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Endogenous Nominal Rigidities and Monetary Policy

Takeshi Kimura*
takeshi.kimura@boj.or.jp

Takushi Kurozumi**
takushi.kurozumi@boj.or.jp

Naoko Hara**
naoko.hara@boj.or.jp

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Bank of Japan
2-1-1 Nihonbashi Hongoku-cho, Chuo-ku, Tokyo 103-8660

* Financial Markets Department
** Research and Statistics Department

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Takeshi Kimura[†] Takushi Kurozumi[‡] Naoko Hara[§]

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Abstract

Recent empirical literature suggests that the degree of nominal rigidities varies over monetary policy regimes. This implies that monetary policy analysis with exogenously given nominal rigidities is subject to the Lucas critique. In a Calvo-style sticky price model, we endogenize nominal rigidities and examine their implications for monetary policy. While some previous studies stress that the frequency of price adjustment changes with a central bank's inflation target, we focus on how this frequency varies in response to changes in policy coefficients of the Taylor rule with a fixed inflation target. We find that a central bank's more aggressive policy response to inflation makes firms less likely to reset their prices. The resulting New Keynesian Phillips curve contains a flatter slope and a smaller variance of disturbances, as observed during the Volcker-Greenspan era. We also find that a central bank's aggressive policy response to inflation can stabilize both inflation and the output gap by exploiting the feedback effects of the bank's policy response on firms' price setting. This supports the good policy hypothesis about the Great Moderation. Finally, we show that changes in the policy coefficients dramatically affect the inflation weight of the social welfare loss function, since this weight increases nonlinearly with the frequency of no price adjustment. To reduce social welfare loss, it is crucial for central banks to take into account that the inflation weight changes endogenously with their policy stances.

JEL classification: E31; E32; E52

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

[‡]Research and Statistics Department, Bank of Japan. 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 these rigidities, monetary policy can exert an influence on real economic activities and its policy impact depends greatly on the degree of the rigidities. Therefore, in order to discuss desirable monetary policy, a model that accurately describes nominal rigidities 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 monetary policy 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. Most recent studies consider the frequency of price adjustment given in these models as a structural parameter in evaluating alternative policy choices. Obviously, such policy evaluation is inappropriate if the frequency depends on the policy choices. In fact, a recent empirical work by Fernández-Villaverde and Rubio-Ramírez (2008) addresses empirically the question of "How structural are structural parameters?" and finds that the frequency of price adjustment has varied over the years in the United States. It particularly changed sometime after Paul Volcker assumed the chairmanship of the Federal Reserve. This empirical finding indeed suggests that monetary policy analysis with exogenously given nominal rigidities is subject to the 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 the cost involved to set a new price. Our approach for endogenous nominal rigidities is similar to previous studies, such as Ball, Mankiw and Romer (1988), Romer (1990), Kiley (2000), Devereux and Yetman (2002), and Levin and Yun (2007). Yet, our analysis differs from theirs in the following important way. These previous studies consider that the probability of price adjustment is chosen in response to changes in steady state inflation or a central bank's inflation target. In this setting, even when the stance of monetary policy changes significantly, the nominal rigidities remain constant unless there are changes in the inflation target. By contrast, we assume that firms choose the probability in response to changes in the Taylor (1993) rule's policy responses to inflation and the output

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

gap. As emphasized in the recent literature, such as Taylor (1999), Clarida, Galí and Gertler (2000), and Lubik and Schorfheide (2004), these policy responses are one of the most important aspects determining the monetary policy stance. We thus allow the degree of nominal rigidities to change according to such policy responses.

In our setting of endogenous nominal rigidities, we examine their implications for monetary policy. Our main findings are the following three.

First of all, a central bank's more aggressive policy response to inflation makes firms less likely to reset their prices and the resulting New Keynesian Phillips curve contains a flatter slope and a smaller variance of disturbances. This is in stark contrast to recent monetary policy studies with exogenously given nominal rigidities. When the central bank responds more aggressively to inflation, each firm's relative price becomes more stable, and thus firms are less likely to reset their prices due to the cost involved to set a new price. This makes the aggregate price and hence inflation less responsive to the output gap, resulting in a flatter slope of the Phillips curve. It also makes inflation less responsive to price shocks (e.g., price markup shocks). As a consequence, the variance of disturbances to the Phillips curve becomes smaller. This is because these disturbances are represented as a price shock multiplied by its coefficient, and the central bank's more aggressive policy response to inflation reduces this coefficient, keeping the variance of the price shock constant. These results are consistent with the findings of the recent empirical literature. Taylor (1999), Clarida, Galí and Gertler (2000), Lubik and Schorfheide (2004) and others show that the Taylor rule contained a much stronger response to inflation in the Volcker-Greenspan period than in the pre-Volcker period. During the same periods, Smets and Wouters (2007) and Fernández-Villaverde and Rubio-Ramírez (2008) find that firms' probability of price adjustment became lower and Lubik and Schorfheide (2004) indicate that the Phillips curve included a flatter slope and a smaller variance of disturbances.

Second, a central bank's aggressive policy response to inflation can stabilize both inflation and the output gap by exploiting the feedback effects of the policy response on firms' price setting. As noted above, a more aggressive policy response to inflation reduces the variance of disturbances to the Phillips curve. Since these disturbances induce a trade-off in monetary policymaking between the stabilization of inflation and the output gap, a smaller variance of the disturbances reduces this trade-off and therefore the central bank can stabilize both inflation and the output gap by responding aggressively to inflation. Thus, taking into account the feedback effects of the central bank's policy stance on firms' price setting is of crucial importance for the conduct of monetary policy. This result offers theoretical support for the good policy hypothesis about the Great Moderation suggested by Bernanke (2004). He points out that the aggressive policy stance toward price stability taken by Paul Volcker and Alan Greenspan affects firms' price-setting behavior and reduces a policymaking trade-off between the stabilization of inflation and real economic activities, thereby stabilizing macroeconomic volatility successfully.

Last but not least, changes in the policy responses dramatically affect the inflation weight of the social welfare loss function. In the model, the maximization of a second-order approximation to a representative household's utility function is equivalent to the minimization of a weighted sum of variances of inflation and the output gap. The inflation weight then increases nonlinearly with the probability of no price adjustment, because an increase in this probability enlarges welfare distortions due to price dispersion. Since the probability of no price adjustment varies with the policy responses, it is crucial for central banks to take into account that the inflation weight changes endogenously with their policy stances. To enhance social welfare, an aggressive policy response to inflation is critical because it can lower both variances of inflation and the output gap. In the absence of the policy response to the output gap, however, an aggressive policy response to inflation induces a large welfare loss from inflation variability, since it leads to a high probability of no price adjustment and hence a large inflation weight. Therefore, to reduce social welfare loss, monetary policy should contain not only an aggressive response to inflation but also a moderate response to the output gap. Although the aggressive response to inflation increases the probability of no price adjustment, the moderate response to the output gap limits such an increase in the probability, thereby preventing the inflation variability from being too costly.

The remainder of the paper proceeds as follows. Section 2 endogenizes nominal rigidities in a Calvo-style sticky price model. Section 3 examines their implications for the resulting New Keynesian Phillips curve and macroeconomic volatility. Section 4 investigates the welfare implications. 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 a canonical model of monetary policy in the recent literature (Walsh, 2003;

Woodford, 2003). Our approach for endogenous nominal rigidities is similar to previous studies, such as Ball, Mankiw and Romer (1988), Romer (1990), Kiley (2000), Devereux and Yetman (2002), and Levin and Yun (2007). That is, we consider firms which choose the probability of price adjustment so as to maximize their expected profit in the face of the cost involved 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 has preferences over C_t consumption of final goods and H_t labor supply, represented by the utility function

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

where E denotes the expectations operator, $\beta \in (0,1)$ is the discount factor, $\sigma > 0$ measures the relative risk aversion, $\eta \geq 0$ is the inverse of the labor supply elasticity, g_t represents a preferences shock, and μ_t^w reflects a friction in the labor market that pushes real wages away from their competitive equilibrium values as in Clarida, Galí and Gertler (2001). The household's budget constraint is given by

$$P_tC_t + B_t = W_tH_t + (1+i_{t-1})B_{t-1} + T_t,$$

where P_t is the price of final goods, W_t denotes the nominal wage, T_t is the 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.

The optimality conditions for the utility maximization with respect to consumption, bond holdings and labor supply then yield

$$C_t^{-\sigma}\exp(g_t) = \beta E_t\left[C_{t+1}^{-\sigma}\exp(g_{t+1})\frac{1+i_t}{1+\pi_{t+1}}\right], \tag{2}$$

$$\frac{H_t^{\eta}\exp(\mu_t^w)}{C_t^{-\sigma}\exp(g_t)} = \frac{W_t}{P_t}, \tag{3}$$

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. By log-linearizing (2) and using the final-goods market

[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 fiscal side of government.

clearing condition $C_t = Y_t$, we have households' Euler equation for optimal spending decisions in terms of the output gap $x_t = y_t - y_t^*$

$$x_t \;=\; E_t x_{t+1} - \sigma^{-1} \left(i_t - E_t \pi_{t+1} - r_t^* \right). \tag{4}$$

Here, y_t and y_t^* are the logs of aggregate output Y_t and its flexible price counterpart that would obtain in the absence of nominal rigidities and variations in the labor market friction and the price markup. Also, r_t^* denotes the natural rate of interest given by $r_t^* = r^* + (g_t - E_t g_{t+1}) - \sigma(y_t^* - E_t y_{t+1}^*)$ and r^* is its steady state value, and thus 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 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

$$i_t \;=\; r^* + \pi^* + \phi_\pi (\pi_t - \pi^*) + \phi_x x_t, \tag{5}$$

where π^* is the bank's target for the inflation rate, which is assumed to be zero for simplicity, and ϕ_π, ϕ_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 continuum of intermediate-goods firms $j \in [0, 1]$, each of which produces and sells one kind of differentiated goods under monopolistic competition. Using these intermediate goods, final-goods firms produce and sell homogeneous goods to households under perfect competition.

