Inflation Dynamics and Monetary Policy: New Keynesian Analysis

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（インフレーション動学と金融政策：ニューケインジアン分析）

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Acknowledgments

I believe that a central bank economist, who is responsible for actual monetary policy making, should have at least the knowledge that has already been accumulated in academics and the ability to conduct original research on policy-oriented issues. These skills can only be acquired through serious and continuous efforts in academic fields. This is why I have spent the last few years pursuing a Ph.D. degree.

Kobe University provided me with the opportunity to accomplish my objective. The well-established graduate curriculum for working professionals enables me to pursue the Ph.D. degree while working at the Bank of Japan. In addition, the curriculum is very helpful because it allows me to obtain the degree in a relatively short period of time. This system considerably promoted the progress of my research. In this respect, I am extremely grateful to Kobe University for providing me with this excellent research environment.

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Chapter 1

Introduction

1.1 New Keynesian Analysis in Macroeconomics

This thesis consists of one empirical and two theoretical studies of New Keynesian analysis on inflation dynamics and monetary policy. New Keynesian models are defined as structural macroeconomic models in which the presence of price stickiness yields (i) the correlation between inflation dynamics and real economy and (ii) the real impact of monetary policy. Owing to some theoretical contributions (such as Clarida, Galí, and Gertler [1999] and Woodford [2003]), New Keynesian models have been developed as the central tools for theoretical analysis of inflation dynamics and monetary policy. Furthermore, New Keynesian models have been extended by some studies (such as Christiano, Eichenbaum, and Evans [2005]) to medium-scale models, which replicate the macroeconomic dynamics observed in vector autoregression (VAR) analysis. Nowadays, some versions of New Keynesian models have been introduced by most central banks as the major tools of monetary policy analysis. In parallel with real business cycle models, the development of New Keynesian models has contributed greatly to the recent advancement of dynamic stochastic general equilibrium (DSGE) models.

One of the prominent features of New Keynesian models is that macroeconomic dynamics crucially depend on private agents' forward-looking expectations about the future state of the economy. According to Woodford [2003], a basic form of the New Keynesian model consists of three equations: (i) the dynamic IS equation, which is derived from households' optimal consumption behavior, (ii) the New Keynesian Phillips curve (NKPC), which is derived from monopolistic competitive firms' optimization under price stickiness, and (iii) a monetary policy rule, which illustrates the central bank's monetary policymaking. In this model, households determine the current expenditure based on their forward-looking expectation for their future income. Firms set the current prices based on their forward-looking expectation for future marginal costs, since they anticipate that they are not able to adjust freely their prices in the future due to the presence of price stickiness.

The dominance of private agents' forward-looking expectations has critical implications for monetary policymaking. Firstly, in the presence of forward-looking expectations, the optimal monetary policy may include the central bank's commitments for future policy. In this respect, Woodford [2005] explains, "In general, the most effective policy (the best outcome, from among the set of possible rational-expectations equilibria) requires that policy be conducted in a *history-dependent way*, so that policy at any time depends not only on conditions then (and what it is considered possible to achieve from then on), but also on *past* conditions, even though these no longer constrain what it is possible to achieve in the present (p. 7)."

Secondly, the central bank's information provision to private agents (central bank transparency) matters for economic dynamics. According to Geraats [2002], central bank transparency is defined as "the absence of asymmetric information between monetary policymakers and other economic agents (p. F533)." If this information has some degree of impact on private agents' forward-looking expectations, central bank transparency potentially influences economic dynamics, and ultimately, social welfare.

Thirdly, the central bank has to avoid the destabilization of private agents' forward-looking expectations. Bernanke and Woodford [1997] suggest that a monetary policy rule should satisfy the determinacy (uniqueness) of the rational expectations equilibrium (REE), to avoid the emergence of sunspot equilibria. Bullard and Mitra [2002] and Evans and Honkapohja [2005] emphasize that a policy rule should guarantee the expectational stability (E-stability) of the REE, which corresponds to the stability under private agents' adaptive learning. These conditions can be viewed as the minimum requirements for monetary policymaking, in the presence of private agents' forward-looking expectations.

Therefore, in New Keynesian models, the central bank needs to appropriately take account of the impact of monetary policy on private agents' forward-looking expectations. Reflecting this point, in this thesis, we are mainly interested in the formation of private agents' forward-looking expectations. Our ultimate objective is to obtain a deep understanding of inflation dynamics and to derive insightful implications for monetary policymaking, in an environment where private agents' forward-looking expectations play significant roles in macroeconomic dynamics.

1.2 Summary of This Thesis

In Chapter 2, we examine the empirical performance of the NKPC, which is the main component of New Keynesian models, using Japanese data. The NKPC was originally developed by Rotemberg [1982a] and Calvo [1983]. In contrast to the traditional Phillips curve, the NKPC has a micro-foundation in which monopolistically competitive firms set prices based on their expectations regarding the future real marginal cost (RMC).

Yet, despite its theoretical importance, empirical studies do not necessarily assess the NKPC as a good description of actual inflation dynamics. For example, Rudd and Whelan [2005a,b, 2006, 2007] show that in the United States there is scarce evidence on the correlation between the inflation rate and the discounted sum of future labor shares, which is the most conventional proxy of real marginal cost (RMC). They also show that the observed good performance of the "hybrid" NKPC, which introduces a lagged inflation term as an additional explanatory variable, is just brought by lagged inflation, not by the discounted sum of future labor shares.

Nevertheless, we can further consider the possibility that the fit of the NKPC is poor only because the labor share is not a good proxy for RMC. Rotemberg and Woodford [1999] explain that the labor share can be viewed as a valid proxy of RMC only in a relatively special environment in which there is no friction in the labor market. They show that some corrections to the labor share would be required to obtain a more realistic measure of RMC, and these corrections would imply that RMC is more procyclical than the labor share.

The analysis of Chapter 2 investigates the empirical performance of Japan's NKPC, focusing especially on the measurement of RMC. To obtain a better proxy for RMC, we correct the labor share by taking account of two kinds of labor market frictions: (i) labor adjustment costs and (ii) real wage rigidity. This can be done because we have a direct measure of the degree of labor market frictions in Japan. As an extension, we also incorporate materials prices in the calculation of RMC, following Batini, Jackson, and Nickell [2005].

Our exercise shows that the fit of the NKPC is poor in Japan if we naively use the labor share as the proxy for RMC. This result is just the same as in the United States. However, the consideration of the two kinds of labor market frictions greatly improves the fit of Japan's NKPC. Furthermore, if we incorporate materials prices, the fit of the NKPC is further improved. Our most important finding is that the inclusion of a lagged inflation term into the NKPC does not improve the fit of the NKPC at all. This result indicates that the conventional backward-looking component is no more needed to explain Japan's inflation dynamics if we use a corrected measure of RMC.

In Chapter 3, we theoretically investigate how central bank transparency influences social welfare. Among the various aspects of central bank transparency, this study focuses on central bank transparency about views of future productivity growth. The reason for this focus is explained by the fact that the central bank usually faces considerable uncertainty as to future productivity growth. In this environment, it is not so straightforward a task to evaluate the value of central bank transparency because the forecast provided by the central bank to private agents might be inaccurate, and an inaccurate forecast might cause economic fluctuations. Therefore, the issue of whether the central bank should be greatly transparent, even if it is quite uncertain about views of future productivity growth, will deserve the attention of monetary policymakers.

The analysis of Chapter 3 investigates this problem in a standard New Keynesian model. In this model, we assume that both the central bank and private agents filter the persistence of productivity growth. Since the central bank and private agents do not know the true value of the signal-to-noise ratio, the gain parameters used in the filtering problems can be heterogeneous. If the central bank is not transparent, private agents must conjecture the central bank's estimate of the *efficient interest rate*, which is the real interest rate that should be realized in the absence of price stickiness and equilibrium markup fluctuations.

Under this setup, we show that central bank transparency does not necessarily improve social welfare. It can potentially yield a welfare loss, depending on (i) the gain parameters used by the central bank and private agents and (ii) private agents' conjecture about the gain parameter used by the central bank. If the gain parameters used by the central bank and private agents are homogeneous, then central bank transparency always improves social welfare. However, if these gain parameters are heterogeneous, central bank transparency can be either welfare-improving or welfare-reducing, because it is possible that private agents' misperception about the central bank's views of future productivity growth offsets the distortion which arises from the heterogeneous forecasts between the central bank and private agents.

In considering large uncertainty and the possible structural changes in the variance of productivity shock, the case of heterogeneous gain could be viewed as a more general case than the case of homogeneous gain. On that ground, it is natural for the central bank to face uncertainty as to the desirability of transparency about views of future productivity growth. The analysis shows that, in this situation, it is sensible for the central bank to respond strongly to the variations of the inflation rate, because the misperceptions about these parameters become the source of the demand shock.

This study is distinct from the previous studies of the central bank's economic transparency (such as Amato and Shin [2003], Morris and Shin [2005], and Walsh [2007]), in that the mechanism through which central bank transparency can be welfare-reducing differs fundamentally from those of the previous studies. In the previous studies, central bank transparency can be harmful for social welfare mainly because private agents might overreact to the information provided by the central bank, in an environment that the central bank or private agents have private information about current economic conditions. In contrast, in our study, central bank transparency can be welfare-reducing, because it eliminates private agents' misperception of the central bank's estimate on the efficient interest rate, which would offset the distortion which arises from the heterogeneous forecasts between the central bank and private agents if the central bank is not transparent. This mechanism is new to the literature of central bank transparency.

In Chapter 4, we examine the E-stability of the REE in a simple New

Keynesian model in which both the central bank and private agents do not have perfect knowledge about the structure of the economy and they engage in adaptive learning to form their forward-looking expectations. In the literature of adaptive learning, Evans and Honkapohja [2001] explain that the necessary and sufficient condition for the economy to converge to the REE is given by the E-stability condition, which is defined as the local asymptotic stability around the REE under the dynamics of adaptive learning. One of the important applications of adaptive learning to monetary economics is Bullard and Mitra [2002]. They examine the E-stability condition in a simple New Keynesian model, which introduces a Taylor-type monetary policy rule. Their results indicate that the so-called Taylor principle, which requires the central bank to adjust the nominal interest rate more than one-for-one with the inflation rate, corresponds to the E-stability condition under some versions of Taylor-type monetary policy rules, including a forward-looking rule that incorporates the expectations for the future inflation rate and output gap, which are assumed to be homogeneous between the central bank and private agents.

However, the environment is still quite simple because the central bank and private agents are assumed independently (or simultaneously) engaged in adaptive learning. The validity of this assumption is empirically arguable when we take account of possible interactions between the central bank and private agents. In this respect, Fujiwara [2005] provides empirical evidence that, in Japan's survey data, the central bank's forecast influences the forecast of private agents (not vice versa). Therefore, his results indicate that the central bank is the *leader* and private agents are the *followers* of expectation formations.

The analysis of Chapter 4 derives the E-stability condition of the REE in a simple New Keynesian model in which private agents engage in adaptive learning by referring to the central bank's forecast. The results show that, in contrast to the situation in which both the central bank and private agents independently engage in adaptive learning (such as the case of Bullard and Mitra [2002]), the E-stability is not attained solely by the Taylor principle. We find that, to ensure the convergence to the REE, the central bank must respond more strongly to the expected inflation rate than the Taylor principle suggests.

This result is obtained because, in a situation in which private agents engage in adaptive learning by referring to the central bank's forecast, private agents' forecast errors, which are defined as the deviations of private agents' expectations from rational expectations, are magnified, compared to the central bank's forecast errors. The reason is twofold. Firstly, private agents make estimation errors in their reduced-form models (perceived law of motions). Secondly, private agents' forecasts are influenced by the central bank's forecast errors around the REE. Summing up these two sources, the total forecast errors of private agents exceed the central bank's forecast errors. Since the central bank introduces the central bank's own forecast in the monetary policy rule, the central bank only responds to the central bank's own forecast errors. This policy response is insufficient to offset the forecast errors of private agents. To ensure the convergence to the REE, the central bank must respond more strongly to the expected inflation rate than the Taylor principle suggests.

On the other hand, the central bank's strong reaction to the expected inflation rate raises the possibility of indeterminacy of the REE (i.e. the emergence of sunspot equilibria), as is pointed out by Bernanke and Woodford [1997]. For this problem, we propose a remedy in which the central bank additionally responds to the contemporaneous data of the inflation rate. We show that by doing so the central bank can simultaneously relax the conditions of determinacy and E-stability. This result suggests that a robust policy strategy entails responding to the contemporaneous movements of the inflation rate to a certain degree.

Chapter 2

Estimating a New Keynesian Phillips Curve with a Corrected Measure of Real Marginal Cost: Evidence in Japan

2.1 Introduction

The New Keynesian Phillips curve (NKPC), which was developed most notably by Rotemberg [1982a] and Calvo [1983], holds a central place in the recent monetary economics. Yet, despite its theoretical importance, empirical studies do not necessarily assess the NKPC as a good description of actual inflation dynamics. In relatively earlier studies, such as Galí and Gertler [1999], Galí, Gertler, and López-Salido [2001], and Sbordone [2002], there has been some consensus that the fit of the NKPC in the U.S. or the Euro area is good if we use labor share (real unit labor cost) as the proxy for real marginal cost (RMC). However, the more recent studies by Rudd and Whelan [2005a,b, 2006, 2007] show that there is scarce evidence on the correlation between inflation rate and the discounted sum of future labor shares as for the U.S. economy. They also show that the observed good performance of the "hybrid" NKPC, which introduces lagged inflation term as an additional explanatory variable, is just brought by lagged inflation, not by the discounted sum of future labor shares.[1] These results imply that the fit of the NKPC is actually poor, and that a backward-looking component plays a more important role in explaining the actual inflation dynamics.

Nevertheless, we can further consider the possibility that the fit of the NKPC is poor only because labor share is not a good proxy for RMC. Rotemberg and Woodford [1999] explain that "while labor share (or equivalently, the ratio of price to unit labor cost) is a familiar and easily interpretable statistic, it represents a valid measure of markup variations only under relatively special assumptions" (p. 1064). They show that some corrections to labor share would be required to obtain a more realistic measure of RMC, and these corrections would imply that RMC is more pro-cyclical than labor share. In the context of the NKPC, Wolman [1999] suggests that "continued progress in empirical evaluation of sticky-price models will require intensive study of the factors determining real marginal cost. With more refined estimates of real marginal cost, it may be possible to reconcile a plausible sticky-price specification with data on inflation".[2]

To apply these ideas, we estimate the NKPC for Japan's economy, focusing on the measurement of RMC. To obtain a better proxy for RMC, we correct labor share by taking account of two kinds of labor market frictions: (i) labor adjustment costs and (ii) real wage rigidity. This can be done because we have a direct measure on the degree of labor market frictions in Japan. As an extension, we also incorporate materials prices in the calculation of RMC, following Batini, Jackson, and Nickell [2005].[3]

[1] As for the Euro area, Bardsen, Jansen, and Nymoen [2004] show that the favorable evidence for the NKPC reported by Galí, Gertler, and López-Salido [2001] depend on specific choices made about estimation methodology. Based on the extended empirical framework (variable addition and encompassing of existing models), they report that the forward-looking aspect is not relevant for the inflation dynamics in the Euro area. However, they still use labor share as the proxy for RMC.

[2] Rudd and Whelan [2005] acknowledge the possibility that the poor performance of the NKPC comes from the discrepancy between labor share and RMC. They describe that "on balance, then, we conclude that it remains possible that some forward-looking model based on a measure of real marginal cost provides a good description of the inflation process, but this conjecture can by no means be considered proven" (p. 311).

[3] Leith and Malley [2007] report that the parameters of the NKPC for the U.S. economy (both in industry-level and aggregate level) are reasonably estimated if the cost of materials, rather than labor share, is used as the proxy for RMC. Our approach is different from theirs because we partially correct labor share by incorporating labor market frictions and the influence of materials prices, rather than perfectly replacing labor share by the costs of materials. However, Leith and Malley [2007] and our study share the idea that obtaining

Our exercise shows that the fit of the NKPC is poor in Japan if we naively use labor share as the proxy for RMC. This result is just the same as the U.S. or the Euro area. However, the consideration of the two kinds of labor market frictions greatly improves the fit of Japan's NKPC. Furthermore, if we incorporate materials prices, the fit of the NKPC is further improved. We find that the inclusion of lagged inflation term into the NKPC does not improve the fit of the NKPC at all. This result indicates that the conventional backward-looking component is no more needed to explain Japan's inflation dynamics if we use a corrected measure of RMC.

Our study contributes to the literature in three respects. First, we present a method to obtain a better proxy of RMC by correcting labor share with the information of labor market frictions. Second, we give an evidence that the fit of the NKPC can be underestimated due to the problem that labor share does not correctly capture the movement of RMC. Third, we show that the role of a backward-looking component can be overestimated due to the discrepancy between labor share and RMC. These findings imply that the argument of Rotemberg and Woodford [1999] is relevant for evaluating the performance of the NKPC, as is predicted by Wolman [1999].

The rest of this chapter is organized as follows. In Section 2.2, we present the form of the NKPC under alternative measures of RMC. In Section 2.3, we estimate the NKPC by using Japanese data. In Section 2.4, we examine the role of a backward-looking component in explaining Japan's inflation dynamics. In Section 2.5, we check the robustness of our results by introducing a model of staggered real wage setting. In Section 2.6, we give concluding remarks.

2.2 The NKPC under Alternative Measures of RMC

In this section, we present the form of the NKPC under alternative measures of RMC.

2.2.1 The Benchmark NKPC

To derive the NKPC as simply as possible, we introduce Rotemberg's [1982a,b] quadratic price adjustment cost function. The representative firm sets the

a better proxy for RMC than labor share is crucial for evaluating the performance of the NKPC.

price (P_t) to minimize the discounted sum of the quadratic price adjustment costs as follows:

$$E_t \sum_{k=0}^{\infty} \beta^k \left[(\ln P_{t+k} - \ln P^*_{t+k})^2 + \gamma(\ln P_{t+k} - \ln P_{t+k-1})^2 \right], \tag{2.1}$$

where P^*_t is the optimal price at t under flexible prices. Under monopolistic competition, P^*_t is given by

$$P^*_t = \mu MC_t, \tag{2.2}$$

where μ is the so-called *desired markup* (or *equilibrium markup*), which is determined by the competitiveness of the goods market, and MC_t is the nominal marginal cost.[4]

If the nominal marginal cost is given, then firms' cost minimization yields the NKPC as follows:

$$\pi_t = \beta E_t \pi_{t+1} + \frac{1}{\gamma} \ln \mu + \frac{1}{\gamma} \ln RMC_t, \tag{2.3}$$

where π_t is the inflation rate and RMC_t is the real marginal cost ($RMC_t \equiv \frac{MC_t}{P_t}$).

In estimating the NKPC, we need to have the proxy for RMC. Consider the following aggregate production function, which is isoelastic with respect to the aggregate labor input (L_t):

$$Y_t = A_t L_t^{\alpha}, \tag{2.4}$$

where Y_t is the aggregate value added and A_t is the exogenous shift factor.[5]

Suppose that firms do not incur any adjustment cost in changing the number of labor input. Then, the real marginal cost is simply calculated as follows:

$$RMC_t = \frac{\partial(\frac{W_t}{P_t} L_t)}{\partial Y_t} = \frac{1}{\alpha} S_t, \tag{2.5}$$

[4] In this study, we do not investigate the mechanism of variations of the desired markup, since this issue is still controversial and it is not clear to which model we should particularly pay attention (see the conclusions of Rotemberg and Woodford [1999]).

[5] We assume that labor is the only variable production input. Therefore, other inputs, such as capital stock, are assumed to be exogenous and are included in the calculation of A_t.

where W_t is the nominal wage rate and S_t is labor share ($S_t \equiv \frac{W_t L_t}{P_t Y_t}$). Therefore, RMC becomes proportional to labor share.

From (2.3) and (2.5), the NKPC is expressed as follows:

$$\pi_t = \beta E_t \pi_{t+1} + \frac{1}{\gamma} \ln \frac{\mu}{\alpha} + \frac{1}{\gamma} \ln S_t. \tag{2.6}$$

We regard (2.6) as the benchmark representation of the NKPC.

2.2.2 The NKPC with Labor Market Frictions

Next, we derive the representation of the NKPC in the presence of two kinds of labor market frictions, such as (i) labor adjustment costs and (ii) real wage rigidity.

Suppose that, at period t, the representative firm incurs nominal adjustment costs (defined as Ω_t) in changing the number of workers. Rather than specifying the exact form of Ω_t, we only assume that Ω_t is a differentiable function of current and past labor input ($\Omega_t = \Omega_t(L_t, L_{t-1}, L_{t-2}, \cdots)$).[6,7] Since Ω_t inter-temporally depends on labor input, the firm's cost-minimization problem becomes dynamic. Then RMC at period t is calculated as follows:

$$RMC_t = \frac{1}{\alpha} S_t \left[1 + \frac{1}{W_t} E_t \sum_{k=0}^{\infty} \beta^k \left(\frac{\partial \Omega_{t+k}}{\partial L_t} \mid_{L_{t+k} = L^*_{t+k} \ \forall \ k} \right) \right], \tag{2.7}$$

where L^*_t is the optimal number of workers under flexible prices.

Note that, except for the special case where the sum of discounted marginal labor adjustment costs is zero ($E_t \sum_{k=0}^{\infty} \beta^k \left(\frac{\partial \Omega_{t+k}}{\partial L_t} \mid_{L_{t+k} = L^*_{t+k} \ \forall \ k} \right) = 0$), RMC does not generally correspond to labor share. Therefore, to obtain a

[6] As for labor adjustment cost function, some previous studies (such as Batini, Jacksosn, and Nickell [2005]) have specifically focused on the symmetric quadratic form. However, we do not specify the exact form of labor adjustment cost function. The reason is twofold. First, the argument on whether such a symmetric quadratic form can approximate the aggregate labor adjustment cost function is still highly controversial in the literature of labor adjustment costs (Caballero and Engel [2004], Cooper and Willis [2002, 2004a,b]). Second, especially in the case of Japan, it seems plausible that the form of labor adjustment cost function is more complex than the U.S. because of the presence of a long-term employment relationship, as indicated in many studies (for example, Hashimoto and Raisian [1985]). The virtue of our approach is to avoid specifying the exact form of labor adjustment cost function.

[7] The reason why Ω_t depends on the labor prior to time $t-1$ ($L_{t-2}, L_{t-3}, \cdots$) is explained by the possibility that firms might have to incur the cost of adjusting labor input more than one period.

proxy for RMC, we need to have the information on the sum of discounted marginal labor adjustment cost.

In the case of Japan, we can obtain this information from the survey data of Japanese firms. Figure 2.1 shows the diffusion index of employment (employment DI) in the Bank of Japan's *Short-Term Economic Survey of Enterprises in Japan* (called the *TANKAN* Survey).[8] The employment DI shows the net percentage of firms which consider that the current number of workers is excessive. As this series indicates, there has been a substantial *labor gap*, which is defined as the deviation of the actual number of workers from the optimal number of workers, for many periods.[9] We view that the series of labor gap implies the presence of labor adjustment costs based on the reasoning that the firms can always attain the optimal number of workers if labor adjustment costs are absent. Therefore, we utilize this information to estimate the size of labor adjustment costs.

To utilize the series of the labor gap in estimating labor adjustment costs, we need to introduce the process of real wage determination because the theoretical relationship between the labor gap and labor adjustment costs depends on this process. In this respect, we take account of the presence of real wage rigidity, by introducing the following process of real wages, which is adopted by Blanchard and Galí [2007] and Christoffel and Linzert [2005]:

$$\ln \frac{W_t}{P_t} = \rho \ln \frac{W_{t-1}}{P_{t-1}} + (1-\rho) \ln Y_t^{\sigma} L_t^{\eta-1}. \tag{2.8}$$

In (2.8), $Y_t^{\sigma} L_t^{\eta-1}$ is the representative household's marginal rate of substitution (MRS) between consumption and labor supply under the standard instantaneous utility function ($U_t = \frac{Y_t^{1-\sigma}}{1-\sigma} - \frac{1}{\eta} L_t^{\eta}$). ρ characterizes the degree of real wage rigidity. Except for the limiting case of perfectly flexible real wage ($\rho = 0$), real wage becomes more sluggish than MRS.[10,11] Under the

[8] The *TANKAN* survey is the broadest survey of the conditions of Japanese enterprises. As of March 2006, it covers 10,087 firms (4,156 manufacturing firms and 5,931 non-manufacturing firms).

[9] The series shows that nearly half of the Japanese firms considered that the number of workers was insufficient around the "bubble" period, and that many firms had excessive labor for a long period after the bursting of the bubble.

[10] We assume that real wage rigidity arises solely due to the problems of the household sector. This implies that firms are wage takers.

[11] In Section 2.5, we check the robustness of our analysis by introducing a micro-founded model of staggered real wage setting, which is explicitly derived from the optimization problem in the Appendix B of Blanchard and Galí [2007].

process of (2.8), we can show that RMC in the presence of labor market frictions is calculated as follows (see Section 2.7.1):

$$\ln RMC_t = \ln\frac{1}{\alpha} + \ln S_t + \left[\alpha - 1 - \frac{(\alpha\sigma+\eta-1)(1-\rho)}{1-\rho B}\right] \left[(1+\gamma+\gamma\beta)LGAP_t^s - \gamma LGAP_{t-1}^s - \gamma\beta E_t LGAP_{t+1}^s\right], \tag{2.9}$$

where $LGAP_t^s$ is the labor gap under sticky prices and B is backshift operator.[12]

By substituting (2.9) into (2.3), we obtain the following representation of the NKPC in the presence of labor market frictions:

$$\pi_t = \beta E_t\pi_{t+1} + \frac{1}{\gamma}\ln\frac{\mu}{\alpha} + \frac{1}{\gamma}\ln S_t + \frac{1}{\gamma}\left[\alpha - 1 - \frac{(\alpha\sigma+\eta-1)(1-\rho)}{1-\rho B}\right] \left[(1+\gamma+\gamma\beta)LGAP_t^s - \gamma LGAP_{t-1}^s - \gamma\beta E_t LGAP_{t+1}^s\right]. \tag{2.10}$$

2.2.3 The NKPC with Labor Market Frictions and Materials Prices

So far, we have not explicitly considered the influence of materials prices in the calculation of RMC. However, Batini, Jackson, and Nickell [2000, 2005] show that, if production technology requires a certain amount of materials to produce one additional unit of gross output, materials prices might influence RMC on value added. They consider the following production function of gross output:

$$Q_t = \min\left(A_t L_t^{\alpha},\ M_t\right), \tag{2.11}$$

$$M_t = m(Q_t)Q_t,\ \text{where } m'(Q_t) \geq 0, \tag{2.12}$$

where Q_t is gross output and M_t is material input, each is represented in real terms.

(2.11) is the standard Leontief production technology of gross output, in which value added and material input are perfect complements. The unique contribution of Batini, Jackson, and Nickell [2000, 2005] is the introduction

[12] The backward shift operator is the function that translates BE_tx_{t+1} into $E_{t-1}x_t$. This operator is more convenient in our analysis than the lag operator (L), which translates LE_tx_{t+1} into x_t.

of (2.12). (2.12) means that the required ratio of material input to gross output (m) depends on the level of gross output (Q_t).[13]

In this setup, Batini, Jackson, and Nickell [2000, 2005] show that RMC additionally includes the following term:

$$\zeta_t = \varepsilon_m \frac{P_{M,t} M_t}{P_t Q_t}, \tag{2.13}$$

where $P_{M,t}$ is the price of materials and ε_m is the elasticity of M_t/Q_t to Q_t.

Then, the representation of the NKPC is modified as follows:

$$\begin{aligned}\pi_t \quad = \quad & \beta E_t \pi_{t+1} + \frac{1}{\gamma} \ln \frac{\mu}{\alpha} + \frac{1}{\gamma} \ln(S_t + \zeta_t) + \frac{1}{\gamma} \left[\alpha - 1 - \frac{(\alpha\sigma + \eta - 1)(1-\rho)}{1 - \rho B} \right] \\ & \left[(1 + \gamma + \gamma\beta) LGAP_t^s - \gamma LGAP_{t-1}^s - \gamma\beta E_t LGAP_{t+1}^s \right]. \qquad (2.14)\end{aligned}$$

2.3 Estimating Japan's NKPC

In this section, we estimate Japan's NKPC under alternative measures of RMC. To this end, we use the present value model (PVM), which is employed by Rudd and Whelan [2005a,b, 2006, 2007].[14]

2.3.1 The Benchmark NKPC

Firstly, we apply the PVM for the estimation of the benchmark NKPC. In the PVM, we estimate the closed form solution of the NKPC. The closed form solution of the benchmark NKPC (2.6) is given by:

$$\pi_t = \frac{1}{\gamma(1-\beta)} \ln \frac{\mu}{\alpha} + \frac{1}{\gamma} E_t \sum_{k=0}^{\infty} \beta^k \ln S_{t+k}. \tag{2.15}$$

To construct the discounted sum of the expected (log of) labor share, we develop an auxiliary VAR as follows:

$$\mathbf{Z}_t = \mathbf{A}\mathbf{Z}_{t-1} + \boldsymbol{\epsilon}_t, \tag{2.16}$$

[13] This corresponds to the situation where the firm has different kinds of labor inputs that vary in terms of the efficiency of the use of materials, and puts a high priority on the use of efficient labor. As a result, in the production margin, the firm must use relatively inefficient labor inputs which require many material inputs to produce one additional unit of gross output.

[14] The PVM was used originally by Campbell and Shiller [1987] in the context of stock price determination.

where $\mathbf{Z}_t$ is the vector of endogenous variables, $\mathbf{A}$ is a parameter matrix, and $\boldsymbol{\epsilon}_t$ is the vector of exogenous shocks. The form of (2.16) can express a general form of VAR, by introducing lagged endogeneous variables into $\mathbf{Z}_t$. As for the benchmark NKPC, we assume that $\mathbf{Z}_t$ includes $\ln S_t$ as the first variable.

The discounted sum of the expected (log of) labor share can be written as:

$$\sum_{k=0}^{\infty} \beta^k E_t \ln S_{t+k} = e_1'(\mathbf{I} - \beta\mathbf{A})^{-1}\mathbf{Z}_t, \tag{2.17}$$

where e_1' is a vector with one in the first row and zeros elsewhere. Then, the closed-form solution of the NKPC is re-expressed as

$$\pi_t = a_0 + a_1 e_1'(\mathbf{I} - \beta\mathbf{A})^{-1}\mathbf{Z}_t, \tag{2.18}$$

where $a_0 = \frac{1}{\gamma(1-\beta)} \ln \frac{\mu}{\alpha}$ and $a_1 = \frac{1}{\gamma}$. This is the estimation form of the benchmark NKPC. We can simply estimate (2.18) by ordinary least squares (OLS).[15]

In estimating the auxiliary VAR, we select some specifications of Woodford [2001] and Rudd and Whelan [2005]. Put concretely, we use one univariate model, which only includes the (log of) labor share, and two multivariate models, which additionally introduce the growth rate of unit labor cost and inflation rate.[16] The lag length is chosen by Schwarz's information criterion. Following the literature, β is set as 0.99 throughout this study. The sample period is 1975/Q1-2004/Q4. See Section 2.7.2 for the data description.

