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Daisuke Ikeda and Takushi Kurozumi

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Post-Crisis Slow Recovery and Monetary Policy

Daisuke Ikeda* and Takushi Kurozumi**

Abstract

In the aftermath of the recent financial crisis and subsequent recession, slow recoveries have been observed and slowdowns in total factor productivity (TFP) growth have been measured in many economies. This paper develops a model that can describe a slow recovery resulting from an adverse financial shock in the presence of an endogenous mechanism of TFP growth, and examines how monetary policy should react to the financial shock in terms of social welfare. It is shown that in the face of the financial shocks, a welfare-maximizing monetary policy rule features a strong response to output, and the welfare gain from output stabilization is much more substantial than in the model where TFP growth is exogenously given. Moreover, compared with the welfare-maximizing rule, a strict inflation or price-level targeting rule induces a sizable welfare loss because it has no response to output, whereas a nominal GDP growth or level targeting rule performs well, although it causes high interest-rate volatility. In the presence of the endogenous TFP growth mechanism, it is crucial to take into account a welfare loss from a permanent decline in consumption caused by a slowdown in TFP growth.

Keywords: Financial shock; Endogenous TFP growth; Slow recovery; Monetary policy; Welfare cost of business cycle

JEL classification: E52, O33

*Director and Senior Economist, Institute for Monetary and Economic Studies, Bank of Japan (E-mail: daisuke.ikeda@boj.or.jp)

**Director and Senior Economist, Institute for Monetary and Economic Studies, Bank of Japan (E-mail: takushi.kurozumi@boj.or.jp)

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1 Introduction

In the aftermath of the recent financial crisis and subsequent recession, slow recoveries have been observed in many economies. GDP has not recovered to its pre-crisis growth trend in the U.S., while it has not returned to even its pre-crisis level in the Euro area. As indicated by recent studies, such as Cerra and Saxena (2008) and Reinhart and Rogoff (2009), financial crises tend to be followed by slow recoveries in which GDP scarcely returns to its pre-crisis growth trend and involves a considerable economic loss. Indeed, since the financial crisis in the 1990s, Japan's GDP has never recovered to its pre-crisis growth trend, and Japan's economy has experienced a massive loss in GDP. The post-crisis slow recoveries therefore cast doubt on the validity of the argument in the literature starting from Lucas (1987) that the welfare costs of business cycles are small enough that they do not justify stabilization policy.¹ Thus our paper addresses the question of whether and to what extent monetary policy can ameliorate social welfare in the face of a severe recession that is caused by a financial factor and is followed by a slow recovery. Particularly, in that situation, should monetary policy focus mainly on inflation stabilization and make no response to output, as advocated in the existing monetary policy literature including Schmitt-Grohé and Uribe (2006, 2007a, b)?²

This paper develops a model that can describe a slow recovery resulting from an adverse financial shock, and examines how monetary policy should react to the financial shock in terms of social welfare. According to the International Monetary Fund (2009), slowdowns in total factor productivity (TFP) growth were a significant cause of slow recoveries following banking crises around the globe over the past 40 years.³ Indeed,

¹Lucas (1987) argues that U.S. business cycles in the postwar period—of course, prior to 1987—involve at most negligible welfare costs. See also Lucas (2003).

²Schmitt-Grohé and Uribe (2006, 2007a, b) show that a welfare-maximizing monetary policy rule features a muted response to output in a dynamic stochastic general equilibrium model (without financial frictions or endogenous mechanisms of TFP growth).

³IMF (2009) also indicates that long-lasting reductions in the employment rate and the capital-labor ratio contribute to the post-crisis slow recoveries as well.

as a main source of Japan’s prolonged stagnation, Hayashi and Prescott (2002) point out a slowdown in TFP growth subsequent to the collapse of asset price bubbles in the early 1990s. Such slowdowns have also been measured after the recent financial crisis, particularly in Europe. Our paper thus introduces a financial friction and an endogenous mechanism of TFP growth in an otherwise canonical dynamic stochastic general equilibrium (DSGE) model.⁴ TFP grows endogenously by expanding the variety of goods through technology innovation and adoption as in Comin and Gertler (2006), who extend the framework of endogenous technological change developed by Romer (1990). The financial friction constrains firms’ borrowing capacity as in Jermann and Quadrini (2012). Then, an adverse shock to the borrowing capacity—which is referred to as an adverse “financial shock” following Jermann and Quadrini—induces a slow recovery through the endogenous mechanism of TFP growth. Specifically, the adverse financial shock tightens firms’ financing and thereby reduces their activity, which in turn has a significant negative impact on the economy as a whole by decreasing activity not only on the demand side but also on the supply side of the economy. In particular, the effect on the supply side induces a permanent decline in output relative to a balanced growth path through a permanent decline in TFP. The possibility of such permanent declines in output and other real variables distinguishes our model from those used in the existing literature on monetary policy. This distinctive feature yields a novel implication for monetary policy in terms of welfare costs of business cycles.

This paper analyzes a class of simple monetary policy rules that adjust the current policy rate in response to the past policy rates and the current rates of inflation and output growth. The paper shows that in the face of the financial shocks, a welfare-

⁴Queraltó (2013) builds a small open-economy real business cycle (RBC) model with the Gertler and Karadi (2011) financial friction and the Comin and Gertler (2006) endogenous mechanism of TFP growth to describe post-crisis slow recoveries observed in emerging market economies. Guerron-Quintana and Jinnai (2014) use U.S. time series, including their measured intangible capital, to estimate (mainly shocks in) an RBC model with the Kiyotaki and Moore (2012) financial friction and the Kung and Schmid (2013) endogenous technological change. They show that around the time of Lehman Brothers’ demise, liquidity declined significantly, inducing the U.S. Great Recession.

maximizing monetary policy rule features a strong response to output. This finding contrasts starkly with Schmitt-Grohé and Uribe (2006, 2007a, b). This contrast arises from two factors. First, the type of the shock considered in deriving a welfare-maximizing rule differs: our paper focuses only on the financial shock, while their papers consider mainly a TFP shock. Second, Schmitt-Grohé and Uribe (2006, 2007a) include a policy response to wage inflation in their policy rules, and Schmitt-Grohé and Uribe (2007b) assume no nominal wage rigidity in their model. Our paper also demonstrates that the welfare gain from output stabilization is much more substantial than in the model where TFP growth is exogenously given. In the presence of the endogenous TFP growth mechanism, it is crucial to take into account a welfare loss from a permanent decline in consumption caused by a slowdown in TFP growth.⁵ Moreover, compared with the welfare-maximizing rule, a strict inflation or price-level targeting rule induces a sizable welfare loss, because it has no response to output. By contrast, a nominal GDP growth or level targeting rule performs well, although it causes relatively high interest-rate volatility.

The paper also conducts a financial crisis scenario simulation under the monetary policy rules analyzed above. In this simulation, a slowdown in TFP growth is much less pronounced under the welfare-maximizing monetary policy rule than under the strict price-level targeting rule. Consequently, output recovers to its pre-crisis growth trend faster under the welfare-maximizing rule, implying that the welfare gain from adopting this rule relative to the strict price-level targeting rule is sizable, as noted above. Under the nominal GDP level targeting rule, the achieved levels of TFP and output are almost the same as those under the welfare-maximizing rule, implying that the welfare gain from adopting the latter rule relative to the former is small, as indicated above. Yet a smaller decline in firms' loans than that in the value of their collateral tightens their borrowing constraint and raises the marginal cost of funds and hence inflation. Under the nominal

⁵Similarly, Barlevy (2004) argues that business cycle fluctuations can affect social welfare by influencing the growth rate of consumption, in contrast to Lucas (1987, 2003).

GDP level targeting rule, this rise in inflation induces an initial increase in the interest rate even in the financial crisis scenario, and then the interest rate is lowered to hit a rate of zero, causing relatively high interest-rate volatility, as noted above.

A closely related and complementary study has been done by Reifschneider, Wascher, and Wilcox (2013). These authors conduct optimal-control exercises using a version of the FRB/US model with an ad hoc loss function that reflects the Federal Reserve’s dual mandate. They argue plausibly that a significant portion of the recent damage to the supply side of the U.S. economy is endogenous to the weakness in aggregate demand,⁶ and such endogeneity provides a strong motivation for a vigorous policy response to a weakening in aggregate demand. Our paper has demonstrated a similar argument to theirs, but has examined a welfare-maximizing monetary policy rule using a fully fledged DSGE model augmented with the Jermann and Quadrini (2012) financial friction and shock and the Comin and Gertler (2006) endogenous mechanism of TFP growth.

The remainder of the paper proceeds as follows. Section 2 briefly reviews recent post-crisis recoveries. Section 3 presents a DSGE model with a financial friction and an endogenous mechanism of TFP growth. Section 4 confirms that this model can describe a slow recovery resulting from an adverse financial shock. Section 5 conducts monetary policy analysis using the model. Section 6 concludes.

2 A Brief Review of Post-Crisis Recoveries

This section briefly reviews the economic developments around recent financial crises to show key features of post-crisis recoveries.⁷ The crises focused on here are the 2007–08 crises in the Euro area, the U.K., and the U.S. and the 1997 crisis in Japan.⁸

⁶Summers (2014) argues—in contrast to Say’s law—that “Lack of Demand creates Lack of Supply.”

⁷For comprehensive studies on post-crisis recoveries, see, e.g., Cerra and Saxena (2008), Reinhart and Rogoff (2009), IMF (2009), and Reinhart and Reinhart (2010).

⁸In 1997, Yamaichi Securities—one of the top four securities companies in Japan at that time—failed, and Hokkaido Takushoku Bank failed, which was the first failure of a city bank in Japan’s postwar history.

For these financial crises, Fig. 1 plots the developments of four key variables: real GDP per capita, TFP (Solow residual), bank lending, and the CPI inflation rate. Note that in each panel of the figure, the scale of years at the top is for Japan only, while that at the bottom is for the other three economies. In Panels (a) and (b), the pre-crisis trend grows at a rate that is average over the four economies during the five years before each crisis. In each panel, the following key feature of post-crisis recoveries is detected.

First, and most importantly, the post-crisis recoveries were quite slow, as shown in Panel (a). Since the onset of the recent crises, GDP has not recovered to the pre-crisis growth trend in the U.S., while it has not returned to even its pre-crisis level in the Euro area and the U.K. Japan's GDP has never recovered to the pre-crisis growth trend since the 1997 crisis, and Japan's economy has experienced a massive loss in GDP. This confirms the empirical evidence of Cerra and Saxena (2008), Reinhart and Rogoff (2009), IMF (2009), and Reinhart and Reinhart (2010): financial crises tend to be followed by slow recoveries in which economic activity scarcely returns to its pre-crisis growth trend, inducing a considerable loss in GDP.

As a main source of Japan's prolonged stagnation, Hayashi and Prescott (2002) indicate a slowdown in TFP growth following the collapse of asset price bubbles in the early 1990s. This slowdown continued in the post-1997 crisis period, as can be seen in Panel (b). Moreover, after the 2007–08 crises, slowdowns in TFP growth have also been measured, particularly in Europe. This is the second key feature of post-crisis recoveries.⁹

The third key feature is that a reduction in the degree of financial intermediation was observed during and after the financial crises, as shown in Panel (c). Bank lending in the Euro area, the U.K., and the U.S. all dropped sharply in 2009 and then remained stagnant. Japan's bank lending was already stagnant because of non-performing-loan problems subsequent to the collapse of asset price bubbles in the early 1990s, and it

⁹IMF (2009) also indicates the importance of slowdowns in TFP growth for slow recoveries that followed banking crises around the globe over the past 40 years.

dropped further in 1999.

Last, the inflation rate was less stable after the financial crises, as shown in Panel (d). In the Euro area, the U.K., and the U.S., the inflation rate measured by CPI dropped after the 2007–08 crises and then continued to fluctuate.¹⁰ In Japan, the CPI inflation rate was already low after the collapse of asset price bubbles in the early 1990s, and it dropped further after the 1997 crisis, falling into deflation.

Based on these features of post-crisis recoveries, the next section develops a model that can describe a slow recovery resulting from an adverse financial shock.

3 A DSGE Model for Slow Recoveries

To describe a post-crisis slow recovery like those reported in the preceding section, our paper introduces a financial friction and an endogenous mechanism of TFP growth in an otherwise canonical DSGE model.¹¹ TFP grows endogenously by expanding the variety of goods through technology innovation and adoption, as in Comin and Gertler (2006). The financial friction constrains the borrowing capacity of intermediate-good firms, as in Jermann and Quadrini (2012). The combination of the financial friction and endogenous TFP growth then generates a powerful amplification mechanism of a shock to the borrowing capacity, which is called a “financial shock” as in Jermann and Quadrini. An adverse financial shock tightens financing of intermediate-good firms and thereby reduces their activity. This in turn has a significant negative impact on the economy as a whole by decreasing activity not only on the demand side but also on the supply side of the economy. In particular, the effect on the supply side, such as technology adopters and innovators, induces a permanent decline in TFP relative to its growth trend and thus

¹⁰Although the sharp drop in the CPI inflation rate in the Euro area and the U.S. partly reflected a decline in energy prices, the inflation rate measured by CPI excluding energy decreased as well.

¹¹Apart from the financial friction and endogenous TFP growth, our model is fairly canonical. Indeed, the model has no habit formation in consumption preferences, no cost in investment adjustment, and no dynamic indexation in price and wage setting. This allows us to focus on a new mechanism generated by the financial friction and endogenous TFP growth in monetary policy analysis.

causes a permanent decline in output relative to a balanced growth path. The possibility of such permanent declines in output and other real variables distinguishes our model from those used in the existing literature on monetary policy. This distinctive feature of our model yields a novel implication for monetary policy in terms of welfare costs of business cycles.

In the model economy, there are final-good firms, intermediate-good firms, retailers, wholesalers, technology adopters, technology innovators, households, employment agencies, and a central bank.¹² The behavior of these agents is described in what follows.

