Slow Post-Financial Crisis Recovery and Monetary Policy

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Globalization Institute Working Paper 347

Research Department

https://doi.org/10.24149/gwp347

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October 2018

Abstract

Post-financial crisis recoveries tend to be slow and be accompanied by slowdowns in TFP and permanent losses in GDP. To prevent them, how should monetary policy be conducted? We address this issue by developing a model with endogenous TFP growth in which an adverse financial shock can induce a slow recovery. In the model, a welfare-maximizing monetary policy rule features a strong response to output, and the welfare gain from output stabilization is much larger than when TFP expands exogenously. Moreover, inflation stabilization results in a sizable welfare loss, while nominal GDP stabilization works well, albeit causing high interest-rate volatility.

JEL Classifications: E52, O33

*The authors are grateful for comments and discussions to Tobias Adrian, Andrea Ajello, Kosuke Aoki, Gadi Barlevy, Toni Braun, Brent Bundick, Jeff Campbell, Stephen Ceccetti, Larry Christiano, Diego Comin, Wouter Den Hann, Michael Devereux, Taeyoung Doh, Martin Eichenbaum, Andrew Filardo, Mark Gertler, Simon Gilchrist (the editor), Marvin Goodfriend, Chris Gust, Andreas Hornstein, Yasuo Hirose, Matteo Iacoviello, Alejandro Justiniano, Enisse Kharroubi, Jinill Kim, Jun Il Kim, Nobuhiro Kiyotaki, Narayana Kocherlakota, Robert Kollman, Andrew Lee Smith, Giovanni Lombardo, Thomas Lubik, Christian Matthes, Jose Mustre-del-Rio, Jun Nie, Ned Prescott, Matthias Paus- tian, Albert Queralto, Jordan Rappaport, Maarten Ridder, Pierre-Daniel Sarte, Stephanie Schmitt-Grohe, Mototsugu Shintani, Jae Sim, Yuta Takahashi, Yuki Teranishi, Mathias Trabandt, Nicholas Trachter, Kozo Ueda, Martin Uribe, Willem Van Zandweghe, Jon Willis, Alex Wolman, Mark Wynne, Kei-Mu Yi, Tack Yun, colleagues at the Bank of Japan, and three anonymous referees, as well as participants at 2014 BOJ-IMES Conference, 22nd SJE International Symposium, BoE-BHC-CEPR-CFM Workshop on Finance, Investment and Productivity, 1st SJTU Workshop on Macro Finance, 10th Dynare Conference, Fall 2014 Midwest Macro Meeting, SWET 2014, 16th Macro Conference, 7th GRIPS International Conference, and seminars at the BIS, the Federal Reserve Board, and the Federal Reserve Banks of Chicago, Kansas City, and Richmond. The views expressed in this paper are those of the authors and do not necessarily reflect the official views of the Bank of Japan, the Federal Reserve Bank of Dallas or the Federal Reserve System.

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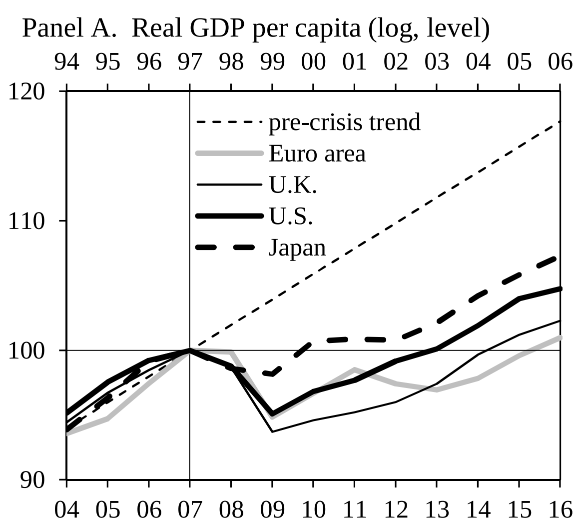
In the aftermath of the global financial crisis of 2007–08, many economies have been faced with slow recoveries from post-crisis recessions. In the euro area, the U.K. and the U.S., for instance, GDP has not recovered to its pre-crisis growth trend since the onset of the crisis, as illustrated in panel A of Figure 1. According to the literature including Cerra and Saxena (2008), Reinhart and Rogoff (2009), and Reinhart and Reinhart (2010), financial crises tend to be followed by slow recoveries in which real economic activity scarcely returns to its original growth trend, resulting in a massive permanent loss of GDP. In fact, since the financial crisis of 1997, Japan has experienced no recovery to the pre-crisis economic growth trend and a considerable permanent loss of GDP, as shown in the panel.[1] The slow post-financial crisis recoveries therefore cast doubt on the validity of the argument in the macroeconomic literature starting from Lucas (1987) that welfare costs of business cycles are small enough that they do not justify stabilization policy.[2]