Table 2.1 summarizes the estimation results. For each VAR specification, the fit of the NKPC is poor, since *Adj*-R^2 is just around 0.1 or 0.2 and there is noticeable serial correlation in the error term.[17] In Figure 2.2, we can graphically confirm the poor fit of the benchmark NKPC. It cannot explain the inflationary pressure in the late 1980s and the deflationary trend since the beginning of 1990s.

[15] To examine the possibility that $\mathbf{Z}_t$ correlates with error term, we have also estimated (2.18) by instrumental variables (IV) method. Using $\mathbf{Z}_{t-1}$ and $\mathbf{Z}_{t-2}$ as instruments, we find that the result is almost the same as OLS.

[16] Woodford [2001] reports that, if the VAR includes labor share and the growth of unit labor cost, the fit of the NKPC is fairly good in the U.S. Rudd and Whelan [2005a] show that including the inflation rate in VAR largely alters the fit of NKPC in the U.S.

[17] As Kurmann [2005] points out, standard errors on the estimated coefficients will be underestimated, because we neglect the standard errors in the auxiliary VAR. So, our argument focuses on the fit of the NKPC in the point estimates (expressed as *Adj*-R^2).

This finding raises two possibilities. The first is that the NKPC is not a suitable model to explain Japan's inflation dynamics. The second is that the NKPC does not fit well only because labor share is not a good proxy for RMC. In the following, we examine the latter possibility.

2.3.2 The NKPC with Labor Market Frictions

In Section 2.2.2, we have derived the representation of the NKPC in the presence of labor market frictions as (2.10). Since we regard that the series of employment DI (denoted as EDI_t) corresponds to the labor gap under sticky prices, we can introduce the following relationship:

$$LGAP_t^s = \delta EDI_t, \tag{2.19}$$

where δ is a scaling parameter.

As in the previous subsection, we apply the PVM for the estimation of the NKPC with labor market frictions. In doing so, we replace the matrix $\mathbf{Z}_t$ in (2.16) to include $\ln S_t$ as the first and EDI_t as the second variable. Then, the closed-form solution of (2.10) is represented as follows (see Section 2.7.3 for the derivation of this solution):

$$\begin{aligned}\pi_t &= b_0 + b_1 e_1'(\mathbf{I}-\beta\mathbf{A})^{-1}\mathbf{Z}_t + b_2\left[b_1 e_2'(\mathbf{I}-\beta\mathbf{A})^{-1}\mathbf{Z}_t + EDI_t - EDI_{t-1}\right] \\ &\quad + b_3\sum_{h=0}^{\overline{h}}\rho^h\left[b_1 e_2'(\mathbf{I}-\beta\mathbf{A})^{-1}\mathbf{Z}_{t-h-1} + EDI_{t-h-1} - EDI_{t-h-2}\right],\end{aligned} \tag{2.20}$$

where $b_0 = \frac{1}{\gamma(1-\beta)}\ln\frac{\mu}{\alpha}$, $b_1 = \frac{1}{\gamma}$, $b_2 = \delta\left[(\alpha-1)-(\alpha\sigma+\eta-1)(1-\rho)\right]$, and $b_3 = -\delta(\alpha\sigma+\eta-1)(1-\rho)\rho$, and e_2' is a vector with one in the second row and zeros elsewhere. Notice that this estimation form has a parameter restriction in a nonlinear way. Therefore, we must estimate it by nonlinear least squares (NLS). The combinations of endogenous variables in VAR are the same as in the previous subsection. The sample period is 1977/Q3-2004/Q4.[18]

Table 2.2 shows the estimation results of (2.20). Compared to Table 2.1,

[18] The sample period is shorter than the previous subsection because we must truncate the sample if we specify the value of $\overline{h}$ as more than 1. Theoretically, $\overline{h}$ should be infinity. However, the choice of a large value of $\overline{h}$ reduces the degree of freedom. So we choose $\overline{h} = 10$. But we have confirmed that the results do not change much as long as we select a sufficiently large $\overline{h}$.

we find that the fit of the NKPC is improved in every specification of VAR. The estimates of ρ are larger than 0.9, which implies that real wages are quite rigid in Japan. Interestingly, these values are almost the same as the autocorrelation coefficient of the U.S. economy's aggregate wage markup (the difference between real wage and MRS), which is estimated by Galí, Gertler, and López-Salido [2007] as 0.94 or 0.95. Figure 2.3 shows that the consideration of real wage rigidity remarkably improves the performance of the NKPC.

Thus, the results in this section show that, if we correct labor share by incorporating two kinds of labor market frictions: (i) labor adjustment costs and (ii) real wage rigidity, the NKPC well explains Japan's inflation dynamics.

2.3.3 The NKPC with Labor Market Frictions and Materials Prices

Here we estimate Japan's NKPC by additionally incorporating the influence of materials prices on RMC. As is shown in (2.13), the influence (ζ) depends on the value of the elasticity ε_m. To check the importance of ζ_t, we estimate the elasticity ε_m. Table 2.3 shows the estimation results for ε_m. Since ε_m is significantly larger than zero ($\varepsilon_m = 0.395$), the null hypothesis that the level of Q_t does not matter to m is rejected. Therefore, we must additionally include ζ_t in the calculation of RMC.

To apply the PVM, we replace the matrix $\mathbf{Z}_t$ to include $\ln(S_t + \zeta_t)$ as the first and EDI_t as the second variable. Then, the closed form of the NKPC with RMC is modified as follows:

$$\begin{aligned} \pi_t &= c_0 + c_1 e_1'(\mathbf{I} - \beta\mathbf{A})^{-1}\mathbf{Z}_t + c_2\left[c_1 e_2'(\mathbf{I} - \beta\mathbf{A})^{-1}\mathbf{Z}_t + EDI_t - EDI_{t-1}\right] \\ &\quad + c_3 \sum_{h=0}^{\overline{h}} \rho^h \left[c_1 e_2'(\mathbf{I} - \beta\mathbf{A})^{-1}\mathbf{Z}_{t-h-1} + EDI_{t-h-1} - EDI_{t-h-2}\right], \end{aligned} \tag{2.21}$$

where $c_0 \simeq \frac{1}{\gamma(1-\beta)}\left(\ln\frac{\mu}{\alpha} + \ln\overline{\zeta}\right)$, $c_1 = \frac{1}{\gamma}$, $c_2 = \delta\left[(\alpha - 1) - (\alpha\sigma + \eta - 1)(1 - \rho)\right]$, and $c_3 = -\delta(\alpha\sigma + \eta - 1)(1 - \rho)\rho$.[19]

The estimation results are presented in Table 2.4. The fit of the NKPC

[19] $\overline{\zeta}$ denotes the steady-state value of ζ_t.

is further improved over Table 2.2 for every specification of VAR.[20] Now we do not have noticeable serial correlation in the error term (see Figure 2.4 for the fit of the NKPC). Therefore, this result suggests that Japan's inflation dynamics are well explained within the framework of the NKPC, if we calculate RMC by incorporating labor market frictions and the influence of materials prices.

2.4 Is a "Backward-Looking" Component Necessary to Explain Japan's Inflation Dynamics?

In this section, we examine the role of a backward-looking component in explaining Japan's inflation dynamics. The role of a backward-looking component has been stressed in many of the previous studies, such as Fuhrer and Moore [1995] and Fuhrer [1997]. In the empirics of the NKPC, the earlier studies, such as Galí and Gertler [1999] and Galí, Gertler, and López-Salido [2001, 2005a], apply the generalized method of moments (GMM) for estimating the so-called "hybrid" NKPC, which includes a lagged inflation term as an additional explanatory variable, and report that the role of a backward-looking component is relatively minor. However, the more recent studies, such as Rudd and Whelan [2005 a,b,2006,2007], Lindé [2005], Roberts [2005], Jondeau and Le Bihan [2005], apply alternative empirical methodologies (the PVM or the maximum likelihood (ML)) for the estimation of the NKPC, and they report that a backward-looking component actually plays a more important role than considered in the earlier studies.[21]

Nevertheless, we can still consider the possibility that these studies overestimate the role of a backward-looking component due to the measurement problem of RMC, because most of the studies naively use labor share as the proxy for RMC. In this respect, our study has some potential to estimate

[20] Readers may wonder whether the obtained $Adj\text{-}R^2$ is large enough to judge that the fit of the NKPC is good. In this respect, Rudd and Whelan [2005a] report that, the specification of PVM in Woodford [2001], who reports that the NKPC with labor share fits well with the U.S. inflation rate, yields an R^2 of 0.44 in their dataset. In considering this result, we view that the $Adj\text{-}R^2$ reported in Table 2.4 indicates the reasonably good fit of Japan's NKPC.

[21] Mavroeidis [2005] show that the problem of weak identification cannot be ruled out in estimating the NKPC with GMM. He demonstrated that when the model is weakly identified, the GMM estimation will be biased in favor of hybrid NKPC with apparently dominant forward-looking behavior, irrespective of the true nature of the forward and backward-looking dynamics of inflation. Rudd and Whelan [2005b] raise similar issues.

more properly the role of a backward-looking component, because we calculate the measure of RMC by incorporating labor market frictions and the influence of materials prices, which have been neglected in most of the studies. To examine the role of a backward-looking component in Japan's inflation dynamics, we apply the approach of Rudd and Whelan [2005 a,b,2006,2007]. Put concretely, we estimate the closed form solution of the NKPC ((2.18), (2.20), and (2.21)), by additionally including the lagged inflation term.

Table 2.5 shows the estimation results of the benchmark NKPC which includes the lagged inflation term. When we include lagged inflation term, *Adj*-R^2 ranges from 0.365 to 0.395. These are much higher than *Adj*-R^2 in the absence of lagged inflation term, which ranges from 0.103 to 0.209 (as in Table 2.1). The coefficient on lagged inflation term (around 0.5) also indicates the substantial role of lagged inflation for the fit of NKPC. In Figure 2.5, we observe that, by including lagged inflation term, the fit of the benchmark NKPC is largely altered. These results indicate that, if we use labor share as the proxy for RMC, a backward-looking component plays an important role in the case of Japan. This is the same situation as in the U.S or the Euro area.

However, the results are dramatically altered by incorporating labor market frictions. Table 2.6 shows the estimation results of the NKPC with labor market frictions which includes lagged inflation term. *Adj*-R^2 ranges from 0.384 to 0.424. These are not much higher than *Adj*-R^2 in the absence of lagged inflation term, which ranges from 0.319 to 0.391 (as in Table 2.2). Figure 2.6 also shows that the inclusion of lagged inflation term only slightly alters the fit of the NKPC. This indicates that the role of lagged inflation becomes less important if we correct labor share by incorporating labor market frictions.

Table 2.7 further shows the estimation results of the NKPC with labor market frictions and materials prices. *Adj*-R^2 ranges from 0.478 to 0.493. At this stage, these values are almost the same as *Adj*-R^2 in the absence of lagged inflation term, which ranges from 0.477 to 0.494 (as in Table 2.4). In addition, the coefficient of lagged inflation now becomes quite small (around 0.1) in every VAR specification. Figure 2.7 also shows that the inclusion of lagged inflation term has almost no influence on the fit of the NKPC. This result implies that lagged inflation is no more needed to explain Japan's inflation dynamics if we correct labor share by incorporating labor market frictions and materials prices.

In sum, the results in this section suggest that the role of backward-looking component can be overestimated due to the measurement problem of RMC. Actually, in the case of Japan, we find that the role of a backward-looking component disappears if we use the corrected measure of RMC. This implies that, at least in Japan, the observed role of a backward-looking component in the benchmark NKPC can be mostly explained by the discrepancy between labor share and RMC.

2.5 Further Consideration on Real Wage Rigidity: The Case of Staggered Real Wage Setting

Until the previous section, we have examined the fit of Japan's NKPC with a corrected measure of RMC, which is calculated by using the model of real wage rigidity (2.8). Readers may wonder whether the results obtained in the previous sections are robust when we introduce alternative models of real wage rigidity, especially models which have more explicit microfoundations.

In this section, we check the robustness of our results by using a model of staggered real wage setting. This model is explicitly derived from an optimization problem in Appendix B of Blanchard and Galí [2007], who apply Calvo [1983]'s staggered price setting for the determination of real wage. In an environment that only a fraction of workers resets their real wage in each period, the model is derived as follows:

$$\ln \frac{W_t}{P_t} = \phi \ln \frac{W_{t-1}}{P_{t-1}} + \phi\beta E_t \ln \frac{W_{t+1}}{P_{t+1}} + \lambda \ln Y_t^{\sigma} L_t^{\eta-1}. \qquad (2.22)$$

Thus, this model differs from (2.8) in that it includes forward-looking expectation ($E_t \ln \frac{W_{t+1}}{P_{t+1}}$). Using backshift operator (B), (2.22) can be rewritten as follows:

$$\ln \frac{W_t}{P_t} = (1 - \xi\beta B^{-1})^{-1}(1 - \xi B)^{-1}\frac{\xi\lambda}{\phi} \ln Y_t^{\sigma} L_t^{\eta-1}, \qquad (2.23)$$

where $\xi = \frac{1+\sqrt{1-4\phi^2\beta}}{2\phi\beta}$. By using (2.23) and by following the same steps in

Section 2.7.1, we obtain the following expression of RMC:

$$
\begin{aligned}
\ln RMC_t &= \ln\frac{1}{\alpha} + \ln S_t \\
&+ \left[(\alpha-1) - (1-\xi\beta B^{-1})^{-1}(1-\xi B)^{-1}\frac{\xi\lambda}{\phi}(\alpha\sigma+\eta-1)\right] \\
&\left[(1+\gamma+\gamma\beta)LGAP_t^s - \gamma LGAP_{t-1}^s - \gamma\beta E_t LGAP_{t+1}^s\right].
\end{aligned} \tag{2.24}
$$

By substituting (2.25) into (2.3), we derive the NKPC as follows:

$$
\begin{aligned}
\pi_t &= \beta E_t\pi_{t+1} + \frac{1}{\gamma}\ln\frac{\mu}{\alpha} + \frac{1}{\gamma}\ln S_t \\
&+\frac{1}{\gamma}\left[(\alpha-1) - (1-\xi\beta B^{-1})^{-1}(1-\xi B)^{-1}\frac{\xi\lambda}{\phi}(\alpha\sigma+\eta-1)\right] \\
&\left[(1+\gamma+\gamma\beta)LGAP_t^s - \gamma LGAP_{t-1}^s - \gamma\beta E_t LGAP_{t+1}^s\right].
\end{aligned} \tag{2.25}
$$

Using the VAR model that is introduced in Section 2.3.2, we can express the closed-form solution of (2.26) as follows[22]:

$$
\begin{aligned}
\pi_t &= d_0 + d_1 e_1'(\mathbf{I}-\beta\mathbf{A})^{-1}\mathbf{Z}_t + d_2\left[d_1 e_2'(\mathbf{I}-\beta\mathbf{A})^{-1}\mathbf{Z}_t + EDI_t - EDI_{t-1}\right] \\
&+d_3\sum_{h=1}^{\infty}\xi^h\left[d_1 e_2'(\mathbf{I}-\beta\mathbf{A})^{-1}\mathbf{Z}_{t-h} + (EDI_{t-h} - EDI_{t-h-1})\right] \\
&+d_3\sum_{j=1}^{\infty}(\xi\beta)^j e_2'\left[d_1\left((\mathbf{I}-\beta\mathbf{A})^{-1} - \sum_{l=1}^{j}\mathbf{A}^l\right) + (\mathbf{A}^j - \mathbf{A}^{j-1})\right]\mathbf{Z}_t,
\end{aligned} \tag{2.26}
$$

where $d_0 = \frac{1}{\gamma(1-\beta)}\ln\frac{\mu}{\alpha}$, $d_1 = \frac{1}{\gamma}$, $d_2 = \delta\left[(\alpha-1) - \frac{\xi}{\phi}\lambda\frac{(\alpha\sigma+\eta-1)}{1-\xi^2\beta}\right]$, $d_3 = -\frac{\xi}{\phi}\lambda\frac{(\alpha\sigma+\eta-1)\delta}{1-\xi^2\beta}$.

The estimation results of (2.26) are presented in Table 2.8. The estimated ξ is quite high in every specification of auxiliary VAR. Therefore, the results indicate that real wage rigidity is important in the calculation of RMC. The fit of the NKPC is shown in Figure 2.8. By incorporating real wage rigidity, the fit of the NKPC is remarkably improved. This result is essentially the same as the result in Section 2.3.2.

Table 2.9 and Figure 2.9 show the estimation results when we addition-

[22] Although the algebra for the derivation of (2.26) is more complex than the derivation of (2.20), we follow essentially the same steps of Section 2.7.3.

ally introduce lagged inflation term into (2.26). The results indicate that the inclusion of lagged inflation only slightly improves the fit of the NKPC. Since the degree of improvement is almost the same as Table 2.6 and Figure 2.6, we judge that the results obtained in Section 2.4 are robust in the explicitly derived micro-founded model of staggered real wage setting.

These results have important implication for the explanation of the fit of the NKPC. In previous studies, many researchers introduce lagged inflation term into the NKPC in somewhat ad-hoc way. However, the results in this study show that the observed important role of backward-looking component is explained by the persistence of RMC, which can be derived in an explicit micro-founded model. Although the fit of the NKPC in this study might seem not so different from that of the hybrid NKPC (as is compared between Table 2.5 and Table 2.8), theoretical implications are quite different between these two results.

2.6 Conclusion

In this chapter, we have estimated a New Keynesian Phillips curve (NKPC) in Japan, focusing on the measurement of real marginal cost (RMC). To obtain a better proxy for RMC, we have corrected labor share by taking account of two kinds of labor market frictions: (i) labor adjustment costs and (ii) real wage rigidity. Our results have shown that the consideration of these labor market frictions greatly improves the fit of Japan's NKPC. Furthermore, if we additionally incorporate materials prices in the calculation of RMC, then the fit of the NKPC is further improved. We find that the conventional backward-looking component is no more needed to explain Japan's inflation dynamics if we use a corrected measure of RMC.

The evidence in Japan's economy provides some important implications for the literature. First, our results suggest that obtaining a good proxy for RMC is crucial for evaluating the performance of the NKPC. This implies that, at least in Japan, the argument of Rotemberg and Woodford [1999] is relevant for evaluating the performance of the NKPC, as predicted by Wolman [1999]. As our study shows, poor proxies of RMC typically lead us to underestimate the fit of the NKPC and to overstate the importance of lagged inflation. Although the existing studies conventionally use labor share as the proxy for RMC, more efforts to find a better proxy for RMC could contribute to the better understanding about the performance of the NKPC.

Second, our results indicate that labor market frictions are the key elements to explain the movements of RMC. This finding is consistent with some recent analysis on the causes of aggregate economic inefficiency. Galí, Gertler, and López-Salido [2007] find that the "wage markup", defined as the deviation of MRS from real wage, explains most of the costs of the U.S. business cycles. Chari, Kehoe, and McGrattan [2007] show that the "labor wedge", which is defined as the deviation of the marginal product of labor from MRS, is the most essential element for the U.S. aggregate economic inefficiency within their framework of business cycle accounting. Based on the same framework, Kobayashi and Inaba [2006] show that the large and persistent movements of the labor wedge may have been a major contributor to Japan's decade-long recession in the 1990s. Although our empirical viewpoint is different from these studies, our evidence also support the idea that labor market frictions are critical factors to understand macroeconomic dynamics.

2.7 Appendix

2.7.1 Relationship between Labor Adjustment Costs and the Labor Gap

In this appendix, we derive the relationship between the sum of discounted marginal labor adjustment costs and the labor gap under sticky prices. To do so, we take the following steps. First, we derive the relationship between the sum of discounted marginal labor adjustment costs and the labor gap under flexible prices. Second, we derive the relationship between the labor gap under flexible prices and the labor gap under sticky prices. Finally, we combine these two relationships.

Here we derive the relationship between the sum of discounted marginal labor adjustment costs and the labor gap under flexible prices.

Under the flexible price economy, the optimality condition for the firm is (2.2). When labor adjustment costs are relevant, real marginal cost is given by (2.7). From (2.2), (2.4) and (2.7), we have the following expression of optimal price under flexible prices (in logarithm):

$$\ln P_t^* = \ln \frac{\theta W_t A_t^{-1} L_t^{*1-\alpha}}{\alpha(\theta-1)} + \ln\left[1+\frac{1}{W_t}E_t\sum_{k=0}^{\infty}\beta^k\left(\frac{\partial\Omega_{t+k}}{\partial L_t}\ |_{L_{t+k}=L_{t+k}^*\ \forall\ k}\right)\right]. \tag{2.27}$$

Next, by combining (2.4) and (2.8), we have another expression of $\ln P_t^*$:

$$\ln P_t^* = \ln W_t - \frac{1-\rho}{1-\rho B}\ln A_t^{\sigma} L_t^{*\alpha\sigma+\eta-1}. \tag{2.28}$$

From (2.27) and (2.28), we obtain the following condition:

$$\ln \frac{\theta A_t^{-1} L_t^{*1-\alpha}}{\alpha(\theta-1)} + \ln\left[1+\frac{1}{W_t}E_t\sum_{k=0}^{\infty}\beta^k\left(\frac{\partial\Omega_{t+k}}{\partial L_t}\ |_{L_{t+k}=L_{t+k}^*\ \forall\ k}\right)\right]$$
$$= -\frac{1-\rho}{1-\rho B}\ln A_t^{\sigma} L_t^{*\alpha\sigma+\eta-1}. \tag{2.29}$$

The condition (2.29) holds in the presence of labor adjustment costs. The corresponding condition in the absence of labor adjustment costs is given by:

$$\ln \frac{\theta A_t^{-1}\overline{L}_t^{*1-\alpha}}{\alpha(\theta-1)} = -\frac{1-\rho}{1-\rho B}\ln A_t^{\sigma}\overline{L}_t^{*\alpha\sigma+\eta-1}. \tag{2.30}$$

Then, from (2.29) and (2.30), we can derive the relationship between the sum of discounted marginal labor adjustment costs and the labor gap under flexible prices, which is defines as $LGAP_t^* \equiv \ln L_t^* - \ln \overline{L}_t^*$, as follows:

$$\ln\left[1+\frac{1}{W_t}E_t\sum_{k=0}^{\infty}\beta^k\left(\frac{\partial\Omega_{t+k}}{\partial L_t}\ |_{L_{t+k}=L_{t+k}^*\ \forall\ k}\right)\right]$$
$$= \left[\alpha-1-\frac{(\alpha\sigma+\eta-1)(1-\rho)}{1-\rho B}\right] LGAP_t^*. \tag{2.31}$$

As the second step, we derive the relationship between the labor gap under flexible prices and the labor gap under sticky prices. From (2.4) and (2.8), we obtain

$$\ln P_t = \ln W_t - \frac{1-\rho}{1-\rho B}\ln A_t^{\sigma} L_t^{\alpha\sigma+\eta-1}. \tag{2.32}$$

Firm's optimality condition under price adjustment cost function (2.1) is given by:

$$\ln \frac{P_t^s}{P_{t-1}^s} = \beta E_t \ln \frac{P_{t+1}^s}{P_t^s} + \frac{1}{\gamma} \ln \frac{P_t^*}{P_t^s}. \tag{2.33}$$

By substituting (2.32) and (2.33), we can derive the following condition:

$$\ln \frac{L_t^s}{L_{t-1}^s} = \beta E_t \ln \frac{L_{t+1}^s}{L_t^s} + \frac{1}{\gamma} \ln \frac{L_t^*}{L_t^s} + \Gamma_t, \tag{2.34}$$

where L_t^s is the optimal number of workers under sticky prices in the presence of labor adjustment costs, and Γ_t represents the purely exogenous factor. Similarly, we can derive the condition about the optimal number of workers under sticky prices in the absence of labor adjustment costs ($\overline{L}_t^s$) as follows:

$$\ln \frac{\overline{L}_t^s}{\overline{L}_{t-1}^s} = \beta E_t \ln \frac{\overline{L}_{t+1}^s}{\overline{L}_t^s} + \frac{1}{\gamma} \ln \frac{\overline{L}_t^*}{\overline{L}_t^s} + \Gamma_t. \tag{2.35}$$

Define the labor gap under sticky prices as $LGAP_t^s \equiv \ln L_t^s - \ln \overline{L}_t^s$. Then, from (2.34) and (2.35), the relationship between $LGAP_t^*$ and $LGAP_t^s$ is derived as follows:

$$LGAP_t^* = (1+\gamma+\gamma\beta)LGAP_t^s - \gamma LGAP_{t-1}^s - \gamma\beta E_t LGAP_{t+1}^s. \tag{2.36}$$

Finally, by substituting (2.36) into (2.31), we obtain the relationship between the sum of discounted marginal labor adjustment costs and the labor gap under sticky prices as follows:

$$\begin{aligned} & \ln \left[1 + \frac{1}{W_t} E_t \sum_{k=0}^{\infty} \beta^k \left(\frac{\partial \Omega_{t+k}}{\partial L_t} \mid_{L_{t+k}=L_{t+k}^* \ \forall \ k} \right) \right] \\ = & \left[\alpha - 1 - \frac{(\alpha\sigma + \eta - 1)(1-\rho)}{1-\rho B} \right] \\ & \left[(1+\gamma+\gamma\beta)LGAP_t^s - \gamma LGAP_{t-1}^s - \gamma\beta E_t LGAP_{t+1}^s \right]. \end{aligned} \tag{2.37}$$

2.7.2 Data Description

As for the inflation rate, we use the seasonally adjusted GDP deflator (quarter-to-quarter). As for labor share, we cannot use the conventional definition, which is the System of National Accounts' (SNA's) "compensation of employees" divided by "national income," because the definition of "compensation of employees" does not include the compensation of the self-employed firms. For this reason, we use the following definition recommended by Batini, Jackson, and Nickell [2000], Kamada and Masuda [2001]:

$$\text{labor share} = \frac{\text{compensation of employees}}{\text{nominal GDP}-(\text{indirect tax}-\text{subsidy})-\text{households' operating surplus}}.$$

This definition assumes that labor share in the self-employed firms is just the same as that in other firms.

As for the material inputs and materials prices, we cannot obtain the quarterly series from SNA. So, we construct a quarterly series of material inputs and the materials prices, following the interpolation method of Chow and Lin [1971]. To estimate the quarterly series of materials prices, we use the price of intermediate materials in the Corporate Goods Price Index (CGPI) published by the Bank of Japan. To estimate the quarterly series of the quantity of nominal material inputs ($P_{M,t}M_t$), we use the series of the Financial Statements Statistics of Corporations published by the Ministry of Finance. The definition is sales subtracted by operating profits, personnel expenses, and depreciation.

2.7.3 Derivation of (2.20)

By repeatedly substituting the expectation term, we rewrite (2.10) as follows:

$$\begin{aligned}\pi_t \quad = \quad & \frac{1}{\gamma(1-\beta)}\ln\frac{\mu}{\alpha} + \frac{1}{\gamma}E_t\sum_{k=0}^{\infty}\beta^k \ln S_{t+k} + \frac{1}{\gamma}\left[\alpha - 1 - \frac{(\alpha\sigma+\eta-1)(1-\rho)}{1-\rho B}\right] \\ & \left[E_t\sum_{k=0}^{\infty}\beta^k LGAP^s_{t+k} + \gamma(LGAP^s_t - LGAP^s_{t-1})\right]. \qquad (2.38)\end{aligned}$$

The discounted present value of employment Di is expressed as follows:

$$\sum_{k=0}^{\infty}\beta^k E_t EDI_{t+k} = e_2'(\mathbf{I}-\beta\mathbf{A})^{-1}\mathbf{Z}_t. \qquad (2.39)$$

From (2.17), (2.19), (2.38) and (2.39), we derive (2.20).

Chapter 3

Productivity Growth, Transparency, and Monetary Policy

3.1 Introduction

In recent years, the implications of central bank transparency have been actively investigated in monetary economics.[1] According to Geraats [2002], central bank transparency is defined as "the absence of asymmetric information between monetary policymakers and other economic agents" (p. F533). If we apply this definition to the context of monetary policy, a large degree of transparency indicates the situation in which the central bank provides private agents with ample information regarding monetary policymaking, such as policy objectives, policy strategy, economic perspective, and so on. If this information has some degree of impact on private agents' activity, especially on their expectation formation, then central bank transparency potentially influences economic dynamics, and ultimately, social welfare.

Among the many aspects of central bank transparency, this study focuses on "economic transparency" in the terminology of Geraats [2002]. Economic transparency concerns the economic information that is used for monetary policy, including economic data, policy models, and central bank forecasts (Geraats [2002], p. F540). In our view, economic transparency is distinct

[1] See Geraats [2002] and Cruijsen and Eijffinger [2007] for a survey of the literature on central bank transparency.

from other kinds of transparency in that it does not deal with the behavior of the central bank itself. Rather, it concerns the central bank's views on economic conditions or economic structures, which are determined mainly by the activities of private agents. In this sense, economic transparency is more indirectly related to the central bank's monetary policymaking than other kinds of transparency, such as political, procedural, policy, and operational transparency, which are mostly related to the behavior of the central bank itself.

In the case of economic transparency, it is arguable whether the central bank should seek to be perfectly transparent, because the central bank usually faces considerable uncertainty as to economic conditions or economic structures. If we take account of this kind of uncertainty, it is not a straightforward task to evaluate the value of central bank transparency, because the information provided by the central bank to private agents might be inaccurate and such inaccurate information might cause economic fluctuations.

The problem of uncertainty becomes particularly serious with respect to the trend growth of aggregate productivity. Trend productivity growth is a key variable for monetary policymaking, because it is the crucial determinant of potential GDP and the equilibrium level of the real interest rate. However, it is widely recognized that it is quite difficult to obtain an accurate estimate of the trend growth of aggregate productivity, especially in real time. Concerning this issue, Bernanke [2005] remarks that "notably, imperfect data and the difficulties of distinguishing permanent from temporary changes will make changes in secular productivity growth exceptionally difficult to identify in real time, both for the private sector and for the Federal Reserve. The need to discern the underlying economic forces and to react appropriately in an environment of incomplete information makes monetary policy an exceptionally challenging endeavor."

Once we take account of the large uncertainty, the issue of whether the central bank should be greatly transparent, even if views of future productivity growth are quite uncertain, will deserve the attention of monetary policymakers. In particular, the issue is complicated because, as is noted by Bernanke, not only the central bank but also private agents face uncertainty regarding the persistence of productivity growth. In such a case, the value of central bank transparency is likely to depend on private agents' forecast of future productivity growth. Furthermore, the value of transparency should depend on private agents' conjecture about the central bank's forecast, because central bank transparency mainly influences private agents' perception about the central bank's forecast.