3.1 Final-good firms

There is a continuum of final-good firms $f \in [0, A_{t-1}]$. Each firm f produces final good $X_{f,t}$ by combining intermediate goods $\{X_{f,t}(h)\}_{h \in [0,1]}$ according to the CES production function $X_{f,t} = [\int_0^1 (X_{f,t}(h))^{(\eta_x-1)/\eta_x} dh]^{\eta_x/(\eta_x-1)}$ with the elasticity of substitution $\eta_x > 1$. The firm sells the final good to wholesalers under perfect competition so as to maximize profit $P_{f,t}^x X_{f,t} - \int_0^1 P_{f,t}^x(h) X_{f,t}(h) dh$, given the final good's price $P_{f,t}^x$ and intermediate goods' prices $\{P_{f,t}^x(h)\}_{h \in [0,1]}$. The first-order condition for profit maximization yields firm f 's demand curve for each intermediate good $X_{f,t}(h)$

$$X_{f,t}(h) = X_{f,t} \left(\frac{P_{f,t}^x(h)}{P_{f,t}^x} \right)^{-\eta_x}. \quad (1)$$

Substituting this demand curve in the production function leads to the price equation for final good $X_{f,t}$, $P_{f,t}^x = [\int_0^1 (P_{f,t}^x(h))^{1-\eta_x} dh]^{1/(1-\eta_x)}$.

3.2 Intermediate-good firms

Intermediate-good firms play a central role in the model. They engage in various types of activity: borrowing, hiring, capital investment, purchase of newly adopted ideas, production, price setting, and dividend payment.

¹²Wholesalers, retailers, and employment agencies are added to the model, only for introducing price and wage rigidities.

There is a continuum of intermediate-good firms $h \in [0, 1]$. Each firm h owns capital $K_{t-1}(h)$ and a continuum of adopted ideas (e.g., patents) $f \in [0, A_{t-1}(h)]$, and adjusts the capital utilization rate $u_t(h)$. For each adopted idea f , the firm uses effective capital $u_t(h)K_{f,t-1}(h)$ and labor $n_{f,t}(h)$ to produce intermediate good $X_{f,t}(h)$ according to the Cobb-Douglas production function $X_{f,t}(h) = (n_{f,t}(h))^{1-\alpha}(u_t(h)K_{f,t-1}(h))^\alpha$ with the capital elasticity of output $\alpha \in (0, 1)$. The symmetry among adopted ideas f implies an identical effective capital-labor ratio in firm h 's production for each intermediate good $X_{f,t}(h)$, $f \in [0, A_{t-1}(h)]$. Then, aggregating firm h 's production functions—along with final-good firms' demand curves (1)—yields

$$\int_0^{A_{t-1}(h)} X_{f,t} \left(\frac{P_{f,t}^x(h)}{P_{f,t}^x} \right)^{-\eta_x} df = (n_t(h))^{1-\alpha} (u_t(h)K_{t-1}(h))^\alpha, \quad (2)$$

where $n_t(h) = \int_0^{A_{t-1}(h)} n_{f,t}(h) df$ and $K_t(h) = \int_0^{A_t(h)} K_{f,t}(h) df$.

Each firm h accumulates capital $K_t(h)$ and adopted ideas $A_t(h)$ according to

$$K_t(h) = (1 - \delta_{k,t}(h)) K_{t-1}(h) + I_t(h), \quad (3)$$

$$A_t(h) = (1 - \delta_a) A_{t-1}(h) + \Delta_{a,t}(h), \quad (4)$$

where $I_t(h)$ is firm h 's capital investment, $\Delta_{a,t}(h)$ is the number of newly adopted ideas firm h purchases from technology adopters, $\delta_{k,t}(h) \in (0, 1)$ is the (time-varying) depreciation rate of capital, and $\delta_a \in (0, 1)$ is the obsolescence rate of ideas. As in Greenwood, Hercowitz, and Huffman (1988) and Comin and Gertler (2006), it is assumed that a higher utilization rate of capital leads to a higher depreciation rate of capital. Specifically, the depreciation rate function takes the form $\delta_{k,t}(h) = \delta_k + \delta_1 (u_t(h) - 1) + (\delta_2/2)(u_t(h) - 1)^2$ with $\delta_k \in (0, 1)$, $\delta_1 > 0$, and $\delta_2 > 0$, as in Schmitt-Grohé and Uribe (2012).

Following Jermann and Quadrini (2012), each firm h uses debt and equity. Debt is preferred to equity because of its tax advantage. Given the gross risk-free (nominal) interest rate r_t , the effective gross (nominal) interest rate for each firm h is $r_t^\tau = 1 + (1 - \tau)(r_t - 1)$, where $\tau \in (0, 1)$ denotes the tax benefit. This benefit is financed by a lump-sum

tax on households. Each firm h starts the period with intertemporal debt $P_{t-1}B_{t-1}(h)$, where P_t is the price of retail goods. It is assumed that the firm must pay for labor $n_t(h)$, capital investment $I_t(h)$, and newly adopted ideas $\Delta_{a,t}(h)$ before its production takes place. To finance this payment, the firm raises funds with an intratemporal loan

$$P_t L_t(h) = P_t W_t n_t(h) + P_t I_t(h) + P_t V_t \Delta_{a,t}(h), \quad (5)$$

where W_t is the real wage and V_t is the real value of an adopted idea.¹³ The intratemporal loan is repaid with no interest at the end of the period. The capacity of the intratemporal loan $P_t L_t(h)$ and intertemporal debt $P_t B_t(h)$ is constrained by the value of capital and adopted ideas held by the firm because of a lack of enforcement. In particular, the firm can default on its debt (both $P_t L_t(h)$ and $P_t B_t(h)$) before the payment for the intratemporal loan is made at the end of the period. In case of default, the capital and adopted ideas held by the firm are seized with probability $\xi_t \in (0, 1)$. Then, it follows from the argument of Jermann and Quadrini (2012) that the intratemporal loan $P_t L_t(h)$ is limited by the borrowing constraint

$$P_t L_t(h) \leq \xi_t \left(P_t K_t(h) + P_t V_t A_t(h) - \frac{P_t B_t(h)}{r_t} \right). \quad (6)$$

It is assumed throughout the paper that this borrowing constraint is always binding and that the log-deviation of the foreclosure probability ξ_t from its steady-state value ξ follows the stationary first-order autoregressive process

$$\log \frac{\xi_t}{\xi} = \rho_\xi \log \frac{\xi_{t-1}}{\xi} + \epsilon_{\xi,t},$$

where $0 \leq \rho_\xi < 1$ and $\epsilon_{\xi,t}$ is white noise and is called a “financial shock.”

After the intratemporal loan arrangement is made, each firm h produces and sells intermediate goods to final-good firms and then pays back the loan. Moreover, the firm

¹³With several specifications of intratemporal loans, Jermann and Quadrini (2012) conduct robustness exercises. Their baseline specification supposes that firms use an intratemporal loan to finance total payment made in the period, including payments for dividends and intertemporal debt. Their alternative specification assumes that only the wage bill is financed by an intratemporal loan. Apart from firms’ purchase of newly adopted ideas, our specification is an intermediate between these two.

renews intertemporal debt and pays dividends $P_t D_t(h)$ to households. Let the sum of the dividends and associated payment costs in terms of retail goods be denoted by $\varphi_t(h) A_{t-1}^*$, where $\varphi_t(h) = D_t(h)/A_{t-1}^* + \kappa_d(D_t(h)/A_{t-1}^* - d)^2$, A_t^* represents the level of technology in the whole economy (defined later), $\kappa_d > 0$ is the elasticity of dividend payment costs, and d is the steady-state value of detrended dividends $d_t(h) = D_t(h)/A_{t-1}^*$. The presence of A_{t-1}^* in the costs ensures a balanced growth path in the model. The firm's budget constraint—along with final-good firms' demand curves (1)—can then be written as

$$\begin{aligned} & P_t W_t n_t(h) + P_t I_t(h) + P_t V_t \Delta_{a,t}(h) + P_t \varphi_t(h) A_{t-1}^* + P_{t-1} B_{t-1}(h) \\ &= \int_0^{A_{t-1}(h)} P_{f,t}^x(h) X_{f,t} \left(\frac{P_{f,t}^x(h)}{P_{f,t}^x} \right)^{-\eta_x} df + \frac{P_t B_t(h)}{r_t^\tau}. \end{aligned} \quad (7)$$

Each firm h chooses dividends $D_t(h)$, capital $K_t(h)$, intertemporal debt $B_t(h)$, labor $n_t(h)$, the utilization rate $u_t(h)$, its products' prices $\{P_{f,t}^x(h)\}_{f \in [0, A_{t-1}(h)]}$, and adopted ideas $A_t(h)$ to maximize the expected discounted value of the present and future dividends $E_0 \sum_{t=0}^{\infty} m_{0,t} D_t(h)$ subject to (2)–(7), where $m_{0,t}$ is the real stochastic discount factor between period 0 and period t . Because intermediate-good firms are symmetric, the firm index h can be deleted from the first-order conditions for dividend maximization. Then, substituting the first-order condition for dividends in those for capital and intertemporal debt yields

$$1 = E_t \left[m_{t,t+1} \frac{\alpha S_{t+1} u_{t+1}^\alpha n_{t+1}^{1-\alpha} / K_t^{1-\alpha} + (1 - \delta_{k,t+1})(1/\varphi'_{t+1} + \mu_{t+1})}{1/\varphi'_t + \mu_t(1 - \xi_t)} \right], \quad (8)$$

$$1 = E_t \left[m_{t,t+1} \frac{r_t^\tau}{\pi_{t+1}} \frac{\varphi'_t}{\varphi'_{t+1}} \right] + \mu_t \xi_t \varphi'_t \frac{r_t^\tau}{r_t}, \quad (9)$$

where $m_{t,t+1} = m_{0,t+1}/m_{0,t}$, $\varphi'_t = \partial \varphi_t / \partial (D_t/A_{t-1}^*) = 1 + 2\kappa_d(D_t/A_{t-1}^* - d)$, S_t and μ_t/P_t are the Lagrange multipliers on the aggregate production function (2) and the borrowing constraint (6), and $\pi_t = P_t/P_{t-1}$ is the gross inflation rate of retail goods' price. Combining the first-order conditions for dividends, labor, and the utilization rate

leads to

$$\frac{1 - \alpha}{\alpha} = \frac{W_t n_t}{\delta'_{k,t} u_t K_{t-1}}, \quad (10)$$

$$S_t = \left(\frac{1}{\varphi'_t} + \mu_t \right) \left(\frac{W_t}{1 - \alpha} \right)^{1 - \alpha} \left(\frac{\delta'_{k,t}}{\alpha} \right)^\alpha, \quad (11)$$

where $\delta'_{k,t} = \partial \delta_{k,t} / \partial u_t = \delta_1 + \delta_2 (u_t - 1)$. Substituting the first-order condition for dividends in those for the prices yields

$$P_{f,t}^x = P_t \theta_x S_t \varphi'_t, \quad (12)$$

where $\theta_x = \eta_x / (\eta_x - 1)$.¹⁴ Moreover, the aggregate production function (2), the budget constraint (7), and the first-order condition for adopted ideas can be rewritten as

$$\int_0^{A_{t-1}} X_{f,t} df = n_t^{1 - \alpha} (u_t K_{t-1})^\alpha, \quad (13)$$

$$W_t n_t + I_t + V_t \Delta_{a,t} + \varphi_t A_{t-1}^* + \frac{B_{t-1}}{\pi_t} = \theta_x S_t \varphi'_t n_t^{1 - \alpha} (u_t K_{t-1})^\alpha + \frac{B_t}{r_t^r}, \quad (14)$$

$$V_t = E_t \left[m_{t,t+1} \frac{(\theta_x - 1) S_{t+1} X_{f,t+1} + (1 - \delta_a) V_{t+1} (1/\varphi'_{t+1} + \mu_{t+1})}{1/\varphi'_t + \mu_t (1 - \xi_t)} \right]. \quad (15)$$

In the amplification mechanism generated by the financial friction and endogenous TFP growth, intermediate-good firms' demand curve for adopted ideas (15) plays an important role. Through this demand curve, an adverse financial shock decreases the value of an adopted idea V_t , because it not only lowers the foreclosure probability ξ_t but also tightens the borrowing constraint (6) and thus increases the associated Lagrange multiplier μ_t . As shown later, such a decrease in the value of an adopted idea causes technology adopters to become less willing to adopt developed but not yet adopted ideas. The resulting decline in newly adopted ideas has a persistent effect because of their accumulation process (4). Therefore, an adverse financial shock induces a permanent decline in output relative to a balanced growth path through the persistent decline in adopted ideas (or equivalently TFP). This mechanism is further strengthened when an adverse financial shock is persistent or is expected to continue occurring.

¹⁴The symmetry among intermediate-good firms implies an identical price for each intermediate good $X_{f,t}(h)$, $h \in [0, 1]$. Thus it follows that $P_{f,t}^x = [\int_0^1 (P_{f,t}^x(h))^{1 - \eta_x} dh]^{1/(1 - \eta_x)} = P_{f,t}^x(h)$ for all h .

