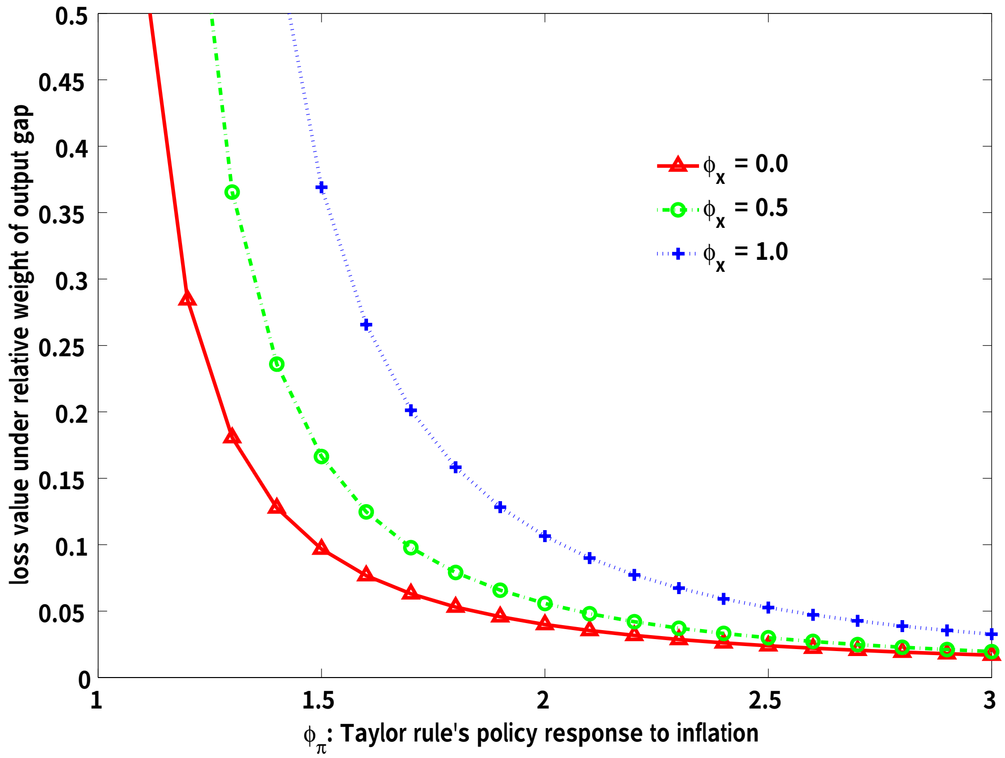



Figure 7: Macroeconomic volatility and Taylor rule's policy response to the output gap.



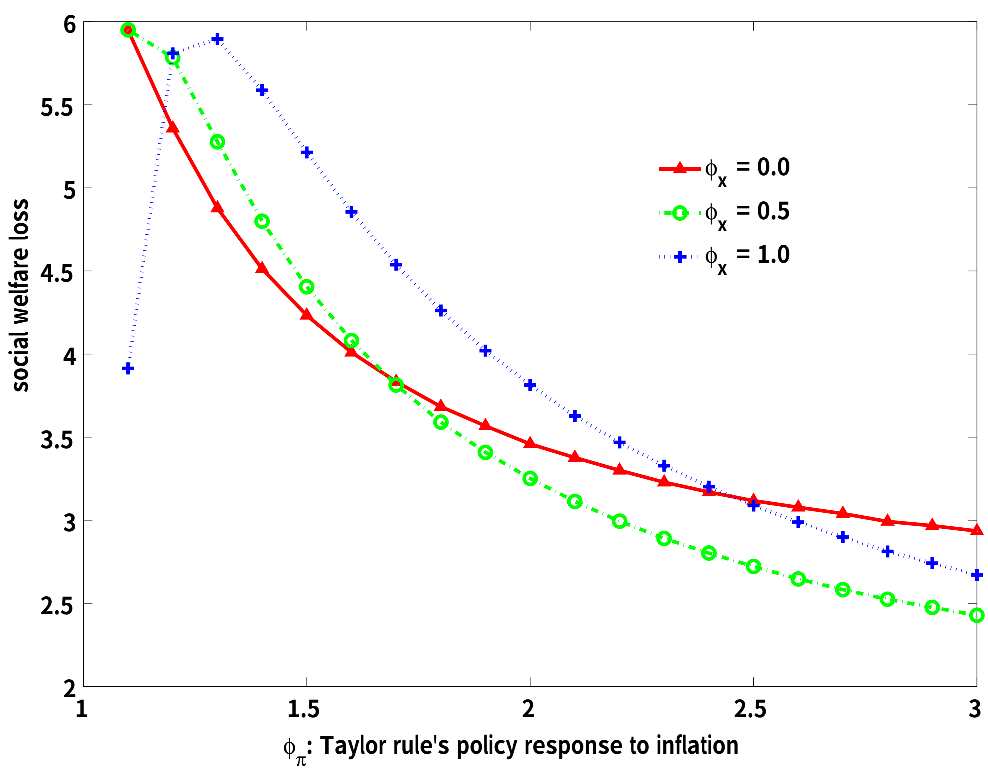




Figure 8: Relative vs. absolute weights.