A representative final-goods firm produces aggregate output Y_t by choosing intermediate inputs $\{Y_{j,t}^d\}$ so as to maximize profit $P_t Y_t - \int_0^1 P_{j,t} Y_{j,t}^d dj$, where $P_{j,t}$ is the price of intermediate goods j, subject to the CES production technology $Y_t = [\int_0^1 (Y_{j,t}^d)^{(\theta_t - 1)/\theta_t} dj]^{\theta_t/(\theta_t - 1)}$, where $\theta_t > 1$ measures the time-varying price elasticity of demand for intermediate goods and induces variations in the price markup. The optimality conditions for the final-goods firm's profit maximization imply its demand for intermediate goods given by $Y_{j,t}^d = Y_t (P_{j,t}/P_t)^{-\theta_t}$, while perfect competition in the final-goods market implies that its price P_t satisfies

$$P_t = \left(\int_0^1 P_{j,t}^{1-\theta_t} dj \right)^{\frac{1}{1-\theta_t}}. \tag{6}$$

Each intermediate-goods firm j produces output $Y_{j,t}$ using the production technology $Y_{j,t} = \exp(z_t)H_{j,t}$, where z_t is an aggregate productivity shock and $H_{j,t}$ is labor input of firm j. Then, all intermediate-goods firms face the same real marginal cost $MC_t = (W_t/P_t)/\exp(z_t)$. These firms set prices of their products, paying a nonnegligible amount of cost $F > 0$. This cost is indeed sufficiently large as emphasized by a recent empirical work of Zbaracki et al. (2004), who find that in setting a new price, firms pay not only managerial costs (i.e. information gathering, decision-making, and communication costs), which are six times larger than menu costs, but also customer costs (i.e. communication and negotiation costs), which are twenty times larger. We assume as in the recent monetary policy literature that each intermediate-goods firm's probability of resetting its price in the subsequent period is independent of this firm's past history of price adjustment. Let α_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 is proportional to, up to second order, $L_t(\alpha_j, \alpha)$ given by

$$L_t(\alpha_j, \alpha) = F + \min_{p_{j,t}} E_t \sum_{k=0}^{\infty} (\beta\alpha_j)^k \left(p_{j,t} - p^*_{j,t+k}\right)^2 + \beta(1-\alpha_j) \sum_{k=1}^{\infty} (\beta\alpha_j)^{k-1} E_t L_{t+k}(\alpha_j, \alpha), \tag{7}$$

where α is other firms' probability of no price adjustment, $p_{j,t}$ is the log price of goods j set by firm j in period t, and $p^*_{j,t}$ denotes the log price of goods j that would obtain if the nominal rigidities were absent in period t. On the right-hand side of (7), the first and second terms reflect, respectively, the cost to set a new price in period t and a loss in profit from keeping this price unchanged thereafter. The final term represents the sum of losses in profit from setting a new price in some future period and then keeping it unchanged thereafter. Letting p_t be the log of the aggregate price P_t, mc_t denote log-deviation of the real marginal cost MC_t from its steady state value, and μ_t represent a price markup shock (i.e. log-deviation of the time-varying price markup from its steady state value), the desired price $p^*_{j,t}$ is given by

$$p^*_{j,t} = p_t + mc_t + \mu_t = p_t + \gamma x_t + u_t, \tag{8}$$

where the second equality follows from the relationship between the real marginal cost and the output gap, $mc_t = \gamma x_t + \mu_t^w$, where $\gamma = \sigma + \eta$,[3] and the definition of price shock, $u_t = \mu_t + \mu_t^w$. This shock represents not only the price markup shock μ_t but also the labor market friction μ_t^w. 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 the expected loss in profit under optimal staggered price setting. In the second step, given this chosen probability, the firm sets an optimal staggered price. To solve this two-step problem, we first begin with the second step. The optimal staggered price in period t, which solves the minimization problem in (7), is given by

$$p_{j,t}^o = (1 - \beta\alpha_j) E_t \sum_{k=0}^{\infty} (\beta\alpha_j)^k p_{j,t+k}^* = (1 - \beta\alpha_j) E_t \sum_{k=0}^{\infty} (\beta\alpha_j)^k \left(p_{t+k} + \gamma x_{t+k} + u_{t+k}\right), \tag{9}$$

where the second equality follows from (8). Next, we consider firms' choice of the probability of price adjustment, namely, we endogenize nominal rigidities in our model. The optimality condition for firm j's choice of the probability $\partial EL_t(\alpha_j, \alpha)/\partial \alpha_j = 0$ is given by

$$F + E \sum_{k=0}^{\infty} (\beta\alpha_j)^{k-1} \left[\beta\alpha_j - k(1 - \beta\alpha_j)\right] \left(p_{j,t}^o - p_{j,t+k}^*\right)^2 = 0, \tag{10}$$

where the Envelope Theorem is used to exclude terms reflecting the fact that firm j's optimal staggered price $p_{j,t}^o$ changes with its choice of the probability α_j. As shown in the Appendix, substituting (8) and (9) into (10) yields

$$\begin{aligned} F + \sum_{k=0}^{\infty} (\beta\alpha_j)^{k-1} &\left[\beta\alpha_j - k(1 - \beta\alpha_j)\right] \\ &\times V\left[\frac{1 - \beta\alpha_j}{1 - \beta\rho_u\alpha_j} u_t - \sum_{h=1}^{k} \pi_{t+h} - \gamma x_{t+k} - u_{t+k} + l_t(\alpha_j, \alpha)\right] = 0, \end{aligned} \tag{11}$$

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 α to be a Nash equilibrium is that the optimality condition (11) holds at $\alpha_j = \alpha$ for every firm j. Then, in such an equilibrium, the aggregate price (6) yields

$$p_t = (1 - \alpha) p_{j,t}^o + \alpha p_{t-1} \tag{12}$$

[3]This relationship can be derived from households' utility-maximizing labor supply condition (3) and firms' cost-minimizing labor input condition $MC_t = (W_t/P_t)/\exp(z_t)$. Note that we consider a flexible price equilibrium in which the price markup remains at its steady state value and there is no friction in the labor market as in Clarida, Galí and Gertler (2001).

and combining (8), (9) and (12) leads to the so-called New Keynesian Phillips curve

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

This suggests that our model indeed endogenizes nominal rigidities in the recently canonical model of monetary policy. The equilibrium probability α can be obtained as follows. Given an α, we solve the system consisting of households' Euler equation (4), the Taylor rule (5), and the Phillips curve (13). We then substitute the obtained equilibrium processes of inflation and the output gap into the right-hand side of the optimality condition (11) with $\alpha_j = \alpha$. Note that the equilibrium processes are unique because this uniqueness is ensured by the assumed Taylor principle. We continue this procedure until we find an α that meets (11) with $\alpha_j = \alpha$. In the next section, we examine features of the equilibrium probability of price adjustment.

3 Implications for Phillips curve and macroeconomic volatility

In this section, we examine implications of the endogenous nominal rigidities introduced above for the New Keynesian Phillips curve and macroeconomic volatility.

3.1 Calibration of model parameters

The ensuing analysis uses a realistic calibration of the model parameters. Our calibration for the quarterly model with annualized inflation and interest rates is summarized in Table 1. As in line with the literature, we set the discount factor at $\beta = 0.99$ and the inverse of the labor supply elasticity at $\eta = 1$. 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 $\gamma = \sigma + \eta$. Finally, we set each firm's price-setting cost at $F = 5.8$ in a similar way to Devereux and Yetman (2002).[4] Lubik and Schorfheide (2004) show that the estimated slope of the Phillips curve (13) is 0.58. Then, the parameter values

[4]This value of F is comparable to its corresponding value in Dotsey, King and Wolman (1999) and Levin and Yun (2007), i.e. 2.9. We also consider this calibration of $F = 2.9$, which generates $\alpha = 0.546$ together with the benchmark calibration of other model parameters and the monetary policy responses of $\phi_\pi = 1.5$ and $\phi_x = 0.5$. Such lower price-setting cost makes firms more likely to reset their prices and the resulting Phillips curve contains a steeper slope and a larger coefficient of the price shock. This, however, does not change the qualitative properties of the results obtained with the benchmark calibration of $F = 5.8$.

specified above generate $\alpha = 0.642$ from the equation $\gamma(1-\alpha)(1-\alpha\beta)/\alpha = 0.58$. This value of α is in line with the recent monetary policy literature (Woodford, 2003). The price-setting cost F is chosen so that the optimality condition (11) with $\alpha_j = \alpha$ holds at $\alpha = 0.642$ when the policy responses to inflation and the output gap in (5) are set at Taylor's (1993) estimates of $\phi_\pi = 1.5$ and $\phi_x = 0.5$.[5]

3.2 Monetary policy stance and nominal rigidities

We now examine features of endogenous nominal rigidities in response to changes in the stance of monetary policy.

3.2.1 Effects of monetary policy stance toward price stability

We first consider the effects of changes in the policy stance toward price stability. The upper panel of Figure 1 shows how an increase in the policy response to inflation from $\phi_\pi = 1.1$ to $\phi_\pi = 3$ alters the equilibrium probability of no price adjustment α in the three cases of the policy response to the output gap $\phi_x = 0, 0.5, 1$. In this figure, we can see that for each policy response to the output gap, the probability of no price adjustment becomes higher as the policy response to inflation increases. For instance, in the case of the policy response to the output gap of $\phi_x = 0.5$, the probability of no price adjustment is $\alpha = 0.383$ under $\phi_\pi = 1.1$, $\alpha = 0.642$ under $\phi_\pi = 1.5$, and $\alpha = 0.808$ under $\phi_\pi = 3$. This suggests that in the face of a central bank's more aggressive policy response to inflation, firms become less likely to reset their prices. Also, we can see that when the policy response to inflation is close to one, a rise in this policy response increases the probability of no price adjustment significantly, but this increase in the probability diminishes as the policy response becomes more aggressive.

The intuition for this result is as follows. If the aggregate price p_t is volatile, (8) implies that the desired price $p^*_{j,t}$ is also volatile. Then, firms are likely to reset their prices even by paying the cost to set a new price. On the contrary, when the aggregate price becomes more stable as a consequence of a 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 its cost. Consequently, firms become less likely to reset their prices.

[5]This computation of the price-setting cost F is based on quarterly, but not annualized, data generated by the system of households' Euler equation (4), the Taylor rule (5), and the Phillips curve (13).