Furthermore, if economic dynamics depend on central bank transparency and the forecasting mechanisms used by the central bank and private agents, an optimal policy response will not be independent of these aspects. Therefore, it is also important to study how optimal monetary policy depends on central bank transparency and the forecasting mechanisms used by the central bank and private agents. In considering this issue, it is particularly important to analyze what kind of monetary policy robustly performs well against a wide variety of private agents' forecasting mechanisms because, in practice, the central bank faces great uncertainty regarding the forecasting mechanism used by private agents.

Based on the above argument, we investigate how central bank transparency about the views on future productivity growth influences social welfare. To this end, we introduce a simple version of a New Keynesian model, which is very close to the models of Galí, Lopez-Salido, and Valles [2003] and Ireland [2004]. Since we judge that central bank transparency mainly influences economic dynamics through the process of private agents' expectation formation, the forward-looking nature of the New Keynesian model is suitable for carrying out our analysis. In addition, we consider that the simplicity of our version of the New Keynesian model is favorable, since we can explicitly calculate the analytical solution and evaluate the impact of central bank transparency in terms of social welfare, not in terms of some ad hoc central bank's loss function.

In this study, we assume that the central bank and private agents cannot fully identify the transitory and persistent components of productivity growth and that they are engaged in filtering problems regarding the persistence of productivity growth. This setup has already been introduced in some previous studies, such as Tambalotti [2003], Edge, Laubach, and Williams [2005, 2007], and Gilchrist and Saito [2007]. These studies have shown that private agents' gradual recognition of the persistence of productivity growth can replicate the persistent movements of major macroeconomic variables, which are usually found in vector autoregression (VAR) analysis. Therefore, these studies imply that the inclusion of a filtering mechanism is beneficial in yielding a realistic impulse response to productivity shocks. However, none of the studies analyze the influence of central bank transparency.

The contribution of our study is that we investigate the influence of central bank transparency in an environment in which both central bank and private agents are filtering with respect to the persistence of productivity growth. In carrying out the analysis, we introduce heterogeneity in the forecasting mechanisms used by the central bank and private agents. Figure 3.1 presents forecasts on real output growth made by the Federal Reserve Board (FRB) and economists in the private sector. This figure shows that the FRB and economists in the private sector do not necessarily share the same forecasts for future output growth in each period.[2] The possibility of heterogeneous forecasts is essential in examining the issue of transparency, because it requires private agents to conjecture the central bank's forecast of future productivity growth and gives rise to the possibility that central bank transparency has some impact on private agents' expectations concerning future monetary policy.

In this analysis, we assume that the heterogeneous forecasts arise because the central bank and private agents use different forecasting rules. More concretely, they use different gain parameters in the filtering problem. The reason why they do this is explained by the uncertainty about the variances of transitory and persistent productivity shocks. The uncertainty on this respect is highly plausible, because some empirical studies (Stock and Watson [1998] and Roberts [2001]) show that the uncertainty regarding these shock variances is large in the U.S. economy, and the recent analysis of Justiniano and Primiceri [2006] further shows that there have been large structural changes in shock variances in the U.S. economy, which explains the decline in the volatility of U.S. major macroeconomic variables. In this study, we assume that whereas the central bank and private agents use the same information set concerning current productivity growth, they can use different gain parameters since they can differently assess the possibility of structural change in shock variances.[3] The heterogeneity in gain parame-

[2]Although output growth does not directly correspond to productivity growth, it is fair to judge that at least some portion of the different forecasts on output growth comes from the heterogeneity in the views on future productivity growth.

[3]In the context of adaptive learning, Honkapohja and Mitra [2005] examine the E-stability condition in an environment where central bank and private agents use heterogeneous constant gain parameters to estimate their subjective reduced-form model. As is well explained in Evans and Honkapohja [2001], constant gain is used when agents take

ters yields the heterogeneous forecasts for future productivity growth, which become the disturbance to economic fluctuations.[4]

We define the central bank as *transparent* (or the central bank as adopting a *transparent regime*) if the central bank announces its forecast on future productivity growth, and we also define the central bank as *opaque* (or the central bank as adopting an *opaque regime*) if the central bank does not announce the forecast. Private agents must conjecture the central bank's forecast of future productivity growth, since the forecast is closely linked with the central bank's estimate of the efficient level of the real interest rate (efficient interest rate), which influences the future interest rate. If the central bank is transparent, private agents accurately recognize the value of the central bank's estimate of the efficient interest rate. However, if the central bank is opaque, private agents have misperceptions about the central bank's estimate of the efficient interest rate.

We evaluate the welfare gains (or possibly the losses) from the central bank transparency. In doing so, we simply examine how welfare losses differ between the transparent regime and the opaque regime. To restrict our attention to the pure impact of the central bank's information provision to private agents, we exclude the possibility that the central bank changes the regime (transparent or opaque) period by period, because this possibility inevitably raises the problem of credibility. For the same reason, we rule out the possibility that central bank announces a forecast of productivity growth that differs from its true forecast.

Our results show that central bank transparency about views of future productivity growth does not necessarily improve social welfare. It can potentially yield a welfare loss, depending on (i) the gain parameters used by the central bank and private agents and (ii) private agents' conjecture about the central bank's gain parameter. If the gain parameters used by the central

account of the possibility of structural change. Although our problem is filtering (not least-squares learning), our usage of heterogeneous gain parameters could be explained by the central bank's and private agents' awareness of the possible future structural change in the variances of productivity shocks.

[4]Bullard and Eusepi [2005] investigate the economic dynamics of the New Keynesian model under a mechanism in which both the central bank and private agents are learning the structural parameters, including the process of productivity growth. Gorodnichenko and Shapiro [2007] compare the performances of inflation targeting and price level targeting in an environment where the central bank and private agents filter the level of current potential output by using subjective gain parameters. Although these analyses are close to ours, they do not investigate the influence of central bank economic transparency.

bank and private agents are homogeneous, then central bank transparency always improves social welfare. However, if these gain parameters are heterogeneous, central bank transparency can be either welfare-improving or welfare-reducing, because it is possible that private agents' misperception about the central bank's forecast offsets the distortion which arises from the heterogeneous forecasts between the central bank and private agents. Our study shows that if the central bank is uncertain about the combination of the gain parameters (including private agents' conjecture), it is sensible for the central bank to respond strongly to the variations of the inflation rate.

Our study is distinct from the previous studies of the central bank's economic transparency (such as Amato and Shin [2003], Morris and Shin [2005], and Walsh [2007]), in that the mechanism through which central bank transparency can be welfare-reducing differs fundamentally from those of the previous studies. In the previous studies, central bank transparency can be harmful for social welfare mainly because private agents might overreact to the information provided by the central bank, in an environment where the central bank or private agents have private information about current economic conditions.[5] In contrast, the key focus of our study is the possibility that private agents' misperception about the central bank's forecast offsets the distortion which arises from the heterogeneous forecasts made by the central bank and private agents. In this environment, central bank transparency can be welfare-reducing, because the central bank's announcement eliminates private agents' misperception of the central bank's estimate on the efficient interest rate, which would offset the distortion of heterogeneous forecasts if the central bank is not transparent. This mechanism is new to the literature of central bank transparency.[6]

[5] We do not explicitly introduce any private information to both agents. As a result, our study does not introduce any strategic interaction between the central bank and private agents in the formation of their expectations for future productivity growth. In relation to this simplifying assumption, Kohn [2005] remarks that "in the United States, we have some indirect evidence that crowding out of private views has not increased even as the Federal Reserve has become more talkative. Market interest rates have continued to respond substantially to surprises in economic data." He also states, "that markets continue to react strongly to incoming data is not surprising. Predicting interest rates far enough into the future is not just about what others—including the central bank—think; over time those rates should be tied to objective factors—for example, the forces of productivity and thrift. Differing views about these factors give scope for opportunities to profit from independent research and betting against the crowd."

[6] Eusepi and Preston [2007] investigate the issue of central bank communication in an environment where private agents engage in adaptive learning. Our study is distinct from

The rest of this chapter is organized as follows. In Section 3.2, we present our model, including the economic structure, the process of productivity growth, and the mechanisms of forecasting future productivity growth used by the central bank and private agents. In Section 3.3, we investigate the influence of central bank transparency on economic dynamics and social welfare. In particular, we clarify under what conditions central bank transparency is welfare-improving or welfare-reducing. In Section 3.4, we investigate how the desirable monetary policy actions depend on central bank transparency and the forecasting mechanisms used by the central bank and private agents. Specifically, we investigate the optimal response to inflation rate in the central bank's simple monetary policy rule. In doing so, we also examine the influence of private agents' learning mechanism regarding the gain parameter used by the central bank. In Section 3.5, we present concluding remarks.

3.2 Model

We use a simple version of a New Keynesian model in which all goods are consumption goods and there are no frictions other than price stickiness and markup fluctuations. This version is quite similar to the models of Galí, Lopez-Salido, and Valles [2003] and Ireland [2004]. However, in contrast to their models, ours introduces a filtering problem in which the central bank and private agents estimate the persistence of productivity growth. In addition, our model illustrates a situation in which private agents conjecture the central bank's views of future productivity growth when the central bank is opaque.

3.2.1 Household

The representative household maximizes the following intertemporal utility function:

$$E_t \sum_{k=0}^{\infty} \beta^k \left(\ln Y_{t+k} - \frac{1}{\eta} N_{t+k}^{\eta} \right), \tag{3.1}$$

theirs in that (i) private agents have knowledge about the structure of the economy, (ii) the value of central bank communication is evaluated in terms of social welfare loss (not in terms of stability under learning), and (iii) the central bank introduces a simple monetary policy rule (not an optimal monetary policy rule).

where Y_t is aggregate consumption (equal to aggregate output), N_t is labor supply, β is the discount factor, and η is the parameter related to labor supply elasticity.[7]

Utility maximization yields the following first-order conditions:

$$\ln Y_t = E_t \ln Y_{t+1} - (i_t - E_t \pi_{t+1} - \rho), \tag{3.2}$$

$$W_t/P_t = Y_t N_t^{\eta - 1}, \tag{3.3}$$

where i_t is the nominal interest rate, π_t is the inflation rate, ρ is the discount rate (calculated as $\rho = -\ln \beta$), W_t is the nominal wage rate, and P_t is the price level.

Y_t^* and r_t^* denote the output and the real interest rate that should be realized in an environment in which both price stickiness and the distortion due to the time-varying markup are absent. Following Galí [2006], we call this environment an "*efficient steady state.*"[8] Similarly, we call Y_t^* "*efficient output*" and r_t^* the "*efficient interest rate.*" These differ from the popular concept of "natural output" and the "natural interest rate," which will be realized in an environment in which only price stickiness is absent. This distinction has an important implication for welfare analysis (see Galí [2006]).

Since the Euler equation (3.2) must also hold in the efficient steady state, Y_t^* and r_t^* satisfy the following relationship:

$$\ln Y_t^* = E_t \ln Y_{t+1}^* - (r_t^* - \rho). \tag{3.4}$$

We define x_t as the output gap ($x_t \equiv \ln Y_t - \ln Y_t^*$).[9] Then, (3.2) and (3.4) yield the following dynamic IS equation:

$$x_t = E_t x_{t+1} - (i_t - E_t \pi_{t+1} - r_t^*). \tag{3.5}$$

[7] In this study, we assume that private agents cannot correctly recognize the variances of temporary and persistent productivity shocks. Therefore, the expectation operator E_t is based on private agents' subjective estimate of shock variances (not on theoretical value of shock variances). In other respects, the calculation of E_t is the same as the usual rational expectation.

[8] In our model, the desired markup varies around a steady-state level. In an efficient steady state, the markup is fixed, though it is not equal to unity. Therefore, the distortion due to the steady-state level of the desired markup remains even in the efficient steady state.

[9] x_t is the welfare-relevant output gap, in the terminology of Galí [2006].

3.2.2 Firm

The representative firm's production function is given by

$$Y_t = A_t N_t, \tag{3.6}$$

where A_t is the level of aggregate productivity. The nominal marginal cost (MC_t) is calculated as follows:

$$MC_t = W_t N_t / Y_t, \tag{3.7}$$

where W_t is the nominal wage rate, which is assumed to be given for each firm.

We define ψ_t as the *desired markup*, which should be realized under a flexible price economy. Under the conventional aggregator ($Y_t \equiv (\int_0^1 Y_t(i)^{\frac{\theta_t - 1}{\theta_t}} di)^{\frac{\theta_t}{\theta_t - 1}}$), ψ_t is determined by the elasticity of substitution among individual goods (θ_t) as follows:

$$\psi_t = \frac{\theta_t}{\theta_t - 1}, \tag{3.8}$$

where θ_t moves around the steady-state value (θ) in each period.

If we apply Calvo's [1983] and Yun's [1996] specification of sticky prices in which each period a measure of $1-\alpha$ firms can reset prices, firms' profit maximization yields the New Keynesian Phillips curve (NKPC) with respect to real marginal cost:

$$\pi_t = \beta E_t \pi_{t+1} + [(1-\alpha)(1-\beta\alpha)/\alpha](\ln RMC_t + \ln \psi_t), \tag{3.9}$$

where RMC_t represents real marginal cost ($RMC_t = MC_t / P_t$).

To rewrite the NKPC in terms of the output gap, we provide the firm's optimality condition in the efficient steady state as follows:

$$P_t = \psi MC_t, \tag{3.10}$$

where ψ is the steady-state value of the desired markup ($\psi = \frac{\theta}{\theta - 1}$). Then, from (3.3), (3.6), (3.7), and (3.10), we can express efficient output Y_t^* as follows:[10]

$$Y_t^* = \psi^{-1/\eta} A_t. \tag{3.11}$$

From (3.3), (3.6), and (3.7), we calculate actual output as follows:

$$Y_t = RMC_t^{1/\eta} A_t. \tag{3.12}$$

Finally, from (3.9), (3.11), and (3.12), we derive the NKPC in terms of the output gap as follows:

$$\pi_t = \beta E_t \pi_{t+1} + \kappa x_t + \zeta_t, \tag{3.13}$$

where κ is the slope of the NKPC ($\kappa \equiv \eta(1-\alpha)(1-\beta\alpha)/\alpha$) and ζ_t is the cost-push shock, which is defined as follows:

$$\zeta_t \equiv (1-\alpha)(1-\beta\alpha)/\alpha(\ln\psi_t - \ln\psi), \quad \zeta_t \sim i.i.d.N(0, \sigma_\zeta).$$

3.2.3 Monetary Policy

The central bank introduces a simple monetary policy rule such as:

$$i_t = r_t^{*C} + \gamma\pi_t + \xi_t, \quad \xi_t \sim i.i.d.N(0, \sigma_\xi), \tag{3.14}$$

where r_t^{*C} is the central bank's estimate of the efficient interest rate, γ is the responsiveness to the inflation rate, and ξ_t is the monetary policy shock. Since we assume that the central bank cannot directly observe the efficient interest rate, the rule introduces the central bank's estimate of the efficient interest rate (r_t^{*C}), not the true value of r_t^*.

Throughout this study, we assume that private agents know the functional form of (3.14), including the value of γ. However, private agents cannot directly observe the value of r_t^{*C} and ξ_t unless the central bank announces these values. In that case, they must conjecture the values of r_t^{*C} and ξ_t. $r_t^{*P[C]}$ and $\xi_t^{P[C]}$ denote these conjectures. Private agents form expectations ($E_t x_{t+1}$ and $E_t\pi_{t+1}$) by using the following monetary policy

[10] As we have already explained, efficient output corresponds to the output that should be realized in the absence of price stickiness and time-varying components of the markup ($\psi_t - \psi$). So the distortion that arises from the steady-state markup (ψ) remains even in the efficient steady state. This is the reason why efficient output depends on ψ.

rule:[11]

$$i_t = r_t^{*P[C]} + \gamma \pi_t + \xi_t^{P[C]}. \tag{3.15}$$

3.2.4 Social Welfare Loss

In the simulations of later sections, we evaluate the value of central bank transparency in terms of social welfare. Woodford [2003] shows that in the simple version of the New Keynesian framework, including our model, social welfare loss (L) can be represented as follows:[12]

$$L = E_t \sum_{k=0}^{\infty} \beta^k \left(\kappa x_{t+k}^2 + \theta \pi_{t+k}^2 \right). \tag{3.16}$$

3.2.5 Process of Productivity Growth

In modeling the process of productivity growth, we follow previous studies, such as Tambalotti [2003], Edge, Laubach, and Williams [2005, 2007], and Gilchrist and Saito [2007]. In these studies, productivity growth is determined as the combination of transitory and persistent components as follows:

$$z_t \equiv \ln A_t - \ln A_{t-1} = \overline{z} + \varepsilon_t + \mu_t, \quad \varepsilon_t \sim i.i.d.N(0, \sigma_\varepsilon), \tag{3.17}$$

$$\mu_t = \phi \mu_{t-1} + \nu_t, \quad \nu_t \sim i.i.d.N(0, \sigma_\nu), \tag{3.18}$$

where z_t is productivity growth, $\overline{z}$ is the long-run equilibrium productivity growth, ε_t is the transitory productivity shock, μ_t is the persistent productivity shock, ϕ is the persistence of μ_t ($0 < \phi < 1$), and ν_t is the innovation to μ_t.

We assume that the central bank and private agents cannot fully identify the values of ε_t and μ_t, though they can observe the values of z_t, $\overline{z}$, and ϕ. So they are engaged in the filtering problem to estimate the persistence of the productivity shock. In the following argument, μ_t^C and μ_t^P denote the subjective estimates about the persistent productivity shocks estimated by the central bank and private agents, respectively.

[11] We assume that private agents regard the process of $\xi_t^{P[C]}$ as i.i.d.

[12] In deriving this social welfare function, we assume the existence of an output subsidy that offsets the distortion due to the presence of the desired markup in the steady state (ψ).

3.2.6 Efficient Interest Rate

The efficient interest rate is the key variable in this study because, under monetary policy rule (3.14), central bank transparency about views of future productivity growth influences economic dynamics through private agents' conjecture about the central bank's estimate of the efficient interest rate.

From (3.4) and (3.11), the true value of the efficient interest rate is calculated as follows:

$$r_t^* = \rho + E_t \ln A_{t+1} - \ln A_t. \tag{3.19}$$

Notice that r_t^* is determined by private agents' forecast of future productivity growth ($E_t \ln A_{t+1} - \ln A_t$). Therefore, r_t^* depends on private agents' information set available at time t. Since we assume that private agents have their subjective estimate of persistent productivity shock (μ_t^P), r_t^* is calculated as follows:

$$r_t^* = \rho + \overline{z} + \phi \mu_t^P. \tag{3.20}$$

Thus, r_t^* depends on private agents' estimate of the persistent productivity shock (μ_t^P), rather than on the true value of the persistent productivity shock (μ_t).

The central bank knows that the efficient interest rate is determined by (3.19). However, the central bank cannot directly observe private agents' forecast of future productivity growth (μ_t^P), because the central bank cannot directly observe private agents' expectations. For this reason, the estimated efficient interest rate (r_t^{*C}), which is included in monetary policy rule (3.14), depends on the central bank's subjective estimate of the persistent productivity shock (μ_t^C):

$$r_t^{*C} = \rho + \overline{z} + \phi \mu_t^C. \tag{3.21}$$

Private agents need to conjecture the value of r_t^{*C} to form the expectations for future output and the inflation rate because, under (3.14), (3.17), (3.18), and (3.21), the future interest rate depends on the central bank's current estimate of the efficient interest rate. We define $\mu_t^{P[C]}$ as private agents' conjecture about the central bank's estimate of the persistent shock (μ_t^C). Then, $r_t^{*P[C]}$ is calculated as follows:

$$r_t^{*P[C]} = \rho + \overline{z} + \phi \mu_t^{P[C]}. \tag{3.22}$$

3.2.7 Filtering Problem

As already explained, neither private agents nor the central bank can directly observe each component of productivity shock (ε_t and μ_t). So they estimate the persistence of productivity growth through filtering.

Notice that (3.17) and (3.18) constitute a state-space model. Therefore, if the central bank and private agents know the true value of the signal-to-noise ratio, which is defined as the relative size in the variances of persistent and transitory productivity shocks ($\sigma_\nu^2/\sigma_\varepsilon^2$), they can obtain the optimal estimate of μ_t by using the optimal Kalman filter algorithm. However, since we assume that the central bank and private agents do not know the true values of shock variances (σ_ν^2 and σ_ε^2), they cannot compute the optimal gain parameter for the filtering problem. Therefore, we assume that the central bank and private agents use their subjective gain parameters (λ^C and λ^P) to obtain their estimates of the persistent productivity shock (μ_t^C and μ_t^P). The algorithms are given by

$$\mu_t^C = \phi\mu_{t-1}^C + \lambda^C[(z_t - \overline{z}) - \phi\mu_{t-1}^C], \tag{3.23}$$

$$\mu_t^P = \phi\mu_{t-1}^P + \lambda^P[(z_t - \overline{z}) - \phi\mu_{t-1}^P]. \tag{3.24}$$

Here λ^C and λ^P are constant values.[13] These are not necessarily equal to the value of the optimal Kalman gain, because the central bank and private agents face large uncertainty about shock variances (σ_ν and σ_ε).[14] In addition, these gain parameters can be heterogeneous, because the central bank and private agents can differently assess the possibility of structural changes in shock variances.

Next, we specify the process through which private agents form their conjecture about the central bank's estimate of the persistent productivity shock (μ_t^C). In this respect, we assume that private agents know the central bank's filtering algorithm (3.23), though they do not know the value of λ^C. In other words, private agents know that the central bank uses the

[13] Edge, Laubach, and Williams [2007] show that the Kalman filter with constant gain can replicate the public and private forecasts on long-run labor productivity growth reported in the survey data.

[14] The optimal Kalman gain is given by

$$\lambda^* \equiv 1 - 2[1 + \sigma_\nu^2/\sigma_\varepsilon^2 + \phi^2 + \left((1-\phi^2)^2 + \left(\sigma_\nu^2/\sigma_\varepsilon^2\right)^2 + 2(1+\phi^2)(\sigma_\nu^2/\sigma_\varepsilon^2)\right)^{1/2}]^{-1}.$$

same information set as theirs regarding current productivity growth (z_t) and that the only difference from private agents is in the value of the gain parameter. Under this assumption, private agents estimate the value of μ_t^C ($\mu_t^{P[C]}$ denotes the estimate) from the following algorithm:

$$\mu_t^{P[C]} = \phi\mu_{t-1}^{P[C]} + \lambda^{P[C]}[(z_t - \overline{z}) - \phi\mu_{t-1}^{P[C]}], \tag{3.25}$$

where $\lambda^{P[C]}$ is private agents' conjecture about the central bank's gain parameter (λ^C). The value of $\lambda^{P[C]}$ is subjectively chosen by private agents, which is assumed to be constant in most of simulations. However, in Section 3.4.3, we introduce a mechanism through which private agents gradually learn the value of λ^C by observing the central bank's policy actions.

3.2.8 Reduced-Form Solution

In this subsection, we derive the reduced-form solution of our model. This solution is useful to obtain an intuitive understanding of simulation results in the later sections.

The key issue in deriving a reduced-form solution is how we specify the process of private agents' expectation formation. In this respect, we assume that private agents possess knowledge about the structure of the economy. That is, private agents know the functional forms and the parameters of structural equations. This is the same assumption as in standard rational expectations. The only difference is that in our study private agents substitute their conjecture about the efficient interest rate into the monetary policy rule if the central bank adopts an opaque regime. In other words, private agents form expectations for the future output gap and inflation rate by using their subjective monetary policy rule (3.15), not the true monetary policy rule (3.14). Then the model for determining private agents' expectations consists of (3.5), (3.13), (3.15), (3.20), and (3.22). By substituting (3.15), (3.20), and (3.22) into (3.5), we obtain the following expression of the dynamic IS equation:

$$x_t = E_t x_{t+1} - (\gamma\pi_t - E_t\pi_{t+1}) - \phi(\mu_t^{P[C]} - \mu_t^P) - \xi_t^{P[C]}. \tag{3.26}$$

Now the model for determining private agents' expectation is reduced to (3.13) and (3.26). To calculate the expectations, we apply the undetermined coefficient method. The simplest solution form of this model is presented as follows:[15]

$$x_t = a_1(\mu_t^{P[C]} - \mu_t^P) + a_2\xi_t^{P[C]} + a_3\zeta_t, \tag{3.27}$$

$$\pi_t = b_1(\mu_t^{P[C]} - \mu_t^P) + b_2\xi_t^{P[C]} + b_3\zeta_t. \tag{3.28}$$

Based on (3.27) and (3.28), the expectations are calculated as follows:

$$E_t x_{t+1} = a_1\phi(\mu_t^{P[C]} - \mu_t^P), \tag{3.29}$$

$$E_t \pi_{t+1} = b_1\phi(\mu_t^{P[C]} - \mu_t^P). \tag{3.30}$$

Then, by substituting (3.27), (3.28), (3.29), and (3.30) into (3.13) and (3.26), the coefficients are computed as follows:

$$a_1 = \frac{-(1-\beta\phi)\phi}{(1-\beta\phi)(1-\phi)+(\gamma-\phi)\kappa},\ a_2 = \frac{-1}{1+\kappa\gamma},\ a_3 = \frac{-\gamma}{1+\kappa\gamma},$$

$$b_1 = \frac{-\kappa\phi}{(1-\beta\phi)(1-\phi)+(\gamma-\phi)\kappa},\ b_2 = \frac{-\kappa}{1+\kappa\gamma},\ \text{and } b_3 = \frac{1}{1+\kappa\gamma}.$$

The intuition for the determination of expectations (3.29) and (3.30) is as follows. As in (3.20), the efficient interest rate is determined by private agents' estimate of the persistent productivity shock (μ_t^P). Suppose that at period t private agents raise μ_t^P by 1 percentage point. In addition, suppose that private agents raise the conjecture about the central bank's estimate of the persistent productivity shock ($\mu_t^{P[C]}$) by 0.6 percentage point. Then, private agents infer that the remaining 0.4 percentage point is not offset by monetary policy at period t. Since private agents assume that μ_t^P and $\mu_t^{P[C]}$ are determined in (3.24) and (3.25), they conclude that the difference between μ_t^P and $\mu_t^{P[C]}$ multiplied by the persistent parameter ϕ ($0.4 \times \phi\%$ in this numerical example) remains at period $t+1$. Then, private agents expect that the output gap and inflation rate at period $t+1$ will not be neutralized by monetary policy at period $t+1$. Therefore, their expectations for the output gap and inflation rate deviate from zero.

Once private agents' expectations are calculated as (3.29) and (3.30), we derive the solutions of the actual output gap and inflation rate by substituting the expectations into the model that includes the central bank's

[15] This solution is called the minimal-state-variable (MSV) solution. We introduce the MSV solution to restrict our attention to bubble-free solutions. See McCallum [1983, 1999] for the details of the MSV solution.

true monetary policy rule (3.14). The model consists of (3.5), (3.13), (3.14), (3.20), and (3.21). By substituting (3.14), (3.20), and (3.21) into (3.5), we obtain the following expression of the dynamic IS equation:

$$x_t = E_t x_{t+1} - (\gamma \pi_t - E_t \pi_{t+1}) - \phi(\mu_t^C - \mu_t^P) - \xi_t. \tag{3.31}$$

The model for determining the output gap and inflation rate is reduced to (3.13) and (3.31). By substituting (3.29) and (3.30) into (3.13) and (3.31), we obtain the reduced-form solution of our model as follows:

$$x_t = c_1(\mu_t^{P[C]} - \mu_t^C) + c_2(\mu_t^C - \mu_t^P) + c_3\zeta_t + c_4\xi_t, \tag{3.32}$$

$$\pi_t = d_1(\mu_t^{P[C]} - \mu_t^C) + d_2(\mu_t^C - \mu_t^P) + d_3\zeta_t + d_4\xi_t, \tag{3.33}$$

where the coefficients are given by

$c_1 = \frac{-\phi^2[1+\kappa-\beta(\kappa\gamma+\phi)]}{(1+\kappa\gamma)[(1-\beta\phi)(1-\phi)+(\gamma-\phi)\kappa]}$, $c_2 = \frac{-\phi(1-\beta\phi)}{(1-\beta\phi)(1-\phi)+(\gamma-\phi)\kappa}$, $c_3 = \frac{-\gamma}{1+\kappa\gamma}$, $c_4 = \frac{-1}{1+\kappa\gamma}$,

$d_1 = \frac{-\kappa\phi^2[1+\kappa+\beta(1-\phi)]}{(1+\kappa\gamma)[(1-\beta\phi)(1-\phi)+(\gamma-\phi)\kappa]}$, $d_2 = \frac{-\kappa\phi}{(1-\beta\phi)(1-\phi)+(\gamma-\phi)\kappa}$, $d_3 = \frac{1}{1+\kappa\gamma}$, and $d_4 = \frac{-\kappa}{1+\kappa\gamma}$.

(3.32) and (3.33) indicate that the output gap and inflation rate are determined by four components: (i) the difference between $\mu_t^{P[C]}$ and μ_t^C; (ii) the difference between μ_t^C and μ_t^P; (iii) the cost-push shock; and (iv) the monetary policy shock. Of these, the first two components are quite important in this study.

The first component $(\mu_t^{P[C]} - \mu_t^C)$ represents private agents' misperception regarding the central bank's estimate of the persistent productivity shock (μ_t^C). If the central bank adopts a transparent regime, the first terms of (3.32) and (3.33) vanish, because private agents correctly recognize the value of μ_t^C. However, if the central bank adopts an opaque regime, the first terms of (3.32) and (3.33) are not necessarily zero. Therefore, economic dynamics can differ under the transparent regime and the opaque regime.

The second component $(\mu_t^C - \mu_t^P)$ represents the heterogeneity between the central bank and private agents regarding the estimates of the persistent productivity shock. The difference between μ_t^C and μ_t^P influences economic dynamics, because it corresponds to the central bank's misperception about the efficient interest rate. Since μ_t^C and μ_t^P are determined respectively by the central bank and private agents, the difference between μ_t^C and μ_t^P does not vanish even if the central bank announces the value of μ_t^C. Thus, the second terms of (3.32) and (3.33) express the direct impact of the central bank's misperception about the efficient interest rate on the current output and inflation rate.[16]

In the next section, we examine the economic dynamics and the influence of central bank transparency. In doing so, we pay particular attention to the first two components of (3.32) and (3.33).