3.3 Retailers

There is a representative retailer. It produces retail goods Y_t by combining wholesale goods $\{Y_{h,t}\}_{h \in [0,1]}$ according to the CES production function $Y_t = \left(\int_0^1 Y_{h,t}^{(\eta_y-1)/\eta_y} dh \right)^{\eta_y/(\eta_y-1)}$ with the elasticity of substitution $\eta_y > 1$. It sells retail goods to households, intermediate-good firms, and technology adopters and innovators so as to maximize profit $P_t Y_t - \int_0^1 P_{h,t} Y_{h,t} dh$, given P_t and wholesale goods' prices $\{P_{h,t}\}_{h \in [0,1]}$. The first-order condition for profit maximization yields the retailer's demand curve for each wholesale good $Y_{h,t}$

$$Y_{h,t} = Y_t \left(\frac{P_{h,t}}{P_t} \right)^{-\eta_y}. \quad (16)$$

Substituting this demand curve in the production function leads to retail goods' price equation

$$P_t = \left(\int_0^1 P_{h,t}^{1-\eta_y} dh \right)^{\frac{1}{1-\eta_y}}. \quad (17)$$

3.4 Wholesalers

There is a continuum of wholesalers $h \in [0, 1]$. Each wholesaler h produces its good $Y_{h,t}$ by combining final goods $\{X_{f,t}\}_{f \in [0, A_{t-1}]}$ according to the CES production function $Y_{h,t} = \left(\int_0^{A_{t-1}} X_{f,t}^{(\eta_a-1)/\eta_a} df \right)^{\eta_a/(\eta_a-1)}$ with the elasticity of substitution $\eta_a > 1$ to minimize cost $\int_0^{A_{t-1}} P_{f,t}^x X_{f,t} df$, given $\{P_{f,t}^x\}_{f \in [0, A_{t-1}]}$. The first-order condition for cost minimization yields wholesaler h 's demand curve for each final good $X_{f,t}$

$$X_{f,t} = Y_{h,t} \left(\frac{P_{f,t}^x}{MC_{h,t}} \right)^{-\eta_a}, \quad (18)$$

where $MC_{h,t}$ is the Lagrange multiplier on wholesaler h 's production function and represents its marginal cost. Substituting this demand curve in the production function leads to $MC_{h,t} = \left[\int_0^{A_{t-1}} (P_{f,t}^x)^{1-\eta_a} df \right]^{1/(1-\eta_a)}$. This shows that the marginal cost is identical among wholesalers. Using the price equations (12), the marginal cost can be reduced to

$$MC_t = P_t \theta_x S_t \varphi_t' A_t^{1-\theta_a}, \quad (19)$$

where $\theta_a = \eta_a/(\eta_a - 1)$. Then, from this equation and equations (12), (13), and (18), the output of wholesale good $Y_{h,t}$ is given by

$$Y_{h,t} = A_{t-1}^{\theta_a-1} n_t^{1-\alpha} (u_t K_{t-1})^\alpha. \quad (20)$$

Using this equation, two more key equations can be derived. First, substituting equations (12), (19), and (20) in wholesalers' demand curve (18) leads to $X_{f,t} = n_t^{1-\alpha} (u_t K_{t-1})^\alpha / A_{t-1}$. Combining this equation and intermediate-good firms' demand curve for adopted ideas (15) yields

$$V_t = E_t \left[m_{t,t+1} \frac{(\theta_x - 1) S_{t+1} n_{t+1}^{1-\alpha} (u_{t+1} K_t)^\alpha / A_t + (1 - \delta_a) V_{t+1} (1/\varphi'_{t+1} + \mu_{t+1})}{1/\varphi'_t + \mu_t (1 - \xi_t)} \right]. \quad (21)$$

Second, aggregating wholesale goods' output equations (20)—along with retailers' demand curves (16)—leads to

$$Y_t = \frac{A_{t-1}^{\theta_a-1} n_t^{1-\alpha} (u_t K_{t-1})^\alpha}{\zeta_{p,t}} = \frac{(A_{t-1}^*)^{1-\alpha} n_t^{1-\alpha} (u_t K_{t-1})^\alpha}{\zeta_{p,t}}, \quad (22)$$

where

$$\zeta_{p,t} = \int_0^1 \left(\frac{P_{h,t}}{P_t} \right)^{-\eta_y} dh \quad (23)$$

represents dispersion of wholesale goods' prices and where

$$A_t^* = A_t^{\frac{\theta_a-1}{1-\alpha}} \quad (24)$$

represents the level of technology in the whole economy and its growth rate $\gamma_t^* = A_t^*/A_{t-1}^*$ shows the gross rate of technological change. Equation (22) shows a standard Cobb-Douglas production function, except that TFP is endogenously determined by

$$TFP_t = \frac{(A_{t-1}^*)^{1-\alpha}}{\zeta_{p,t}}. \quad (25)$$

Under monopolistic competition, each wholesaler h sets its product's price on a staggered basis as in Calvo (1983) and Yun (1996). In each period, a fraction $\xi_p \in (0, 1)$ of wholesalers sets prices according to the indexation rule $P_{h,t} = \pi P_{h,t-1}$, where π is the

steady-state value of the inflation rate π_t , while the remaining fraction $1 - \xi_p$ chooses the price $\tilde{P}_{h,t}$ that maximizes the associated profit

$$E_t \sum_{f=0}^{\infty} \xi_p^f M_{t,t+f} \left(\pi^f \tilde{P}_{h,t} - MC_{t+f} \right) Y_{h,t+f|t},$$

given the marginal cost MC_{t+f} and retailers' demand curve $Y_{h,t+f|t} = Y_{t+f} (\pi^f \tilde{P}_{h,t} / P_{t+f})^{-\eta_y}$, where $M_{t,t+f}$ is the nominal stochastic discount factor between period t and period $t+f$.

The first-order condition for the optimal staggered price $\tilde{P}_{h,t}$ yields

$$\frac{\tilde{P}_{h,t}}{P_t} = \theta_y \frac{v_{p1,t}}{v_{p2,t}}, \quad (26)$$

where $\theta_y = \eta_y / (\eta_y - 1)$ and the auxiliary variables $v_{p1,t}$ and $v_{p2,t}$ are defined recursively by

$$v_{p1,t} = \frac{MC_t Y_t}{P_t C_t} + \beta \xi_p E_t \left[\left(\frac{\pi}{\pi_{t+1}} \right)^{-\eta_y} v_{p1,t+1} \right], \quad (27)$$

$$v_{p2,t} = \frac{Y_t}{C_t} + \beta \xi_p E_t \left[\left(\frac{\pi}{\pi_{t+1}} \right)^{1-\eta_y} v_{p2,t+1} \right], \quad (28)$$

where the equilibrium condition $M_{t,t+h} = (\beta^h C_t / C_{t+h}) / \pi_{t+h}$ —which is derived later—is used, $\beta \in (0, 1)$ is the subjective discount factor, and C_t is consumption. Moreover, under the staggered price setting, retail goods' price equation (17) and the price dispersion equation (23) can be reduced respectively to

$$1 = (1 - \xi_p) \left(\frac{\tilde{P}_{h,t}}{P_t} \right)^{1-\eta_y} + \xi_p \left(\frac{\pi}{\pi_t} \right)^{1-\eta_y}, \quad (29)$$

$$\zeta_{p,t} = (1 - \xi_p) \left(\frac{\tilde{P}_{h,t}}{P_t} \right)^{-\eta_y} + \xi_p \left(\frac{\pi}{\pi_t} \right)^{-\eta_y} \zeta_{p,t-1}. \quad (30)$$

3.5 Technology adopters

There is a continuum of technology adopters. Each adopter owns a developed but not yet adopted idea that is in the interval between A_{t-1} and Z_{t-1} . This adopter makes an

investment $I_{a,t}$ for technology adoption in terms of retail goods. The adopter successfully adopts the idea with probability $\lambda_t \in (0, 1)$. This probability takes the form

$$\lambda_t = \lambda_0 \left(\frac{A_{t-1}}{A_{t-1}^*} I_{a,t} \right)^\omega, \quad (31)$$

with $\lambda_0 > 0$ and $\omega \in (0, 1)$, as in Comin and Gertler (2006). Thus, the probability λ_t increases with investment $I_{a,t}$, and there is a spillover effect from already adopted ideas A_{t-1} to individual adoption. The presence of A_{t-1}^* keeps the probability λ_t stationary. Because $A_{t-1}/A_{t-1}^* = A_{t-1}^{(2-\alpha-\theta_a)/(1-\alpha)}$, the spillover effect is positive as long as $\alpha + \theta_a < 2$, which holds under our parameterization of the model presented later.

After the adoption, a fraction δ_a of adopted ideas becomes obsolete. Thus, the amount of newly adopted ideas sold to intermediate-good firms is given by

$$\Delta_{a,t} = (1 - \delta_a) \lambda_t (Z_{t-1} - A_{t-1}). \quad (32)$$

The value of a developed but not yet adopted idea is given by

$$J_t = \max_{\tilde{I}_{a,t}} \left\{ -\tilde{I}_{a,t} + (1 - \delta_a) [\lambda_t V_t + (1 - \lambda_t) E_t m_{t,t+1} J_{t+1}] \right\}. \quad (33)$$

A developed idea, if successfully adopted, is sold to intermediate-good firms at the real price V_t . Otherwise, the value of the idea is given by its expected discounted value $E_t m_{t,t+1} J_{t+1}$.

The first-order condition for investment $I_{a,t}$ yields

$$I_{a,t} = \omega (1 - \delta_a) \lambda_t (V_t - E_t m_{t,t+1} J_{t+1}). \quad (34)$$

Thus, a decline in the value of an adopted idea V_t directly decreases technology adoption investment $I_{a,t}$, which in turn lowers the probability of technology adoption λ_t and thus further decreases the investment $I_{a,t}$. This spiral slows the rate of technology adoption and hence the growth rates of A_t and TFP. Moreover, substituting equation (34) in equation (33) leads to

$$J_t = (1 - \delta_a) \{ (1 - \omega) \lambda_t V_t + [1 - (1 - \omega) \lambda_t] E_t m_{t,t+1} J_{t+1} \}, \quad (35)$$

which shows that a decline in the value of an adopted idea V_t decreases the value of a developed but not yet adopted idea J_t .

3.6 Technology innovators

There is a representative technology innovator. This innovator transforms one unit of retail goods into Φ_t units of developed ideas. Given the obsolescence rate δ_a , the frontier of developed ideas, Z_t , follows the law of motion

$$Z_t = (1 - \delta_a) Z_{t-1} + \Phi_t I_{d,t}, \quad (36)$$

where $I_{d,t}$ is R&D investment. As in Comin and Gertler (2006), the R&D productivity Φ_t takes the form

$$\Phi_t = \chi_z \frac{Z_{t-1}}{(A_{t-1}^*)^\rho I_{d,t}^{1-\rho}}, \quad (37)$$

with $\chi_z > 0$ and $\rho \in (0, 1)$. The zero-profit condition under perfect competition can be reduced to

$$1 = \Phi_t (1 - \delta_a) E_t m_{t,t+1} J_{t+1}. \quad (38)$$

Combining this condition and the law of motion of developed ideas (36) yields

$$I_{d,t} = (1 - \delta_a) [Z_t - (1 - \delta_a) Z_{t-1}] E_t m_{t,t+1} J_{t+1}. \quad (39)$$

Thus, a decline in the expected discounted value of a developed but not yet adopted idea $E_t m_{t,t+1} J_{t+1}$ —which arises from a decline in the expected discounted value of an adopted idea $E_t m_{t,t+1} V_{t+1}$ because a lower value of V_t decreases J_t as in (35)—decreases R&D investment $I_{d,t}$. This then slows the growth rate of Z_t and constrains TFP growth.

3.7 Households and employment agencies

Households are standard as in the literature on DSGE models. There is a continuum of households with measure unity, each of which is endowed with one type of specialized labor $f \in [0, 1]$. Households have monopolistic power over wages for specialized

labor, and the wages are set in a staggered manner.¹⁵ A representative employment agency transforms specialized labor into homogeneous labor and provides the latter to intermediate-good firms.

The problem of households consists of three parts: a consumption-saving problem, the employment agency's problem, and a wage-setting problem. In the consumption-saving problem, each household chooses consumption C_t and savings B_t to maximize the utility function

$$E_0 \sum_{t=0}^{\infty} \beta^t \left(\log(C_t) - \frac{\chi_n}{1 + 1/\nu} n_{f,t}^{1+1/\nu} \right), \quad (40)$$

subject to the budget constraint

$$P_t C_t + \frac{P_t B_t}{r_t} = P_t W_{f,t} n_{f,t} + P_{t-1} B_{t-1} + T_{f,t}, \quad (41)$$

where $\nu > 0$ is the elasticity of labor supply, $\chi_n > 0$ is the coefficient on labor disutility relative to contemporaneous consumption utility, $W_{f,t}$ and $n_{f,t}$ are the real wage and the supply of specialized labor f , and $T_{f,t}$ is the sum of intermediate-good firms' dividend payout $P_t D_t$, the other firms' profits, a lump-sum public transfer, and a net flow from contingent claims on the opportunity of wage changes. The presence of the contingent claims allows the model to keep a representative-household framework.

Combining the first-order conditions for the consumption-saving problem yields

$$1 = E_t \beta \frac{C_t}{C_{t+1}} \frac{r_t}{\pi_{t+1}}, \quad (42)$$

which leads to $M_{t,t+h} = m_{t,t+h}/\pi_{t+h} = (\beta^h C_t/C_{t+h})/\pi_{t+h}$.

The retail-good market clearing condition is now given by

$$Y_t = C_t + I_t + (\varphi_t A_{t-1}^* - D_t) + I_{a,t}(Z_{t-1} - A_{t-1}) + I_{d,t}. \quad (43)$$

The output Y_t equals households' consumption C_t , intermediate-good firms' capital investment I_t , their dividend payment costs $(\varphi_t A_{t-1}^* - D_t)$, technology adopters' investment $I_{a,t}(Z_{t-1} - A_{t-1})$, and technology innovators' R&D investment $I_{d,t}$.

¹⁵Nominal wage rigidity is an important factor to describe a slow recovery resulting from an adverse financial shock in the model, as shown later.