3.2.2 Effects of monetary policy stance toward output gap stability

We turn next to the effects of changes in the policy stance toward stability of the output gap. The lower panel of Figure 1 shows how an increase in the policy response to the output gap from $\phi_x = 0$ to $\phi_x = 1$ alters the equilibrium probability of no price adjustment α in the three cases of the policy response to inflation $\phi_\pi = 1.1, 1.5, 3$. This figure illustrates that for each policy response to inflation, the probability of no price adjustment becomes lower as the policy response to the output gap increases. For instance, in the case of the policy response to inflation of $\phi_\pi = 1.5$, the probability of no price adjustment is $\alpha = 0.703$ under $\phi_x = 0$, $\alpha = 0.642$ under $\phi_x = 0.5$, and $\alpha = 0.560$ under $\phi_x = 1$. Thus, in the face of a central bank's more aggressive policy response to the output gap, firms become more likely to reset their prices. The figure also shows that this feature of endogenous nominal rigidities is more apparent when the policy response to inflation is closer to one, but once this policy response is aggressive enough, the decrease in the probability of no price adjustment is minimal. The intuition for these results is that a more aggressive policy response to the output gap makes inflation more volatile due to a trade-off in policymaking between the stabilization of inflation and the output gap and hence the price adjustment is more likely to pay, but this inflation volatility does not become large when the policy response to inflation is aggressive enough.

3.3 Monetary policy stance and New Keynesian Phillips curve

We have seen how changes in the monetary policy stance affect the degree of nominal rigidities. We next consider its implications for the New Keynesian Phillips curve (13). In this curve, the equilibrium probability of no price adjustment α enters its slope (i.e. the output gap elasticity of inflation) and the coefficient of the price shock.

3.3.1 Effects of monetary policy stance toward price stability

In the three cases of the policy response to the output gap $\phi_x = 0, 0.5, 1$, Figure 2 shows how changes in the monetary policy stance on price stability alter the slope $\gamma(1-\alpha)(1-\alpha\beta)/\alpha$ and the price shock coefficient $(1-\alpha)(1-\alpha\beta)/\alpha$ in the New Keynesian Phillips curve. In the upper panel of Figure 2, we can see that a rise in the policy response to inflation leads to a flatter slope of the Phillips curve. In particular, this slope decreases substantially when the policy response to inflation is close to one, and as this policy response becomes more aggressive, the decrease in the slope diminishes. This is because, as noted above, the equilibrium probability of no price adjustment α rises significantly when the policy response is close to one, and as it becomes more aggressive, the rise in the probability is slighter. When a central bank responds more aggressively to inflation, firms become less likely to reset their prices and thereby the aggregate price p_t becomes less likely to reflect the optimal staggered price $p^o_{j,t}$ and hence the output gap. This makes the slope of the Phillips curve flatter.

The lower panel of Figure 2 illustrates that a rise in the policy response to inflation reduces the price shock coefficient of the Phillips curve and that this coefficient decreases substantially for the policy response close to one and such a decrease in the coefficient becomes slighter for the more aggressive policy response. As a consequence of a central bank's more aggressive policy response to inflation, firms become less likely to reset their prices and hence the aggregate price becomes less likely to reflect the price shock via the optimal staggered price. Therefore, the price shock coefficient of the Phillips curve becomes smaller.

3.3.2 Effects of monetary policy stance toward output gap stability

Next, Figure 3 shows how changes in the monetary policy stance on the stability of the output gap alter the slope and the price shock coefficient of the New Keynesian Phillips curve (13) in the three cases of the policy response to inflation $\phi_\pi = 1.1, 1.5, 3$. In contrast to the effects of the policy stance toward price stability, the upper panel of Figure 3 illustrates that a rise in the policy response to the output gap generates a steeper slope of the Phillips curve, but this increase in the slope is limited when the policy response to inflation is sufficiently aggressive. As noted above, there is the trade-off in policymaking between the stabilization of inflation and the output gap. When the policy response to inflation is close to one, the effects of the policy stance toward output gap stability are stronger than those toward price stability. But, as this policy response becomes more aggressive, the latter effects come to dominate the former. In particular, a realistic policy response to inflation of $\phi_\pi = 1.5$ leads to a small change in the slope of the Phillips curve for a realistic range of the policy response to the output gap, $0 \leq \phi_x \leq 0.5$. This is because firms are more likely to reset their prices if inflation is more volatile, but a sufficiently aggressive policy response to inflation stabilizes prices, regardless of the policymaking trade-off between the stabilization of inflation and the output gap.

These features of the slope of the Phillips curve are also true for the coefficient of the price shock. The lower panel of Figure 3 shows that a rise in the policy response to the output gap enlarges the price shock coefficient of the Phillips curve. This increase in the coefficient, however, is limited when the policy response to inflation is aggressive enough.

3.4 New Keynesian Phillips curve and impulse responses to shocks

As shown above, changes in the monetary policy stance alter the slope and the price shock coefficient of the New Keynesian Phillips curve. This suggests that when the policy stance changes, the equilibrium dynamics of the model differ between the case of endogenous nominal rigidities and that of exogenously given ones. Thus, we first examine impulse responses to shocks.

3.4.1 Effects of monetary policy stance toward price stability

Figure 4 shows how the impulse responses to shocks differ between the cases of endogenous nominal rigidities and exogenously given ones, when the policy response to inflation increases from the benchmark value of $\phi_\pi = 1.5$ to $\phi_\pi = 3$ (keeping the policy response to the output gap fixed at $\phi_x = 0.5$). In Figure 4.a, we add a one standard deviation of innovations to the natural interest rate shock in period one. In the case of exogenously given nominal rigidities, we can see that for the positive shock to the natural interest rate, the increase in the policy response to inflation leads to a smaller rise in inflation and hence a smaller rise in the output gap. Consequently, monetary policy raises the nominal interest rate more weakly. Relative to these impulse responses under exogenously given nominal rigidities, inflation and nominal interest rates rise less and the output gap rises further under endogenous nominal rigidities. This is because, as noted above, a more aggressive policy response to inflation results in a flatter slope of the New Keynesian Phillips curve (i.e. a smaller elasticity of inflation with respect to the output gap) under endogenous nominal rigidities. Then, the output gap rises more strongly in order to stabilize inflation. As a consequence, inflation rises more weakly, and the nominal interest rate also rises more weakly due to the large policy response to inflation relative to the one to the output gap. One point we emphasize here is that under endogenous nominal rigidities, the natural interest rate shock induces a trade-off in policymaking between the stabilization of inflation and the output gap. As shown in Figure 4.a, the increase in the policy response to inflation generates a smaller rise in inflation but a larger rise in the output gap for the positive natural interest rate shock. This is in stark contrast with the case of exogenously given nominal rigidities, in which the natural interest rate shock never induces such a trade-off.

In Figure 4.b, we add a one standard deviation of innovations to the price shock in period one. When nominal rigidities are exogenously given, this figure shows that as the policy response to inflation increases, inflation rises more weakly but the output gap falls more strongly for the positive price shock. This is due to the fact that the price shock is a source of a trade-off in policymaking between the stabilization of inflation and the output gap. Monetary policy then raises the nominal interest rate more weakly. In comparison with these impulse responses under exogenously given nominal rigidities, endogenous nominal rigidities lead to smaller rises in inflation and nominal interest rates and to a smaller decline in the output gap. As noted above, the Phillips curve contains a smaller coefficient of the price shock when the policy response to inflation becomes more aggressive. This smaller price shock coefficient causes inflation to rise less under endogenous nominal rigidities. It also causes the output gap to fall less, since the smaller price shock coefficient reduces the policymaking trade-off. The nominal interest rate rises more weakly reflecting the large policy response to inflation.

3.4.2 Effects of monetary policy stance toward output gap stability

When the policy response to the output gap increases from the benchmark value of $\phi_x = 0.5$ to $\phi_x = 1$ (keeping the policy response to inflation fixed at $\phi_\pi = 1.5$), Figure 5 shows how the impulse responses to shocks differ between the cases of endogenous nominal rigidities and exogenously given ones. In Figure 5.a, we can see that when nominal rigidities are exogenously given, the increase in the policy response to the output gap leads to a smaller rise in the output gap and hence a smaller rise in inflation for a one standard deviation of innovations to the natural interest rate shock added in period one. Therefore, monetary policy raises the nominal interest rate more weakly. When nominal rigidities are endogenous, we can see that the output gap rises less than under exogenously given nominal rigidities, but inflation rises further and this inflation rise is almost the same as that in the case of the benchmark policy response to the output gap of $\phi_x = 0.5$. A more aggressive policy response to the output gap makes the rise in the output gap smaller, but it also makes the slope of the New Keynesian Phillips curve steeper and thus the rise in inflation is larger than under exogenously given nominal rigidities. Reflecting such an inflation rise, monetary policy raises the nominal interest rate more strongly.

Figure 5.b shows the impulse responses to a one standard deviation of innovations to the

price shock added in period one. As can be seen in this figure, the increase in the policy response to the output gap generates a weaker decline in the output gap but a stronger rise in inflation due to the policymaking trade-off in the case of exogenously given nominal rigidities. Hence, monetary policy raises the nominal interest rate more strongly. In the case of endogenous nominal rigidities, the output gap falls further than under exogenously given nominal rigidities and this fall is almost the same as that in the case of the benchmark policy response to the output gap of $\phi_x = 0.5$. Also, inflation rises more strongly. These impulse responses are based on the fact that the Phillips curve contains a larger coefficient of the price shock when the policy response to the output gap becomes more aggressive. Such a larger price shock coefficient leads to a stronger rise in inflation and also generates a larger fall in the output gap because it induces a more serious trade-off in policymaking between the stabilization of inflation and the output gap. Therefore, monetary policy raises the nominal interest rate more strongly.

3.5 New Keynesian Phillips curve and macroeconomic volatility

We turn next to another aspect of the implications for the equilibrium dynamics of the model. Here we examine how macroeconomic volatility alters in response to changes in the monetary policy stance.