3.3 Economic Dynamics

3.3.1 Parameter Setting

In setting parameters, we refer to previous studies.[17] The discount factor is $\beta = 0.99$, as in many studies. As for the slope of NKPC, we set $\kappa = 0.10$, following Ireland [2007]. The elasticity of substitution between each individual good is $\theta = 3.778$, following Christiano, Eichenbaum, and Evans [2005].[18] The policy responsiveness to the inflation rate is $\gamma = 1.5$. The parameters for the process of productivity growth are $\phi = 0.95$, $\sigma_\varepsilon = 0.01$, and $\sigma_\nu = 0.001$, following Gilchrist and Saito [2007]. These values suggest that the optimal gain parameter is $\lambda^* = 0.0614$. The standard error of the monetary policy shock is $\sigma_\xi = 0.000975$, which is estimated in Christiano, Eichenbaum, and Evans [1999]. The standard error of the cost-push shock is $\sigma_\xi = 0.0007$, following the estimation result of Ireland [2007].

3.3.2 Impulse Response in a Transparent Regime

Here, we examine the impulse response to transitory and persistent productivity shocks when the central bank adopts a transparent regime. In this regime, the central bank announces the estimate of the persistent productivity shock (μ_t^C). This announcement implies the central bank's disclosure about the estimate of the efficient interest rate (r_t^{*C}), because there is a one-to-one correspondence between μ_t^C and r_t^{*C}, as in (3.21).

[16] Orphanides and Williams [2002, 2005] investigate the direct impact of the central bank's misperception of the natural interest rate.

[17] The data frequency is quarterly.

[18] This value corresponds to the case of unconditional price indexation in Christiano, Eichenbaum, and Evans [2005].

In a transparent regime, private agents do not have any misperception about the central bank's estimate of the persistent productivity shock (μ_t^C). Therefore, $\mu_t^{P[C]}$ is always equal to μ_t^C. However, μ_t^P can differ from μ_t^C, because μ_t^C and μ_t^P are determined by the gain parameters respectively set by the central bank and private agents (λ^C and λ^P). To examine the influence of heterogeneity between λ^C and λ^P, we compare the impulse responses in two cases: the case of a homogeneous gain ($\lambda^C = \lambda^P = 0.05$) and the case of a heterogeneous gain ($\lambda^C = 0.05$ and $\lambda^P = 0.10$).

Figure 3.2 shows the impulse response to one standard deviation of a transitory productivity shock (ε_t) in a transparent regime. In response to the transitory productivity shock, μ_t^C and μ_t^P immediately increase, and then gradually decrease to zero. This represents the gradual recognition of the persistence of the productivity shock, which is shown by some previous studies (Tambalotti [2003], Edge, Laubach, and Williams [2005, 2007], and Gilchrist and Saito [2007]) as the key mechanism to replicate the persistent movements of major macroeconomic variables.

In the case of the homogeneous gain (the solid line), the movements of μ_t^C and μ_t^P are exactly the same. Then, the output gap and the inflation rate are always zero. This means that in the case of the homogeneous gain, the central bank perfectly stabilizes the output gap and inflation rate by completely offsetting the variations in the efficient interest rate. However, in the case of the heterogeneous gain (the dashed line), the output gap and inflation rate are never neutralized. In this case, the initial rise of μ_t^C is less than that of μ_t^P, which means that the central bank underestimates the rise of the efficient interest rate. Since this implies that the tightening of monetary policy is insufficient, the output gap and inflation rate are pushed upward for some sustained periods.

Figure 3.3 indicates the impulse response to one standard deviation of a persistent productivity shock (ν_t). Now the responses of μ_t^C and μ_t^P are hump-shaped, because the shock itself is sustained in the case of persistent productivity shock. However, the contrast between the cases of a homogeneous gain and a heterogeneous gain is essentially the same as in Figure 2. That is, the output gap and inflation rate are always zero in the case of a homogeneous gain, though they go upward in the case of a heterogeneous gain.

3.3.3 Impulse Response in an Opaque Regime

Next, we examine the impulse response to productivity shocks when the central bank adopts an opaque regime. In an opaque regime, the impulse response depends not only on the gain parameters of private agents and the central bank themselves (λ^C and λ^P), but also on private agents' conjecture about the central bank's gain parameter ($\lambda^{P[C]}$).

Figure 3.4 shows the impulse response to a transitory productivity shock in the case of a homogeneous gain ($\lambda^C = \lambda^P = 0.05$). Evidently, the impulse response depends on the value of $\lambda^{P[C]}$. Note that the case of $\lambda^{P[C]} = 0.05$ (the solid line) corresponds to a transparent regime, because private agents do not have any misperception about λ^C. Then, the output gap and inflation rate are always zero. This replicates the result in the previous subsection.

In contrast to this result, when $\lambda^{P[C]}$ is not equal to 0.05, the output gap and inflation rate are not neutralized even if λ^C and λ^P are homogeneous. If $\lambda^{P[C]} = 0.00$ (the dashed line), $\mu_t^{P[C]}$ does not respond to a transitory shock. Then, the output gap and inflation rate are pushed upward. Note that in this case, the central bank perfectly offsets the movement of the efficient interest rate, because the rise of μ_t^C is exactly the same as the rise of μ_t^P. Nevertheless, the output gap and inflation rate are not neutralized.[19]

This result is explained as follows. If $\lambda^{P[C]} = 0.00$ (or 0.10), private agents consider that the central bank underestimates (or overestimates) the rise of the efficient interest rate. Since the efficient interest rate is determined by the persistent productivity shock, private agents expect that the central bank's misperception about the efficient interest rate remains at the next period. Based on this reasoning, private agents raise (or lower) the expectations for the output gap ($E_t x_{t+1}$) and inflation rate ($E_t \pi_{t+1}$). This process is shown in (3.29) and (3.30). Then, the increases (or decreases) of $E_t x_{t+1}$ and $E_t \pi_{t+1}$ raise (or lower) the current output gap and inflation rate through the dynamic IS equation (3.5) and the NKPC (3.13). This is the basic mechanism working in Figure 3.4.

Next, we examine the impulse response in the case of a heterogeneous gain. Figure 3.5 shows the impulse response to a transitory productivity shock when the central bank's gain parameter is smaller than private agents' gain parameter ($\lambda^C = 0.05$, $\lambda^P = 0.10$). The solid line is the case of $\lambda^{P[C]} =$

[19] These results can be also confirmed in the case of a persistent productivity shock.

0.05, which corresponds to the transparent regime (the same as the dashed line in Figure 3.2). Since λ^C and λ^P differ, monetary policy does not offset the movements of the efficient interest rare. Therefore, the output gap and inflation rate are not neutralized even if the central bank adopts a transparent regime.

In the case of a heterogeneous gain, we find that the variations of the output gap and inflation rate in an opaque regime can become either smaller or larger than in the transparent regime, depending on the value of $\lambda^{P[C]}$. If $\lambda^{P[C]} = 0.00$ (the dashed line), the responses of the output gap and inflation rate are larger in an opaque regime than in the transparent regime. However, if $\lambda^{P[C]} = 0.10$ (the dotted line), the result is overturned. In this case, the responses are smaller in an opaque regime than in a transparent regime. This result implies that the welfare loss becomes smaller in an opaque regime than in a transparent regime. This result might be surprising, because central bank transparency is widely recognized as welfare-improving.

However, this does not mean that central bank transparency is always welfare-reducing when $\lambda^{P[C]}$ is larger than λ^C. Notice that, if $\lambda^{P[C]}$ takes a still larger value, such as $\lambda^{P[C]} = 0.25$, then the drop in the inflation rate becomes quite large. Under our parameter setting, the welfare loss becomes larger in an opaque regime than in a transparent regime. Therefore, the result shows that central bank transparency improves social welfare when $\lambda^{P[C]}$ is far greater than λ^C. This implies that whether central bank transparency improves social welfare or not depends on the direction and the magnitude of private agents' misperception about λ^C.[20]

In sum, the impulse response in an opaque regime depends on the value of $\lambda^{P[C]}$. When $\lambda^{P[C]}$ differs from λ^C, the central bank cannot perfectly stabilize the output gap and inflation rate even if the central bank completely offsets the variations of the efficient interest rate. In addition, if λ^C and λ^P are heterogeneous, central bank transparency can either improve or worsen social welfare, depending on the value of $\lambda^{P[C]}$. In the next subsection, we examine exactly how the influence of central bank transparency depends on the combinations of λ^C, λ^P, and $\lambda^{P[C]}$.

[20] We have confirmed that essentially the same result can be obtained in the case of a persistent productivity shock.

3.3.4 Impact of Transparency

The previous subsection has shown that welfare loss in an opaque regime can be smaller than in a transparent regime, depending on the value of $\lambda^{P[C]}$. This result could be considered striking, because central bank transparency is widely recognized as welfare-improving.

To understand the reason for this result, it is useful to look at the reduced-form solutions (3.32) and (3.33). If we ignore the cost-push shock and monetary policy shock, the output gap and inflation rate are determined by private agents' misperception about the central bank's gain parameter (the difference between $\mu_t^{P[C]}$ and μ_t^C) and the heterogeneity of gain parameters used by the central bank and private agents (the difference between μ_t^C and μ_t^P). Consider the case of homogeneous gain ($\mu_t^C = \mu_t^P$). Then, the second terms of (3.32) and (3.33) become zero. This is the situation in which the central bank perfectly offsets the variations of the efficient interest rate. Then, the welfare loss is minimized when the first terms of (3.32) and (3.33) are zero, which is attained in the absence of private agents' misperception of μ_t^C ($\mu_t^{P[C]} = \mu_t^C$). Therefore, in the case of a homogeneous gain, central bank transparency is always desirable, because private agents' misperception of μ_t^C is merely a source of disturbance to the economy.

However, in the case of a heterogeneous gain, private agents' misperception of μ_t^C is not necessarily harmful to the economy. Suppose that μ_t^C is much smaller than μ_t^P, which means that the central bank largely underestimates the level of the efficient interest rate. Then, the second terms of (3.32) and (3.33) take large positive values, which means that the output gap and inflation rate are pressured upward by the central bank's unintentional monetary easing. In this environment, private agents' misperception of μ_t^C might mitigate the impact of monetary easing. That is, if $\mu_t^{P[C]}$ is larger than μ_t^C (but smaller than μ_t^P), then the first terms of (3.32) and (3.33) become negative and they offset the positive impacts of the second terms of (3.32) and (3.33). Intuitively, this occurs because private agents underestimate the strength of current monetary easing and, for that reason, the expectations for the future output gap and inflation rate are sustained at a lower level than that under the transparent regime.

So far, we have explained the influence of central bank transparency by regarding μ_t^P, μ_t^C, and $\mu_t^{P[C]}$ as given. However, since μ_t^P, μ_t^C, and $\mu_t^{P[C]}$ depend on the gain parameters (λ^P, λ^C, and $\lambda^{P[C]}$), we can clarify how the welfare loss depends on these gain parameters. For this purpose, we carry out stochastic simulations, in which we introduce one standard deviation of all the stochastic shocks (the transitory and persistent productivity shocks, cost-push shock, and monetary policy shock). Then we simply compare the social welfare loss in a transparent regime and in an opaque regime. For this comparison, we calculate the "*welfare improvement from transparency*", which is defined as the welfare loss in an opaque regime minus the welfare loss in a transparent regime. If the welfare improvement from transparency is positive (or negative), central bank transparency is welfare-improving (welfare-reducing).

The upper panel of Figure 3.6 shows the welfare improvement from transparency in the case of a homogeneous gain ($\lambda^C = \lambda^P = 0.05$). In this case, the welfare improvement from transparency is minimized when $\lambda^{P[C]}$ is equal to λ^C. If $\lambda^{P[C]}$ takes a different value from λ^C, the welfare improvement from transparency becomes strictly positive. Therefore, central bank transparency always improves social welfare in the case of a homogeneous gain.[21]

However, in the case of a heterogeneous gain, transparency can either improve or worsen social welfare. The middle panel of Figure 3.6 corresponds to the case where the central bank's gain parameter is smaller than private agents' gain parameter ($\lambda^C = 0.05$ and $\lambda^P = 0.10$). Now the welfare improvement from transparency can be either positive or negative, depending on the value of $\lambda^{P[C]}$. If $\lambda^{P[C]}$ is smaller than λ^C, the welfare improvement from transparency is positive. This is because, in this case, private agents overestimate the magnitude of heterogeneity between the central bank and private agents ($\left|\lambda^C - \lambda^P\right|$). In this situation, central bank transparency contributes to reduce private agents' overestimation of heterogeneity.

However, if $\lambda^{P[C]}$ is larger than λ^C and smaller than the critical value ($\overline{\lambda}$), private agents' misperception offsets the distortion due to the heterogeneity between λ^C and λ^P. Then, the central bank's disclosure about the value of λ^C removes this offsetting effect of private agents' misperception. This is the reason why central bank transparency is undesirable in this case.

[21] Readers may wonder why the welfare improvement from transparency does not depend on the deviations of gain parameters from the optimal value ($\lambda^* = 0.0614$). The reason is explained by the fact that the social welfare loss, which is derived as (3.18), captures the distortion which arises due to the existence of price stickiness. Since the deviation of gain parameter from the optimal value affects social welfare in both flexible price economy and sticky price economy, the impact of non-optimality of gain parameter is cancelled out in the calculation of social welfare loss (3.18).

However, if $\lambda^{P[C]}$ is a still larger value (such as $\lambda^{P[C]} = 0.25$), then the welfare improvement from transparency again becomes positive. This is because the central bank's disclosure about λ^C removes the distortion due to private agents' large misperception of heterogeneity in gain parameters ($\lambda^P - \lambda^{P[C]} < 0$), which is in completely opposite direction to the actual heterogeneity ($\lambda^P - \lambda^C > 0$). This result implies that if private agents' misperception of λ^C is quite large, central bank transparency is desirable regardless of the sign of misperception ($\lambda^{P[C]} - \lambda^C < 0$ or > 0). In other words, transparency can be welfare-reducing only if private agents' misperception of λ^C is not too large.

Therefore, in the case of heterogeneous gain, central bank transparency can be either welfare-improving or welfare-reducing, because it is possible that private agents' misperception about the central bank's gain parameter offsets the distortion which arises due to the heterogeneity of the gain parameters used by the central bank and private agents. In considering large uncertainty and the possible structural changes in the variances of transitory and persistent productivity shocks (σ_ε^2 and σ_ν^2), the case of heterogeneous gain could be viewed as a more general case than the case of homogeneous gain. On that ground, it is natural for the central bank to face uncertainty as to the desirability of transparency about views of future productivity growth.

3.4 Implications for Monetary Policy Actions

In the previous section, we have examined how central bank transparency influences social welfare. However, we have not examined how the desirable monetary policy action depends on central bank transparency or the forecasting mechanisms used by the central bank and private agents. To investigate this issue, we specifically examine the optimal policy response to the inflation rate (i.e., the optimal value of γ in monetary policy rule (3.14)) under a transparent regime and under an opaque regime, respectively.

3.4.1 Optimal Response to Inflation in a Transparent Regime

To investigate the optimal policy response to the inflation rate, we first calculate the optimal value of γ in a case where productivity shocks are absent. This also corresponds to the case of a homogeneous gain in a transparent regime, because productivity shocks become irrelevant to the economic dynamics in that case. We regard this case as the benchmark in this section.

To calculate the optimal value of γ in the benchmark case, we substitute (3.32) and (3.33) into welfare function (3.16), and minimize (3.16) with respect to γ. As a result, we obtain the optimal value of γ in the absence of a productivity shock, denoted as γ^*, as follows:[22]

$$\gamma^* = \theta + (1 + \theta\kappa)\kappa \frac{\sigma_\xi^2}{\sigma_\zeta^2}. \tag{3.34}$$

Thus, γ^* depends on the relative sizes of the variances of the monetary policy shock and cost-push shock ($\sigma_\xi^2/\sigma_\zeta^2$). If the monetary policy shock is absent ($\sigma_\xi = 0$), then γ^* becomes exactly equal to θ. However, if the variance of the monetary policy shock is nonzero, then γ^* becomes larger than θ. Under our parameter setting, γ^* is 4.045, which is slightly larger than $\theta = 3.778$.

Figure 3.7 shows the welfare loss when the central bank adopts a transparent regime. Here, we assume that λ^C is 0.05. Since the central bank is transparent, $\lambda^{P[C]}$ becomes 0.05. The welfare loss depends on the value of λ^P. In the case of a homogeneous gain ($\lambda^P = 0.05$), welfare loss is minimized when the central bank chooses $\gamma = \gamma^*$. However, in the cases of a heterogeneous gain ($\lambda^P = 0.00$, 0.02, 0.08, and 0.10), the loci of the welfare loss are shifted to the upper-right region of Figure 3.7. Then the optimal value of γ for each value of λ^P becomes larger than γ^*, since the central bank can reduce the welfare loss by setting the value of γ greater than γ^*. The optimal value of γ is especially large when the difference between λ^C and λ^P is large, such as the case of $\lambda^P = 0.00$ or 0.10.

We can understand the reason for these results by looking at (3.31). In (3.31), the difference between μ_t^C and μ_t^P appears as the disturbance to the dynamic IS equation. Therefore, the difference between μ_t^C and μ_t^P plays essentially the same role as the monetary policy shock (ξ_t), since it constitutes the source of the demand shock. As in (3.34), the optimal value of γ is large when the variance of the demand shock is large. This is the reason why the optimal value of γ is large when the heterogeneity between λ^C and λ^P is prominent.

[22]When we set $\gamma = \gamma^*$, the policy rule (3.14) corresponds to optimal discretionary policy in the absence of a productivity shock.

3.4.2 Optimal Response to Inflation in an Opaque Regime

In this subsection, we investigate the optimal policy response to the inflation rate when the central bank adopts an opaque regime. In an opaque regime, the welfare loss depends on the value of $\lambda^{P[C]}$, since the economic dynamics depend on $\lambda^{P[C]}$, as shown in Section 3.3.3.

Figure 3.8 summarizes the welfare loss in an opaque regime. The upper panel shows the case of a homogeneous gain ($\lambda^C = 0.05$ and $\lambda^P = 0.05$). The case of $\lambda^{P[C]} = 0.05$ corresponds to a transparent regime, in which the optimal value of γ is γ^*. If $\lambda^{P[C]}$ differs from 0.05 (such as $\lambda^{P[C]} = 0.00$, 0.10, and 0.20), the optimal value of γ is larger than γ^*. The optimal value of γ is particularly large when the difference between $\lambda^{P[C]}$ and λ^C is large, such as the case of $\lambda^{P[C]} = 0.20$.

The middle and bottom panels of Figure 3.8 show the case of a heterogeneous gain ($\lambda^C \neq \lambda^P$). In the case of a heterogeneous gain, the welfare loss for the given value of γ is not minimized in a transparent regime. This can be confirmed in the middle panel. There, the welfare loss for the given value of γ becomes larger in a transparent regime than in the opaque regime of $\lambda^{P[C]} = 0.10$. In addition, the optimal value of γ is larger in a transparent regime than in the opaque regime of $\lambda^{P[C]} = 0.10$. Furthermore, the optimal value of γ is not necessarily monotonically increasing with the difference between λ^P and λ^C.

The reason for these results can be explained as follows. As we have seen in the previous subsection, the difference between μ_t^C and μ_t^P plays the role of the demand shock. However, in contrast to a transparent regime, it is possible that the expectations for the output gap ($E_t x_{t+1}$) and inflation rate ($E_t \pi_{t+1}$) at least partially offset the impact of heterogeneity between μ_t^C and μ_t^P in (3.31) because, as in (3.29) and (3.30), these expectations depend on the value of $\mu_t^{P[C]}$ in an opaque regime. This happens in the case of $\lambda^{P[C]} = 0.10$ in the middle panel of Figure 3.8 and also in the case of $\lambda^{P[C]} = 0.05$ in the bottom panel of Figure 3.8

In sum, the social welfare loss depends on the combinations of λ^C, λ^P, and $\lambda^{P[C]}$ in an opaque regime. As a result, the optimal value of γ in an opaque regime depends on these gain parameters. A problem here is that the values of λ^P and $\lambda^{P[C]}$ are not directly observable by the central bank. In this sense, the central bank faces uncertainty about the optimal policy response. However, in any case, the optimal value of γ is at least larger than (or equal to) γ^*. In other words, any value less than γ^* cannot be optimal in all the combinations of λ^C, λ^P, and $\lambda^{P[C]}$. Therefore, if the central bank is uncertain about the values of λ^C, λ^P, and $\lambda^{P[C]}$, then it is sensible for the central bank to respond strongly to the variations of the inflation rate.

3.4.3 Influence of Private Agents' Learning on λ^C

Until the previous subsection, we have assumed that private agents' conjecture on the gain parameter used by the central bank ($\lambda^{P[C]}$) is time-invariant. However, we can consider the possibility that private agents gradually learn the value of λ^C by observing the central bank's policy actions. If we introduce such a learning mechanism, the optimal value of γ depends on the speed of learning of the private agents.

As for the mechanism of the private agents' learning, we introduce a recursive procedure in forming the value of $\lambda^{P[C]}$. First, we define a variable h_t as below:

$$h_t = i_t - \gamma\pi_t - (\rho + \overline{z}). \tag{3.35}$$

h_t represents the residual of policy action, which is calculated as the variation of the nominal interest rate except for the response to the inflation rate ($\gamma\pi_t$) and the steady-state value of the real interest rate ($\rho + \overline{z}$). Since we assume that private agents can observe i_t and π_t, h_t is computable to private agents at period t.

From (3.14) and (3.35), h_t can be expressed as follows:

$$h_t = \phi\mu_t^C + \xi_t. \tag{3.36}$$

Thus, h_t is the amalgam of $\phi\mu_t^C$ and ξ_t. By substituting (3.23) into (3.36), we obtain the following equation:

$$S_t = \lambda^C X_t + \xi_t, \tag{3.37}$$

where S_t and X_t are defined as $S_t \equiv h_t - \phi^2\mu_{t-1}^C$ and $X_t \equiv \phi(z_t - \overline{z}) - \phi^2\mu_{t-1}^C$, respectively. Private agents can estimate λ^C by regressing equation (3.36) with recursive least squares (RLS), because they know the values of S_t and X_t at period t. Suppose that private agents initially conjecture the value of λ^C as $\lambda_0^{P[C]}$. Then we can apply the following recursive formula to obtain the estimate of $\lambda_t^{P[C]}$ in each period:

$$\lambda_t^{P[C]} = \lambda_{t-1}^{P[C]} + \omega^P R_t^{-1} X_t (S_t - \lambda_{t-1}^{P[C]} X_t), \tag{3.38}$$

$$R_t = R_{t-1} + \omega^P (X_t^2 - R_{t-1}), \tag{3.39}$$

where ω^P is the constant gain and R_t is the moment matrix of X_t.[23]

Once we obtain the value of $\lambda_t^{P[C]}$, the estimate of μ_{t-1}^C, which is denoted as $\mu_t^{P[C]}$, can be calculated as follows:

$$\mu_t^{P[C]} = \phi \mu_{t-1}^{P[C]} + \lambda_t^{P[C]} [(z_t - \overline{z}) - \phi \mu_{t-1}^{P[C]}]. \tag{3.40}$$

In numerical simulations, we set two alternative values for constant gain ω^P (0.025 and 0.10). As Figure 3.9 shows, $\lambda_t^{P[C]}$ converges to the true value of λ^C. The speed of convergence is slower when the value of ω^P is smaller.

Figure 3.10 shows the welfare loss in the case where private agents update the value of $\lambda_t^{P[C]}$ by using $\omega^P = 0.025$. The difference between Figure 3.8 and Figure 3.10 simply reflects the influence of private agents' learning on λ^C. Because of the learning mechanism, each locus of the welfare loss in Figure 3.10 shifts away from the corresponding locus in Figure 3.8. In some cases, these shifts are downward. This could be regarded as natural consequences, since private agents' learning reduces their misperception of the value of λ^C. However, in other cases (such as the cases of $\lambda_0^{P[C]} = 0.10$ in the middle panel and $\lambda_0^{P[C]} = 0.20$ in the bottom panel), the shifts are upward. These results suggest that private agents' learning mechanism does not necessarily reduce the social welfare loss for a given value of γ. This finding indicates that the optimal value of γ does not necessarily approach γ^* with the introduction of private agents' learning mechanism.[24]

We can understand the reason for this result by looking at Figure 3.6. In the case of a homogeneous gain, social welfare monotonically decreases while $\lambda_t^{P[C]}$ approaches λ^C. However, in the case of a heterogeneous gain, social

[23] See Evans and Honkapohja [2001] for the details of the RLS formula. The use of constant gain implies that private agents consider the possibility that the central bank shifts the gain parameter (λ^C).

[24] Notice that the welfare loss in the case that private agents initially guess correctly ($\lambda_0^{P[C]} = 0.05$ in the upper panels of Figure 3.10 and Figure 3.11) is not the same as the welfare loss in the transparent regime. This is because private agents do not know that the true value of λ^C is 0.05 and revise the estimate $\lambda_t^{P[C]}$ in each period even though they initially guess correctly on λ^C.

welfare does not necessarily decrease through the process of learning. For example, in the middle panel, if the initial value of $\lambda_t^{P[C]}$ is just the same as λ^P, private agents' learning process increases the social welfare loss. This is because, as explained in Section 3.3.4, private agents' initial misperception of λ^C reduces the magnitude of the demand shock in this case. In this environment, private agents' learning process magnifies the volatility of the demand shock by eliminating the influence of private agents' misperception that has been favorable to social welfare.

Figure 3.11 shows the welfare loss in the case where private agents learn the value of λ^C by using $\omega^P = 0.10$. In this case, the welfare losses converge for each value of $\lambda_0^{P[C]}$. This result is natural, since the high constant gain implies that private agents quickly learn the value of λ^C. As a result, the optimal values of γ in an opaque regime converge across the alternative values of $\lambda_0^{P[C]}$. In this sense, the central bank faces smaller uncertainty about the optimal policy response when the value of ω^P is higher.

But, a problem here is that the central bank cannot directly observe the value of ω^P. This means that the central bank faces uncertainty about the speed of convergence of private agents' learning. Nevertheless, the optimal value of γ is still larger at least than γ^* for both values of $\omega^P = 0.025$ and 0.10. This suggests that, for any value of ω^P, the central bank should set the value of γ larger than γ^*. Therefore, it is sensible for the central bank to respond strongly to the variations of the inflation rate even if we introduce the influence of private agents' learning on λ^C.

3.5 Conclusion

In this chapter, we have investigated how central bank transparency about views of future productivity growth influences social welfare. To this end, we have used a New Keynesian framework in which both the central bank and private agents filter the persistence of productivity growth. Since the central bank and private agents do not know the true value of the signal-to-noise ratio, the gain parameters used in the filtering problems can be heterogeneous. If the central bank is not transparent, private agents must conjecture the central bank's estimate of the efficient interest rate.

Under this setup, we have shown that central bank transparency does not necessarily improve social welfare. It can potentially yield a welfare loss, depending on (i) the gain parameters used by the central bank and private agents and (ii) private agents' conjecture about the gain parameter used by the central bank. If the gain parameters used by the central bank and private agents are homogeneous, then central bank transparency always improves social welfare. However, if these gain parameters are heterogeneous, central bank transparency can be either welfare-improving or welfare-reducing, because it is possible that private agents' misperception of the central bank's forecast offsets the distortion which arises due to the heterogeneity of the gain parameters used by the central bank and private agents.

In considering large uncertainty and the possible structural changes in the variance of productivity shock, the case of heterogeneous gain could be viewed as a more general case than the case of homogeneous gain. On that ground, it is natural for the central bank to face uncertainty as to the desirability of transparency about views of future productivity growth. Our study has shown that, in this situation, it is sensible for the central bank to respond strongly to the variations of the inflation rate, because the misperceptions about these parameters become the source of the demand shock.

Chapter 4

Monetary Policy and Learning from the Central Bank's Forecast

4.1 Introduction

Since the development of adaptive learning in macroeconomics (Evans and Honkapohja [2001]), many studies have investigated the expectational stability (E-stability) conditions of the rational expectations equilibrium (REE) in various macroeconomic models. One of the important applications to monetary economics is Bullard and Mitra [2002]. They examine the E-stability condition in a simple class of the New Keynesian model, which consists of an IS equation, a New Keynesian Phillips curve (NKPC), and a Taylor-type monetary policy rule.[1] Their results indicate that the so-called *Taylor principle*, which requires the central bank to adjust the nominal interest rate by more than one-for-one with the inflation rate, corresponds to the E-stability condition under some versions of Taylor-type monetary policy rules, including a forward-looking rule that incorporates the expectations for the future inflation rate and output gap, which are assumed to be homogeneous between the central bank and private agents.[2]

[1] Evans and Honkapohja [2003a] review the studies of adaptive learning in New Keynesian models.

[2] The issue of stability under learning when the central bank introduces an interest-rate rule is originally raised by Howitt [1992] in an IS-LM model with a New Classical Phillips curve.

Honkapohja and Mitra [2005] extend the analysis of Bullard and Mitra [2002] to introduce heterogeneous expectations between the central bank and private agents. They show that, even if the central bank and private agents initially have different expectations, the correspondence between the E-stability condition and the Taylor principle holds, as long as the learning algorithms used by these two agents are asymptotically identical. However, they further show that, if the difference of learning algorithms remains even in the long run, the Taylor principle does not generally correspond to the E-stability condition. Therefore, their analysis points out that the heterogeneity between the central bank and private agents is a key issue for determining the E-stability condition in a simple New Keynesian model.

However, we should note that the environments of these previous studies are still quite simple because the studies assume that the central bank and private agents independently (or simultaneously) engage in adaptive learning. In other words, the previous studies assume that there is no interaction in the learning process of the central bank and private agents. Of course, as Honkapohja and Mitra [2005] noted, this assumption is introduced as a natural benchmark.[3] However, the validity of this assumption is empirically arguable when we take account of possible interactions between the central bank and private agents. In this respect, Fujiwara [2005] provides empirical evidence that, in Japan's survey data, the central bank's forecast influences the forecast of private agents (not vice versa). Therefore, his results indicate that the central bank is the *leader* and private agents are the *followers* of expectation formations.[4]

In this study, we examine the E-stability of the REE in a simple New Keynesian model in which the central bank is the leader and private agents are the followers of expectation formations. This means that private agents engage in adaptive learning by referring to the central bank's forecast.[5] This

[3] Honkapohja and Mitra [2005] stated that, "We will focus on the situation in which both the private sector and the central bank use their own forecasts in their decision-making and the forecasts are not available to the other agents. Consequently, the forecasts have no strategic role. This case can be seen as a natural benchmark."

[4] Fujiwara [2005] suggests, "In the learning context, it would be better to suppose that the central bank is a leader rather than a follower when analyzing monetary policy in Japan, since the results in this paper indicate that professional forecasters tend to learn from the central bank rather than to influence it (p. 261)."

[5] In this study, we restrict our attention to a Taylor-type simple monetary policy rule. Thus, we do not examine the E-stability under optimal monetary policy. The property of optimal monetary policy in the presence of adaptive learning is examined in Evans and

kind of leader-follower relationship of adaptive learning has already been introduced by Granato, Guse, and Wong [2007] in the traditional "cobweb" model. However, their analysis investigates the heterogeneous expectations among private agents. In contrast, the distinctive feature of our study is that it investigates the heterogeneous expectations between the policymaker (namely, the central bank) and private agents.