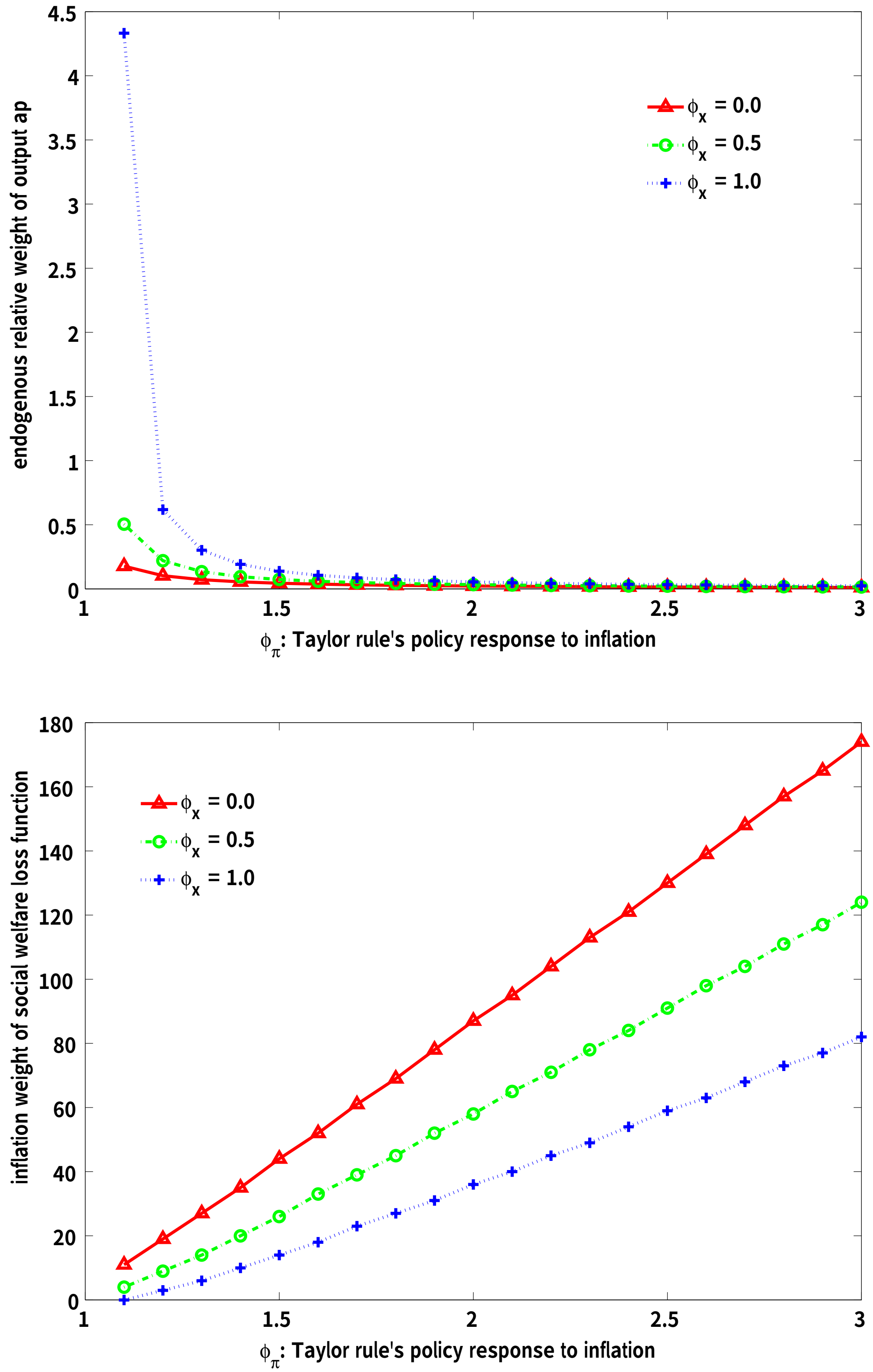



Figure 9: Relative output gap weight and absolute inflation weight.