3.5.1 Effects of monetary policy stance toward price stability

Figure 6 shows variances of quarterly inflation and the output gap when the policy response to inflation increases from $\phi_\pi = 1.1$ to $\phi_\pi = 3$ in the three cases of the policy response to the output gap $\phi_x = 0, 0.5, 1$. In Figure 6.a, we consider the case of exogenously given nominal rigidities and set the probability of no price adjustment at the benchmark value of $\alpha = 0.642$. We can see in this figure that when the policy response to inflation becomes more aggressive, it reduces the variance of inflation but increases that of the output gap in each case of the policy response to the output gap. This indeed shows the trade-off in policymaking between the stabilization of inflation and the output gap, induced by the price shock. As shown in Figure 4.b, a more aggressive policy response to inflation leads to a smaller rise in inflation but a larger fall in the output gap for a positive price shock.

Figure 6.b shows the case of endogenous nominal rigidities. In stark contrast with the case of exogenously given nominal rigidities, we can see that a more aggressive policy response to

inflation reduces both variances of inflation and the output gap. This is because when the policy response to inflation increases, the coefficient of the price shock becomes smaller and as a consequence, the policymaking trade-off is reduced.[6] In fact, as shown in Figure 4.b, when nominal rigidities are endogenous, the increase in the policy response to inflation generates a smaller fall in the output gap as well as a smaller rise in inflation for a positive price shock.

3.5.2 Effects of monetary policy stance toward output gap stability

In the three cases of the policy response to inflation $\phi_\pi = 1.1, 1.5, 3$, Figure 7 shows how variances of quarterly inflation and the output gap alter as the policy response to the output gap increases from $\phi_x = 0$ to $\phi_x = 1$. Figure 7.a shows the case of exogenously given nominal rigidities in which the probability of no price adjustment is set at $\alpha = 0.642$. We can see again the policymaking trade-off between the stabilization of inflation and the output gap. A more aggressive policy response to the output gap reduces the variance of the output gap but increases that of inflation. This is due to the fact that such a policy response generates a smaller fall in the output gap but a larger rise in inflation for a positive price shock, as shown in Figure 5.b.

Figure 7.b illustrates the case of endogenous nominal rigidities. We can see that when the policy response to inflation is close to one, a more aggressive policy response to the output gap reduces the variance of the output gap slightly but increases that of inflation substantially. Once the policy response to inflation is aggressive enough, the variance of inflation increases slightly but that of the output gap decreases for a more aggressive policy response to the output gap. This is because, as can be seen in Figure 5.b, when the policy response to inflation is close to one, the increase in the policy response to the output gap generates a larger rise in inflation for a positive price shock, but a fall in the output gap induced by this shock changes slightly. For a sufficiently aggressive policy response to inflation, the price shock coefficient of the New Keynesian Phillips curve remains small for any realistic policy response to the output gap, as shown in Figure 1.b. Hence, the policymaking trade-off also remains minimal.

The findings above suggest that in the conduct of monetary policy, a central bank should take into account the feedback effects of its policy stance on firms' price setting. By exploiting these feedback effects, the central bank's aggressive policy response to inflation can reduce both

[6] The effects of the policymaking trade-off induced by the natural interest rate shock under endogenous nominal rigidities are negligible at least in our calibration of model parameters.

variances of inflation and the output gap. Also, with a sufficiently aggressive policy response to inflation, the bank can lower the variance of the output gap by responding aggressively to the output gap at the cost of a slight increase in the variance of inflation.

3.6 Implications for the U.S. economy in Volcker-Greenspan era

In the previous sections, we have seen that changes in the monetary policy stance alter the degree of nominal rigidities and hence they have crucial influence not only on the New Keynesian Phillips curve but also on the impulse responses to shocks and the macroeconomic volatility. These consequences of endogenous nominal rigidities in response to changes in the policy stance are consistent with the findings of the recent empirical literature. As pointed out by Taylor (1999), Clarida, Galí and Gertler (2000), Lubik and Schorfheide (2004) and others, the Taylor rule's policy response to inflation became much more aggressive in the Volcker-Greenspan period than in the pre-Volcker period, due to the change in monetary policy stance sometime after Paul Volcker assumed the chairmanship of the Federal Reserve. During the same periods, Smets and Wouters (2007) and Fernández-Villaverde and Rubio-Ramírez (2008) show that firms' probability of price adjustment became lower. Lubik and Schorfheide (2004) also indicate that the Phillips curve contained a flatter slope and a smaller variance of disturbances during these periods. Further, as emphasized in many studies such as Blanchard and Simon (2001), macroeconomic volatility fell substantially during the Volcker-Greenspan era, the so-called Great Moderation.

It is important to stress that our model with endogenous nominal rigidities offers theoretical support for the good policy hypothesis about the Great Moderation suggested by Bernanke (2004). He indicates that the Great Moderation was caused mainly by the Volcker-Greenspan monetary policy and not merely by good luck such as small shocks to the U.S. economy. He then emphasizes the following three points. First of all, "monetary policy that brought down and stabilized inflation may have led to stabilizing changes in the structure of the economy as well, in line with the prediction of the famous Lucas (1976) critique that economic structure depends on the policy regime." Second, "changes in monetary policy could conceivably affect the size and frequency of shocks hitting the economy." Last, "monetary policy can also affect the distribution of measured shocks by changing the sensitivity of pricing and other economic decisions to exogenous outside shocks." These views of the Great Moderation can be explained by our model with endogenous nominal rigidities. The aggressive policy stance toward price stability taken by Paul Volcker and Alan Greenspan affects firms' price-setting behavior and reduces a trade-off in policymaking between the stabilization of inflation and real economic activities, thereby stabilizing macroeconomic volatility successfully.

4 Welfare implications

From the results of the positive analysis presented in the previous sections, we can see that our model with endogenous nominal rigidities provides a realistic framework for monetary policy analysis. In this section, we use this model for normative policy analysis, namely, we examine welfare implications of endogenous nominal rigidities.

Following Woodford (2003), we can show that the maximization of a second-order approximation to the representative household's utility function is equivalent to the minimization of a loss function given by[7]

$$SWL \;=\; \frac{\alpha\theta}{(1-\alpha)(1-\alpha\beta)}V(\pi_t) + \gamma V(x_t). \tag{14}$$

In this social welfare loss function, only the weight of inflation variability depends on the degree of nominal rigidities, the equilibrium probability of no price adjustment α. Also, this inflation weight increases nonlinearly with the probability, since a higher probability of no price adjustment enlarges welfare distortions due to price dispersion. These facts are crucial in discussing what monetary policy enhances social welfare under endogenous nominal rigidities. In the ensuing analysis, we set the steady state price elasticity of demand at $\theta = 7.88$, which is the estimates of Rotemberg and Woodford (1997).

The upper panel of Figure 8 shows how the inflation weight $\alpha\theta/[(1-\alpha)(1-\alpha\beta)]$ changes when the policy response to inflation increases from $\phi_\pi = 1.1$ to $\phi_\pi = 3$ in the three cases of the policy response to the output gap $\phi_x = 0, 0.5, 1$. In this figure, we can see that for each policy response to the output gap, the inflation weight becomes larger as the policy response to inflation increases. As shown in the upper panel of Figure 1, a more aggressive policy response

[7]The second-order approximation to the household's utility function also contains terms independent of policy, where only the initial value of price dispersion depends on the equilibrium probability of no price adjustment α. This value, however, is zero because firms are identical at the beginning of the economy, and thus the term of initial price dispersion does not appear in the social welfare loss function (14). Also, this social loss function does not depend on the price-setting cost F because of the presence of final-goods firms.

to inflation leads to a rise in the equilibrium probability of no price adjustment α, which makes the inflation weight larger. We can also see that given a policy response to inflation, the inflation weight becomes smaller as the policy response to the output gap increases. This is because a more aggressive policy response to the output gap lowers the probability of no price adjustment α due to the policymaking trade-off between the stabilization of inflation and the output gap and hence it makes the inflation weight smaller. In the presence of such feedback effects of the policy responses on the inflation weight, the lower panel of Figure 8 shows what policy responses to inflation and the output gap can reduce the social welfare loss given by (14). This figure illustrates that desirable monetary policy which lowers the welfare loss responds aggressively to inflation and moderately to the output gap. The figure also shows that no policy response to the output gap is not desirable relative to an aggressive response of $\phi_x = 1$, since the former generates a larger welfare loss than the latter does, when the policy response to inflation is sufficiently aggressive. To enhance social welfare, an aggressive policy response to inflation is critical because it can lower both variances of inflation and the output gap, as shown in Figure 6.b. In the absence of the policy response to the output gap, however, an aggressive policy response to inflation induces a large welfare loss from inflation variability, since it leads to a high probability of no price adjustment and hence a large inflation weight. Thus, to reduce the social welfare loss, monetary policy should contain not only an aggressive response to inflation but also a moderate response to the output gap. Although the aggressive response to inflation increases the inflation weight, the moderate response to the output gap limits such an increase in the inflation weight, thereby preventing the inflation variability from being too costly. Therefore, it is crucial for central banks to take into account that the inflation weight of the social welfare loss function changes endogenously with their policy stances.

Before proceeding to the concluding section, it is worth while to mention that the relative output-gap weight used in recent monetary policy studies suggests a policy prescription distinct from that based on the social welfare loss function. The loss function with the relative weight of output gap variability to inflation variability is given by

$$L \ = \ V(\pi_t) + \frac{\gamma(1-\alpha)(1-\alpha\beta)}{\alpha\theta} V(x_t), \tag{15}$$

where the weight of output gap variability is indeed the ratio of the output-gap weight γ to the inflation weight $\alpha\theta/[(1-\alpha)(1-\alpha\beta)]$ in the social welfare loss function (14). The upper panel of Figure 9 shows how the relative output-gap weight $\gamma(1-\alpha)(1-\alpha\beta)/(\alpha\theta)$ changes for the increase in the policy response to inflation in the three cases of the policy response to the output gap. In this figure we can see that for each policy response to the output gap, the relative output-gap weight becomes smaller as the policy response to inflation increases. We can also see that given a policy response to inflation, the relative output-gap weight becomes smaller as the policy response to the output gap becomes closer to zero. These imply that the loss of output gap variability measured by (15) becomes smaller when the policy response to inflation increases and when the policy response to the output gap decreases. Therefore, the lower panel of Figure 9 shows that monetary policy which is desirable from the perspective of the loss function with the relative output-gap weight (15) responds aggressively to inflation but never responds to the output gap. This is in stark contrast with the welfare-based desirable monetary policy, which responds moderately to the output gap. This distinct policy prescription about the policy response to the output gap is due to the fact that the loss function with the relative output-gap weight (15) underestimates the welfare loss from output gap variability.