The employment agency transforms specialized labor $\{n_{f,t}\}_{f \in [0,1]}$ into homogeneous labor n_t according to the CES aggregation function $n_t = (\int_0^1 n_{f,t}^{(\eta_n-1)/\eta_n} df)^{\eta_n/(\eta_n-1)}$ with the elasticity of substitution $\eta_n > 1$. The agency then chooses the amount of all types of specialized labor $\{n_{f,t}\}_{f \in [0,1]}$ to maximize profit $P_t W_t n_t - \int_0^1 P_t W_{f,t} n_{f,t} df$, given homogeneous labor's wage $P_t W_t$ and specialized labor's wages $\{P_t W_{f,t}\}_{f \in [0,1]}$. The first-order condition for profit maximization yields the employment agency's demand curve for each type of specialized labor

$$n_{f,t} = n_t \left(\frac{P_t W_{f,t}}{P_t W_t} \right)^{-\eta_n}. \quad (44)$$

Substituting this demand curve in the aggregation function leads to homogeneous labor's wage equation

$$P_t W_t = \left[\int_0^1 (P_t W_{f,t})^{1-\eta_n} df \right]^{\frac{1}{1-\eta_n}}. \quad (45)$$

The wage of each type of specialized labor is set on a staggered basis as in Erceg, Henderson, and Levin (2000). In each period, a fraction $\xi_w \in (0, 1)$ of wages is set according to the indexation rule $P_t W_{f,t} = \pi_w P_{t-1} W_{f,t-1}$, where $\pi_w = \pi \gamma^*$ is the gross steady-state wage inflation rate and γ^* is the steady-state value of the gross rate of technological change γ_t^* , while the remaining fraction $1 - \xi_w$ is set at the wage $P_t \tilde{W}_{f,t}$ that maximizes

$$E_t \sum_{h=0}^{\infty} (\beta \xi_w)^h \left(\Psi_{t+h} \pi_w^h P_t \tilde{W}_{f,t} n_{f,t+h|t} - \frac{\chi_n}{1 + 1/\nu} n_{f,t+h|t}^{1+\frac{1}{\nu}} \right),$$

given the employment agency's demand curve $n_{f,t+h|t} = n_{t+h} [\pi_w^h P_t \tilde{W}_{f,t} / (P_{t+h} W_{t+h})]^{-\eta_n}$, where Ψ_t is the Lagrange multiplier on the budget constraint (41). The first-order condition for the optimal staggered wage $P_t \tilde{W}_{f,t}$ yields

$$\left(\frac{P_t \tilde{W}_{f,t}}{P_t W_t} \right)^{1+\frac{\eta_n}{\nu}} = \theta_n \chi_n \frac{v_{w1,t}}{v_{w2,t}}, \quad (46)$$

where $\theta_n = \eta_n / (\eta_n - 1)$ and the auxiliary variables $v_{w1,t}$ and $v_{w2,t}$ are defined recursively

by

$$v_{w1,t} = n_t^{1+\frac{1}{\nu}} + \beta\xi_w E_t \left[\left(\frac{\pi}{\pi_{t+1}} \frac{\gamma^* W_t}{W_{t+1}} \right)^{-\eta_n(1+\frac{1}{\nu})} v_{w1,t+1} \right], \quad (47)$$

$$v_{w2,t} = \frac{W_t n_t}{C_t} + \beta\xi_w E_t \left[\left(\frac{\pi}{\pi_{t+1}} \frac{\gamma^* W_t}{W_{t+1}} \right)^{1-\eta_n} v_{w2,t+1} \right]. \quad (48)$$

Under the staggered wage setting, homogeneous labor's wage equation (45) can be reduced to

$$1 = (1 - \xi_w) \left(\frac{P_t \tilde{W}_{f,t}}{P_t W_t} \right)^{1-\eta_n} + \xi_w \left(\frac{\pi}{\pi_t} \frac{\gamma^* W_{t-1}}{W_t} \right)^{1-\eta_n}. \quad (49)$$

3.8 The central bank

The central bank follows a Taylor (1993)-type rule that adjusts the current policy rate in response to the past policy rate and the current rates of price inflation and output growth of retail goods

$$\log r_t = \phi_r \log r_{t-1} + (1 - \phi_r) \left[\log r + \phi_\pi (\log \pi_t - \log \pi) + \phi_{dy} \left(\log \frac{Y_t}{Y_{t-1}} - \log \gamma^* \right) \right], \quad (50)$$

where r is the steady-state policy rate, $\phi_r \in [0, 1)$ represents the degree of policy rate smoothing, and ϕ_π and ϕ_{dy} are the policy responses to inflation and output growth.¹⁶

The equilibrium conditions consist of equations (3)–(6) (without the index h and with the equality holding in (6)), (8)–(11), (14), (19), (21), (22), (24)–(32), (34)–(38), (42), (43), (46)–(49), and (50). Appendix A presents equilibrium conditions and the steady state in terms of stationary variables.

4 A Slow Recovery from an Adverse Financial Shock

This section confirms that the model presented in the preceding section possesses the capability to describe a slow recovery resulting from an adverse financial shock. To this

¹⁶No output gap is included in the monetary policy rules considered in the paper. This is because in the model, where monetary policy can affect TFP, it is not clear which output gap monetary policymakers ought to stabilize. The gap between actual output and potential output that could be obtained in the absence of nominal rigidities—which has been considered as a theoretically appropriate output gap for monetary policymakers in models where TFP is exogenously given—seems to be inappropriate, because welfare losses arise not only from nominal rigidities but also from the endogenous TFP mechanism.

end, the model is parameterized, linearized around the steady state, and solved for the rational expectations equilibrium. Then, impulse responses show how an adverse financial shock induces a slow recovery. Last, two key factors to describe the slow recovery—the endogenous mechanism of TFP growth and nominal wage rigidity—are explained.

4.1 Parameterization of the model

This section begins by parameterizing the model. The model parameters are divided into three sets. The first set contains parameters that are standard in DSGE models. The second set pertains to the technology innovation and adoption. The values of parameters in this set are chosen on the basis of Comin and Gertler (2006). The third set pertains to the financial friction. For this set, the parameter values calibrated by Jermann and Quadrini (2012) are employed. Table 1 lists the parameterization of the quarterly model.

Regarding the parameters in the first set, this paper chooses the subjective discount factor at $\beta = 0.9975$ and the steady-state gross rate of technological change at $\gamma^* = 1.0025$, implying an annualized steady-state real interest rate of 2 percent. Steady-state labor is normalized to unity, i.e., $n = 1$. The paper also sets the elasticity of labor supply at $\nu = 1$, the capital elasticity of output at $\alpha = 0.36$, the steady-state capital utilization rate at $u = 1$, the steady-state capital depreciation rate at $\delta_k = 0.025$ (i.e., an annualized rate of 10 percent), the steady-state elasticity of capital depreciation at $\delta_2/\delta_1 = 0.5$, the degrees of price and wage rigidities at $\xi_p = \xi_w = 0.75$, the elasticities of substitution among wholesale goods and among labor at $\eta_y = \eta_n = 11$ (i.e., $\theta_y = \theta_n = 1.1$), the steady-state gross inflation rate at $\pi = 1.005$ (i.e., an annualized rate of 2 percent), the degree of policy rate smoothing at $\phi_r = 0.7$, and the policy responses to inflation and output growth at $\phi_\pi = 1.5$ and $\phi_{dy} = 0.25$. These parameter values are more or less within the values calibrated or estimated in previous studies with DSGE models.

Next, the values of the parameters that pertain to the technology innovation and adoption are explained. This paper follows Comin and Gertler (2006) to set the elasti-

ties of substitution among intermediate goods and among final goods at $\eta_x = \eta_a = 2.67$ (i.e., $\theta_x = \theta_a = 1.6$), the steady-state probability of technology adoption at $\lambda = 0.025$ (i.e., an average duration of technology adoption of 10 years), the elasticity of the probability of technology adoption at $\omega = 0.95$, and the elasticity of R&D productivity at $\rho = 0.8$. The steady-state ratio of R&D investment to output is chosen at $i_d/y = 0.025$.¹⁷

Last, the values of the parameters that pertain to the financial friction are presented. This paper follows Table 2 of Jermann and Quadrini (2012) to set the steady-state probability of foreclosure at $\xi = 0.1634$, the elasticity of the dividend payment costs at $\kappa_d = 0.146$, the tax benefit at $\tau = 0.35$, and the financial shock persistence at $\rho_\xi = 0.9703$.

4.2 Impulse responses to an adverse financial shock

Using the model parameterization presented above, this subsection analyzes impulse responses to an adverse financial shock.¹⁸

Fig. 2 presents impulse responses of intratemporal loans L_t , labor n_t , capital investment I_t , output Y_t , consumption C_t , the inflation rate π_t , the interest rate r_t , and TFP TFP_t to the adverse financial shock $\epsilon_{\xi,1} = -0.01$. This figure expresses labor in terms of percentage deviations from its steady-state value and the rates of inflation and interest in terms of percentage differences from their steady-state values, while the others are expressed in terms of percentage deviations from their steady-state growth paths starting from period 0. The solid line, called the “benchmark,” represents the case of the model presented in the preceding section. When the adverse financial shock $\epsilon_{\xi,1}$ hits the economy in period 1, it lowers the foreclosure probability ξ_t and tightens the borrowing constraint (6), so that intratemporal loans to intermediate-good firms, L_t , drop. The

¹⁷The values of the obsolescence rate of ideas δ_a and the scaling parameter of R&D productivity χ_z are calculated from steady-state conditions, as shown in Appendix A.2.

¹⁸Regarding impulse responses to a monetary policy shock (i.e., a shock added to the monetary policy rule (50)), we confirm that the model possesses standard properties for monetary policy analysis. That is, in response to a contractionary monetary policy shock, the interest rate rises, and then output, labor, consumption, and investment all decline. Inflation decreases as well. Overall, these impulse responses are consistent with those in canonical DSGE models.

firms then reduce labor n_t , capital investment I_t , and purchase of newly adopted ideas $\Delta_{a,t}$. This in turn has a negative impact on the economy as a whole. The declines in labor and capital investment decrease output Y_t and consumption C_t , as well as inflation π_t , inducing a recession.¹⁹ In reaction to the declines in inflation and output growth, the monetary policy rule (50) lowers the interest rate r_t . On the other hand, the decline in the purchase of newly adopted ideas lowers technology adoption and innovation, so that TFP falls permanently relative to its steady-state growth path through the endogenous mechanism embedded in the model. As noted above, an adverse financial shock decreases the value of an adopted idea V_t through intermediate-good firms' demand curve for adopted ideas (21). This decline in the value of an adopted idea reduces technology adopters' investment $I_{a,t}$ through equation (34) and lowers the adoption probability λ_t through equation (31), thereby slowing the growth rates of A_t and TFP. Moreover, because the adverse financial shock is persistent, it lowers the expected discounted value of an adopted idea, $E_t m_{t,t+1} V_{t+1}$, and decreases the expected discounted value of a developed but not yet adopted idea, $E_t m_{t,t+1} J_{t+1}$, through equation (35). This decrease in the latter expected discounted value reduces R&D investment $I_{d,t}$ through equation (39) and slows the growth rate of Z_t , which constrains TFP growth and causes TFP to fall permanently (relative to the steady-state growth path). As a consequence of this mechanism, neither output, consumption, nor capital investment returns to the steady-state balanced growth path after the adverse financial shock hits the economy. Indeed, output drops below the steady-state balanced growth path by about 0.9 percentage point and then recovers by less than half of the drop, remaining below the path by about 0.6 percentage point even after 40 quarters (10 years). From these observations, we confirm

¹⁹In response to the adverse financial shock, inflation declines because of a decrease in wholesalers' real marginal cost MC_t/P_t . Equation (19) shows that $MC_t/P_t = \theta_x (S_t/A_{t-1}^{\theta_a-1}) \varphi'_t$. As can be seen in Panel (h) of Fig. 2, TFP—its main component $A_{t-1}^{\theta_a-1} (= (A_{t-1}^*)^{1-\alpha})$ in particular—falls in response to the shock. Although this fall adds an upward pressure on the real marginal cost, a drop in intermediate-good firms' real marginal cost of dividend payments φ'_t generates the decline in wholesalers' real marginal cost MC_t/P_t . Such a drop in φ'_t is because in response to the shock, intermediate-good firms cut dividends, which reduces their real marginal cost of dividend payments φ'_t .

that the model possesses the capability to describe a slow recovery resulting from an adverse financial shock.

4.3 Key factors for a slow recovery from an adverse financial shock

Before proceeding to monetary policy analysis, this subsection investigates which factor in the model is important for describing a slow recovery from an adverse financial shock. In Fig. 2, the dashed line, labeled the “no endogenous TFP growth,” represents the case of the model without the endogenous mechanism of TFP growth for understanding the role of this mechanism in the slow recovery. The dotted line, called the “no nominal wage rigidity,” represents the case of the model without nominal wage rigidity to examine the role of this rigidity for the slow recovery.

The model without the endogenous TFP growth mechanism assumes that TFP grows exogenously at the same steady-state rate, as shown in Panel (h) of the figure. In the model there is neither technology innovation nor adoption. In short, such a model is a standard DSGE model with the financial friction and shock as in Jermann and Quadrini (2012). When the adverse financial shock $\epsilon_{\xi,1} = -0.01$ hits the economy in period 1, output drops below the steady-state balanced growth path (starting from period 0) by about 0.4 percentage point, about less than half of the drop in the benchmark model. It then returns to the path, in sharp contrast with the permanent decline in output (relative to the path) in the benchmark model. Therefore, the endogenous mechanism of TFP growth is a crucially important factor for describing the slow recovery from the adverse financial shock.

Another important factor for describing the slow recovery is nominal wage rigidity. The model without such a rigidity assumes that the degree of the rigidity is set at $\xi_w = 0$. In response to the adverse financial shock $\epsilon_{\xi,1} = -0.01$, output drops below the steady-state balanced growth path (starting from period 0) by about 0.8 percentage

point and then approaches the path faster than in the benchmark model. Although output does not return to the path because of the presence of the endogenous TFP growth mechanism, the magnitude of the permanent decline in output (relative to the path) is much smaller than in the benchmark model. In 40 quarters (10 years), output approaches the path much more closely than in the benchmark model. In reaction to the adverse financial shock, nominal wage rigidity causes nominal wages to decline less and labor to drop more than in the absence of the rigidity. This drop in labor reduces output Y_t directly through the aggregate production function (22). Moreover, in the presence of nominal wage rigidity, the level of labor continues to be lower than in the absence of the rigidity, which decreases the value of an adopted idea V_t through intermediate-good firms' demand curve for adopted ideas (21). This decline in the value of an adopted idea slows the growth rates of A_t and TFP, as indicated above. Consequently, the permanent decline in output is larger in the benchmark model. Therefore, nominal wage rigidity is another key factor for describing the slow recovery from the financial shock.