Since we assume that private agents refer to the central bank's forecast, our study introduces the heterogeneity concerning the perceived law of motion (PLM) used by the central bank and private agents. However, as for the learning algorithm, we assume that both the central bank and private agents use the recursive least squares (RLS) with decreasing gain, which is the most standard algorithm in the literature.[6] In these respects, the environment of our study contrasts sharply with that of Honkapohja and Mitra [2005], which assumes that the PLMs are homogeneous and that the learning algorithms are heterogeneous.

The rest of this chapter is organized as follows. In Section 4.2, we present our simple version of the New Keynesian model. We show that, if the central bank and private agents are independently learning, the E-stability condition corresponds to the Taylor principle, as reported by Bullard and Mitra [2002]. In Section 4.3, we examine the E-stability condition when private agents engage in adaptive learning by referring to the central bank's forecast. In Section 4.4, we investigate the relationship between the E-stability and the determinacy (uniqueness) of the REE. In Section 4.5, we examine the E-stability in the reverse situation in which the central bank engages in adaptive learning by referring to the forecast of private agents. In Section 4.6, we conclude our analysis.

Honkapohja [2003b, 2006].

[6] An alternative algorithm is RLS with constant gain, which is typically used to describe a situation in which agents take account of the possibility of structural changes (as is explained by Evans and Honkapohja [2001]). Honkapohja and Mitra [2005] introduce heterogeneous constant gains between the central bank and private agents. They show that, if the difference of constant gains remains in the long run, then it matters for the E-stability condition.

4.2 Framework

4.2.1 Model

We use a simple version of the New Keynesian model. Our model is simpler than that of Bullard and Mitra [2002] or Honkapohja and Mitra [2005], since we introduce a static version of the IS equation, in which the current output gap does not depend on the expectation for the future output gap. We choose this formulation because (i) we can analytically derive the E-stability condition and (ii) we can numerically obtain essentially the same results in an extended model which introduces a dynamic version of the IS equation.[7] Therefore, we consider that the current version of our model is useful to investigate the essence of our problem.

The static IS equation and the NKPC are given as follows:

$$x_t = -\sigma(r_t - r_t^n - E_t^P \pi_{t+1}), \tag{4.1}$$

$$\pi_t = \beta E_t^P \pi_{t+1} + \kappa x_t, \tag{4.2}$$

where x_t is the output gap, π_t is the inflation rate, r_t is the nominal interest rate, and r_t^n is the natural rate of real interest. Each variable is defined as the deviation from its steady state.[8] In particular, r_t is the deviation of the nominal interest rate from its steady-state level, which is consistent with zero inflation and steady-state output growth. E_t^P denotes private agents' subjective (possibly nonrational) expectation. σ, β, and κ are the structural parameters which satisfy $\sigma > 0$, $1 \geq \beta > 0$, and $\kappa > 0$.

[7] By using the model of Bullard and Mitra [2002], which introduces a dynamic version of the IS equation, we numerically obtain the result that the Taylor principle is not a sufficient condition for the E-stability of the REE if private agents engage in by referring to the central bank's forecast, which is the main finding of this study.

[8] Preston [2006] examines the E-stability of the REE in a New Keynesian model, in which private agents make current decisions about spending and pricing based on the long-horizon forecasts. He shows that the Taylor principle is not a sufficient condition for the E-stability under a forward-looking version of the Taylor rule. This result differs from Bullard and Mitra [2002]. However, Evans, Honkapohja, and Mitra [2003] show that the approaches of Preston [2006] and Bullard and Mitra [2002] are not inconsistent, because if the law of iterated expectations at an individual and aggregate levels holds, then the IS equation and the NKPC with long-horizon forecasts correspond to those with one-period-ahead forecasts. Since this study assumes that the law of iterated expectations at an individual and aggregate levels holds, we introduce the NKPC with a one-period-ahead forecast.

The process of natural rate of real interest is given by

$$r_t^n = \rho r_{t-1}^n + \varepsilon_t, \tag{4.3}$$

where ρ satisfies $1 > \rho > 0$ and ε_t follows i.i.d. with zero mean.

The central bank introduces a forward-looking monetary policy rule:

$$r_t = \phi E_t^{CB} \pi_{t+1}, \tag{4.4}$$

where ϕ is the responsiveness to the expected inflation rate. E_t^{CB} denotes the central bank's subjective expectation. In this study, we investigate mainly the situation in which the central bank and private agents have heterogeneous expectations (at least in the short run). Therefore, the central bank's expectations (E_t^{CB}) and private agents' expectations (E_t^P) are potentially different.

The model can be reduced to the model of inflation dynamics:

$$\pi_t = A + BE_t^P \pi_{t+1} + CE_t^{CB} \pi_{t+1} + Dr_t^n, \tag{4.5}$$

where $A = 0$, $B = \kappa\sigma + \beta$, $C = -\kappa\sigma\phi$, and $D = \kappa\sigma$.

4.2.2 E-stability When the Central Bank and Private Agents Are Independently Learning

Next, we present the E-stability condition of the REE when the central bank and private agents independently engage in adaptive learning. Following Bullard and Mitra [2002], we introduce a simplifying assumption that the central bank and private agents have an identical PLM such as

$$\pi_t = \widetilde{a} + \widetilde{b} r_t^n, \tag{4.6}$$

where $\widetilde{a}$ and $\widetilde{b}$ are coefficients, which are updated in every period. Since the functional form of (4.6) corresponds to the minimal state variables (MSV) solution of the system (4.5), we call the learning process of (4.6) "MSV learning."

Based on PLM, the one-period-ahead expectation is calculated as follows:

$$E_t^{CB} \pi_{t+1} = E_t^P \pi_{t+1} = \widetilde{a} + \rho \widetilde{b} r_t^n. \tag{4.7}$$

By substituting (4.7) into (4.5), we derive the actual law of motion (ALM) as follows:

$$\pi_t = A + (B + C)\widetilde{a} + (\rho(B + C)\widetilde{b} + D)r_t^n. \tag{4.8}$$

From (4.6) and (4.8), the mapping functions (T-maps) from PLM to ALM are as follows:

$$\begin{aligned} T_a(\widetilde{a}) &= A + (B + C)\widetilde{a}, & (4.9) \\ T_b(\widetilde{b}) &= \rho(B + C)\widetilde{b} + D. & (4.10) \end{aligned}$$

The REE with the MSV form (MSV solution) is obtained as the fixed point of T-maps. The parameters of the MSV solution ($\overline{a}$ and $\overline{b}$) are computed as follows:

$$\overline{a} = (1 - (B + C))^{-1}A,\ \overline{b} = (1 - \rho(B + C))^{-1}D.$$

Note that the combination of $\overline{a}$ and $\overline{b}$ is unique. It means that, if we restrict attention to the MSV form, the solution is unique, regardless of the values of structural parameters. For the moment (except for Section 4.4), we focus on the MSV solution.

Next, we derive the E-stability condition of the REE. In this study, we assume that both the central bank and private agents use RLS with decreasing gain. Then, the E-stability of the REE is defined as the local asymptotic stability of the ordinary differential equations (ODEs) associated with the T-maps ((4.9) and (4.10)):

$$\begin{aligned} h_a(\widetilde{a}) &\equiv \frac{da}{d\tau} = T_a(\widetilde{a}) - \widetilde{a} = A + (B + C - 1)\widetilde{a}, & (4.11) \\ h_b(\widetilde{b}) &\equiv \frac{db}{d\tau} = T_a(\widetilde{b}) - \widetilde{b} = (\rho(B + C) - 1)\widetilde{b} + D, & (4.12) \end{aligned}$$

where τ is "notional" or "artificial" time.

From these ODEs, the E-stability condition is derived as two inequalities:

$$\begin{aligned} Dh_a(\widetilde{a}) &= B + C - 1 < 0, & (4.13) \\ Dh_b(\widetilde{b}) &= \rho(B + C) - 1 < 0. & (4.14) \end{aligned}$$

Since $1 > \rho > 0$, (4.14) holds if (4.13) holds. Therefore, the necessary and sufficient condition for the E-stability of the REE is (4.13). (4.13) is rewritten as follows:

$$\phi > 1 + \frac{\beta - 1}{\kappa\sigma}. \tag{4.15}$$

Since β is usually very close to unity (such as 0.99), (4.15) indicates that the E-stability corresponds to the Taylor principle, which requires the central bank to adjust the nominal interest rate by more than one-for-one with the inflation rate. This is one of the main findings of Bullard and Mitra [2002].

4.3 E-stability When Private Agents Are Learning from the Central Bank's Forecast

In this section, we examine the E-stability condition when private agents engage in adaptive learning by referring to the central bank's forecast. It means that the central bank is the leader and private agents are the followers of expectation formations.

4.3.1 PLM and ALM

As in the previous section, we assume that the central bank engages in MSV learning. Then, the central bank's PLM is the same as in the previous section:

$$\pi_t = \widetilde{a} + \widetilde{b} r_t^n. \tag{4.16}$$

At the beginning of period t, the central bank updates the parameters of $\widetilde{a}$ and $\widetilde{b}$ by using the data of period $t-1$ (y_{t-1} and r_{t-1}^n). Then, the central bank observes the realization of the natural rate of real interest at period t (r_t^n). By using the newest estimates of $\widetilde{a}$ and $\widetilde{b}$, the central bank calculates the forward-looking expectations as follows:

$$E_t^{CB}\pi_{t+1} = \widetilde{a} + \rho\widetilde{b} r_t^n. \tag{4.17}$$

After calculating (4.17), the central bank announces this forecast to private agents.

The expectation formation of private agents is the core part of this analysis. In this respect, we assume that private agents can observe the central bank's forecast $E_t^{CB}\pi_{t+1}$ when they form the expectation $E_t^P\pi_{t+1}$. However, we also assume that private agents do not know how the central bank calculates the forecast $E_t^{CB}\pi_{t+1}$. Namely, private agents do not know the model used by the central bank. This is a usual assumption of adaptive learning, in which agents do not use structural knowledge to form their expectations.

We assume that private agents determine how to utilize the central bank's forecast in forming their expectations by evaluating the historical performance of the central bank's forecast. Specifically, we assume that private agents estimate the following PLM:

$$\pi_t = \widetilde{c} + \widetilde{d} E_{t-1}^{CB}\pi_t. \tag{4.18}$$

By estimating (4.18) with RLS, private agents assess the historical performance of the central bank's forecast.[9] If the forecast has historically performed well, the constant term $\widetilde{c}$ approximates zero, and the slope $\widetilde{d}$ should be close to unity. In contrast, if the central bank's forecast has performed poorly, $\widetilde{c}$ approximates the sample average of π_t, and $\widetilde{d}$ should be close to zero.[10]

Private agents update the parameters of $\widetilde{c}$ and $\widetilde{d}$ by using the data of period $t-1$ (π_{t-1} and $E_{t-2}^{CB}\pi_{t-1}$). Since private agents are the followers, they can use the central bank's forecast $E_t^{CB}\pi_{t+1}$ in forming their expectations at period t ($E_t^P\pi_{t+1}$). To calculate $E_t^P\pi_{t+1}$, private agents use their evaluation of the performance of the central bank's forecast as follows:

$$E_t^P\pi_{t+1} = \widetilde{c} + \widetilde{d} E_t^{CB}\pi_{t+1}. \tag{4.19}$$

(4.19) indicates that the forecast of private agents is influenced by the central bank's forecast. In addition, the influence of the central bank's forecast on the forecast of private agents is determined by the estimated parameter $\widetilde{d}$. Therefore, (4.19) illustrates a situation in which private agents refer to the central bank's forecast, depending on its historical performance.

By inserting both agents' expectations ((4.17) and (4.19)) into the system

[9] As is seen in the next subsection, the use of RLS in estimating (4.18) is consistent with the REE.

[10] This means that private agents do not automatically follow the central bank's forecast (if such is the case, the coefficients are fixed as $\widetilde{c} = 0$ and $\widetilde{d} = 1$, which corresponds to the case of homogeneous learning). This is a natural assumption, because private agents do not have any reason to follow the central bank's forecast if the historical performance of central bank forecast is very poor. The empirical analysis of Fujiwara [2005] supports this idea, because his results show that private agents do not perfectly equalize their forecast as the central bank's forecast even after observing the forecast.

of (4.5), we derive ALM for π_t as follows:

$$\pi_t = A + B(\widetilde{c} + \widetilde{d}\widetilde{a}) + C\widetilde{a} + (\rho(B\widetilde{d} + C)\widetilde{b} + D)r_t^n. \tag{4.20}$$

4.3.2 Equilibrium

Next, we derive the T-maps from PLM to ALM. From (4.16) and (4.20), the T-maps about parameters of $\widetilde{a}$ and $\widetilde{b}$ are given as follows:

$$T_a(\widetilde{a}) = A + B(\widetilde{c} + \widetilde{d}\widetilde{a}) + C\widetilde{a}, \tag{4.21}$$

$$T_b(\widetilde{b}) = \rho(B\widetilde{d} + C)\widetilde{b} + D. \tag{4.22}$$

Since private agents' PLM (4.18) is not the MSV form, we must derive the T-maps from the relevant orthogonality conditions.[11] From (4.17) and (4.18), private agents' "projected" ALM is defined as follows:

$$\pi_t = T_c + T_d(\widetilde{a} + \rho\widetilde{b}r_{t-1}^n). \tag{4.23}$$

The corresponding orthogonality conditions are given by

$$E\left[1 \cdot \left(\pi_t - T_c - T_d(\widetilde{a} + \rho\widetilde{b}r_{t-1}^n)\right)\right] = 0, \tag{4.24}$$

$$E\left[(\widetilde{a} + \rho\widetilde{b}r_{t-1}^n)\left(\pi_t - T_c - T_d(\widetilde{a} + \rho\widetilde{b}r_{t-1}^n)\right)\right] = 0. \tag{4.25}$$

From (4.20), (4.24), and (4.25), we derive the T-maps about $\widetilde{c}$ and $\widetilde{d}$ as follows:

$$T_c(\widetilde{c}) = A + B\widetilde{c} + (1 - \rho)(B\widetilde{d} + C)\widetilde{a} - \widetilde{b}^{-1}D\widetilde{a}, \tag{4.26}$$

$$T_d(\widetilde{d}) = \rho B\widetilde{d} + \rho C + \widetilde{b}^{-1}D. \tag{4.27}$$

The equilibrium is derived as the fixed points of the T-maps ((4.21), (4.22), (4.26), and (4.27)). The coefficients at the equilibrium are given as follows:

$$\overline{a} = (1 - (B + C))^{-1}A, \overline{b} = (1 - \rho(B + C))^{-1}D, \overline{c} = 0, \overline{d} = 1.$$

[11] See Branch [2004] for the derivation of T-maps using orthogonality conditions.

Note that, at the equilibrium, (4.19) becomes as follows:

$$E_t^P \pi_{t+1} = E_t^{CB} \pi_{t+1} = (1-(B+C))^{-1}A + \rho(1-\rho(B+C))^{-1}Dr_t^n. \quad (4.28)$$

Therefore, at the equilibrium, expectations become homogeneous between the central bank and private agents. Furthermore, these expectations are the same as the expectation at the MSV solution in Section 4.2. Therefore, the expectation of (4.28) is the rational expectation and this equilibrium is the REE. This means that the economic dynamics at equilibrium are exactly the same in the two cases: (i) the case in which the central bank and private agents are independently learning and (ii) the case in which private agents engage in adaptive learning by referring to the central bank's forecast. However, in considering the transition dynamics under adaptive learning, the E-stability conditions of the REE can differ between these two cases. In the next subsection, we examine this issue.

4.3.3 E-stability

Next, we examine the E-stability condition. The E-stability of the equilibrium is the local asymptotic stability of ODEs associated with the T-maps of (4.21), (4.22), (4.26), and (4.27). Although these T-maps are interdependent, $T_b(\widetilde{b})$ and $T_d(\widetilde{d})$ only depend on $\widetilde{b}$ and $\widetilde{d}$. Therefore, we can examine the stability of $\widetilde{b}$ and $\widetilde{d}$, independently of the stability of $\widetilde{a}$ and $\widetilde{c}$.

To examine the stability of $\widetilde{b}$ and $\widetilde{d}$, we define the ODEs associated with the T-maps of $\widetilde{b}$ and $\widetilde{d}$ ((4.22) and (4.27)) as follows:

$$h\begin{pmatrix} \widetilde{b} \\ \widetilde{d} \end{pmatrix} \equiv \begin{pmatrix} T_b(\widetilde{b}) - \widetilde{b} \\ T_d(\widetilde{d}) - \widetilde{d} \end{pmatrix} = \begin{pmatrix} \rho(B\widetilde{d} + C)\widetilde{b} + D - \widetilde{b} \\ \rho B\widetilde{d} + \rho C + \widetilde{b}^{-1}D - \widetilde{d} \end{pmatrix}. \quad (4.29)$$

Given the convergence of $\widetilde{b}$ and $\widetilde{d}$, we can examine the stability of $\widetilde{a}$ and $\widetilde{c}$ by using the following ODEs:

$$h\begin{pmatrix} \widetilde{a} \\ \widetilde{c} \end{pmatrix} \equiv \begin{pmatrix} T_a(\widetilde{a}) - \widetilde{a} \\ T_c(\widetilde{c}) - \widetilde{c} \end{pmatrix} = \begin{pmatrix} A + B(\widetilde{c} + \widetilde{d}\widetilde{a}) + C\widetilde{a} - \widetilde{a} \\ A + B\widetilde{c} + (1-\rho)(B\widetilde{d} + C)\widetilde{a} - \widetilde{b}^{-1}D\widetilde{a} - \widetilde{c} \end{pmatrix}. \quad (4.30)$$

We derive the E-stability condition as the necessary and sufficient condition for the ODEs of (4.29) and (4.30) to be locally asymptotically stable around the REE. The result is given by the following proposition.

Proposition 1 *Suppose that the central bank engages in MSV learning and all private agents engage in adaptive learning by referring to the central bank's forecast. Then, the REE of (4.5) is E-stable if and only if (4.31) and (4.32) hold.*

$$\phi > 2 + \frac{2(\beta - 1)}{\kappa\sigma}, \tag{4.31}$$

$$\phi > 1 + \frac{\beta - 1}{\kappa\sigma}. \tag{4.32}$$

Proof. *See Appendix 4.7.1.* ■

Proposition 1 leads to the following corollary.

Corollary 2 *Suppose that the central bank engages in MSV learning and all private agents engage in adaptive learning by referring to the central bank's forecast. Then, if $\kappa\sigma > 1 - \beta$, the REE of (4.5) is E-stable if and only if (4.31) holds.*

Since β is close to unity, $\kappa\sigma > 1 - \beta$ holds for a wide range of parameter sets (κ and σ). Then, the Taylor principle, which is expressed as (4.32), is not a sufficient condition for the E-stability, because the E-stability condition corresponds to (4.31). This means that, to satisfy the E-stability condition, the central bank must adjust the nominal interest rate by more than double the rise of central bank's expected inflation rate.

Thus, the E-stability condition in this situation is quite different from the condition in the benchmark case analyzed in Section 4.2. Although the equilibrium dynamics of these two cases are exactly the same, the E-stability condition is severer in the environment of this section. This means that, if private agents engage in adaptive learning by referring to the central bank's forecast, the central bank must respond to the expected inflation rate more strongly than the Taylor principle suggests.

4.3.4 Intuition for the Result

As is shown in the previous subsection, if private agents engage in adaptive learning by referring to the central bank's forecast, the central bank has to respond more strongly to the expected inflation rate than the Taylor principle suggests.

The basic intuition for the result is given by the fact that, in the situation of this section, private agents' forecast errors, which are defined as the deviations of private agents' expectations from rational expectations, are magnified, compared to the central bank's forecast errors. The reason is twofold. Firstly, private agents can make estimation errors concerning the parameters $\widetilde{c}$ and $\widetilde{d}$, which are introduced in their PLM (4.18). These estimation errors are the first source of private agents' forecast errors. Secondly, as in (4.19), the central bank's forecast errors influence the forecast of private agents. Since the parameter $\widetilde{d}$ is almost unity around the equilibrium, the central bank's forecast errors bring about almost the same amount of forecast errors as those of private agents. This is the second source of private agents' forecast errors. Summing up these two sources, the total forecast errors of private agents exceed the central bank's forecast errors.

Since the central bank introduces its own forecast in the monetary policy rule (4.4), the central bank responds to its own forecast errors. However, this policy response is insufficient to offset the forecast errors of private agents. Because private agents have larger forecast errors than the central bank, the central bank must respond very strongly to its own forecast, in order to ensure the convergence of economy to the REE. This is why the E-stability is not attained solely by the Taylor principle.

4.3.5 E-stability When Part of Private Agents Are Learning from the Central Bank's Forecast

So far, we have assumed that all private agents refer to the central bank's forecast in adaptive learning. However, this could be regarded as an extreme case.[12] In this subsection, therefore, we consider a more realistic environment in which some private agents engage in adaptive learning by referring to the central bank's forecast.

Suppose that a proportion μ of private agents engage in adaptive learning by referring to the central bank's forecast ($1 \geq \mu \geq 0$). The remaining $1 - \mu$ of private agents engage in MSV learning. Denote $E_t^{P1}\pi_{t+1}$ as the forecast of the former private agents and $E_t^{P2}\pi_{t+1}$ as the forecast of the latter private

[12] In this respect, Kohn [2005] judges that private agents do not rely perfectly on the central bank's expectation. He remarks that "in the United States, we have some indirect evidence that crowding out of private views has not increased even as the Federal Reserve has become more talkative. Market interest rates have continued to respond substantially to surprises in economic data."

agents. Note that the forecast made by the latter is just the same as the central bank's forecast. Therefore, the aggregate forecast of private agents ($E_t^P \pi_{t+1}$) can be expressed as follows:[13]

$$\begin{aligned} E_t^P \pi_{t+1} &= \mu E_t^{P1} \pi_{t+1} + (1-\mu) E_t^{P2} \pi_{t+1} \\ &= \mu E_t^{P1} \pi_{t+1} + (1-\mu) E_t^{CB} \pi_{t+1}. \end{aligned} \tag{4.33}$$

By substituting (4.33) into (4.5), we obtain the following ALM:

$$\pi_t = A + \widehat{B} E_t^{P1} \pi_{t+1} + \widehat{C} E_t^{CB} \pi_{t+1} + D r_t^n, \tag{4.34}$$

where $\widehat{B} = \mu B$ and $\widehat{C} = (1-\mu)B + C$.

(4.34) has the same form as (4.5). Therefore, in order to examine the E-stability of the REE, we can follow the same steps of the Sections 4.3.2 and 4.3.3, by replacing the matrices of B and C with $\widehat{B}$ and $\widehat{C}$. Then, the result for the E-stability of the REE is given by the following proposition.[14]

Proposition 3 *Suppose that the central bank and a proportion $1-\mu$ of private agents engage in MSV learning. In addition, suppose that a proportion μ of private agents engage in adaptive learning by referring to the central bank's forecast. Then, the REE of (4.5) is E-stable if and only if (4.35) and (4.36) hold.*

$$\phi > 1 + \mu + \frac{(1+\mu)\beta - 2}{\kappa\sigma}, \tag{4.35}$$

$$\phi > 1 + \frac{\beta - 1}{\kappa\sigma}. \tag{4.36}$$

Proof. *See Appendix 4.7.2.* ■

Proposition 2 leads to the following corollary.

Corollary 4 *Suppose that the central bank and a proportion $1-\mu$ of private agents engage in MSV learning. In addition, suppose that a proportion μ of*

[13] Guse [2005] incorporates a convex combination of heterogeneous forecasts into a simple macroeconomic model with multiple equilibria. Branch and McGough [2006] present the underlying assumptions for the validity of a convex combination of heterogeneous forecasts. These include (i) the identical expectations at steady state, (ii) some linearity properties of expectations, and (iii) the law of iterated expectations at both an individual and aggregate level. We assume that all of these assumptions are satisfied.

[14] We can easily find that the equilibrium of (4.34) is just the same as the REE of (4.5).

private agents engage in adaptive learning by referring to the central bank's forecast. Then, if $\mu \geq (\kappa\sigma + \beta)^{-1}$, the REE of (4.5) is E-stable if and only if (4.35) holds. If $\mu < (\kappa\sigma + \beta)^{-1}$, the REE of (4.5) is E-stable if and only if (4.36) holds.

Thus, if μ is relatively low, then the Taylor principle is the necessary and sufficient condition for the E-stability.[15] However, if μ is relatively high, to ensure the convergence to the REE, the central bank must respond more strongly to the expected inflation rate than the Taylor principle suggests.

4.4 Determinacy and E-stability

In the previous sections, we have examined the E-stability condition of the REE. However, in the standard analysis, the condition for determinacy (uniqueness) of the REE is also regarded as the minimum criterion which should be satisfied in monetary policy rules. In this regard, Bernanke and Woodford [1997] point out that the issue of determinacy is especially relevant when the central bank introduces a forward-looking monetary policy rule, such as (4.4). The reason why the determinacy condition has not been examined in the previous sections is that we have restricted our attention to the MSV solution, which is unique in our model. However, if we broaden our scope to introduce the solution forms other than the MSV form (i.e., sunspot equilibria), we must examine the condition for determinacy of the REE.[16] In particular, we must investigate the relationship between the determinacy condition and the E-stability condition. In this section, we examine this issue.

4.4.1 Determinacy of the REE

The determinacy condition is presented by Blanchard and Kahn [1980]. Since the system is reduced as the univariate model of (4.5), the derivation of determinacy condition is easy. In the REE, the system of (4.5) is

[15] Note that, for a wide range of parameter sets, the value of $(\kappa\sigma + \beta)^{-1}$ is between 0 to 1, since β is almost unity.

[16] Honkapohja and Mitra [2004] examine the existence of learnable sunspot equilibria in a simple New Keynesian model with a forward-looking Taylor rule. In contrast to our study, they introduce a benchmark assumption that the central bank and private agents engage in independently adaptive learning. They show that learnable sunspot equilibria can exist even if the policy rule satisfies the Taylor principle.

rewritten as follows:

$$\pi_t = A + (B + C)E_t\pi_{t+1} + Dr_t^n. \tag{4.37}$$

Blanchard and Kahn [1980] show the determinacy condition of (4.37) as $|B + C| < 1$. This leads to the following proposition.

Proposition 5 *The economy of (4.5) has a unique REE if and only if the following condition holds:*

$$1 + \frac{\beta + 1}{\kappa\sigma} > \phi > 1 + \frac{\beta - 1}{\kappa\sigma}. \tag{4.38}$$

Thus, the determinacy condition sets the upper bound of ϕ. This result means that the central bank should not respond to the expected inflation rate very strongly, because such a strong response causes the emergence of sunspot equilibria. This is the issue raised by Bernanke and Woodford [1997].

4.4.2 Relationship between Determinacy and E-stability

Next, we examine the relationship between the determinacy condition and the E-stability condition. Specifically, we investigate a situation in which all private agents engage in adaptive learning by referring to the central bank's forecast.[17] In this case, the E-stability condition is given by Proposition 1 and Corollary 1. By combining these with Proposition 3, we obtain the following proposition.

Proposition 6 *Suppose that the central bank engages in MSV learning and all private agents engage in adaptive learning by referring to the central bank's forecast. Then, the following statements hold.*

(i) If $1 > \beta + \kappa\sigma$, the necessary and sufficient condition for the REE of (4.5) to be E-stable and determinate is given by

$$1 + \frac{\beta + 1}{\kappa\sigma} > \phi > 1 + \frac{\beta - 1}{\kappa\sigma}. \tag{4.39}$$

(ii) If $3 \geq \beta + \kappa\sigma \geq 1$, the necessary and sufficient condition for the

[17] The extension to the situation in which some private agents engage in adaptive learning by referring to the central bank's forecast is straightforward.

REE of (4.5) to be E-stable and determinate is given by

$$1 + \frac{\beta + 1}{\kappa\sigma} > \phi > 2 + \frac{2(\beta - 1)}{\kappa\sigma}. \tag{4.40}$$

(iii) If $\beta + \kappa\sigma > 3$, the REE of (4.5) cannot be both E-stable and determinate for any value of ϕ.

The condition (4.39) is the same as the determinacy condition (4.38). This means that, in the case (i), the determinacy condition is a sufficient condition for the E-stability of the REE. However, this is a relatively special case, because $\beta + \kappa\sigma$ is usually more than unity (since β is close to unity).

Therefore, for a wide range of the parameter sets, determinacy is not a sufficient condition for the E-stability of the REE. This is an important finding in the literature, because McCallum [2007] points out that, if the current-period information is available in the process of adaptive learning, determinacy becomes a sufficient condition for the E-stability of the REE, in a broad class of linear models. In contrast to the argument of McCallum [2007], Proposition 4 indicates that the determinacy is not necessarily a sufficient condition for the E-stability, even though both the central bank and private agents calculate the expectations ($E_t^{CB}\pi_{t+1}$ and $E_t^P\pi_{t+1}$) by using the information at period t. This result suggests that, in the presence of the leader-follower relationship in adaptive learning, the determinacy does not automatically guarantee the E-stability of the REE.

Since $\beta+\kappa\sigma$ is usually greater than unity, the cases of (ii) and (iii) deserve our attention. In the case (ii), the region of E-stable and determinate REE is narrow. This means that the central bank's choice of the value ϕ is highly restrictive. The environment of the case (iii) is even severer, because the central bank cannot simultaneously satisfy the conditions of determinacy and E-stability. In the case (iii), we obtain the following proposition.

Proposition 7 *Suppose that the central bank engages in MSV learning and all private agents engage in adaptive learning by referring to the central bank's forecast. Then, under the condition of $\beta + \kappa\sigma \geq 3$, the following statements hold.*

(i) The REE of (4.5) is E-stable and indeterminate if

$$\phi > 2 + \frac{2(\beta - 1)}{\kappa\sigma}. \tag{4.41}$$

(ii) The REE of (4.5) is E-unstable and determinate if

$$1 + \frac{\beta + 1}{\kappa\sigma} > \phi > 1 + \frac{\beta - 1}{\kappa\sigma}. \tag{4.42}$$

(iii) The REE of (4.5) is E-unstable and indeterminate if

$$2 + \frac{2(\beta - 1)}{\kappa\sigma} \geq \phi \geq 1 + \frac{\beta + 1}{\kappa\sigma} \quad or \quad 1 + \frac{\beta - 1}{\kappa\sigma} > \phi. \tag{4.43}$$

Thus, if $\beta + \kappa\sigma > 3$, the central bank must choose either determinacy or E-stability. If the monetary policy rule satisfies (4.41), then the E-stable sunspot equilibria emerge. This is the situation investigated by Honkapohja and Mitra [2004]. In this case, the central bank's strong reaction to the expected inflation rate guarantees the E-stability. However, the endogenous fluctuations can occur, because multiple REE satisfy the E-stability. Honkapohja and Mitra [2004] recommend that the monetary policy rule should rule out this possibility. However, if the central bank avoids the emergence of E-stable sunspot equilibria, the REE must be E-unstable. In this sense, the central bank faces a serious trade-off.