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 the implications for monetary policy. Specifically, we have considered firms which choose the probability of price adjustment so as to maximize their expected profit in the face of the cost involved to set a new price and in response to changes in the monetary policy stance toward price stability and output gap stability. This is in stark contrast with previous studies which stress that the probability of price adjustment changes with a central bank's inflation target. We have shown that when a central bank responds more aggressively to inflation, firms become less likely to reset their prices and the resulting New Keynesian Phillips curve contains a flatter slope and a smaller variance of disturbances, as observed during the Volcker-Greenspan era. We have also shown that a central bank's aggressive policy response to inflation can stabilize both inflation and the output gap by exploiting the feedback effects of the policy response on firms' price setting. This suggests that a central bank should take into account such feedback effects in the conduct of monetary policy. It also provides theoretical support for the good policy hypothesis about the Great Moderation suggested by Bernanke (2004). Further, we have shown that changes in the policy responses dramatically affect the inflation weight of the social welfare loss function, since this weight increases nonlinearly with the probability of no price adjustment. To reduce social welfare loss, it is crucial for central banks to take into account that the inflation weight changes endogenously with their policy stances. We have also found that the relative output-gap weight used in recent monetary policy studies underestimates the welfare loss from output gap variability and hence suggests no policy response to the output gap, which is in stark contrast with the policy prescription based on the social welfare loss function.

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 a central bank should conduct monetary policy under such uncertainty.[8] In these studies, however, nominal rigidities are assumed to be exogenously given, and thus there are no feedback effects of monetary policy on firms' price setting. Therefore, such previous studies are subject to the Lucas (1976) critique. The same argument is also true for other issues in monetary policy analysis. Our paper then suggests that the consideration of endogenous nominal rigidities may alter policy implications obtained in the previous literature.

This paper has investigated only the features of endogenous nominal rigidities in response to changes in the stance of monetary policy. Our model with endogenous nominal rigidities can also be used for analysis on 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 reduced-form Phillips curve in Japan became flat in the past decade. Like this exercise, our model with endogenous nominal rigidities can be applied to various issues in macroeconomics.

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

Appendix: Derivation of (11)

To derive (11), it suffices to show that

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

Substituting (8) into (9) yields

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

Then, this can be reduced to

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

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 (8) and (17), we have (16).

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Table 1: Benchmark calibration of model parameters

β	discount factor	0.99
η	inverse of labor supply elasticity	1
σ	relative risk aversion	1.86
ρ_r	persistence parameter of natural interest rate shocks	0.83
v_r	variance of innovations to natural interest rate shocks	$(0.18\,\sigma)^2$
ρ_u	persistence parameter of price shocks	0.85
v_u	variance of innovations to price shocks	$(0.64\,\gamma)^2$
F	price-setting cost	5.8
θ	steady state price elasticity of demand	7.88

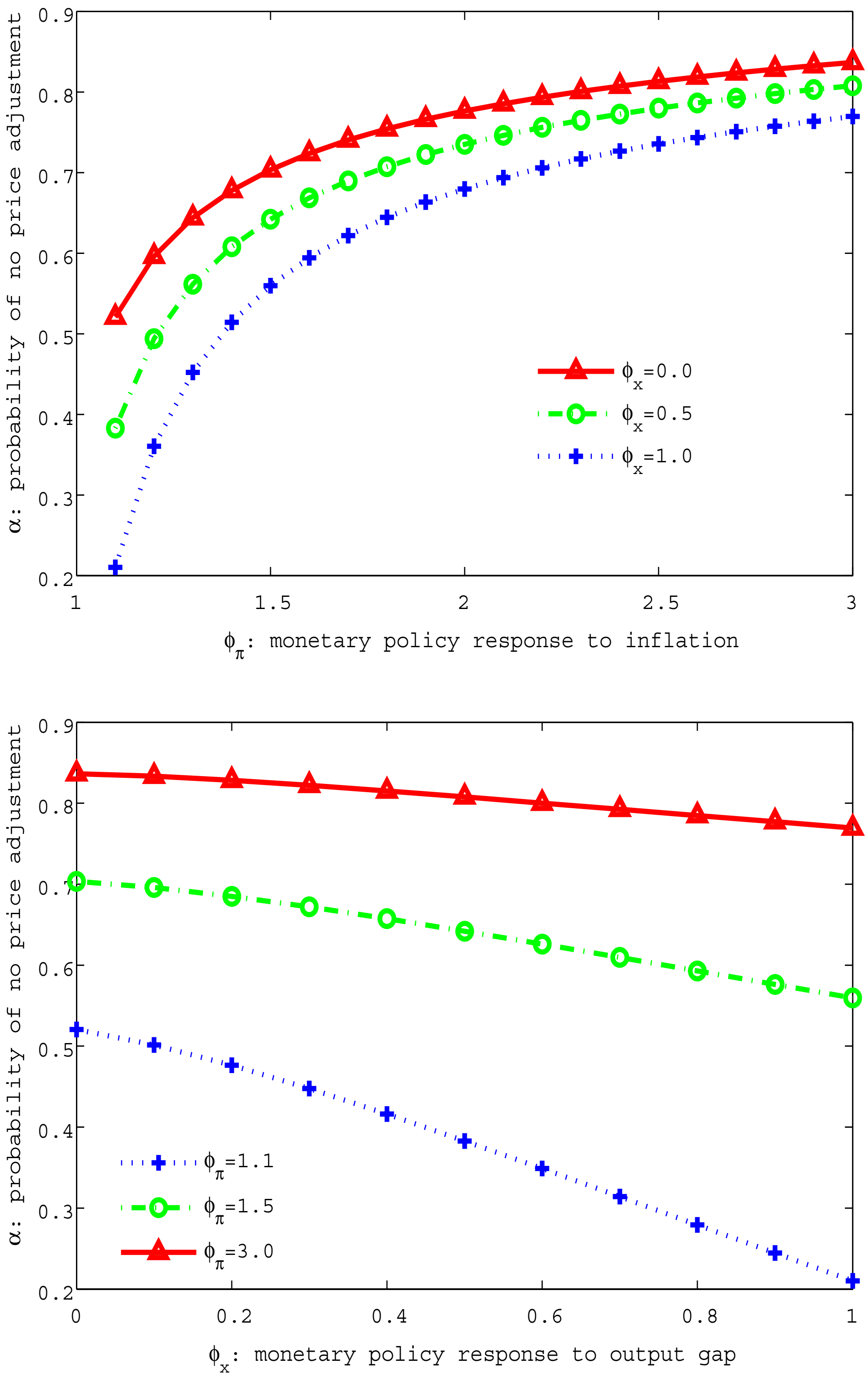
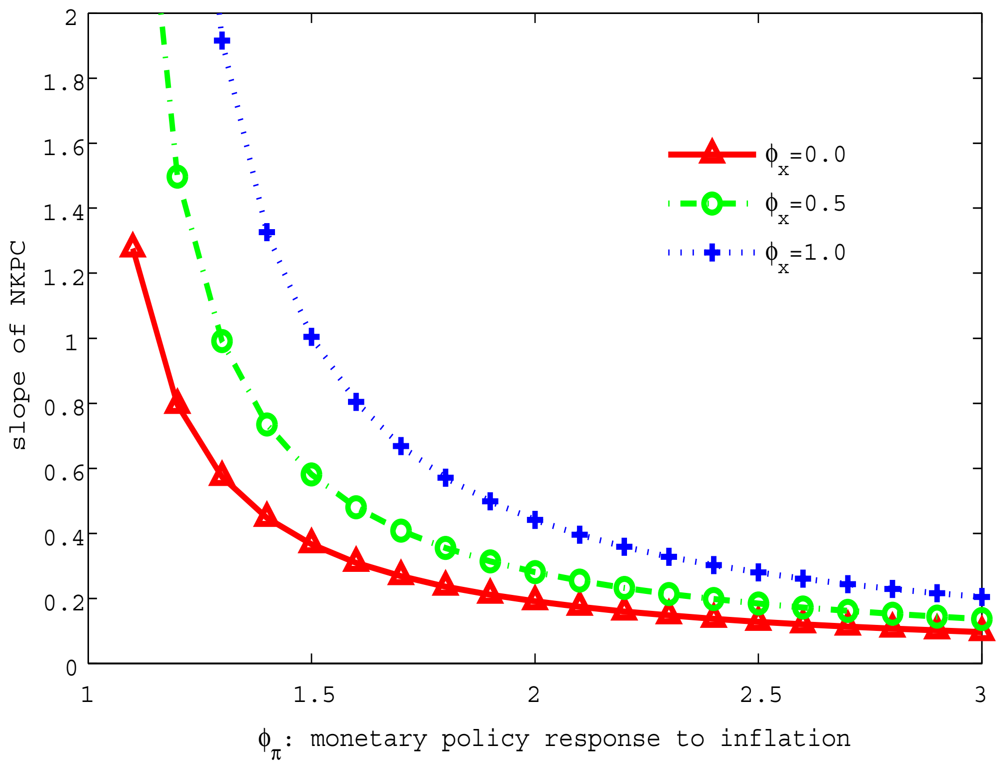