5 Monetary Policy Analysis

This section examines how monetary policy should react to the financial shocks. To this end, the section begins by deriving a welfare measure from the utility functions of households. With this welfare measure, a welfare-maximizing monetary policy rule is computed and characterized. Last, under the welfare-maximizing rule and other rules, a financial crisis scenario simulation is carried out.

5.1 Welfare measure

The welfare measure is the unconditional expectation of the average utility function over households, given by

$$SW = (1 - \beta)E \left[\int_0^1 \sum_{t=0}^{\infty} \beta^t \left(\log(C_t) - \frac{\chi_n}{1 + 1/\nu} n_{f,t}^{1+1/\nu} \right) df \right], \quad (51)$$

where E is the unconditional expectation operator, and the scaling factor $(1 - \beta)$ is multiplied for normalization. Because TFP grows endogenously over time, a deterministic trend with the steady-state rate of technological change γ^* is subtracted from this welfare measure SW for the ease of computation. Letting SW^* denote the resulting stationary welfare measure, Appendix B shows that this welfare measure can be approximated around the steady state, up to the second order, as

$$SW^* \approx - \left[\frac{Var(c_t)}{2c^2} + \frac{\beta}{1-\beta} \frac{Var(\gamma_t^*)}{2(\gamma^*)^2} + \frac{\chi_n}{\nu} \frac{Var(n_t)}{2} \right] + \frac{\varepsilon_c}{c} + \frac{\beta}{1-\beta} \frac{\varepsilon_{\gamma^*}}{\gamma^*} - \chi_n \varepsilon_n - \frac{\chi_w}{1+1/\nu} \varepsilon_{\zeta_w}, \quad (52)$$

where Var denotes the unconditional variance operator, $c_t (= C_t/A_{t-1}^*)$ is detrended consumption, c is its steady-state value, $\varepsilon_x = E(x_t) - x$ is the “bias” between the unconditional mean and the steady-state value of variable x_t , and $\zeta_{w,t} = \int_0^1 (W_{f,t}/W_t)^{-\eta_n(1+1/\nu)} df$ denotes wage dispersion arising from the staggered wage setting of households. Note that in the second-order approximation, the bias can exist; that is, the unconditional mean does not necessarily coincide with the steady-state value. The approximation (52) shows that the stationary welfare measure SW^* is negatively related to the bias in labor and wage dispersion and the unconditional variances of detrended consumption, the rate of technological change, and labor (i.e., ε_n , ε_{ζ_w} , $Var(c_t)$, $Var(\gamma_t^*)$, $Var(n_t)$) and is positively related to the bias in detrended consumption and the rate of technological change (i.e., ε_c , ε_{γ^*}). A distinctive feature of the welfare measure (52) lies in the presence of the terms related to the rate of technological change γ_t^* (i.e., ε_{γ^*} , $Var(\gamma_t^*)$). In standard DSGE models where TFP growth is exogenously given, the bias and the unconditional variance of the rate of technological change are also exogenously given and independent of policy. In our model, however, TFP grows endogenously and depends on policy, so that the γ_t^* -related terms constitute social welfare relevant to policy evaluation.

Let SW_b^* and SW_a^* denote the values of the welfare measure SW^* attained under the benchmark monetary policy rule (i.e., the rule (50) with the benchmark parameterization presented in Table 1) and under an alternative monetary policy rule, and let

$\Delta SW = SW_a^* - SW_b^*$. Then, this difference also equals the corresponding difference in terms of the welfare measure (51); that is, $\Delta SW = SW_a - SW_b$, where SW_b and SW_a denote the values of the welfare measure (51) under the benchmark rule and under the alternative rule, because the subtracted deterministic trend in the technological level A_t^* is identical between SW_b and SW_a . Therefore, the welfare difference ΔSW , if it is positive, represents the welfare gain from adopting the alternative rule relative to the benchmark rule. Moreover, $g = 1 - (1 - 2\Delta SW)^{1/2}$ represents the welfare gain in terms of permanent increase in consumption, because by definition, this welfare gain measure g must satisfy

$$SW_a = (1 - \beta)E \left[\int_0^1 \sum_{t=0}^{\infty} \beta^t \left(\log((1 + g) C_{b,t}) - \frac{\chi_n}{1 + 1/\nu} n_{b,f,t}^{1+1/\nu} \right) df \right],$$

where $\{C_{b,t}, \{n_{b,f,t}\}\}$ is the pair of equilibrium consumption and labor under the benchmark monetary policy rule, and then it follows

$$SW_b + \Delta SW = SW_a = SW_b + \log(1 + g) \approx SW_b + \left(g - \frac{1}{2}g^2 \right),$$

where the last approximation uses the second-order approximation to $\log(1 + g)$ around $g = 0$.

Using the welfare measure (52) and the welfare gain measure g , the next subsections analyze a welfare-maximizing monetary policy rule in reaction to the financial shocks.

5.2 Features of welfare-maximizing monetary policy rule in reaction to financial shocks

This paper considers a class of simple monetary policy rules that adjust the current policy rate in response to the past policy rates and the current rates of inflation and output growth. Specifically, two forms of such rules are analyzed. One form is, of course, the rule (50). The present paper refers to this rule as “flexible inflation targeting.” Moreover, in this form, the specification of $\phi_{dy} = 0$ is called “strict inflation targeting,” while the specification of $\phi_{\pi} = \phi_{dy}$ is called “nominal GDP growth targeting.” The other form is

the so-called “first-difference rule,” where the change in the policy rate responds to its past change and the current rates of inflation and output growth²⁰

$$\log r_t - \log r_{t-1} = \phi_r(\log r_{t-1} - \log r_{t-2}) + (1 - \phi_r) \left[\phi_\pi(\log \pi_t - \log \pi) + \phi_{dy} \left(\log \frac{Y_t}{Y_{t-1}} - \log \gamma^* \right) \right]. \quad (53)$$

This rule is referred to as “flexible price-level targeting,” and in this form, the specification of $\phi_{dy} = 0$ is called “strict price-level targeting” and the specification of $\phi_\pi = \phi_{dy}$ is called “nominal GDP level targeting.”²¹ These labels are because these specifications are implied respectively by such targeting rules.²²

In each specification of the monetary policy rules, three requirements are imposed on the coefficients, following Schmitt-Grohé and Uribe (2007b). First, the coefficients guarantee local determinacy of the rational expectations equilibrium. Second, they satisfy $1 \leq \phi_\pi \leq 10$, $0 \leq \phi_{dy} \leq 10$, and $0 \leq \phi_r < 1$. Last, they meet the condition on the volatility of the policy rate, $2(\text{Var}(r_t))^{0.5} < r - 1$. Then, a combination of the coefficients that fulfills these three requirements and maximizes the welfare measure (52) is computed using the second-order approximation to the equilibrium conditions of the model around the steady state.

In deriving a welfare-maximizing monetary policy rule, this paper focuses on the financial shock only. That is, such a rule is derived under the condition that only the financial shocks occur in the economy. This exclusive focus allows us to characterize the welfare-maximizing rule from the perspective of the financial shock, which not only constitutes one of the most important driving forces in U.S. business cycles, as argued by Jermann and Quadrini (2012), but also causes a slow recovery in our model, as shown in

²⁰For first-difference rules, see, e.g., Orphanides (2003).

²¹For recent discussions on nominal GDP level targeting, see, for example, Woodford (2012) and English, López-Salido, and Tetlow (2013).

²²One point emphasized here is that our specifications of the price-level targeting rules and the nominal GDP level targeting rule are more implementable than the “original” specifications in which the current policy rate is adjusted in response to the past policy rate and the current deviations of the price-level and the GDP level from their target paths, because the original specifications grant leeway in the choice of the target paths.

the preceding section. Therefore, the financial shock is worth analyzing independently from other shocks. In computing the welfare-maximizing rule, the standard deviation of the financial shock is set at 0.98 percent as in Table 2 of Jermann and Quadrini (2012).

For each specification of the monetary policy rules, Table 2 shows a welfare-maximizing combination of its coefficients in reaction to the financial shocks. In this table, three findings are detected. First of all, a welfare-maximizing monetary policy rule features a strong response to output. Within the rule specifications and coefficient requirements, the welfare-maximizing rule is the flexible inflation-targeting rule (50) with $\phi_\pi = 1$, $\phi_{dy} = 10$, and $\phi_r = 0.98$. In this rule, the policy response to output hits its upper bound, while the one to inflation hits its lower bound. Even if the policy response to wage inflation, $\phi_{\pi_w} (\log(\pi_t W_t / W_{t-1}) - \log(\pi_w))$, is introduced in the rule (50) as in Schmitt-Grohé and Uribe (2006, 2007a), along with the requirement $0 \leq \phi_{\pi_w} \leq 10$, the welfare-maximizing rule remains the same as in the absence of such a policy response (i.e., the welfare-maximizing coefficients are $\phi_\pi = 1$, $\phi_{dy} = 10$, $\phi_r = 0.98$, and $\phi_{\pi_w} = 0$).²³

The finding that the welfare-maximizing rule calls for a strong response to output contrasts starkly with Schmitt-Grohé and Uribe (2006, 2007a, b), who argue that a welfare-maximizing monetary policy rule features a muted response to output. This contrast arises from two factors. First, the type of the shock considered in deriving a welfare-maximizing monetary policy rule is different. Our paper focuses only on the financial shock, while their papers consider mainly a TFP shock. Second, Schmitt-Grohé and Uribe (2006, 2007a) include a policy response to wage inflation in their policy rules, and Schmitt-Grohé and Uribe (2007b) assume no nominal wage rigidity in their model. Indeed, when an exogenous TFP shock is introduced in our model instead of

²³As emphasized in the preceding section, nominal wage rigidity is a crucially important factor for describing a slow recovery from an adverse financial shock. In the absence of this rigidity, the magnitude of a permanent decline in output in response to an adverse financial shock is much smaller than in the presence of the rigidity. As a consequence, if the rigidity is abstracted from our model as in Schmitt-Grohé and Uribe (2007b), the flexible inflation-targeting rule (50) has its welfare-maximizing coefficients $\phi_\pi = 3.84$, $\phi_{dy} = 2.85$, and $\phi_r = 0.87$.

the financial shock and follows the stationary first-order autoregressive process with the persistence parameter of 0.9457 and the innovation standard deviation of 0.45 percent as in Table 2 of Jermann and Quadrini (2012), the flexible inflation-targeting rule (50) contains its welfare-maximizing coefficients $\phi_\pi = 10$, $\phi_{dy} = 5.86$, and $\phi_r = 0.86$, so that the rule shows a stronger response to inflation than to output. Then, if the rule (50) allows a policy response to wage inflation, the resulting rule has its welfare-maximizing coefficients $\phi_\pi = 4.39$, $\phi_{dy} = 0$, $\phi_r = 0$, and $\phi_{\pi_w} = 10$, so that it shows no response to output in line with their result. Furthermore, if nominal wage rigidity is abstracted from our model as in Schmitt-Grohé and Uribe (2007b), the flexible inflation-targeting rule (50) has its welfare-maximizing coefficients $\phi_\pi = 10$, $\phi_{dy} = 0$, and $\phi_r = 0$, so that it shows no response to output in line with their result.

The second finding we can see in the table is that the welfare gain from output stabilization is much more substantial than in the model where TFP growth is exogenously given. The welfare gain from adopting the welfare-maximizing rule relative to the benchmark rule (i.e., the flexible inflation-targeting rule (50) with $\phi_\pi = 1.5$, $\phi_{dy} = 0.25$, and $\phi_r = 0.7$) is huge. It is indeed a permanent increase in consumption of 22.40 percentage points. This gain is about two orders of magnitude greater than that attained under the welfare-maximizing rule in the model without the endogenous mechanism of TFP growth, which is the flexible price-level targeting rule (53) with $\phi_\pi = 7.82$, $\phi_{dy} = 4.36$, and $\phi_r = 0$.²⁴ Moreover, the table demonstrates that the huge welfare gain arises mostly from an improvement in the bias of the rate of technological change γ_t^* in the welfare measure (52). An adverse financial shock generates a slowdown in TFP growth and hence balanced growth, and thereby causes a permanent decline in consumption. This decline induces a welfare loss, which is captured as a decrease in the bias of the rate of technological change. In the model, monetary policy has an influence on TFP. Thus, the

²⁴Notice that in the model without the endogenous TFP growth mechanism, output stabilization is not welfare-maximizing, so that there is a welfare loss from it relative to the welfare-maximizing rule.

strong policy response to output under the welfare-maximizing rule subdues the slowdown in TFP growth and thereby ameliorates social welfare through an improvement in the bias.

Last, the strict inflation or price-level targeting rule induces a sizable welfare loss relative to the welfare-maximizing rule. The strict inflation targeting rule with its welfare-maximizing coefficients $\phi_\pi = 10$ and $\phi_r = 0$ yields lower welfare by a 1.38 percentage point permanent decline in consumption relative to the welfare-maximizing rule, and the strict price-level targeting rule with its welfare-maximizing coefficients $\phi_\pi = 10$ and $\phi_r = 0$ generates lower welfare by a 1.21 percentage point permanent decline in consumption. This is because these rules have no policy response to output and thus cannot directly mitigate a slowdown in TFP growth caused by an adverse financial shock. On the other hand, the nominal GDP growth or level targeting rule performs well, even compared with the welfare-maximizing rule. Indeed, the welfare gain from adopting the welfare-maximizing rule relative to the nominal GDP growth targeting rule with its welfare-maximizing coefficients $\phi_\pi = \phi_{dy} = 10$ and $\phi_r = 0.96$ is a permanent increase in consumption of only 0.04 percentage point, while the one relative to the nominal GDP level targeting rule with its welfare-maximizing coefficients $\phi_\pi = \phi_{dy} = 1$ and $\phi_r = 0.68$ is a permanent increase in consumption of only 0.03 percentage point. Because the actual policy responses to inflation in the welfare-maximizing rule, the nominal GDP growth targeting rule, and the nominal GDP level targeting rule, $\phi_\pi(1 - \phi_r)$, are respectively 0.02, 0.39, and 0.32, the welfare-maximizing rule contains a much weaker response to inflation than the two nominal GDP targeting rules. This implies that the size of the policy response to inflation has a minor effect on welfare in reacting to the financial shocks. One point emphasized here is that both the nominal GDP targeting rules induce higher interest-rate volatility than the welfare-maximizing rule. This higher volatility arises from the stronger policy response to inflation under the nominal GDP targeting rules.