In sum, the results indicate that, if private agents engage in adaptive learning by referring to the central bank's forecast, the central bank's policymaking must be more restrictive than in the benchmark case in which both the central bank and private agents independently engage in adaptive learning. This means that, if the central bank is the leader of expectation formation, a forward-looking monetary policy rule has more serious problems than those pointed out in Bernanke and Woodford [1997].

4.4.3 A Remedy

As in the previous subsection, we find that a forward-looking policy rule has serious problems when private agents engage in adaptive learning by referring to the central bank's forecast. A possible remedy for this problem is that the central bank additionally introduces the contemporaneous data of the inflation rate into a policy rule. Suppose that the central bank introduces the following monetary policy rule:

$$r_t = \phi E_t^{CB} \pi_{t+1} + \gamma \pi_t, \tag{4.44}$$

where γ is the responsiveness to the contemporaneous data of the inflation rate. Then, the reduced model has the same form of (4.5). However, the coefficients are replaced by $A = 0$, $B = \frac{\kappa\sigma+\beta}{1+\kappa\sigma\gamma}$, $C = \frac{-\kappa\sigma\phi}{1+\kappa\sigma\gamma}$, and $D = \frac{\kappa\sigma}{1+\kappa\sigma\gamma}$.

As in Section 4.4.1, the determinacy condition is obtained as $|B + C| < 1$. This leads to the following proposition.

Proposition 8 *The economy of (4.1), (4.2), (4.3), and (4.44) has a unique REE if and only if the following condition holds:*

$$1 + \gamma + \frac{\beta + 1}{\kappa\sigma} > \phi > 1 - \gamma + \frac{\beta - 1}{\kappa\sigma}. \tag{4.45}$$

Thus, the central bank can relax the determinacy condition by increasing the value of γ. This is a natural consequence because previous studies (including Bullard and Mitra [2002]) have shown that the rule with contemporaneous data is more robust for determinacy than the rule with forward-looking expectations. By responding to the contemporaneous data of the inflation rate, the central bank can reduce the sensitivity of the economic system to forward-looking expectations. This is why determinacy is more easily satisfied under rule (4.44) than (4.4).

Next, we examine the E-stability condition under rule (4.44). Suppose that all private agents engage in adaptive learning by referring to the central bank's forecast. Then, we can derive the E-stability condition, following the same steps in Section 4.3. The result is given by the following proposition.

Proposition 9 *Suppose that the central bank engages in MSV learning and all private agents engage in adaptive learning by referring to the central bank's forecast. Then, the REE of (4.1), (4.2), (4.3), and (4.44) is E-stable if and only if (4.46) and (4.47) hold.*

$$\phi + 2\gamma > 2 + \frac{2(\beta - 1)}{\kappa\sigma}, \tag{4.46}$$

$$\phi + \gamma > 1 + \frac{\beta - 1}{\kappa\sigma}. \tag{4.47}$$

Thus, the E-stability condition is relaxed by introducing the coefficient γ. By increasing the value of γ, the central bank can easily attain the E-stability of the REE. The reason for this result is explained by the fact that, in the NKPC (4.3), the contemporaneous inflation rate is determined by private agents' expected inflation rate. Because of this property, the central bank can respond to the forecast errors of private agents, by responding to the contemporaneous data of the inflation rate.

Therefore, the central bank can simultaneously relax the conditions of determinacy and E-stability, by responding to the contemporaneous movements of the inflation rate. This result suggests that it is dangerous for the central bank to introduce a purely forward-looking monetary policy rule. A more robust policy strategy is to respond to the contemporaneous movements of the inflation rate to a certain degree.

4.5 E-stability in the Reverse Situation

In this study, we have examined the situation in which private agents engage in adaptive learning by referring to the central bank's forecast. Readers may be interested in the E-stability condition in the reverse situation in which the central bank engages in adaptive learning by referring to the forecast of private agents.

The derivation of the E-stability condition is just the same as in Section 4.3. Following similar steps, we obtain the following proposition.

Proposition 10 *Suppose that all private agents engage in MSV learning and the central bank engages in adaptive learning by referring to the aggregate forecast of private agents. Then, the REE of (4.5) is E-stable if and only if (4.15) holds.*
Proof. *See Appendix 4.7.3.* ■

Therefore, in this reverse situation, the E-stability condition corresponds to the Taylor principle. Intuitively, this result can be interpreted as follows. In this situation, the central bank's forecast errors exceed the forecast errors of private agents (following the exactly opposite logic of Section 4.3.4). Therefore, in order to offset private agents' forecast errors, the central bank's reaction to its own forecast need not to be as large as the Taylor principle suggests (i.e. ϕ can be smaller than unity). However, to offset the central bank's own forecast errors, the Taylor principle is still required. This is why the E-stability condition is given by the Taylor principle.

Therefore, if private agents are the leaders and the central bank is the follower, the E-stability condition is just the same as in the benchmark case, which is investigated in Section 4.2. In this environment, the central bank can guarantee both the E-stability and determinacy of the REE by satisfying the Taylor principle. This implies that the central bank can more easily ensure macroeconomic stability in a case in which the central bank is the follower, rather than the leader of expectation formation.

4.6 Conclusion

In this chapter, we have examined the E-stability of the REE in a simple New Keynesian model in which private agents engage in adaptive learning by referring to the central bank's forecast. In contrast to a situation in which both the central bank and private agents independently (or simultaneously) engage in adaptive learning (such as the case of Bullard and Mitra [2002]), the E-stability is not attained solely by the so-called Taylor principle. To ensure the convergence to the REE, the central bank must respond more strongly to the expected inflation rate than the Taylor principle suggests. On the other hand, the central bank's strong reaction to the expected inflation rate raises the possibility of indeterminacy of the REE, as pointed out in Bernanke and Woodford [1997]. In considering these problems, a robust policy strategy is to respond to the contemporaneous data of the inflation rate to a certain degree.

4.7 Appendix

4.7.1 Proof of Proposition 1

The local asymptotic stability of $\widetilde{b}$ and $\widetilde{d}$ is satisfied if and only if all the eigenvalues of the Jacobian of (4.29) at the REE, which is expressed in (4.48), have negative real parts:

$$Dh\begin{pmatrix} \overline{b} \\ \overline{d} \end{pmatrix}\Big|_{\widetilde{b}=\overline{b},\widetilde{d}=\overline{d}} = \begin{pmatrix} \rho(B+C)-1 & \rho B(1-\rho(B+C))^{-1}D \\ -(1-\rho(B+C))^2 D^{-1} & \rho B-1 \end{pmatrix}. \tag{4.48}$$

The characteristic polynomial of (4.48) is given as follows:

$$\lambda^2 + (2-2\rho B-\rho C)\lambda + 1-\rho B-\rho C = 0. \tag{4.49}$$

All the eigenvalues of (4.48) have negative real parts if and only if $(2-$

$2\rho B - \rho C) > 0$ and $1 - \rho B - \rho C > 0$. From the definition of B and C, it corresponds to the following conditions:

$$\phi > 2 + \frac{2(\beta - \rho^{-1})}{\kappa\sigma}, \tag{4.50}$$

$$\phi > 1 + \frac{\beta - \rho^{-1}}{\kappa\sigma}. \tag{4.51}$$

Next, we examine the local asymptotic stability of $\widetilde{a}$ and $\widetilde{c}$. The Jacobian of (4.30) is derived as follows:

$$Dh \begin{pmatrix} \widetilde{a} \\ \widetilde{c} \end{pmatrix} |_{\widetilde{b}=\overline{b}, \widetilde{d}=\overline{d}} = \begin{pmatrix} B + C - 1 & B \\ B + C - 1 & B - 1 \end{pmatrix}. \tag{4.52}$$

The characteristic polynomial of (4.52) is as follows:

$$\lambda^2 + (2 - 2B - C)\lambda + 1 - B - C = 0. \tag{4.53}$$

Therefore, the local asymptotic stability of (4.52) at REE is satisfied if and only if $2 - 2B - C > 0$ and $1 - B - C > 0$. These correspond to the following conditions:

$$\phi > 2 + \frac{2(\beta - 1)}{\kappa\sigma}, \tag{4.54}$$

$$\phi > 1 + \frac{\beta - 1}{\kappa\sigma}. \tag{4.55}$$

Note that, since $1 > \rho > 0$, (4.50) holds if (4.54) holds. Similarly, (4.51) holds if (4.55) holds. Therefore, the E-stability condition corresponds to (4.54) and (4.55).

4.7.2 Proof of Proposition 2

If the central bank and a fraction of $1 - \mu$ of private agents engage in MSV learning and a fraction of μ of private agents engage in adaptive learning by referring to the central bank's forecast, the relevant characteristic polynomials are given as follows:

$$\lambda^2 + (2 - 2\rho\widehat{B} - \rho\widehat{C})\lambda + 1 - \rho\widehat{B} - \rho\widehat{C} = 0, \tag{4.56}$$

$$\lambda^2 + (2 - 2\widehat{B} - \widehat{C})\lambda + 1 - \widehat{B} - \widehat{C} = 0. \tag{4.57}$$

Then, the E-stability condition corresponds to that in which all of $2 - \rho\widehat{B} - 2\rho\widehat{C}$, $1 - \rho\widehat{B} - \rho\widehat{C}$, $2 - \widehat{B} - 2\widehat{C}$, and $1 - \widehat{B} - \widehat{C}$ are strictly positive. These are equivalent to the following conditions:

$$\phi > 1 + \mu + \frac{(1+\mu)\beta - 2\rho^{-1}}{\kappa\sigma}, \tag{4.58}$$

$$\phi > 1 + \frac{\beta - \rho^{-1}}{\kappa\sigma}. \tag{4.59}$$

$$\phi > 1 + \mu + \frac{(1+\mu)\beta - 2}{\kappa\sigma}, \tag{4.60}$$

$$\phi > 1 + \frac{\beta - 1}{\kappa\sigma}. \tag{4.61}$$

Since $1 > \rho > 0$, (4.58) holds if (4.60) holds. Similarly, (4.59) holds if (4.61) holds. Therefore, the E-stability conditions are (4.60) and (4.61).

4.7.3 Proof of Proposition 8

If all private agents engage in MSV learning and the central bank engages in adaptive learning by referring to the aggregate forecast of private agents, the relevant characteristic polynomials are given as follows:

$$\lambda^2 + (2 - \rho B - 2\rho C)\lambda + 1 - \rho B - \rho C = 0, \tag{4.62}$$

$$\lambda^2 + (2 - B - 2C)\lambda + 1 - B - C = 0. \tag{4.63}$$

Then, the E-stability condition corresponds to that in which all of $2 - \rho B - 2\rho C$, $1 - \rho B - \rho C$, $2 - B - 2C$, and $1 - B - C$ are strictly positive. These are equivalent to the following conditions:

$$\phi > \frac{1}{2} + \frac{\beta - 2\rho^{-1}}{2\kappa\sigma}, \tag{4.64}$$

$$\phi > 1 + \frac{\beta - \rho^{-1}}{\kappa\sigma}, \tag{4.65}$$

$$\phi > \frac{1}{2} + \frac{\beta - 2}{2\kappa\sigma}, \tag{4.66}$$

$$\phi > 1 + \frac{\beta - 1}{\kappa\sigma}. \tag{4.67}$$

Since $1 > \rho > 0$, (4.64) holds if (4.66) holds. Similarly, (4.65) holds if (4.67) holds. Furthermore, (4.66) holds if (4.67) holds. Therefore, the E-stability condition is given by (4.67).

Chapter 5

Concluding Remarks

In this thesis, we have presented one empirical and two theoretical studies on inflation dynamics and monetary policy which are based on the New Keynesian framework. In Chapter 2, we find that the New Keynesian Phillips Curve (NKPC) well explains Japanese inflation dynamics, if we use a corrected measure of real marginal cost (RMC). In Chapter 3, we show that central bank transparency about views on future productivity growth can be either welfare-improving or welfare-reducing, if the central bank and private agents can have heterogeneous forecasts. In Chapter 4, we indicate that the expectational stability (E-stability) of the rational expectations equilibrium (REE) of a simple New Keynesian model does not correspond to the so-called Taylor principle, if private agents engage in adaptive learning by referring to the central bank's forecast.

Some possible extensions of these studies are as follows. In Chapter 2, we find that the fit of Japan's NKPC, which introduces a corrected measure of RMC, is somewhat unsatisfactory in the recent deflationary period. One possible reason for this could be the existence of structural changes in Japan's labor market. An important task is to investigate more closely the change in the size of labor adjustment costs or the degree of real wage rigidity. Another research direction is to examine more thoroughly the nature of forward-looking expectations. In Chapter 2, we assume that private agents form the forward-looking expectations based on the estimated vector autoregression (VAR). However, the VAR includes only limited information concerning the determinant of the future inflation rate. To incorporate additional information, it is worth incorporating a dynamic factor model, which is introduced by Stock and Watson [1999] or Bernanke and Boivin [2003]. Another important extension is to examine the optimal monetary policy in the presence of these labor market frictions. In Chapter 2, we find that labor market frictions are crucial elements of macroeconomic dynamics. This suggests that it is extremely important to examine the implications of these labor market frictions for social welfare and an optimal monetary policy.

In Chapter 3, we have focused on a specific aspect of central bank transparency, that is, central bank transparency about views on future productivity growth. Investigating broader aspects of central bank transparency is certainly an important research agenda. Nowadays, some central banks, such as the Reserve Bank of New Zealand, the Norges Bank and the Riksbank, publish their projections for the future path of short-term interest rates. From the viewpoint of our analysis, the welfare implication of this kind of transparency is not straightforward, because it depends on how private agents interpret the central bank's projection of the future interest rates. In particular, a situation wherein the projections of the central bank and private agents are considerably different, the latter must identify the reason for the differences in forecast. To examine such an issue, it is worth extending our framework to incorporate the heterogeneity and misperceptions about economic data or forecasting models used by the central bank and private agents.

Another research direction is to examine empirically the implications of Chapter 3. In our framework, if the central bank is perfectly transparent, the difference in the forecasts between the central bank and private agents should be negatively correlated with the output gap and inflation rate. In other words, if the central bank's forecast of the future productivity growth is higher than that of the private agents, the heterogeneity should have a negative impact on the output gap or inflation rate. However, if private agents have misperceptions about the central bank's forecast, the impact can be either negative or positive. Therefore, to investigate how private agents form their conjecture about the central bank's forecast, it would be worth empirically examining the manner in which the heterogeneous forecasts influence on the output gap and the inflation rate.

In Chapter 4, we assume that the leader-follower relationship between the central bank and private agents is fixed. Introducing the mechanism of endogenous determination of the leader-follower relationship is an interesting topic of research. In this respect, Branch and Evans [2006] provide a theoretical framework in which agents choose their forecasting models based on the relative forecasting performance. Investigating the emergence of the leader-follower relationship is a theoretically important topic of study. Another issue worth examining is the E-stability of the REE in an environment in which the central bank introduces an optimal monetary policy rule. Evans and Honkapohja [2003b] reveal that the expectations-based optimal discretionary rule satisfies the E-stability of the REE though the fundamentals-based optimal discretionary rule does not. However, they assume that the central bank and private agents follow homogeneous learning. It is of interest to examine whether the expectations-based rule satisfies the E-stability of the REE even when private agents engage in adaptive learning by referring to the central bank's forecast.

Another issue worth considering is to determine some other policy strategies that robustly satisfy both the determinacy and the E-stability of the REE. In Chapter 4, we have recommended the central bank to respond to the current inflation rate to a certain degree. However, this might not be a unique solution. Bullard and Mitra [2007] demonstrate that, a case where the central bank and private agents are homogeneously learning, interest rate smoothing is effective to ensure the determinacy without violating the E-stability. While considering this result, we should examine whether interest rate smoothing is effective, even when there is a leader-follower relationship of adaptive learning between the central bank and private agents.

Although the abovementioned issues remain unresolved, we believe that this thesis contributes to acquiring a better understanding of inflation dynamics and deriving some insightful implications for monetary policy-making. In particular, in Chapters 3 and 4, the same policy implication is obtained, that is, the central bank's strong reaction to the current inflation rate performs robustly even when the central bank or private agents have some misperceptions with respect to exogenous shocks or economic structures. The reason for obtaining this result is explained by the fact that these misperceptions yield (i) private agents' forecast errors regarding the output gap and inflation rate or (ii) the central bank's control errors with respect to policy instruments, both of which constitute the source of demand shocks.

We believe that this nature is considerably robust in various versions of the New Keynesian models.

We conjecture that some future extensions of the New Keynesian models incorporate some frictions other than price stickiness, such as, labor market frictions or financial market frictions. These extensions will determine the trade-offs between the inflation rate and other variables. Such possible trade-offs imply that the central bank should strike a balance among multiple policy objectives. However, the analysis conducted in this thesis indicates that the central bank should be inclined to stabilize the inflation rate, particularly in an environment where the uncertainty of future economy is considerably large. This is because such an inclination is desirable from the viewpoint of the robustness of monetary policy-making. This provides, not only, but at least one important rationale for the central bank to pursue price stability.

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Tables

	VAR specifications		
	$\begin{bmatrix} lnS_t \end{bmatrix}$	$\begin{bmatrix} lnS_t \\ \Delta ULC_t \end{bmatrix}$	$\begin{bmatrix} lnS_t \\ \pi_t \end{bmatrix}$
a_0	0.186	0.317	0.240
t-value	(4.42)	(3.87)	(5.79)
a_1	0.004	0.008	0.006
t-value	(4.33)	(3.82)	(5.70)
$Adj\text{-}R^2$	0.130	0.103	0.209
D.W.	*0.823*	*0.828*	*0.861*
VAR lags	2	1	2

Note: The dependent variable is the GDP deflator (non-annualized). The estimation method is OLS. The sample period is 1975/Q1-2004/Q4. VAR lags are chosen by Schwarz's information criterion.

Table 2.1: Benchmark NKPC

	VAR specifications		
	$\begin{pmatrix} lnS_t \\ EDI_t \end{pmatrix}$	$\begin{pmatrix} lnS_t \\ EDI_t \\ \Delta ULC_t \end{pmatrix}$	$\begin{pmatrix} lnS_t \\ EDI_t \\ \pi_t \end{pmatrix}$
b_0	0.382	0.373	0.456
t-value	(5.83)	(5.71)	(6.87)
b_1	0.009	0.009	0.011
t-value	(5.78)	(5.66)	(6.82)
b_2	-0.008	-0.008	-0.014
t-value	(-0.52)	(-0.57)	(-0.99)
b_3	-0.016	-0.016	-0.017
t-value	(-2.58)	(-2.56)	(-2.98)
ρ	0.939	0.941	0.940
t-value	(11.83)	(11.78)	(13.75)
$Adj\text{-}R^2$	0.328	0.319	0.391
D.W.	1.492	1.480	1.547
VAR lags	2	2	2

Note: The dependent variable is the GDP deflator (non-annualized). The estimation method is NLS. The sample period is 1977/Q3-2004/Q4. VAR lags are chosen by Schwarz's information criterion.

Table 2.2: NKPC with Labor Market Frictions

ε_m	0.395
t-value	(6.36)
const	-0.008
t-value	(-2.91)
trend	0.000
t-value	(1.95)
R^2	0.257
D.W.	2.311

Note: The dependent variable is $\ln(M_t/Q_t)-\ln(M_{t-1}/Q_{t-1})$. The explanatory variables are $\ln(Q_t)-\ln(Q_{t-1})$, constant, and time-trend. The estimation method is OLS. The sample period is 1975/Q1-2004/Q4.

Table 2.3: Elasticity of Materials/Output Ratio to the Level of Output

	VAR specifications		
	$\begin{pmatrix} \ln(S_t+\zeta_t) \\ EDI_t \end{pmatrix}$	$\begin{pmatrix} \ln(S_t+\zeta_t) \\ EDI_t \\ \Delta ULC_t \end{pmatrix}$	$\begin{pmatrix} \ln(S_t+\zeta_t) \\ EDI_t \\ \pi_t \end{pmatrix}$
c_0	0.084	0.081	0.086
t-value	(9.28)	(9.04)	(9.33)
c_1	0.003	0.003	0.004
t-value	(8.97)	(8.72)	(9.02)
c_2	0.008	0.008	0.007
t-value	(0.60)	(0.56)	(0.55)
c_3	-0.013	-0.013	-0.013
t-value	(-2.44)	(-2.44)	(-2.46)
ρ	0.958	0.961	0.961
t-value	(11.54)	(11.62)	(11.72)
$Adj\text{-}R^2$	0.490	0.477	0.494
D.W.	*1.870*	*1.835*	*1.857*
VAR lags	2	2	2

Note: The dependent variable is the GDP deflator (non-annualized). The estimation method is NLS. The sample period is 1977/Q3-2004/Q4. VAR lags are chosen by Schwarz's information criterion.

Table 2.4: NKPC with Labor Market Frictions and Materials Prices

	VAR specifications		
	$\begin{bmatrix} lnS_t \end{bmatrix}$	$\begin{pmatrix} lnS_t \\ \Delta ULC_t \end{pmatrix}$	$\begin{pmatrix} lnS_t \\ \pi_t \end{pmatrix}$
a_0	0.082	0.129	0.124
t-value	(2.12)	(1.75)	(3.02)
a_1	0.002	0.003	0.003
t-value	(2.09)	(1.73)	(2.98)
inflation lag	0.506	0.520	0.461
t-value	(6.82)	(7.06)	(6.10)
Adj-R^2	0.372	0.365	0.395
D.W.	*2.128*	*2.155*	*2.057*
VAR lags	2	1	2

Note: The dependent variable is the GDP deflator (non-annualized). The estimation method is OLS. The sample period is 1975/Q1-2004/Q4. VAR lags are chosen by Schwarz's information criterion.

Table 2.5: Benchmark NKPC with Inflation Lag

	VAR specifications		
	$\begin{pmatrix} lnS_t \\ EDI_t \end{pmatrix}$	$\begin{pmatrix} lnS_t \\ EDI_t \\ \Delta ULC_t \end{pmatrix}$	$\begin{pmatrix} lnS_t \\ EDI_t \\ \pi_t \end{pmatrix}$
b_0	0.251	0.241	0.332
t-value	(3.67)	(3.56)	(4.53)
b_1	0.006	0.006	0.008
t-value	(3.64)	(3.53)	(4.50)
b_2	0.001	0.001	-0.005
t-value	(0.10)	(0.09)	(-0.35)
b_3	-0.014	-0.014	-0.016
t-value	(-2.21)	(-2.18)	(-2.61)
ρ	0.908	0.908	0.923
t-value	(9.23)	(9.13)	(11.49)
inflation lag	0.305	0.313	0.241
t-value	(3.41)	(3.50)	(2.73)
Adj-R^2	0.389	0.384	0.424
D.W.	2.257	2.260	2.143
VAR lags	2	2	2

Note: The dependent variable is the GDP deflator (non-annualized). The estimation method is NLS. The sample period is 1977/Q3-2004/Q4. VAR lags are chosen by Schwarz's information criterion.

Table 2.6: NKPC with Labor Market Frictions and Inflation Lag

	VAR specifications		
	$\begin{pmatrix} ln(S_t+\zeta_t) \\ EDI_t \end{pmatrix}$	$\begin{pmatrix} ln(S_t+\zeta_t) \\ EDI_t \\ \Delta ULC_t \end{pmatrix}$	$\begin{pmatrix} ln(S_t+\zeta_t) \\ EDI_t \\ \pi_t \end{pmatrix}$
c_0	0.076	0.071	0.078
t-value	(6.14)	(5.91)	(6.20)
c_1	0.003	0.003	0.003
t-value	(6.01)	(5.78)	(6.07)
c_2	0.009	0.009	0.009
t-value	(0.69)	(0.68)	(0.64)
c_3	-0.013	-0.013	-0.013
t-value	(-2.29)	(-2.26)	(-2.31)
ρ	0.944	0.944	0.948
t-value	(10.36)	(10.21)	(10.54)
inflation lag	0.088	0.108	0.087
t-value	(0.92)	(1.13)	(0.92)
$Adj\text{-}R^2$	0.489	0.478	0.493
D.W.	*2.070*	*2.081*	*2.057*
VAR lags	2	2	2

Note: The dependent variable is the GDP deflator (non-annualized). The estimation method is NLS. The sample period is 1977/Q3-2004/Q4. VAR lags are chosen by Schwarz's information criterion.

Table 2.7: NKPC with Labor Market Frictions, Materials Prices, and Inflation Lag

	VAR specifications		
	$\begin{pmatrix} lnS_t \\ EDI_t \end{pmatrix}$	$\begin{pmatrix} lnS_t \\ EDI_t \\ \Delta ULC_t \end{pmatrix}$	$\begin{pmatrix} lnS_t \\ EDI_t \\ \pi_t \end{pmatrix}$
d_0	0.664	0.669	0.860
t-value	(7.53)	(7.84)	(10.22)
d_1	0.016	0.016	0.020
t-value	(7.48)	(7.79)	(10.17)
d_2	0.000	0.006	0.012
t-value	(-0.02)	(0.32)	(0.72)
d_3	-0.018	-0.021	-0.026
t-value	(-2.83)	(-3.15)	(-4.35)
ξ	0.909	0.878	0.851
t-value	(12.48)	(12.77)	(16.59)
$Adj\text{-}R^2$	0.287	0.302	0.427
D.W.	1.463	1.487	1.534
VAR lags	2	2	2

Note: The dependent variable is the GDP deflator (non-annualized). The estimation method is NLS. The sample period is 1977/Q3-2004/Q4. VAR lags are chosen by Schwarz's information criterion.

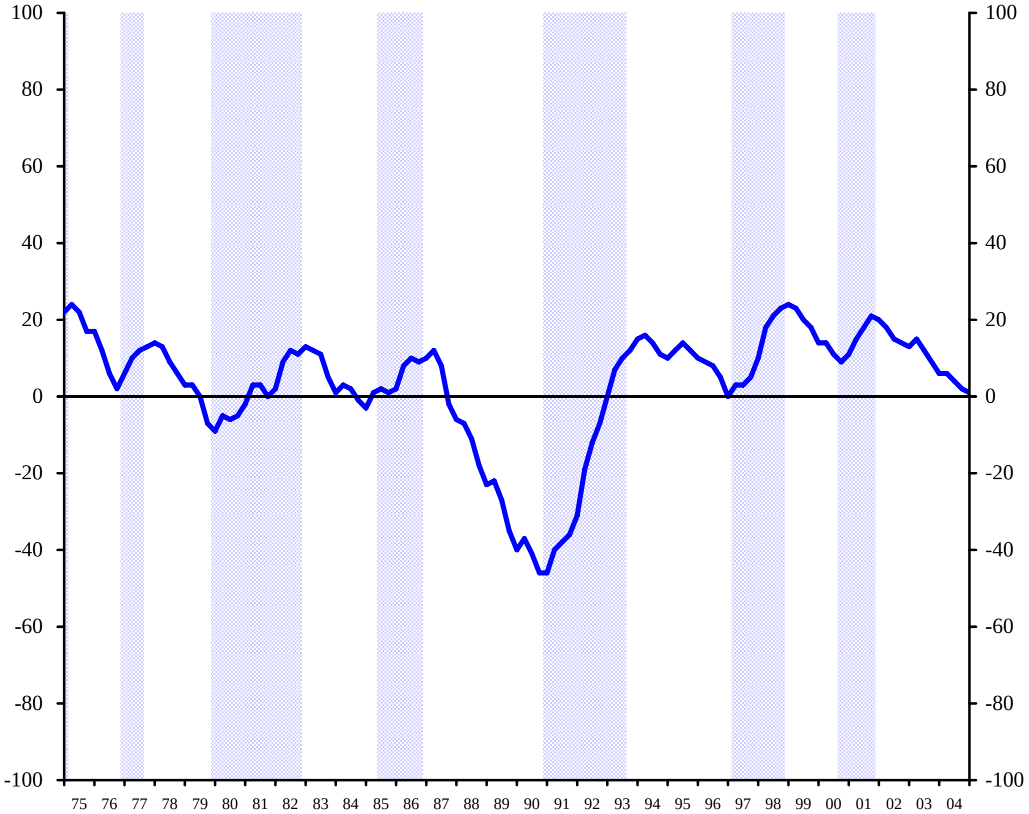
Table 2.8: NKPC with Labor Market Frictions
(With Model of Staggered Real Wage Setting)

	VAR specifications		
	$\begin{pmatrix} lnS_t \\ EDI_t \end{pmatrix}$	$\begin{pmatrix} lnS_t \\ EDI_t \\ \Delta ULC_t \end{pmatrix}$	$\begin{pmatrix} lnS_t \\ EDI_t \\ \pi_t \end{pmatrix}$
d_0	0.480	0.492	0.719
t-value	(4.88)	(5.11)	(7.31)
d_1	0.011	0.012	0.017
t-value	(4.86)	(5.09)	(7.29)
d_2	0.006	0.011	0.016
t-value	(0.35)	(0.61)	(0.97)
d_3	-0.018	-0.020	-0.026
t-value	(-2.72)	(-3.00)	(-4.25)
ξ	0.906	0.880	0.854
t-value	(11.93)	(12.21)	(16.23)
inflation lag	0.319	0.308	0.217
t-value	(3.64)	(3.52)	(2.60)
Adj-R^2	0.360	0.369	0.456
D.W.	2.232	2.231	2.066
VAR lags	2	2	2

Note: The dependent variable is the GDP deflator (non-annualized). The estimation method is NLS. The sample period is 1977/Q3-2004/Q4. VAR lags are chosen by Schwarz's information criterion.