Figure 1: Monetary policy stance and endogenous nominal rigidities



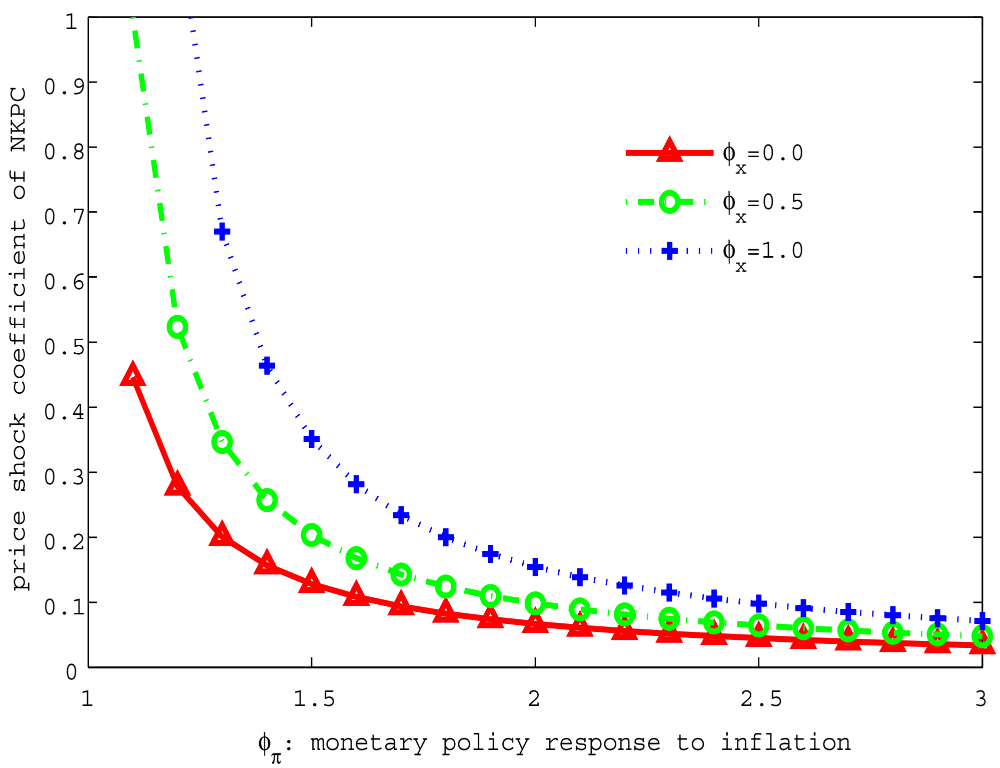
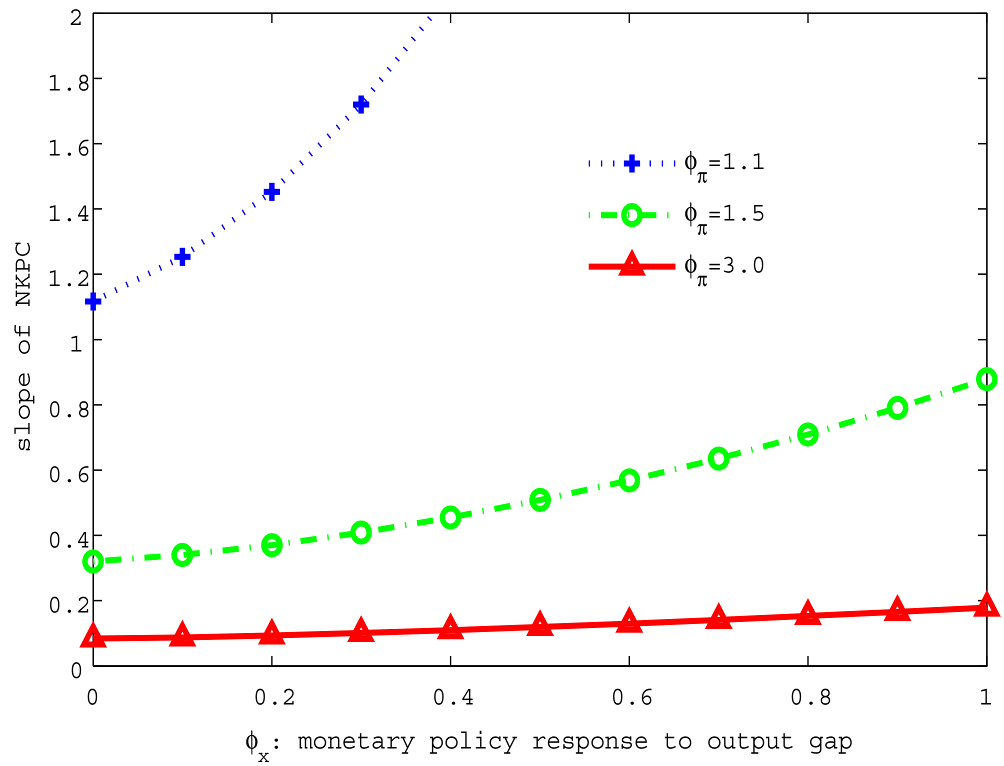


Figure 2: Monetary policy stance on price stability and New Keynesian Phillips curve (NKPC)



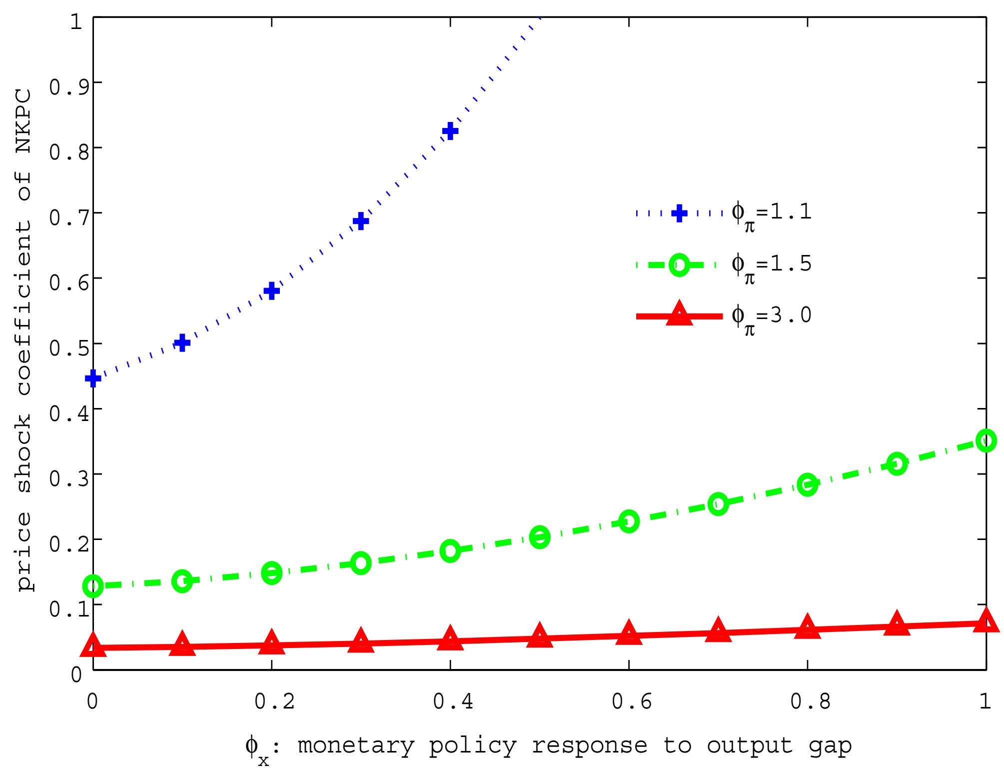


Figure 3: Monetary policy stance on output gap stability and New Keynesian Phillips curve (NKPC)

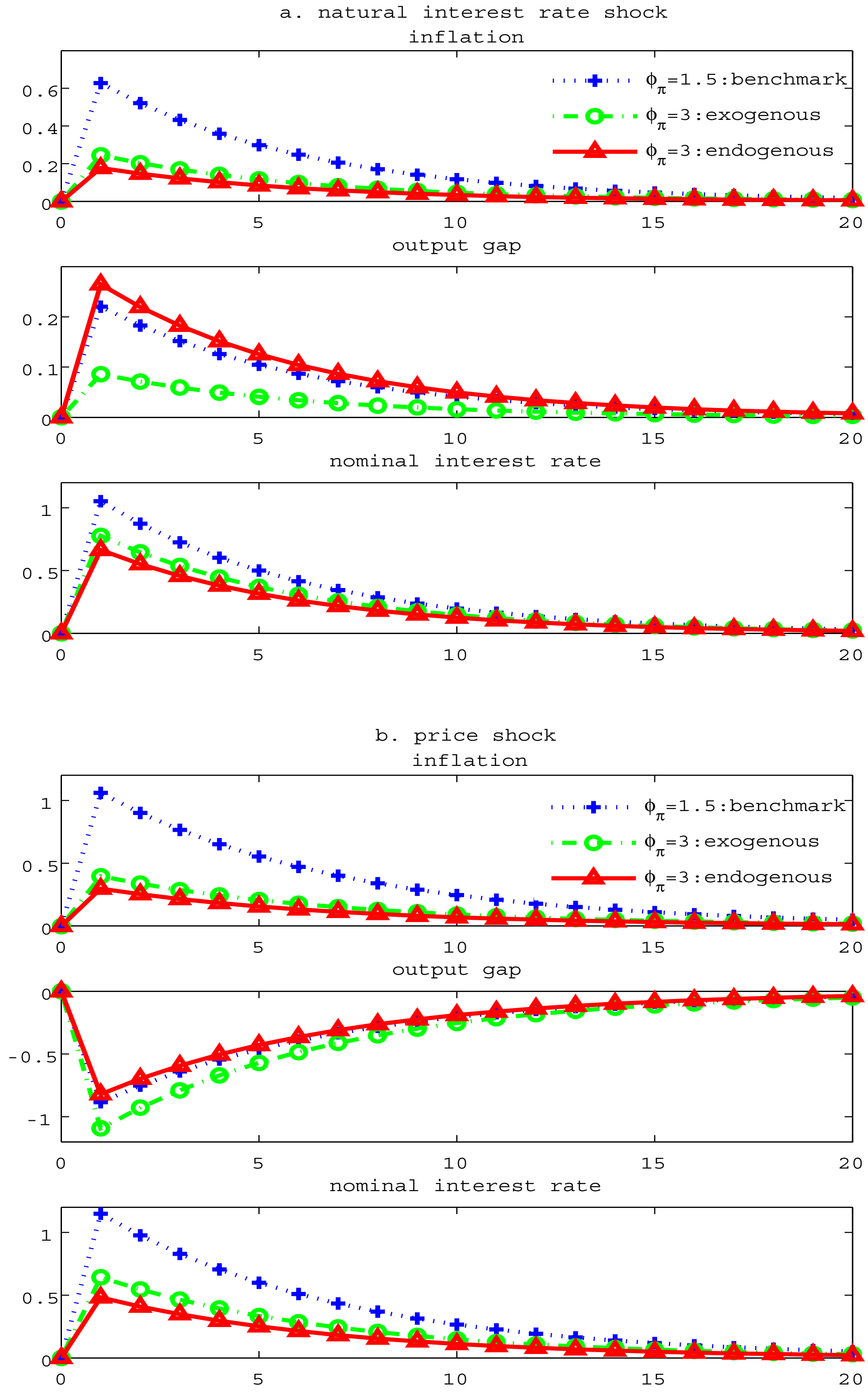


Figure 4: Monetary policy stance on price stability and impulse responses ($\phi_x = 0.5$)