5.3 Financial crisis scenario simulations

Under the welfare-maximizing monetary policy rule and other rules analyzed above, this subsection conducts simulations in an illustrative financial crisis scenario.

In the scenario, the economy is hit by an adverse financial shock of $\epsilon_{\xi,t} = -0.04$ for three periods ($t = 1, 2, 3$), and this is anticipated by all economic agents in the model when the first shock emerges in period 1. A financial shock of a similar size occurred in the U.S. during the Great Recession, as can be seen in the estimate of the financial shock by Jermann and Quadrini (2012).²⁵ The anticipated financial shocks subsequent to the emergence of the first shock seem to be reasonable, because once a financial crisis occurs, the resulting financial turbulence tends to continue unfolding.

Fig. 3 plots the developments of intratemporal loans, total investment (i.e., the sum of capital investment, technology adoption investment, and R&D investment), TFP, output, the (annualized) inflation rate, and the (annualized) interest rate under the benchmark monetary policy rule (the solid line), the welfare-maximizing rule (the dashed line), the nominal GDP level targeting rule (the dotted line), and the strict price-level targeting rule (the dot-dashed line) in the financial crisis scenario. Note that the coefficients in the nominal GDP level targeting rule and the strict price-level targeting rule are the welfare-maximizing ones presented in Table 2. The figure provides us with three findings.

First, in response to the severe financial shocks, intratemporal loans drop sharply under the benchmark rule, whereas the decline in the loans is subdued under the welfare-maximizing rule. Hence, slowdowns in total investment growth and TFP growth are much less pronounced under the welfare-maximizing rule than under the benchmark rule. Consequently, output approaches the pre-crisis balanced growth path under the welfare-maximizing rule, while it does not under the benchmark rule, implying that the welfare gain from adopting the former rule relative to the latter is huge, as shown in the

²⁵ According to Fig. 2 of Jermann and Quadrini (2012), their estimated financial shock decreased by 4 percentage points, from about 1 percent to about -3 percent during the Great Recession.

preceding subsection. The inflation rate then drops under the benchmark rule, whereas it rises under the welfare-maximizing rule. This rise is because the decline in intratemporal loans of intermediate-good firms is smaller than that in the value of their collateral (i.e., net assets held by the firms), which tightens the borrowing constraint (6) and increases the associated Lagrange multiplier μ_t (i.e., real marginal cost of funds), thereby raising wholesalers' real marginal cost and hence inflation. According to these developments of inflation and output growth, the benchmark rule lowers the interest rate below a rate of zero, while the interest rate cut is subdued and the rate does not hit a rate of zero under the welfare-maximizing rule, which contains a weak policy response to inflation, i.e., $\phi_\pi(1 - \phi_r) = 0.02$.

Second, under the nominal GDP level targeting rule, the achieved levels of output and total investment are almost the same as those under the welfare-maximizing rule, implying that the welfare gain from adopting the welfare-maximizing rule relative to the nominal GDP level targeting rule is small, as shown in the preceding subsection. The inflation rate then rises for the same reason as that under the welfare-maximizing rule mentioned above. This rise in inflation induces an initial increase in the interest rate under the nominal GDP level targeting rule—which contains a relatively strong response to inflation, i.e., $\phi_\pi(1 - \phi_r) = 0.32$ —even in the financial crisis scenario, and then the interest rate is lowered to hit a rate of zero, causing relatively high interest-rate volatility, as noted in the preceding subsection.

Last, under the strict price-level targeting rule, its strong policy response to inflation (i.e., $\phi_\pi(1 - \phi_r) = 10$) stabilizes inflation much more than under the welfare-maximizing rule, which contains a weak response to inflation (i.e., $\phi_\pi(1 - \phi_r) = 0.02$). Yet the strict price-level targeting rule cannot directly mitigate a slowdown in TFP growth caused by the severe financial shocks, because it has no response to output. Consequently, output and total investment recover to the pre-crisis balanced growth path more slowly than under the welfare-maximizing rule, implying that the welfare loss from the strict price-

level targeting rule relative to the welfare-maximizing rule is sizable, as shown in the preceding subsection.

6 Concluding Remarks

This paper has developed a model that can describe a slow recovery resulting from an adverse financial shock such as the slow recoveries observed in many economies after the recent financial crisis and subsequent recession. Specifically, the Jermann and Quadrini (2012) financial friction and shock and the Comin and Gertler (2006) endogenous TFP growth mechanism have been introduced into an otherwise canonical DSGE model. With this model, the paper has examined how monetary policy should react to the financial shock in terms of social welfare. It has been shown that in the face of the financial shocks, a welfare-maximizing monetary policy rule features a strong response to output, and the welfare gain from output stabilization is much more substantial than in the model where TFP growth is exogenously given. In the presence of the endogenous TFP growth mechanism, it is crucial to take into account a welfare loss from a permanent decline in consumption caused by a slowdown in TFP growth. Moreover, compared with this rule, a strict inflation or price-level targeting rule induces a sizable welfare loss, whereas a nominal GDP growth or level targeting rule performs well, although it causes relatively high interest-rate volatility.

The paper also has conducted a financial crisis scenario simulation under the monetary policy rules. In this simulation, a slowdown in TFP growth is much less pronounced under the welfare-maximizing monetary policy rule than under the strict price-level targeting rule, and as a consequence, output recovers to its pre-crisis growth trend faster under the welfare-maximizing rule. Under the nominal GDP level targeting rule, the achieved levels of TFP and output are almost the same as those under the welfare-maximizing rule, and a smaller decline in firms' loans than that in the value of their collateral tightens their borrowing constraint and raises the marginal cost of funds and

hence inflation. Under the nominal GDP level targeting rule, this rise in inflation induces an initial increase in the interest rate even in the crisis scenario, and then the interest rate is lowered to hit a rate of zero, causing relatively high interest-rate volatility.

This paper has studied interest rate policy only. After lowering the policy rate virtually to the zero lower bound, central banks in advanced economies have been underpinning economic recovery in the wake of the recent global financial crisis using unconventional policy tools, such as forward guidance and asset purchases. The analysis of these unconventional policies in the model is left for future work.

Appendix

A Equilibrium conditions and the steady state of the model

This appendix presents equilibrium conditions and the steady state of the model in terms of stationary variables.

A.1 Equilibrium conditions

With 33 stationary variables $y_t = Y_t/A_{t-1}^*$, $c_t = C_t/A_{t-1}^*$, $i_t = I_t/A_{t-1}^*$, $k_t = K_t/A_{t-1}^*$, $w_t = W_t/A_{t-1}^*$, $l_t = L_t/A_{t-1}^*$, $d_t = D_t/A_{t-1}^*$, $b_t = B_t/A_{t-1}^*$, $i_{d,t} = I_{d,t}/A_{t-1}^*$, $s_t = S_t/A_{t-1}^{\theta_a-1}$, $i_{a,t} = I_{a,t}A_{t-1}/A_{t-1}^*$, $v_t = V_tA_{t-1}/A_{t-1}^*$, $j_t = J_tA_{t-1}/A_{t-1}^*$, $a_t = A_t/Z_t$, $\gamma_t = A_t/A_{t-1}$, $\gamma_t^* = A_t^*/A_{t-1}^*$, $\gamma_t^{TFP} = TFP_t/TFP_{t-1}$, λ_t , π_t , $\zeta_{p,t}$, $v_{p1,t}$, $v_{p2,t}$, $v_{w1,t}$, $v_{w2,t}$, u_t , n_t , r_t , μ_t , r_t^τ , φ_t , φ_t' , $\delta_{k,t}$, and $\delta_{k,t}'$, the system of equilibrium conditions consists of the following 33 equations.

$$\varphi_t = d_t + \kappa_d (d_t - d)^2, \quad (\text{A1})$$

$$\varphi_t' = 1 + 2\kappa_d (d_t - d), \quad (\text{A2})$$

$$\gamma_t^* = \gamma_t^{\frac{\theta_a-1}{1-\alpha}}, \quad (\text{A3})$$

$$\gamma_t^{TFP} = \frac{\zeta_{p,t-1}}{\zeta_{p,t}} (\gamma_{t-1}^*)^{1-\alpha}, \quad (\text{A4})$$

$$\delta_{k,t} = \delta_k + \delta_1 (u_t - 1) + \frac{\delta_2}{2} (u_t - 1)^2, \quad (\text{A5})$$

$$\delta_{k,t}' = \delta_1 + \delta_2 (u_t - 1), \quad (\text{A6})$$

$$r_t^\tau = 1 + (1 - \tau)(r_t - 1), \quad (\text{A7})$$

$$l_t = w_t n_t + i_t + v_t [\gamma_t - (1 - \delta_a)], \quad (\text{A8})$$

$$l_t = \xi_t \left(k_t + v_t \gamma_t - \frac{b_t}{r_t} \right), \quad (\text{A9})$$

$$0 = \theta_x s_t \varphi_t' n_t^{1-\alpha} \left(\frac{u_t k_{t-1}}{\gamma_{t-1}^*} \right)^\alpha + \frac{b_t}{r_t^\tau} - w_t n_t - i_t - v_t [\gamma_t - (1 - \delta_a)] - \varphi_t - \frac{b_{t-1}}{\gamma_{t-1}^* \pi_t}, \quad (\text{A10})$$

$$\frac{1 - \alpha}{\alpha} = \frac{w_t n_t}{\delta_{k,t}' u_t k_{t-1} / \gamma_{t-1}^*}, \quad (\text{A11})$$

$$s_t = \left(\frac{1}{\varphi'_t} + \mu_t \right) \left(\frac{w_t}{1 - \alpha} \right)^{1 - \alpha} \left(\frac{\delta'_{k,t}}{\alpha} \right)^\alpha, \quad (\text{A12})$$

$$1 = E_t \left[\frac{\beta c_t}{\gamma_t^* c_{t+1}} \frac{\alpha s_{t+1} u_{t+1}^\alpha \left(\frac{n_{t+1}}{k_t / \gamma_t^*} \right)^{1 - \alpha} + (1 - \delta_{k,t+1}) (1 / \varphi'_{t+1} + \mu_{t+1})}{1 / \varphi'_t + \mu_t (1 - \xi_t)} \right], \quad (\text{A13})$$

$$1 = E_t \left[\frac{\beta c_t}{\gamma_t^* c_{t+1}} \frac{r_t^\tau}{\pi_{t+1}} \frac{\varphi'_t}{\varphi'_{t+1}} \right] + \mu_t \xi_t \varphi'_t \frac{r_t^\tau}{r_t}, \quad (\text{A14})$$

$$v_t = E_t \left[\frac{\beta c_t}{\gamma_t c_{t+1}} \frac{(\theta_x - 1) s_{t+1} n_{t+1}^{1 - \alpha} \left(\frac{u_{t+1} k_t}{\gamma_t^*} \right)^\alpha + (1 - \delta_a) v_{t+1} (1 / \varphi'_{t+1} + \mu_{t+1})}{1 / \varphi'_t + \mu_t (1 - \xi_t)} \right], \quad (\text{A15})$$

$$y_t = \frac{1}{\zeta_{p,t}} n_t^{1 - \alpha} \left(\frac{u_t k_{t-1}}{\gamma_{t-1}^*} \right)^\alpha, \quad (\text{A16})$$

$$1 = (1 - \xi_p) \left(\theta_y \frac{v_{p1,t}}{v_{p2,t}} \right)^{1 - \eta_y} + \xi_p \left(\frac{\pi}{\pi_t} \right)^{1 - \eta_y}, \quad (\text{A17})$$

$$v_{p1,t} = \theta_x s_t \varphi'_t \frac{y_t}{c_t} + \beta \xi_p E_t \left[\left(\frac{\pi}{\pi_{t+1}} \right)^{-\eta_y} v_{p1,t+1} \right], \quad (\text{A18})$$

$$v_{p2,t} = \frac{y_t}{c_t} + \beta \xi_p E_t \left[\left(\frac{\pi}{\pi_{t+1}} \right)^{1 - \eta_y} v_{p2,t+1} \right], \quad (\text{A19})$$

$$\zeta_{p,t} = (1 - \xi_p) \left(\theta_y \frac{v_{p1,t}}{v_{p2,t}} \right)^{-\eta_y} + \xi_p \left(\frac{\pi}{\pi_t} \right)^{-\eta_y} \zeta_{p,t-1}, \quad (\text{A20})$$

$$k_t = (1 - \delta_{k,t}) \frac{k_{t-1}}{\gamma_{t-1}^*} + i_t, \quad (\text{A21})$$

$$\lambda_t = \lambda_0 i_{a,t}^\omega, \quad (\text{A22})$$

$$\gamma_t = (1 - \delta_a) \left[1 + \lambda_t \left(\frac{1}{a_{t-1}} - 1 \right) \right], \quad (\text{A23})$$

$$j_t = -i_{a,t} + (1 - \delta_a) \left\{ \lambda_t v_t + (1 - \lambda_t) E_t \left[\frac{\beta c_t}{\gamma_t c_{t+1}} j_{t+1} \right] \right\}, \quad (\text{A24})$$

$$i_{a,t} = \omega (1 - \delta_a) \lambda_t \left(v_t - E_t \left[\frac{\beta c_t}{\gamma_t c_{t+1}} j_{t+1} \right] \right), \quad (\text{A25})$$

$$\frac{1}{a_t} = (1 - \delta_a) \frac{1}{\gamma_t a_{t-1}} + \chi_z \frac{i_{d,t}^\rho}{\gamma_t a_{t-1}}, \quad (\text{A26})$$