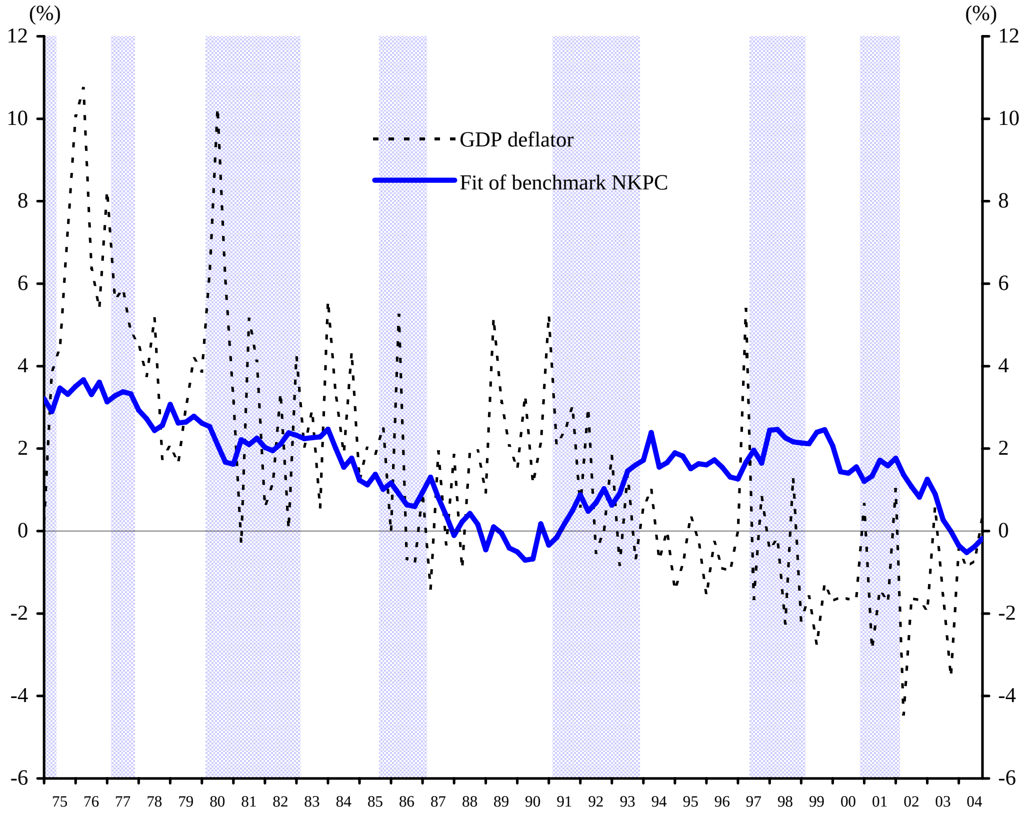
Table 2.9: NKPC with Labor Market Frictions and Inflation Lag
(With Model of Staggered Real Wage Setting)

Figures



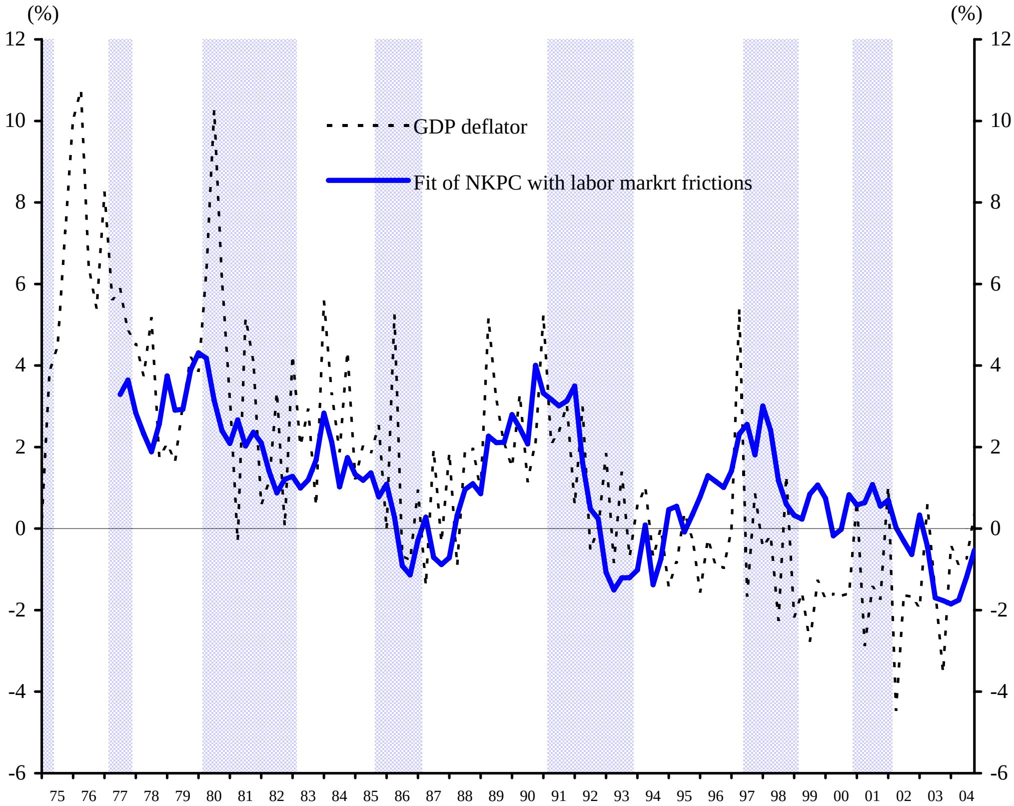
Note: The figure shows the employment DI in the Bank of Japan's *Tankan* survey.
Shaded areas indicate recession dates.

Figure 2.1: Labor Gap in Japan



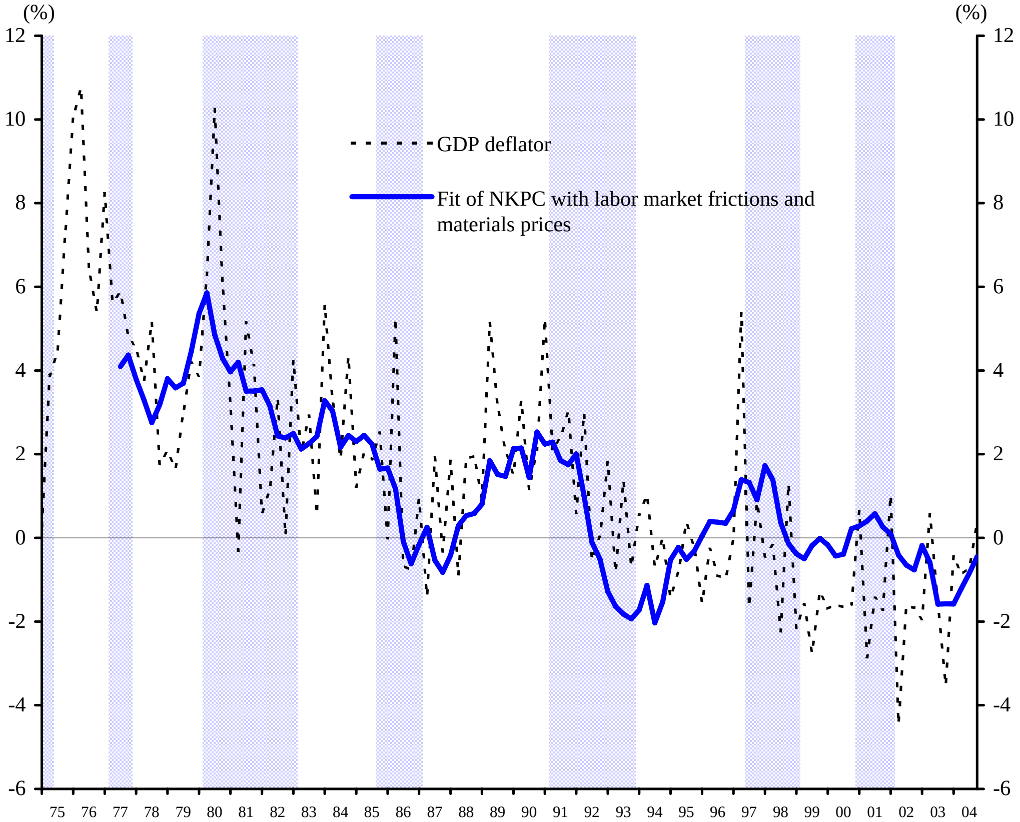
Note: The NKPC is based on the auxiliary VAR that includes only lnS_t.

Figure 2.2: Benchmark NKPC



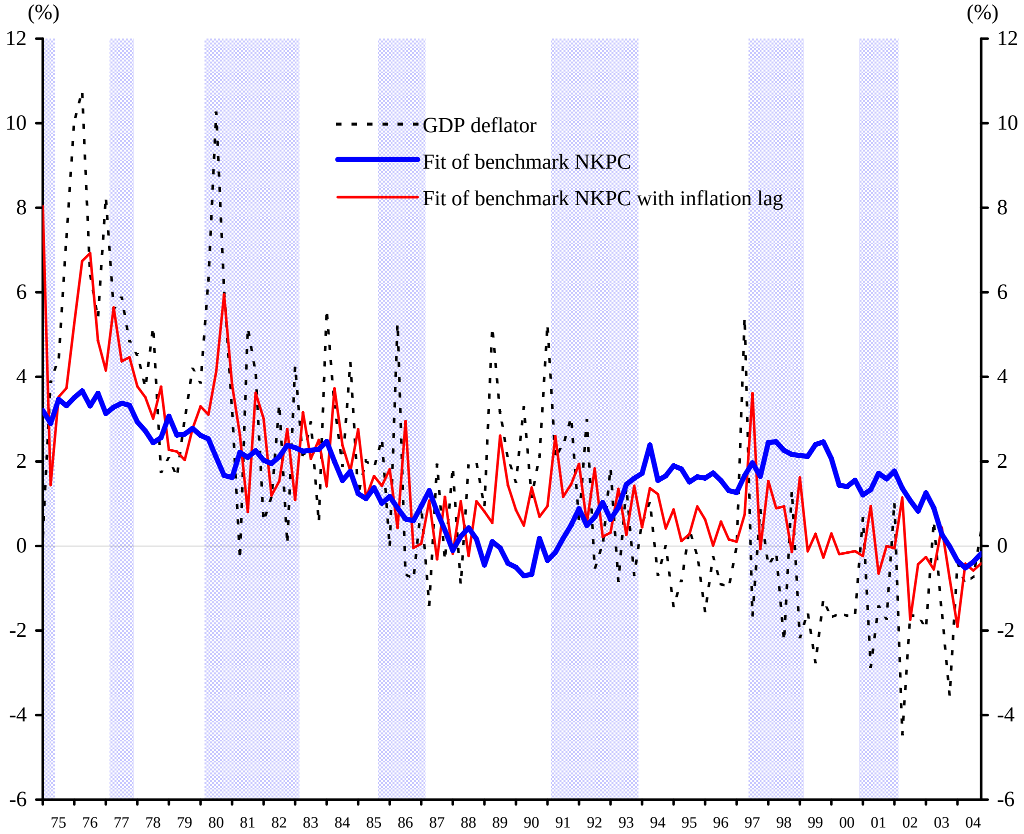
Note: The NKPC is based on the auxiliary VAR that includes lnS_t and EDI_t.

Figure 2.3: NKPC with Labor Maket Frictions



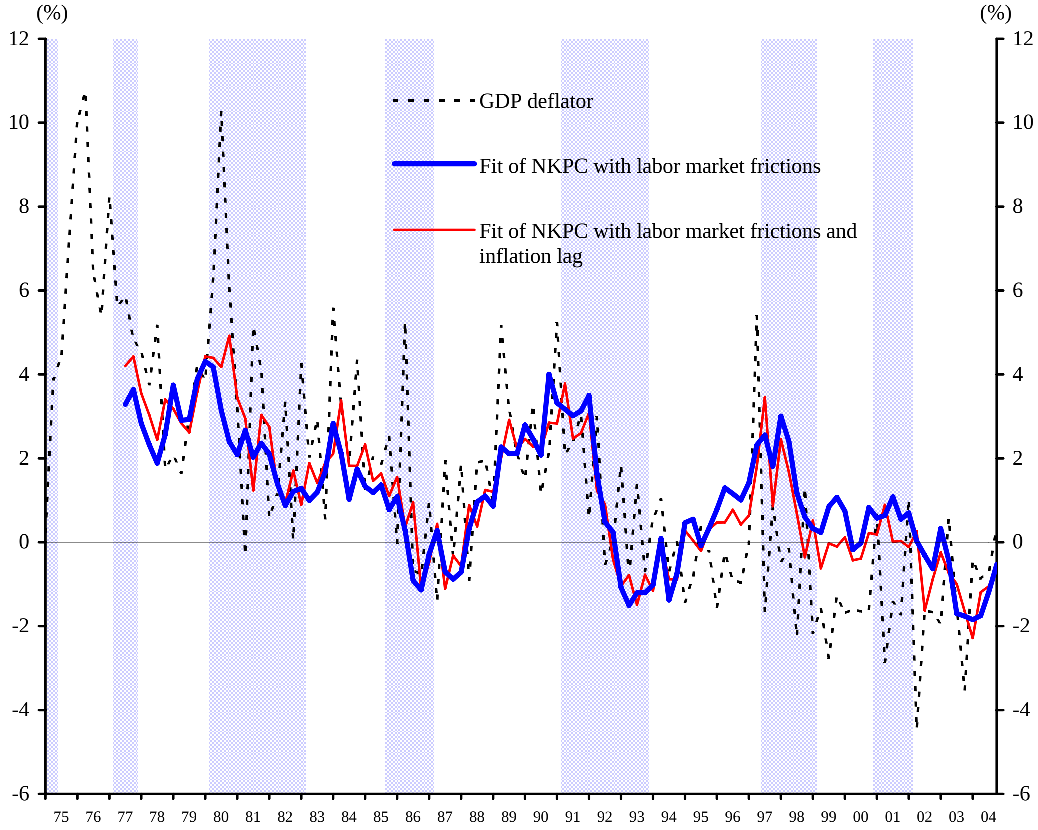
Note: The NKPC is based on the auxiliary VAR that includes $ln\,(S_t + \zeta_t)$ and EDI_t.

Figure 2.4: NKPC with Labor Market Frictions and Materials Prices



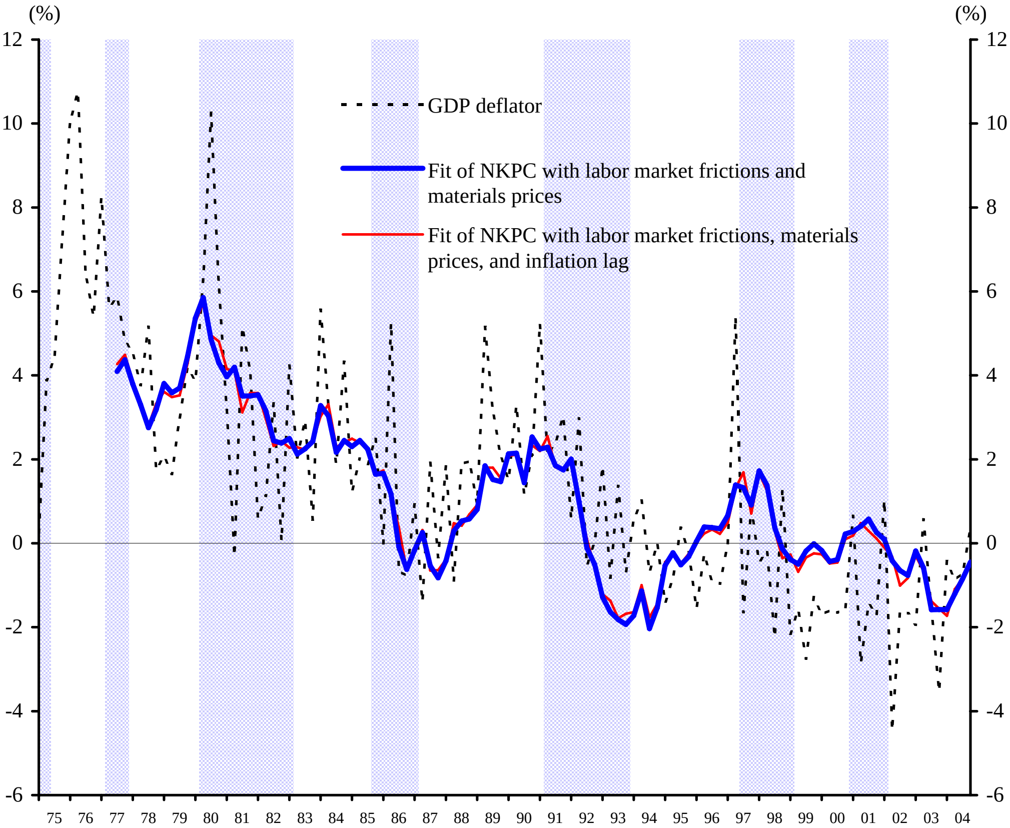
Note: The NKPC is based on the auxiliary VAR that includes only lnS_t.

Figure 2.5: Benchmark NKPC with Inflation Lag



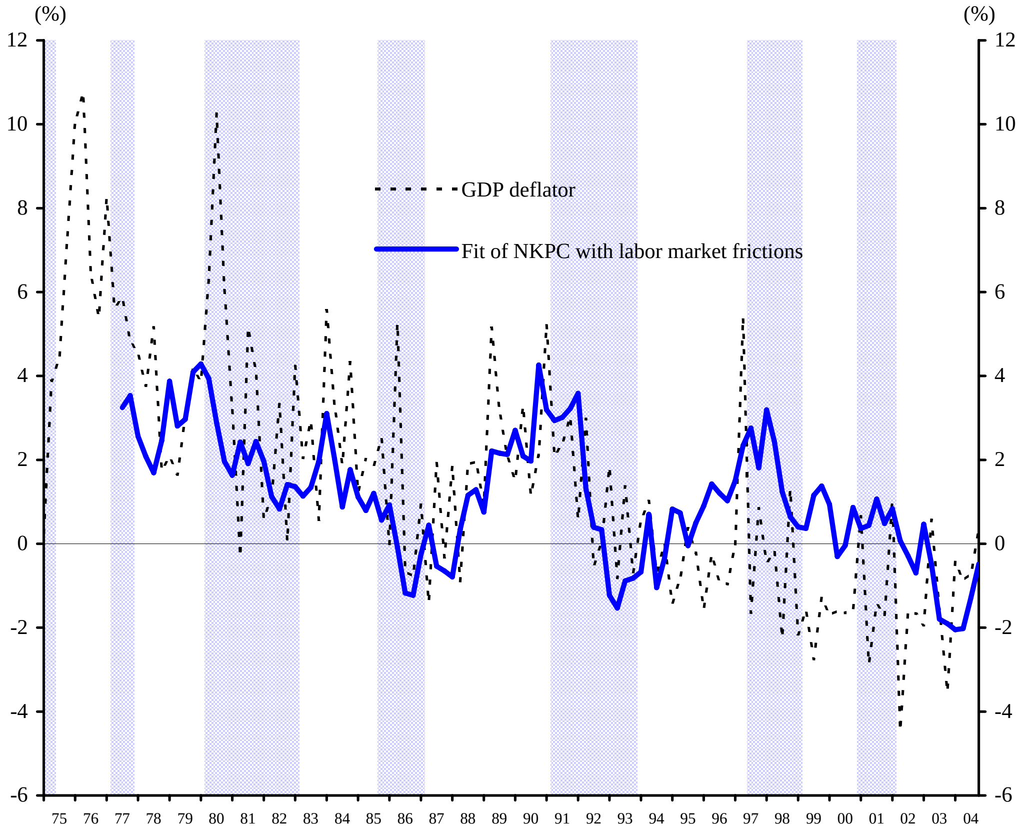
Note: The NKPC is based on the auxiliary VAR that includes $ln\,S_t$ and EDI_t.

Figure 2.6: NKPC with Labor Market Frictions and Inflation Lag



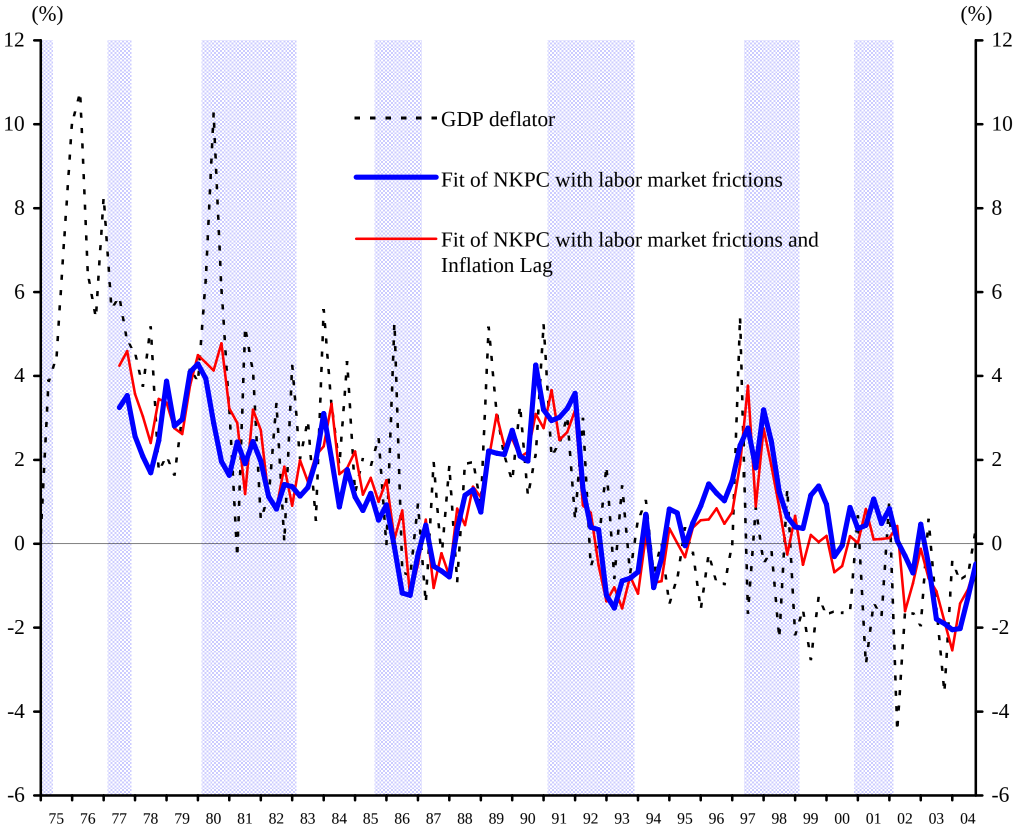
Note: The NKPC is based on the auxiliary VAR that includes $ln\,(S_t+\zeta_t)$ and EDI_t.

Figure 2.7: NKPC with Labor Market Frictions, Materials Prices, and Inflation Lag



Note: The NKPC is based on the auxiliary VAR that includes $ln(S_t)$ and EDI_t.

Figure 2.8: NKPC with Labor Market Frictions
(With Model of Staggered Real Wage Setting)



Note: The NKPC is based on the auxiliary VAR that includes $ln(S_t)$ and EDI_t.

Figure 2.9: NKPC with Labor Market Frictions and Inflation Lag
(With Model of Staggered Real Wage Setting)

Note: "Forecast by the FRB" denotes the Greenbook projections of the Board of Governors of the Federal Reserve System. "Forecast by economists in the private sector" is the Survey of Professional Forecasters released by the Federal Reserve Bank of Philadelphia. Each series indicates one-year-ahead forecasts made at the beginning of each year (January or February).

Figure 3.1: Forecasts for Output Growth in the U.S. Economy

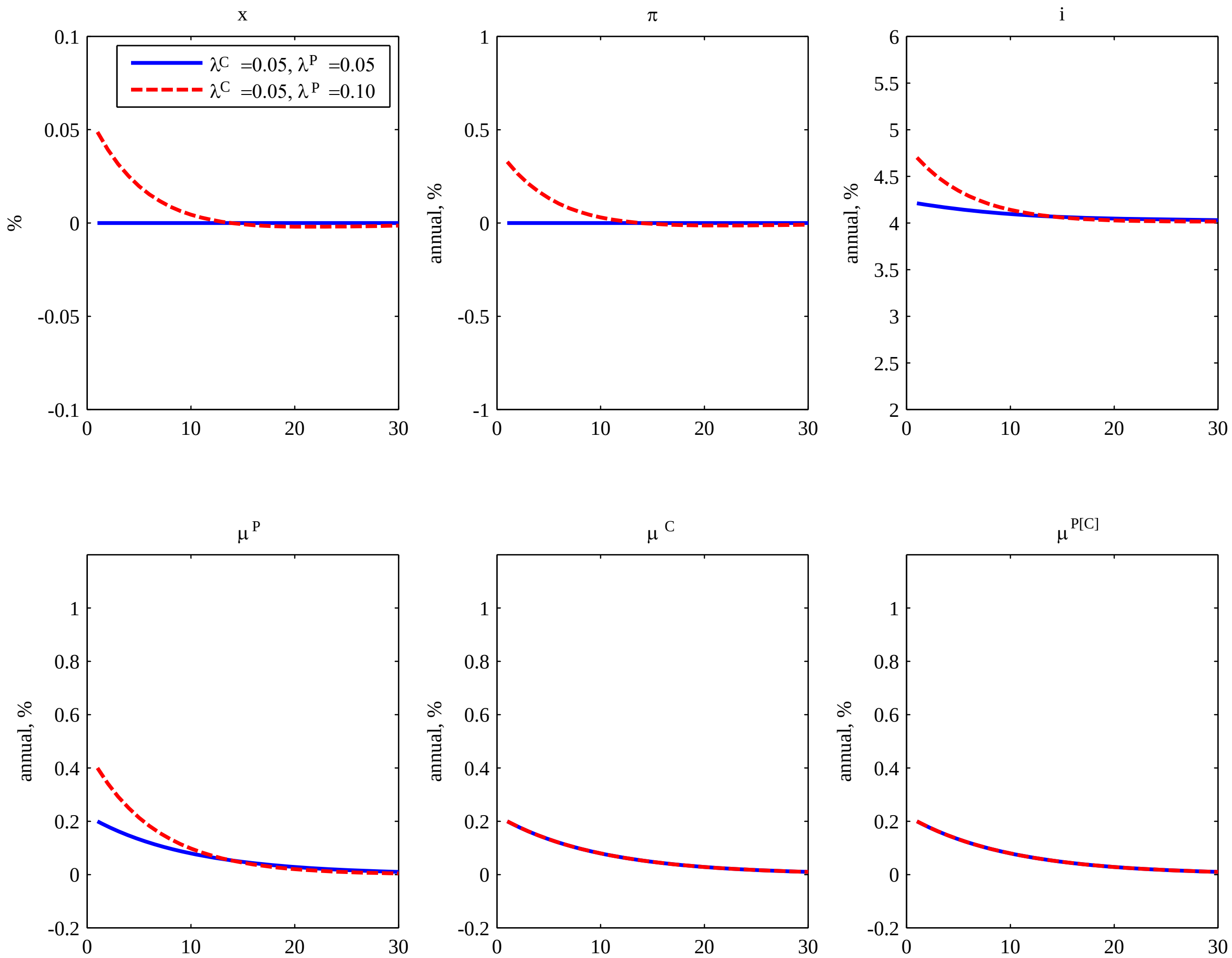


Figure 3.2: Response to a Transitory Productivity Shock in a Transparent Regime

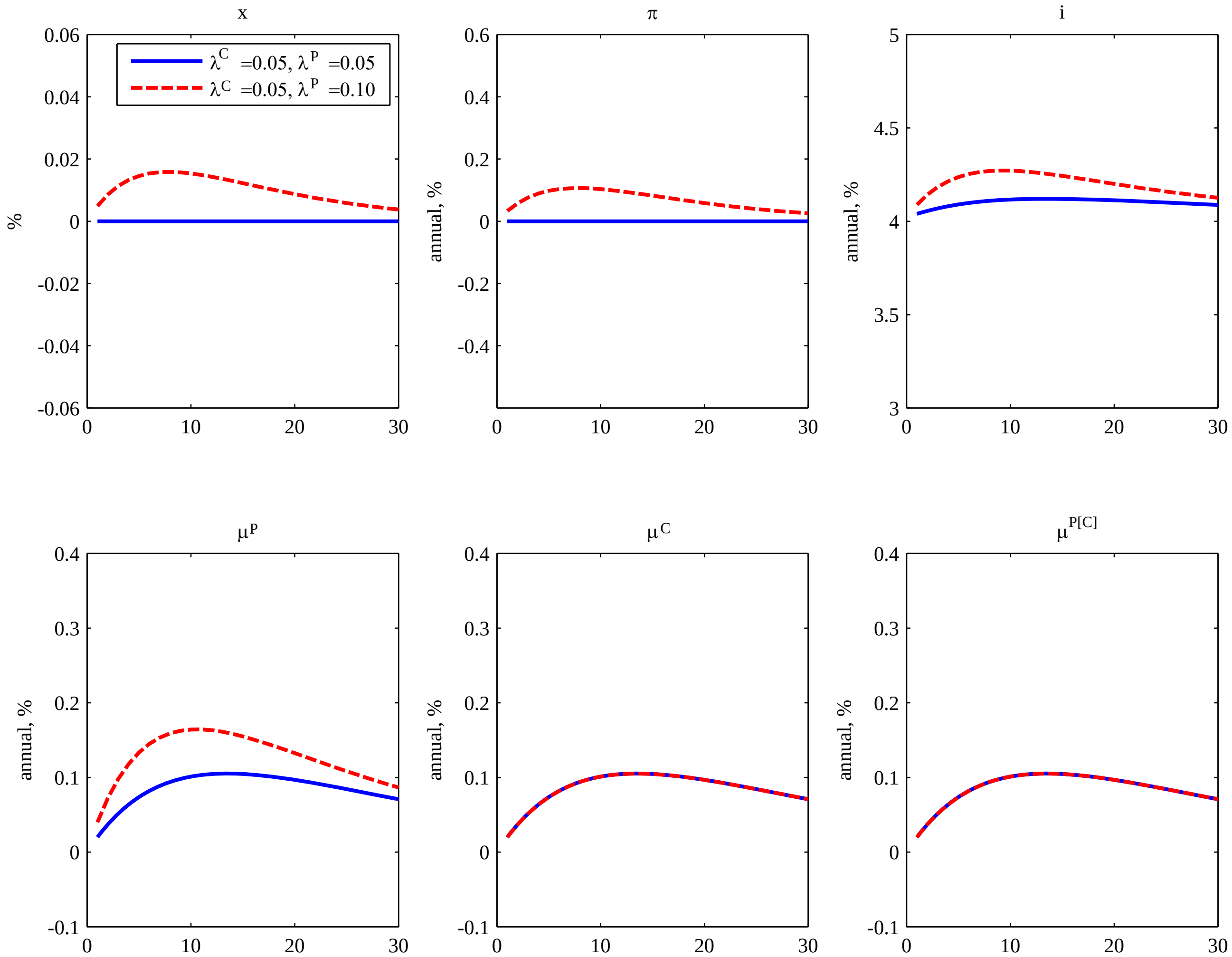


Figure 3.3: Response to a Persistent Productivity Shock in a Transparent Regime

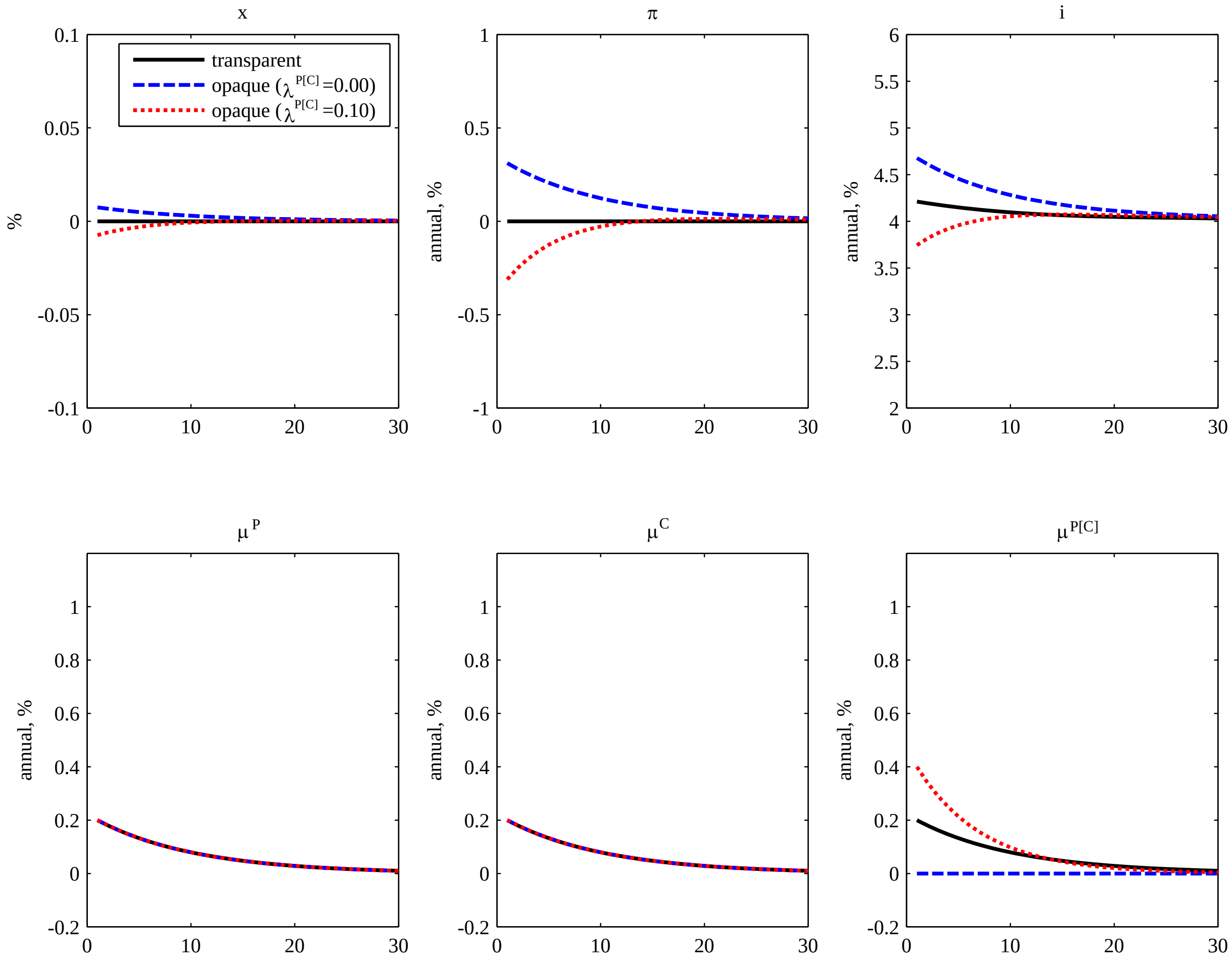


Figure 3.4: Response to a Transitory Productivity Shock in an Opaque Regime (λ^C=0.05, λ^P =0.05)