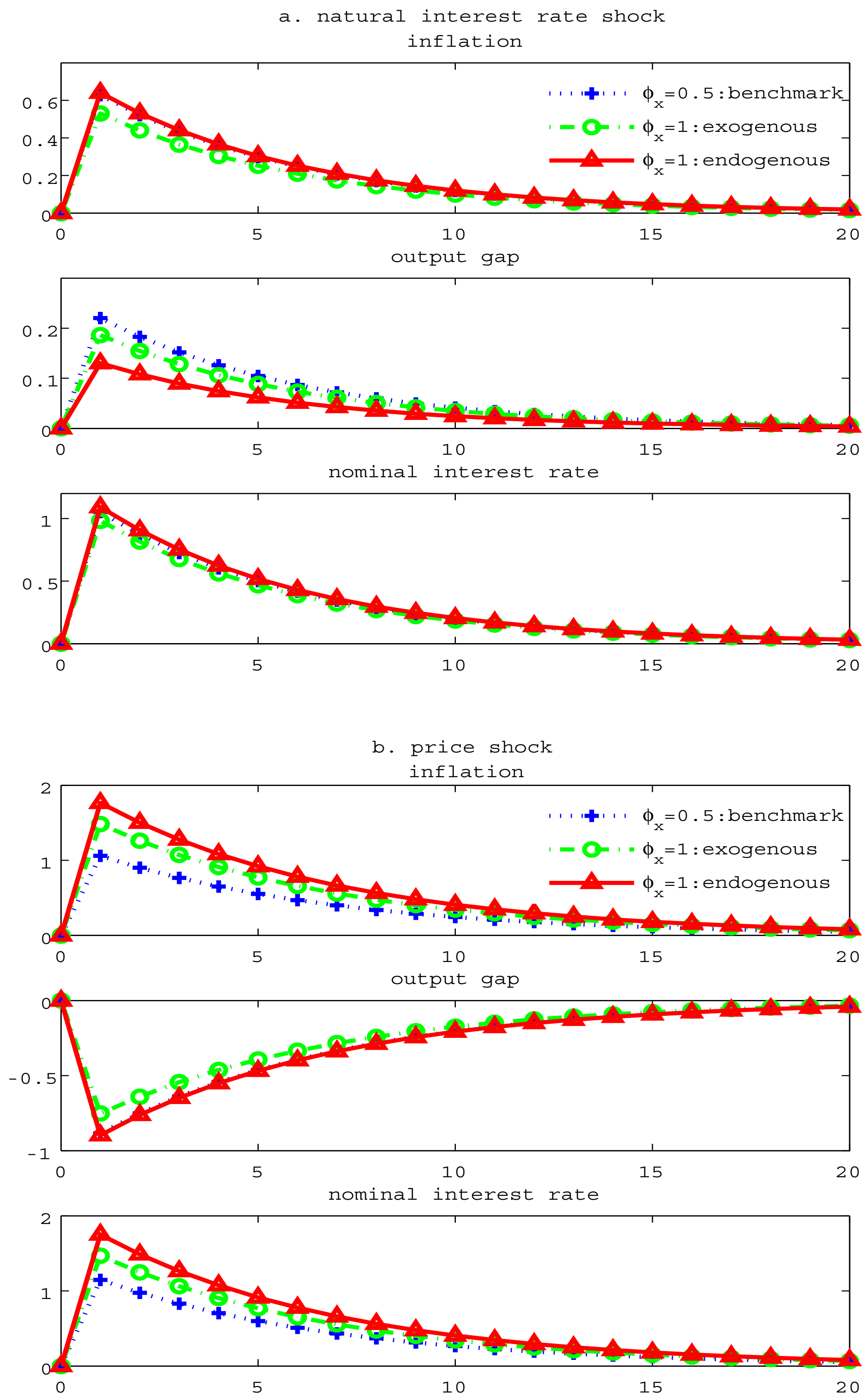


Figure 5: Monetary policy stance on output gap stability and impulse responses ($\phi_\pi = 1.5$)