$$1 = \chi_z (1 - \delta_a) \frac{1}{a_{t-1} i_{d,t}^{1 - \rho}} E_t \left[\frac{\beta c_t}{\gamma_t c_{t+1}} j_{t+1} \right], \quad (\text{A27})$$

$$1 = E_t \left[\frac{\beta c_t}{\gamma_t^* c_{t+1}} \frac{r_t}{\pi_{t+1}} \right], \quad (\text{A28})$$

$$y_t = c_t + i_t + \kappa_d (d_t - d)^2 + i_{a,t} \left(\frac{1}{a_{t-1}} - 1 \right) + i_{d,t}, \quad (\text{A29})$$

$$1 = (1 - \xi_w) \left(\theta_n \chi_n \frac{v_{w1,t}}{v_{w2,t}} \right)^{\frac{1-\eta_n}{1+\eta_n/\nu}} + \xi_w \left(\frac{\pi}{\pi_t} \frac{w_{t-1}}{w_t} \frac{\gamma^*}{\gamma_{t-1}^*} \right)^{1-\eta_n}, \quad (\text{A30})$$

$$v_{w1,t} = n_t^{1+\frac{1}{\nu}} + \beta \xi_w E_t \left[\left(\frac{\pi}{\pi_{t+1}} \frac{w_t}{w_{t+1}} \frac{\gamma^*}{\gamma_t^*} \right)^{-\eta_n(1+\frac{1}{\nu})} v_{w1,t+1} \right], \quad (\text{A31})$$

$$v_{w2,t} = \frac{w_t n_t}{c_t} + \beta \xi_w E_t \left[\left(\frac{\pi}{\pi_{t+1}} \frac{w_t}{w_{t+1}} \frac{\gamma^*}{\gamma_t^*} \right)^{1-\eta_n} v_{w2,t+1} \right], \quad (\text{A32})$$

$$\log \frac{r_t}{r} = \phi_r \log \frac{r_{t-1}}{r} + (1 - \phi_r) \left(\phi_\pi \log \frac{\pi_t}{\pi} + \phi_{dy} \log \frac{y_t}{y_{t-1}} \frac{\gamma_{t-1}^*}{\gamma^*} \right). \quad (\text{A33})$$

When a (stationary) TFP shock is introduced in the model, it will appear in the equilibrium conditions (A4), (A10), (A12), (A13), (A15), and (A16).

A.2 The steady state

The strategy for computing the steady state is to set target values for labor n , the rate of technological change γ^* , the technology adoption rate λ , and the R&D investment-output ratio i_d/y and to pin down the values of the parameters χ_n , χ_z , λ_0 , and δ_a instead.

In the steady state, labor is normalized to unity, i.e., $n = 1$. The capital utilization rate is unity, i.e., $u = 1$. Equilibrium conditions (A2)–(A5), and (A28) yield

$$\varphi' = 1, \quad \gamma = (\gamma^*)^{\frac{1-\alpha}{\theta_a-1}}, \quad \gamma^{TFP} = (\gamma^*)^{1-\alpha}, \quad \delta_k = \delta_k, \quad r = \frac{\gamma^* \pi}{\beta},$$

and then (A7) and (A14) lead to

$$r^\tau = 1 + (1 - \tau)(r - 1), \quad \mu = \frac{1}{\xi} \left(\frac{r}{r^\tau} - 1 \right).$$

Combining (A17)–(A20) generates

$$s = \frac{1}{\theta_x \theta_y}, \quad \zeta_p = 1.$$

Equilibrium conditions (A11)–(A13), (A16), and (A21) yield

$$k = \gamma^* \left(\frac{1}{\alpha s} \left\{ \frac{\gamma^* [1 + \mu(1 - \xi)]}{\beta} - (1 - \delta_k)(1 + \mu) \right\} \right)^{-\frac{1}{1-\alpha}}, \quad \delta_1 = \frac{s\alpha}{1 + \mu} \left(\frac{\gamma^*}{k} \right)^{1-\alpha},$$

$$w = \frac{s(1 - \alpha)}{1 + \mu} \left(\frac{k}{\gamma^*} \right)^\alpha, \quad y = \left(\frac{k}{\gamma^*} \right)^\alpha, \quad i = \left(1 - \frac{1 - \delta_k}{\gamma^*} \right) k,$$

and then (A6) leads to

$$\delta'_k = \delta_1.$$

For each value of δ_a , the equations below generate a value of i_d/y . Thus, seek a value of δ_a that attains the target value for i_d/y . Equilibrium condition (A15) yields

$$v = \frac{\beta s(\theta_x - 1)}{\gamma[1 + \mu(1 - \xi)] - \beta(1 - \delta_a)(1 + \mu)} \left(\frac{k}{\gamma^*} \right)^\alpha,$$

and then (A8)–(A10) lead to

$$\begin{aligned} l &= w + i + v[\gamma - (1 - \delta_a)], & b &= r \left(k + v\gamma - \frac{l}{\xi} \right), \\ d &= \theta_x s \left(\frac{k}{\gamma^*} \right)^\alpha + \left(\frac{1}{r^\tau} - \frac{1}{\gamma^* \pi} \right) b - w - i - v[\gamma - (1 - \delta_a)]. \end{aligned}$$

Besides, (A1) generates

$$\varphi = d.$$

Solving (A24) and (A25) for j and i_a leads to

$$j = \frac{\gamma \lambda v(1 - \delta_a)(1 - \omega)}{\gamma - \beta(1 - \delta_a)[1 - \lambda(1 - \omega)]}, \quad i_a = \frac{\omega \lambda v(1 - \delta_a)[\gamma - \beta(1 - \delta_a)]}{\gamma - \beta(1 - \delta_a)[1 - \lambda(1 - \omega)]}.$$

Equilibrium conditions (A22) and (A23) yield

$$\lambda_0 = \frac{\lambda}{i_a^\omega}, \quad a = \left[1 + \frac{1}{\lambda} \left(\frac{\gamma}{1 - \delta_a} - 1 \right) \right]^{-1}.$$

Solving (A26) and (A27) for i_d and χ_z leads to

$$i_d = \frac{\beta(1 - \delta_a)[\gamma - (1 - \delta_a)]}{\gamma a} j, \quad \chi_z = \frac{\gamma - (1 - \delta_a)}{i_d^\rho},$$

so that i_d/y can be obtained.

Equilibrium condition (A29) yields

$$c = y - i - i_a \left(\frac{1}{a} - 1 \right) - i_d.$$

Combining (A30)–(A32) generates

$$v_{w1} = \frac{1}{1 - \beta \xi_w}, \quad v_{w2} = \frac{1}{1 - \beta \xi_w} \frac{w}{c}, \quad \chi_n = \frac{w}{\theta_n c}.$$

Last, (A18) and (A19) lead to

$$v_{p1} = \frac{\theta_x s}{1 - \beta \xi_p} \frac{y}{c}, \quad v_{p2} = \frac{1}{1 - \beta \xi_p} \frac{y}{c}.$$

B The second-order approximation to the welfare of households

This appendix derives a second-order approximation around the steady state to the unconditional expectation of the average utility function over households, given by (51). Substituting the demand curve for each type of specialized labor, (44), in equation (51) yields

$$SW = (1 - \beta)E \left[\sum_{t=0}^{\infty} \beta^t \left(\log(C_t) - \frac{\chi_n}{1 + 1/\nu} n_t^{1+\frac{1}{\nu}} \zeta_{w,t} \right) \right],$$

where $\zeta_{w,t}$ denotes wage dispersion given by

$$\zeta_{w,t} = \int_0^1 \left(\frac{W_{f,t}}{W_t} \right)^{-\eta_n(1+\frac{1}{\nu})} df.$$

Under the staggered wage setting of households, $\zeta_{w,t}$ can be expressed recursively as

$$\zeta_{w,t} = (1 - \xi_w) \left(\theta_n \chi_n \frac{v_{w1,t}}{v_{w2,t}} \right)^{-\frac{\eta_n(1+1/\nu)}{1+\eta_n/\nu}} + \xi_w \left(\frac{\pi}{\pi_t} \frac{w_{t-1}}{w_t} \frac{\gamma^*}{\gamma_{t-1}^*} \right)^{-\eta_n(1+\frac{1}{\nu})} \zeta_{w,t-1}, \quad (\text{B1})$$

and its steady-state value is $\zeta_w = 1$. Using $c_t = C_t/A_{t-1}^*$, the welfare measure SW can be rewritten as

$$SW = (1 - \beta) E \left[\sum_{t=0}^{\infty} \beta^t \left(\log(c_t) + \log(A_{t-1}^*) - \frac{\chi_n}{1 + 1/\nu} n_t^{1+1/\nu} \zeta_{w,t} \right) \right]. \quad (\text{B2})$$

Because $\log(A_t^*)$ follows, by definition, the process $\log(A_t^*) = \log(A_{t-1}^*) + \log(\gamma_t^*)$, subtracting $(1 - \beta) \sum_{t=0}^{\infty} \beta^t \log(\bar{A}_{t-1}^*)$, where \bar{A}_t^* is the deterministic trend governed by $\bar{A}_{-1}^* = A_{-1}^*$, $\bar{A}_t^* = \gamma^* \bar{A}_{t-1}^*$, from both sides of (B2) makes the resulting welfare measure SW^* stationary, given by

$$\begin{aligned} SW^* &= SW - (1 - \beta) \sum_{t=0}^{\infty} \beta^t \log(\bar{A}_{t-1}^*) \\ &= (1 - \beta) E \left[\sum_{t=0}^{\infty} \beta^t \left(\log(c_t) + \log\left(\frac{A_{t-1}^*}{\bar{A}_{t-1}^*}\right) - \frac{\chi_n}{1 + 1/\nu} n_t^{1+\frac{1}{\nu}} \zeta_{w,t} \right) \right]. \end{aligned} \quad (\text{B3})$$

We now approximate the stationary welfare measure SW^* around the steady state up to the second order. The term related to detrended consumption c_t^* in (B3) is ap-

proximated around the steady state as

$$(1 - \beta)E \left[\sum_{t=0}^{\infty} \beta^t \log(c_t) \right] \approx \log(c) + \frac{\varepsilon_c}{c} - \frac{Var(c_t)}{2c^2}, \quad (\text{B4})$$

where $\varepsilon_c = E(c_t) - c$ denotes the bias associated with detrended consumption c_t and is of the second order. The term related to $A_{t-1}^*/\bar{A}_{t-1}^*$ in (B3) is approximated as

$$\begin{aligned} (1 - \beta)E \left[\sum_{t=0}^{\infty} \beta^t \log \left(\frac{A_{t-1}^*}{\bar{A}_{t-1}^*} \right) \right] &= (1 - \beta) \sum_{t=0}^{\infty} \beta^t E \left[\log \left(\prod_{h=0}^{t-1} \frac{\gamma_h^*}{\gamma^*} \right) \right] \\ &= (1 - \beta) \sum_{t=0}^{\infty} \beta^t E \left[\sum_{h=0}^{t-1} \log \left(\frac{\gamma_h^*}{\gamma^*} \right) \right] = E \left[\log \left(\frac{\gamma_t^*}{\gamma^*} \right) \right] (1 - \beta) \sum_{t=0}^{\infty} \beta^t t \\ &= \frac{\beta}{1 - \beta} E \left[\log \left(\frac{\gamma_t^*}{\gamma^*} \right) \right] \approx \frac{\beta}{1 - \beta} \left(\frac{\varepsilon_{\gamma^*}}{\gamma^*} - \frac{Var(\gamma_t^*)}{2(\gamma^*)^2} \right), \end{aligned} \quad (\text{B5})$$

where $\varepsilon_{\gamma^*} = E(\gamma_t^*) - \gamma^*$ denotes the bias associated with the rate of technological change γ_t^* and is of the second order. The term related to labor in (B2) is approximated as

$$(1 - \beta)E \sum_{t=0}^{\infty} \beta^t n_t^{1+\frac{1}{\nu}} \zeta_{w,t} \approx 1 + \left(1 + \frac{1}{\nu} \right) \varepsilon_n + \varepsilon_{\zeta_w} + \frac{1 + 1/\nu}{\nu} \frac{Var(n_t)}{2}, \quad (\text{B6})$$

where $n = \zeta_w = 1$ is used to derive this approximation and where $\varepsilon_n = E(n_t) - n$ and $\varepsilon_{\zeta_w} = E(\zeta_{w,t}) - \zeta_w$ denote the biases associated with labor n_t and with the wage dispersion $\zeta_{w,t}$ and are of the second order.

From (B4)–(B6), the second-order approximation to SW^* in (B3) around the steady state is given by (52), where terms independent of monetary policy are subtracted.

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Table 1: Parameterization of the quarterly model.

Parameter	Description	Value
<i>Standard parameters in DSGE models</i>		
β	Subjective discount factor	0.9975
γ^*	Steady-state gross rate of technological change	1.0025
n	Steady-state labor	1
ν	Elasticity of labor supply	1
α	Capital elasticity of output	0.36
u	Steady-state capital utilization rate	1
δ_k	Steady-state capital depreciation rate	0.025
δ_2/δ_1	Steady-state elasticity of capital depreciation	0.5
ξ_p, ξ_w	Degree of price/wage rigidity	0.75
η_y, η_n	Elasticity of substitution among wholesale goods/labor	11
π	Steady-state gross inflation rate	1.005
ϕ_r	Policy rate smoothing	0.7
ϕ_π	Policy response to inflation	1.5
ϕ_{dy}	Policy response to output growth	0.25
<i>Parameters regarding technology innovation and adoption</i>		
η_x, η_a	Elasticity of substitution among intermediate/final goods	2.67
λ	Steady-state probability of technology adoption	0.025
ω	Elasticity of technology adoption probability	0.95
ρ	Elasticity of R&D productivity	0.8
i_d/y	Steady-state ratio of R&D investment to output	0.025
<i>Parameters regarding financial friction and shock</i>		
ξ	Steady-state probability of foreclosure	0.1634
κ_d	Elasticity of dividend payment costs	0.146
τ	Tax benefit	0.35
ρ_ξ	Financial shock persistence	0.9703

Table 2: Welfare-maximizing combinations of coefficients of monetary policy rules in reaction to financial shocks.