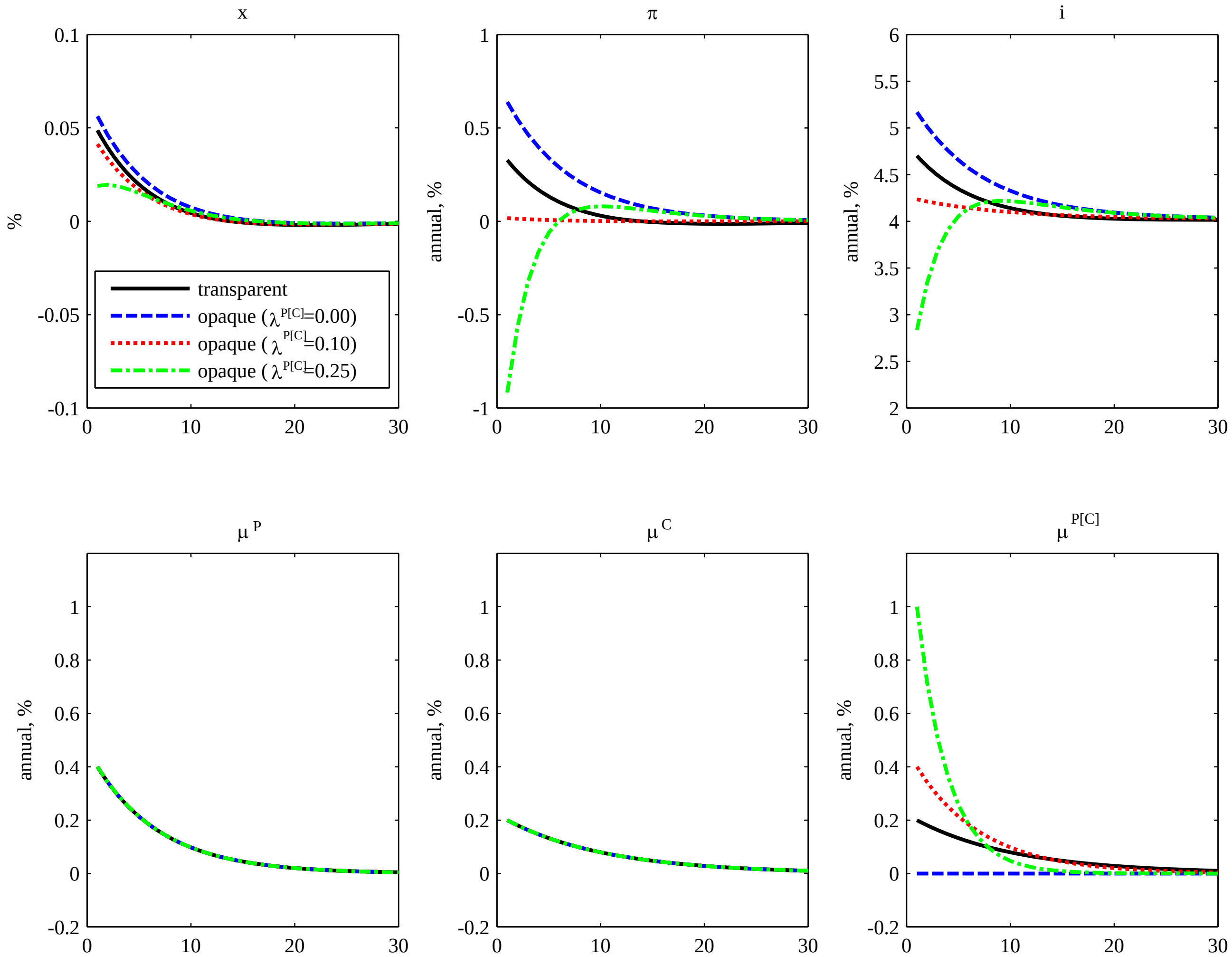
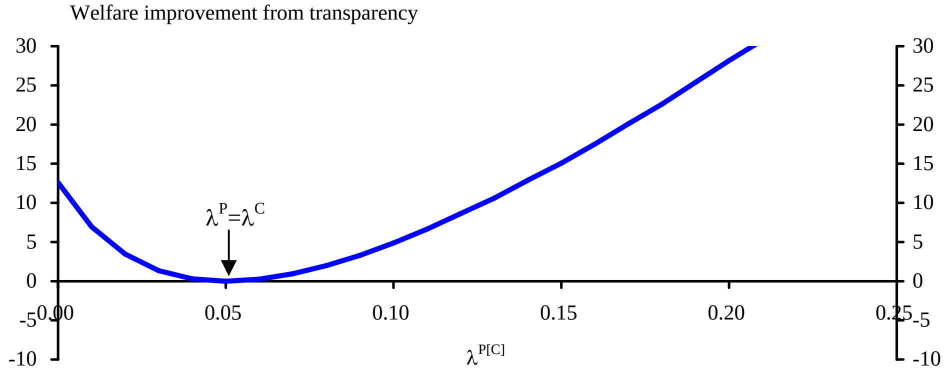
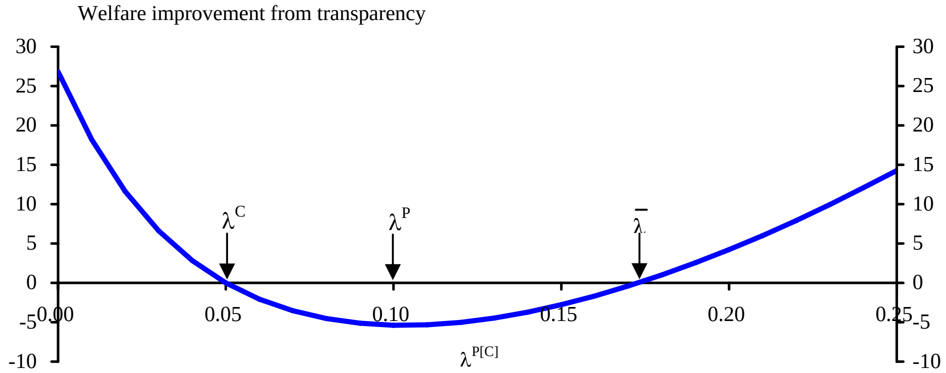


Figure 3.5: Response to a Transitory Productivity Shock in an Opaque Regime (λ^C=0.05,λ^P =0.10).

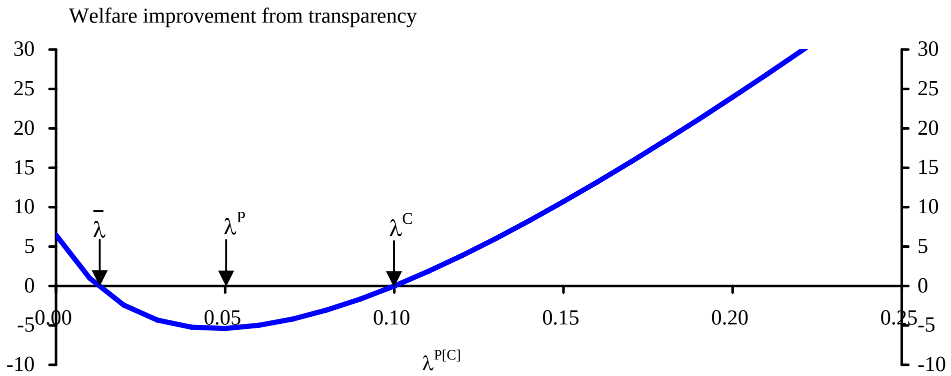
1. $\lambda^C=0.05$, $\lambda^P=0.05$



2. $\lambda^C=0.05$, $\lambda^P=0.10$

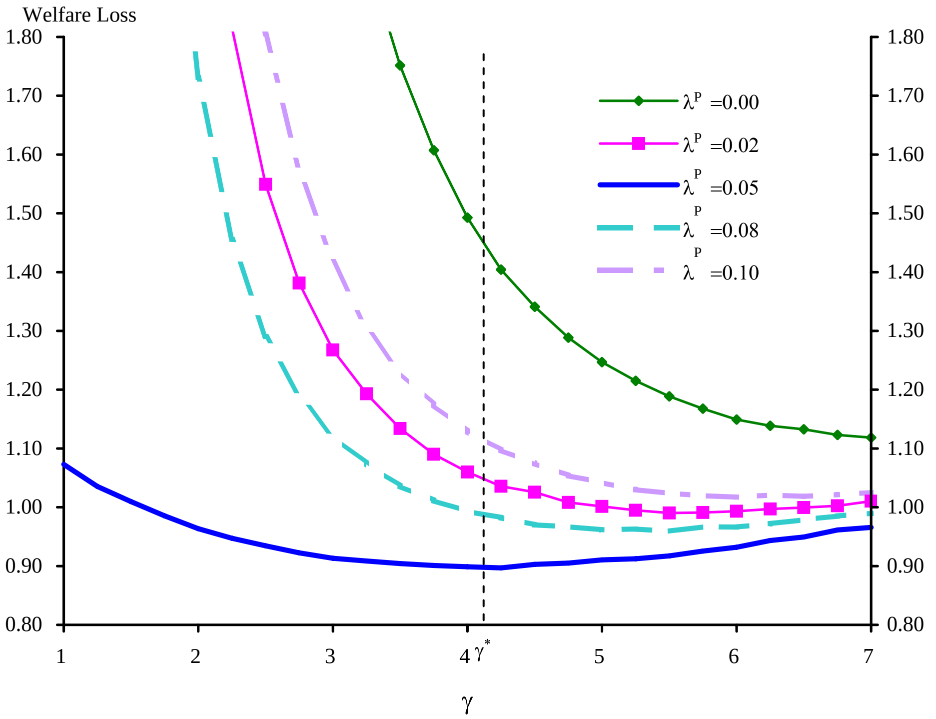


3. $\lambda^C=0.10$, $\lambda^P=0.05$



Note: "Welfare improvement from transparency" shows the deviation of social welfare loss in opaque regime from social welfare loss in transparent regime.

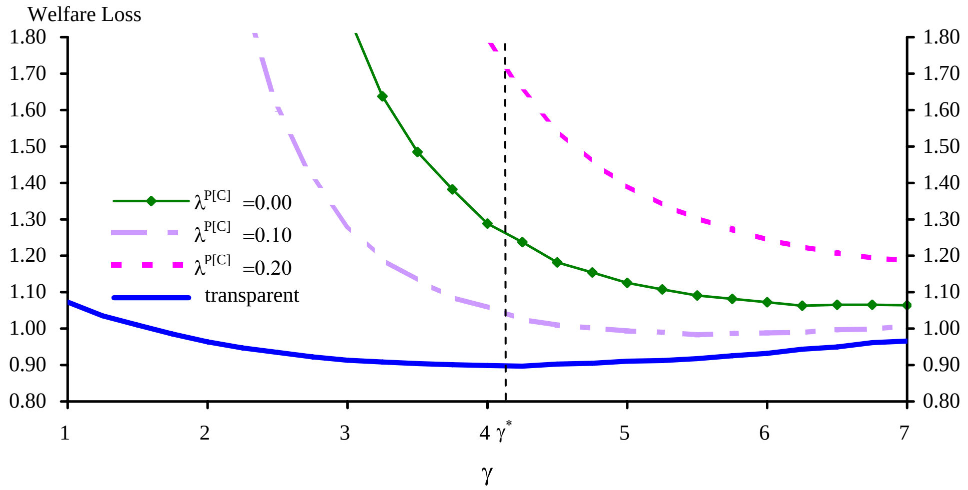
Figure 3.6: Impact of Transparency



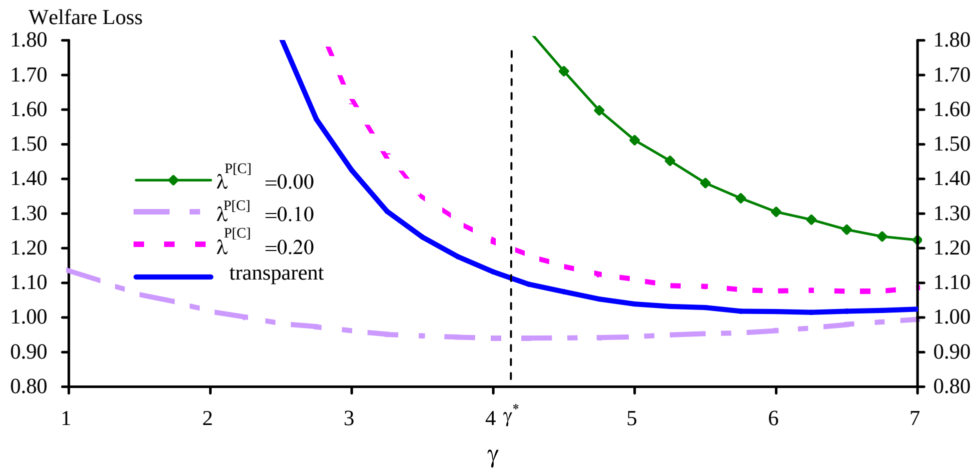
Note: λ^C=$\lambda^{P[C]}$=0.05 in all cases.

Figure 3.7: Social Welfare in Transparent Regime

1. $\lambda^{C}=0.05$, $\lambda^{P}=0.05$



2. $\lambda^{C}=0.05$, $\lambda^{P}=0.10$



3. $\lambda^{C}=0.10$, $\lambda^{P}=0.05$

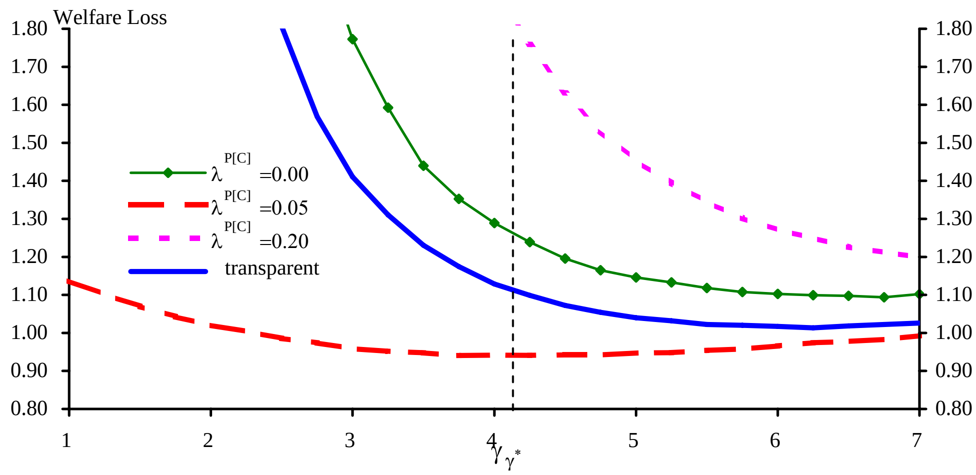
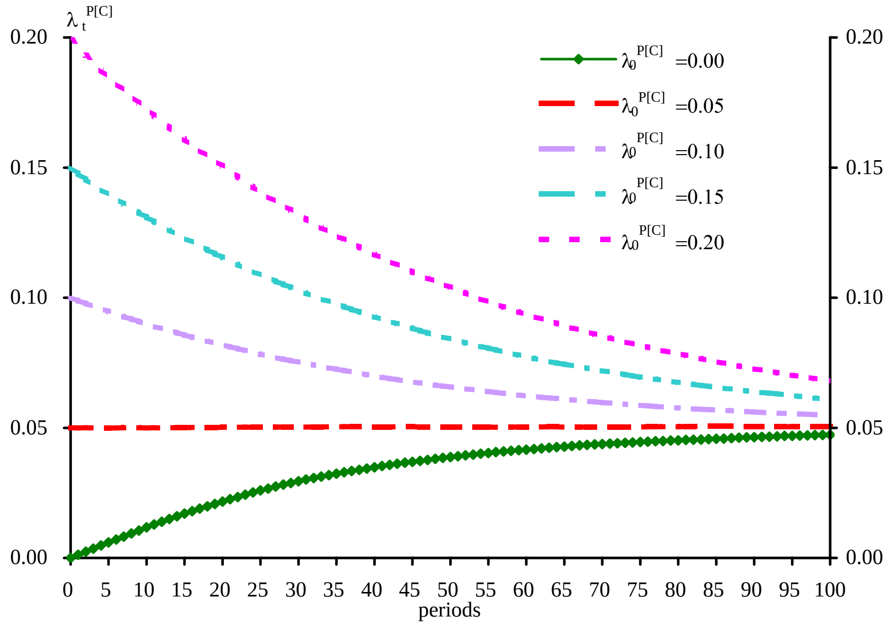


Figure 3.8: Social Welfare in an Opaque Regime

1. ω^P=0.025



2. ω^P=0.10

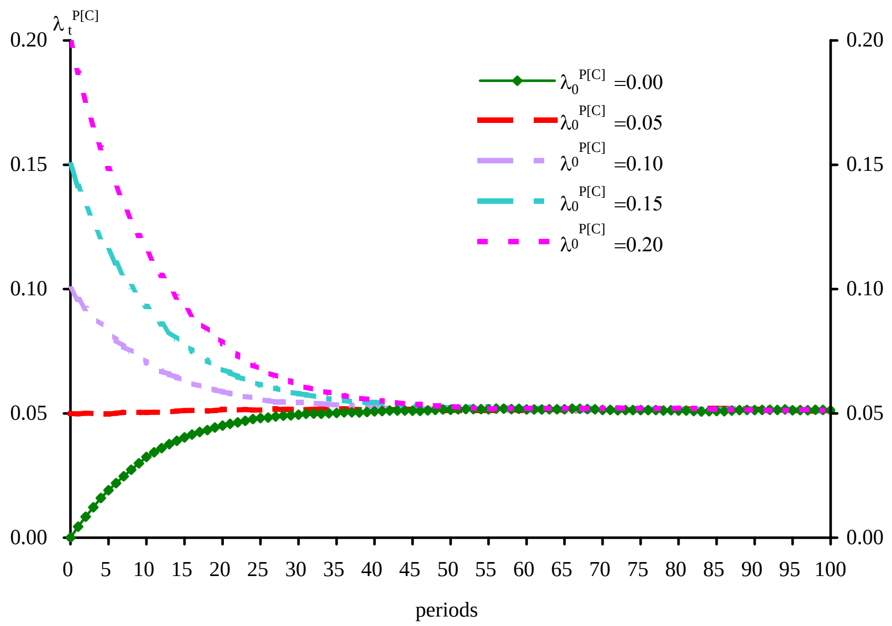
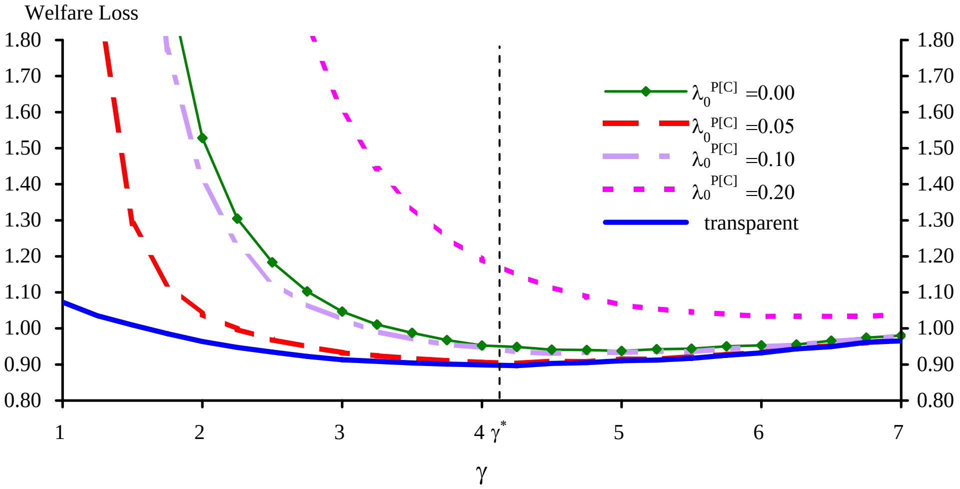
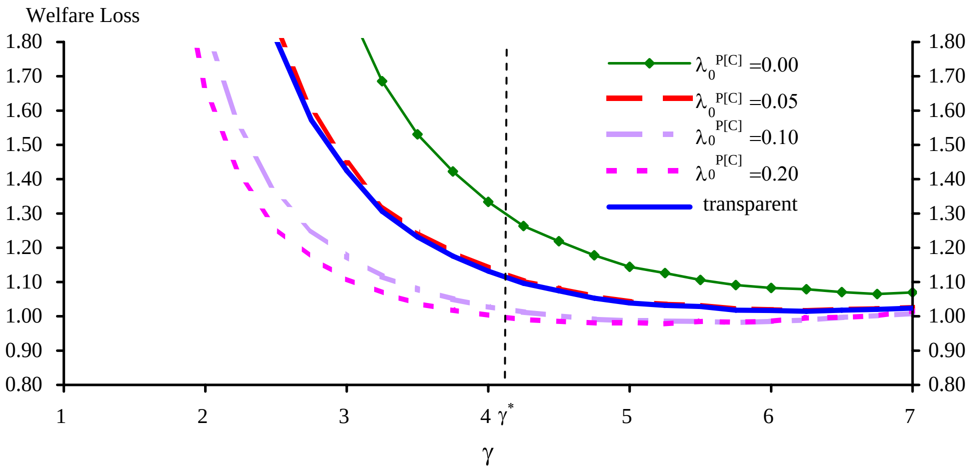


Figure 3.9: Speed of Convergence of $\lambda_t^{P[C]}$

1. $\lambda^{C}=0.05$, $\lambda^{P}=0.05$



2. $\lambda^{C}=0.05$, $\lambda^{P}=0.10$



3. $\lambda^{C}=0.10$, $\lambda^{P}=0.05$

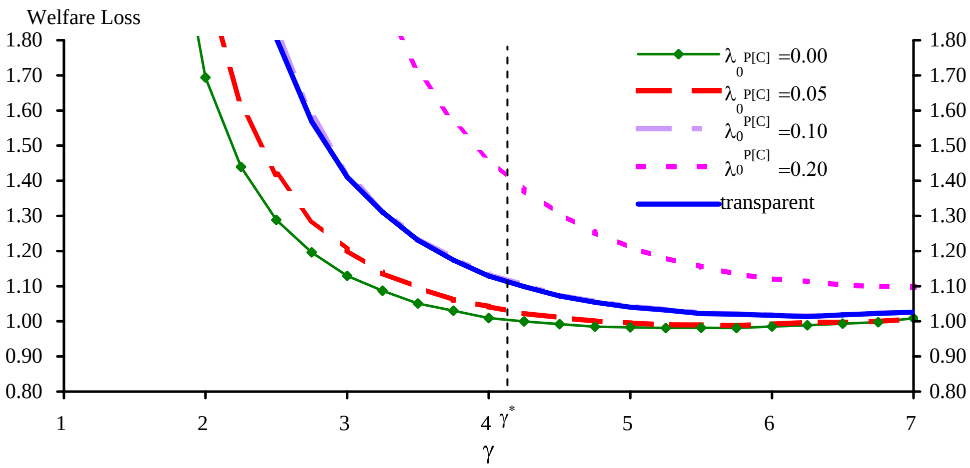
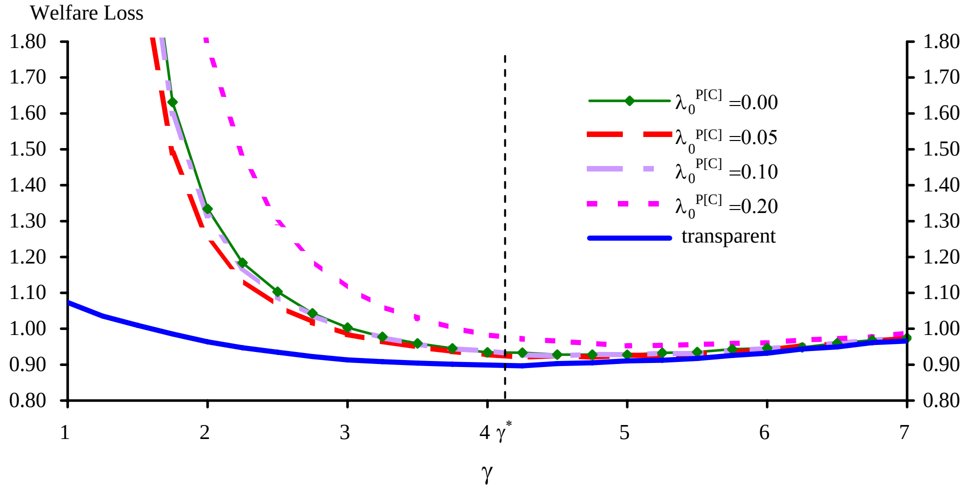
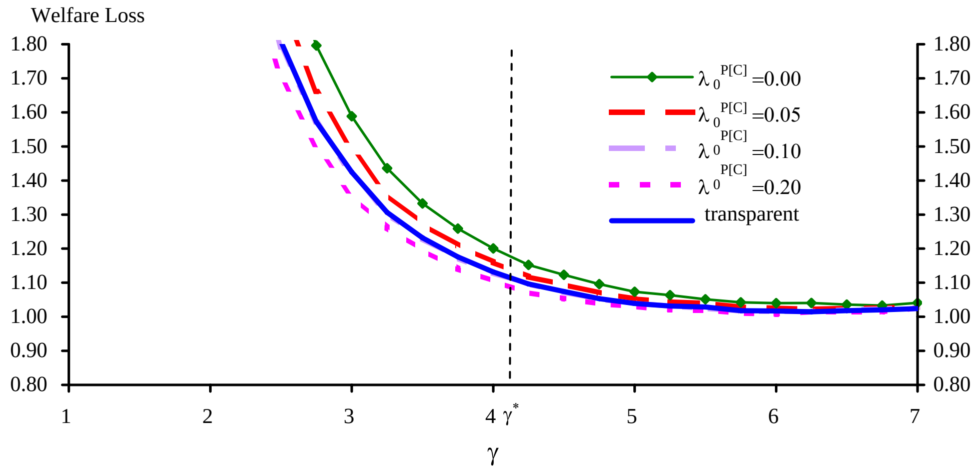


Figure 3.10: Social Welfare When Private Agents Learn About λ^{C} ($\omega^{P}=0.025$)

1. $\lambda^C=0.05, \lambda^P=0.05$



2. $\lambda^C=0.05, \lambda^P=0.10$



3. $\lambda^C=0.10, \lambda^P=0.05$

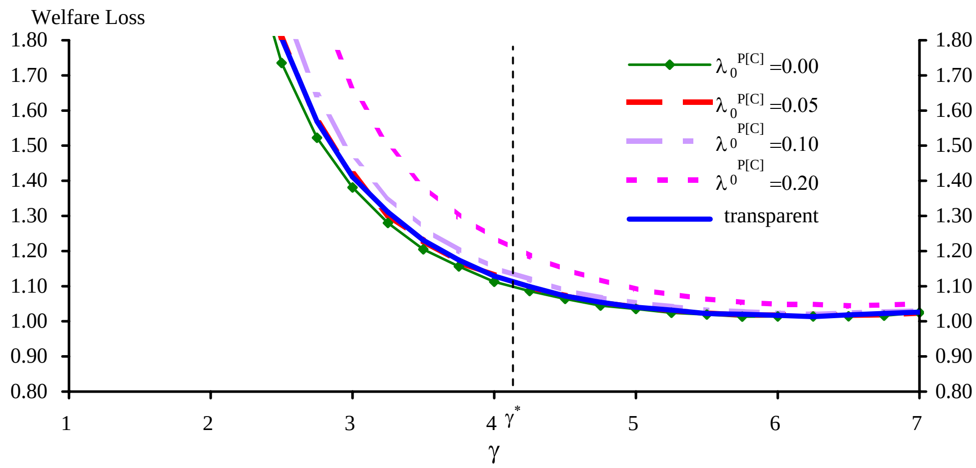


Figure 3.11: Social Welfare When Private Agents Learn About λ^C ($\omega^P=0.10$)