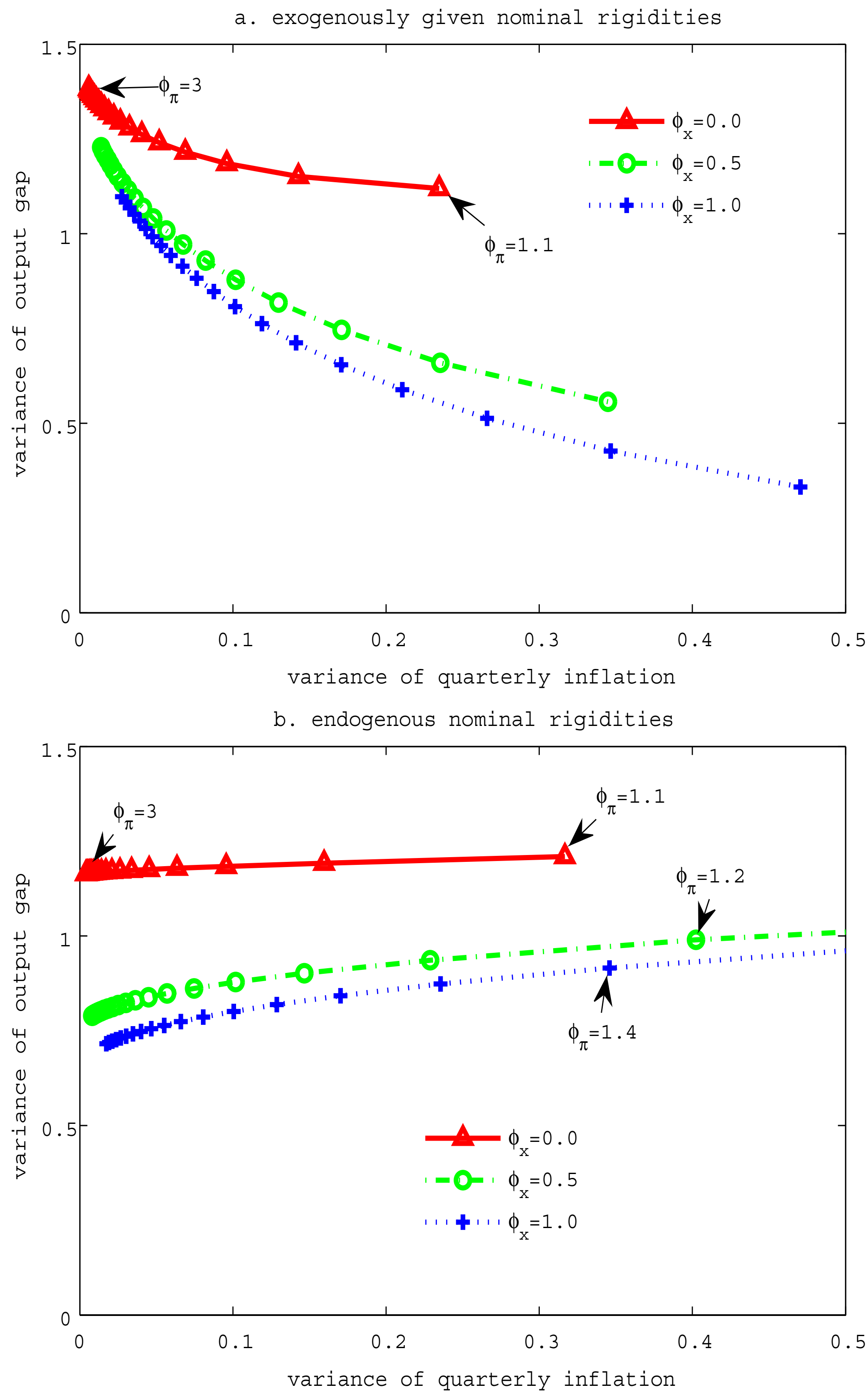


Figure 6: Monetary policy stance on price stability and macroeconomic volatility

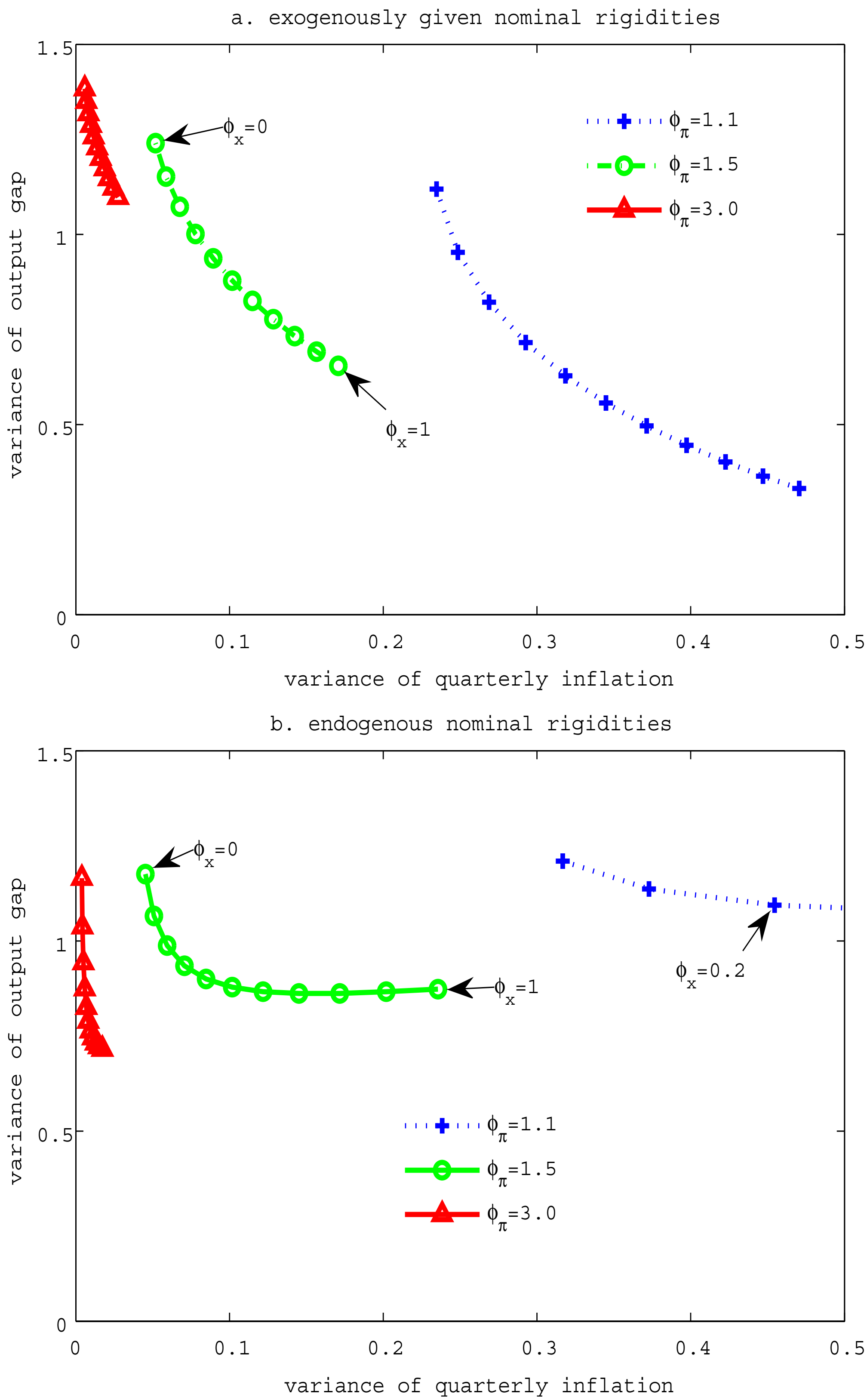


Figure 7: Monetary policy stance on output gap stability and macroeconomic volatility

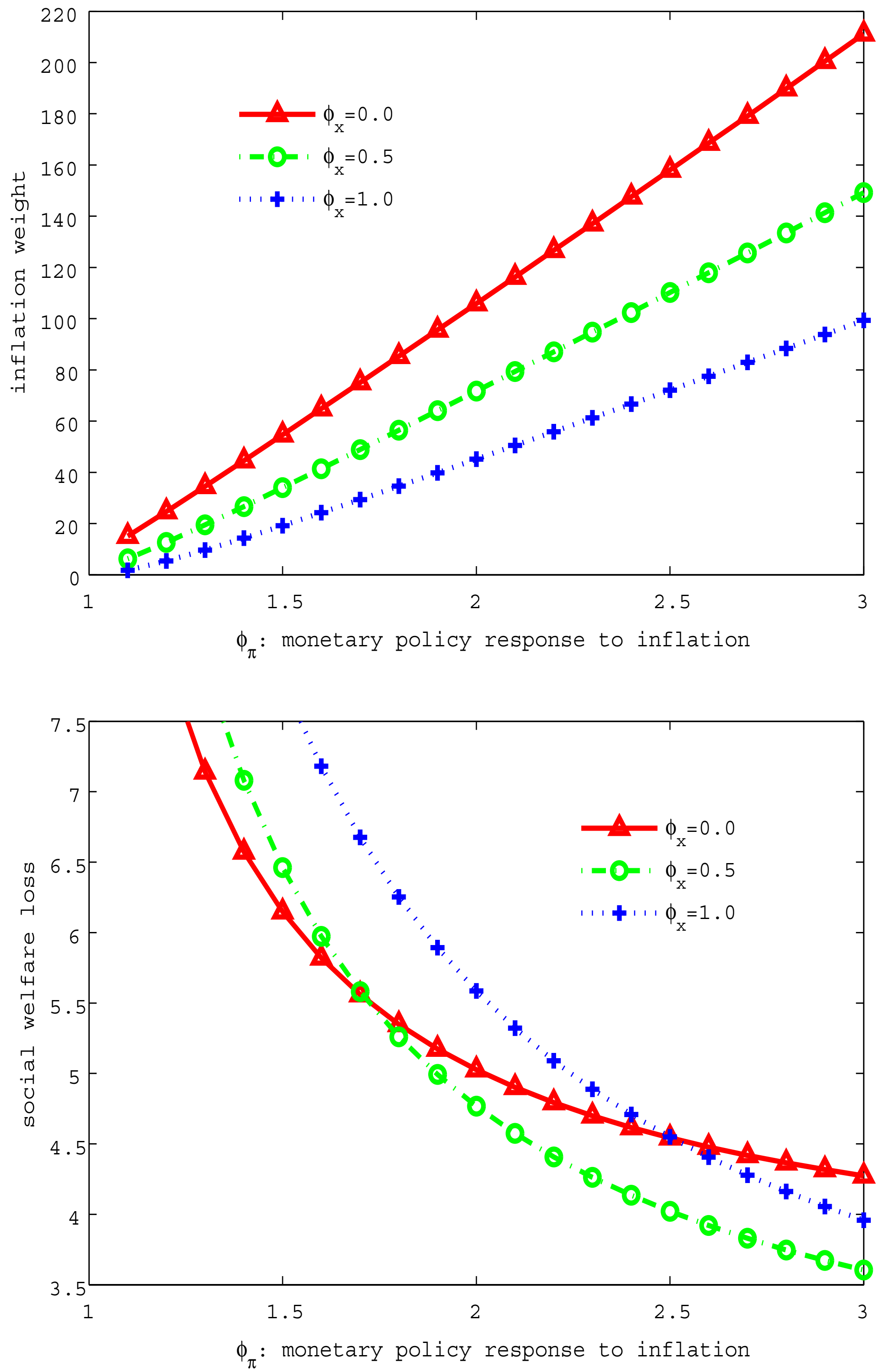


Figure 8: Social welfare loss

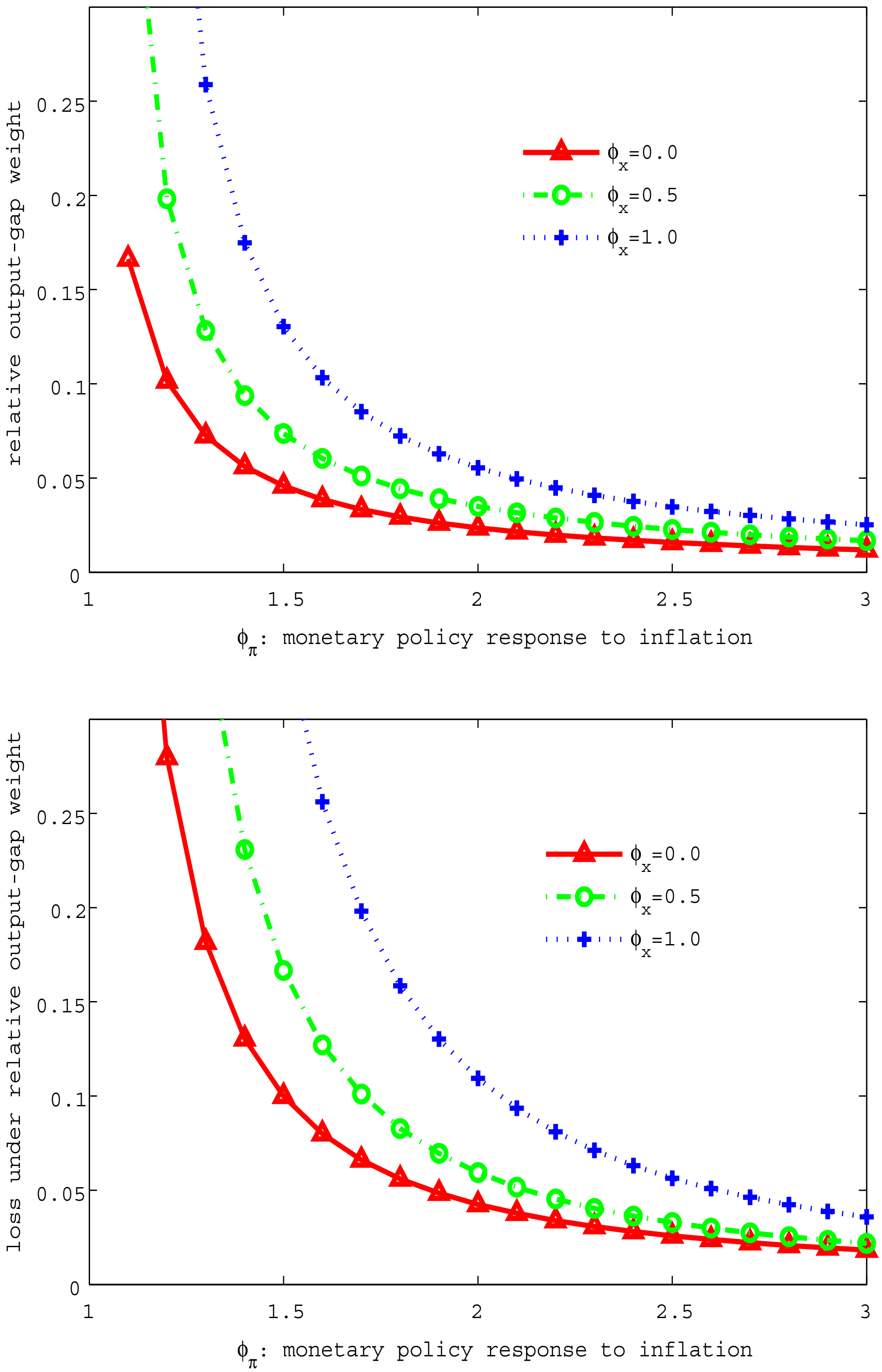


Figure 9: loss under relative output-gap weight