Policy rule specification	ϕ_π	ϕ_{dy}	ϕ_r	$(Var(r_t))^{0.5}$	Welfare gain g	γ^* -bias
<i>Benchmark model</i>						
Flexible inflation targeting	1.00	10.00	0.98	0.138%	22.3953%	99.6%
Strict inflation targeting	10.00	—	0.00	0.095%	21.0159%	100.5%
Nominal GDP growth targeting	10.00	10.00	0.96	0.237%	22.3584%	99.6%
Flexible price-level targeting	1.00	10.00	0.98	0.319%	22.3946%	99.7%
Strict price-level targeting	10.00	—	0.00	0.072%	21.1864%	100.4%
Nominal GDP level targeting	1.00	1.00	0.68	0.278%	22.3676%	99.5%
<i>Model without the endogenous TFP growth mechanism</i>						
Flexible inflation targeting	3.33	2.84	0.96	0.063%	0.0625%	—
Flexible price-level targeting	7.82	4.36	0.00	0.245%	0.1070%	—

Note: For each of the monetary policy rules, the welfare gain g denotes the one from adopting this rule relative to the benchmark rule (i.e., the flexible inflation-targeting rule (50) with $\phi_\pi = 1.5$, $\phi_{dy} = 0.25$, and $\phi_r = 0.7$) in terms of a permanent increase in consumption, and the term “ γ^* -bias” shows the fraction in the total welfare gain of the welfare gain arising from an improvement in the bias of the rate of technological change γ_t^* .

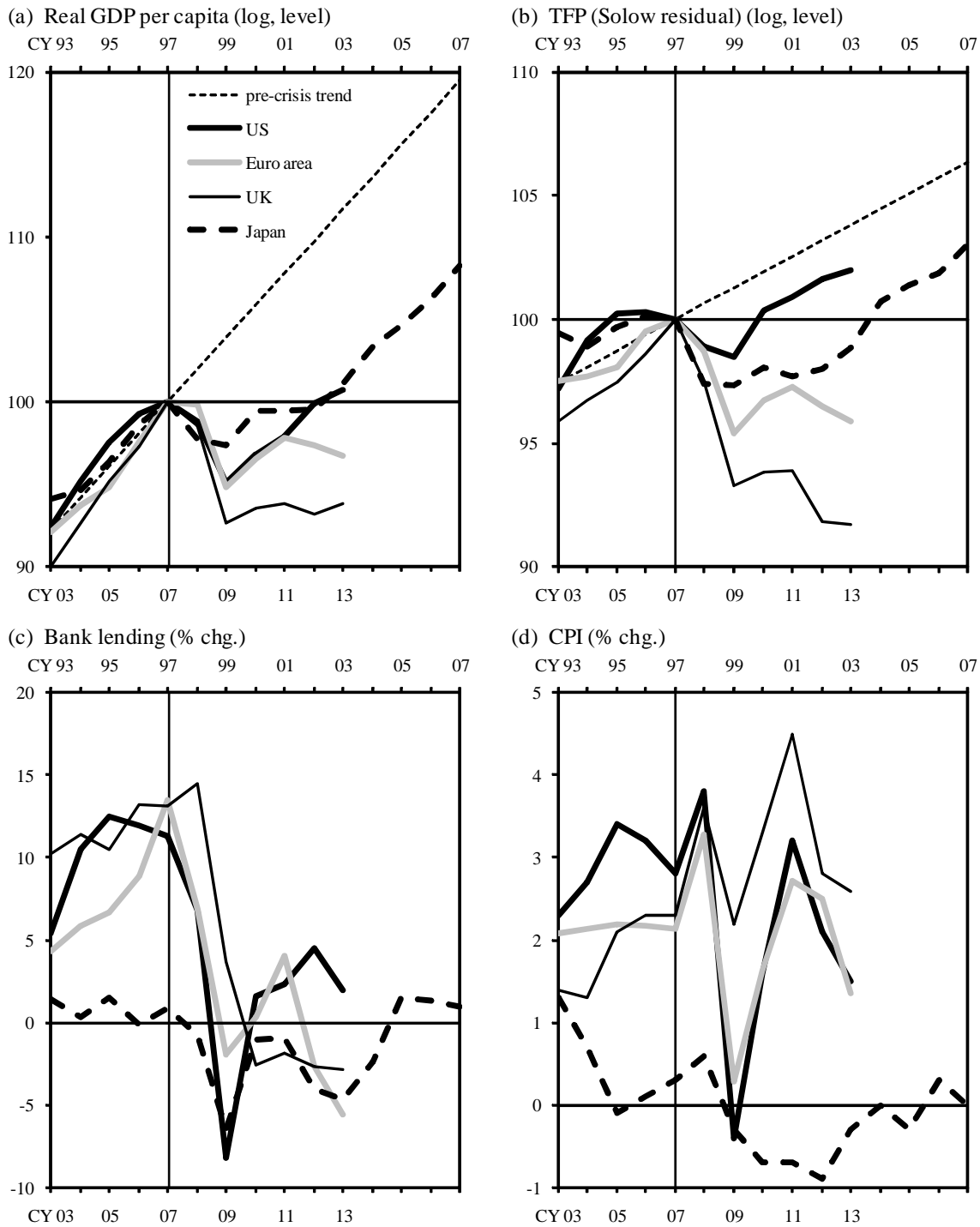


Figure 1: Economic developments around recent financial crises. Notes: In each panel of the figure, the scale of years at the top is for Japan only, while that at the bottom is for the other three economies. In Panels (a) and (b), the pre-crisis trend grows at a rate that is average over the four economies during the five years before each crisis. The data on TFP come from the Conference Board Total Economy Database.

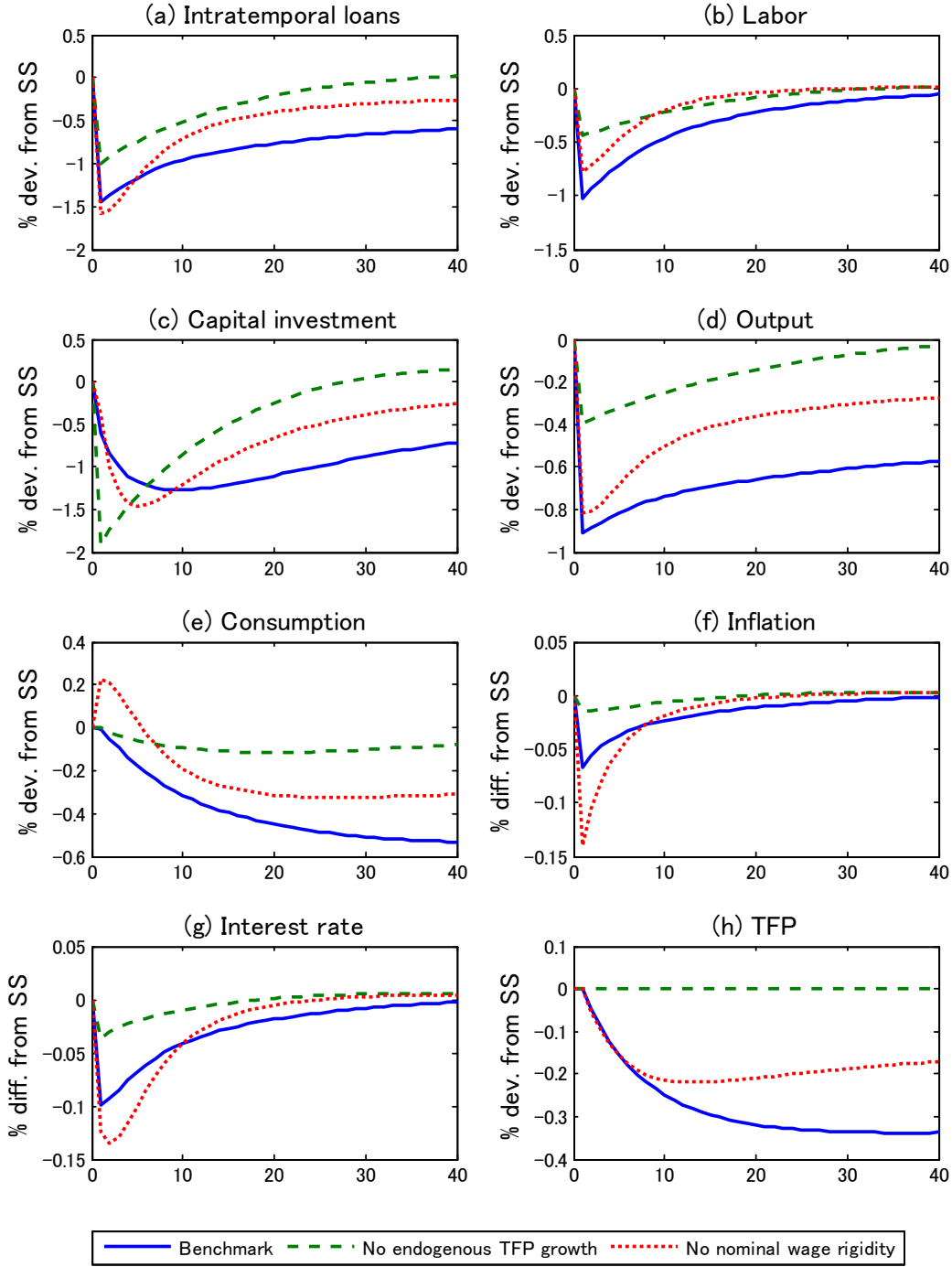


Figure 2: Impulse responses to an adverse financial shock. Note: This figure expresses labor in terms of percentage deviations from its steady-state value and the rates of inflation and interest in terms of percentage differences from their steady-state values, while the others are expressed in terms of percentage deviations from their steady-state growth paths starting from period 0.

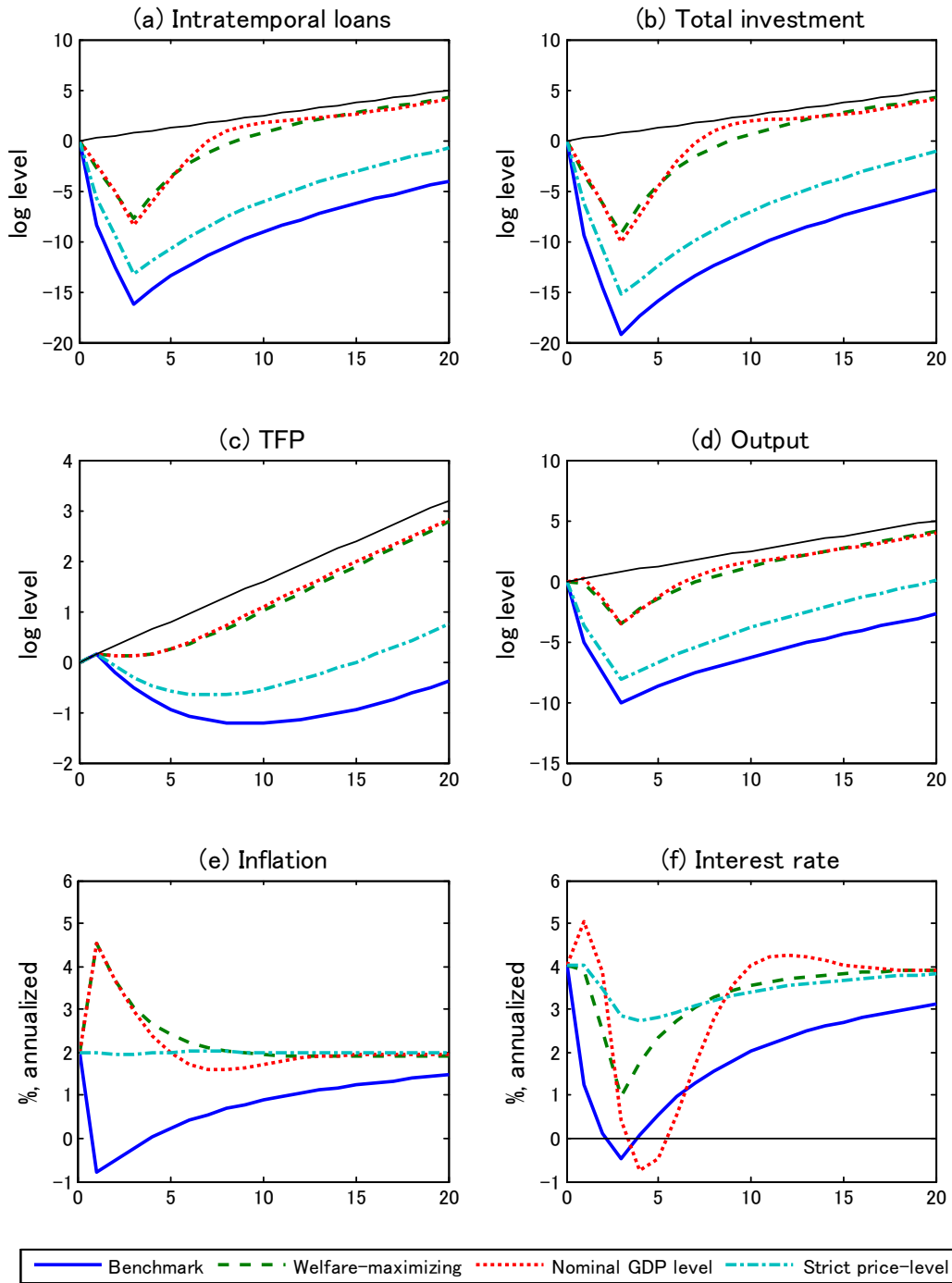


Figure 3: Financial crisis scenario simulations. Note: The coefficients in each monetary policy rule are presented in Table 2, where the welfare-maximizing monetary policy rule is the flexible inflation targeting one in the benchmark model.