Figure 1: Economic developments around the most recent financial crises



Notes: The figure plots the developments of real GDP per capita and TFP (Solow residual) around the global financial crisis of 2007–08 in the euro area, the U.K., and the U.S. and around the financial crisis of 1997 in Japan. In each panel, the scale of years at the top is for Japan only, while that at the bottom is for the other three economies The pre-crisis trend is an average over the four economies during the five years up to each crisis. The TFP data is the adjusted series in The Conference Board Total Economy Database.

[1] In 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.

[2] Lucas (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).

Against the backdrop, this paper addresses the questions of whether and to what extent monetary policy is able to ameliorate social welfare in the face of a financial crisis that is followed by a slow recovery—no recovery of GDP to its pre-crisis growth trend. More specifically, 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)?[3] To examine the questions, this paper develops a model in which an adverse financial shock can induce a severe recession and a subsequent slow recovery. The paper then investigates how monetary policy should react to the financial shock in terms of social welfare, and derives implications for monetary policy.

Our model is motived by the observation of International Monetary Fund (2009) that slowdowns in total factor productivity (TFP) were a significant cause of slow recoveries following banking crises around the globe during the past 40 years.[4] Indeed, as a main source of Japan's prolonged stagnation, Hayashi and Prescott (2002) point to a TFP slowdown in the wake of the collapse of asset price bubbles in the early 1990s. This slowdown continued in the post-1997 financial crisis period, as displayed in panel B of Figure 1. This panel also shows that, since the onset of the global financial crisis of 2007–08, TFP slowdowns have been measured as well, particularly in the euro area and the U.K. Our paper thus introduces not only a financial friction and shock but also endogenous TFP growth in an otherwise canonical dynamic stochastic general equilibrium (DSGE) model with nominal rigidities and monetary policy rules that can be found in the literature including Christiano, Eichenbaum, and Evans (2005) and Smets and Wouters (2007).

In the model, 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). An adverse shock to the

[3] Schmitt-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 (with neither financial friction nor endogenous TFP growth).

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

borrowing capacity—which is called a "financial shock" following Jermann and Quadrini—is amplified by endogenous TFP growth and nominal rigidities as well as the financial friction, thus inducing a slow recovery. Specifically, the adverse financial shock tightens firms' financing and thereby dampens their activities, which in turn has a significant negative impact on the economy as a whole by decreasing activities not only on the demand side but also on the supply side of the economy. The effect on the supply side, such as the sectors of R&D and technology adoption, induces a persistent decline in TFP and thus can cause a permanent decline in output relative to a pre-shock balanced growth path. The possibility of permanent declines in output and other real variables relative to the path 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 utilizes the model to analyze a class of monetary policy rules that adjust the current policy rate in response to the contemporaneous rates of inflation and output growth as well as the past policy rates. To make the analysis more empirically plausible, the model includes multiple shocks, such as not only the financial shock but also a TFP shock and a government spending shock, which are all estimated using U.S. data.

Our paper finds that a welfare-maximizing monetary policy rule features a strong response to output and a weak response to inflation in the model. This feature is inherited from a welfare-maximizing rule that is derived when considering only the financial shock. Our finding contrasts sharply with the result of Schmitt-Grohé and Uribe (2006, 2007a, b) that a welfare-maximizing rule features a muted response to output and focuses on inflation stabilization in their models. There are two reasons for the contrast. First, TFP grows endogenously in our model, whereas it expands exogenously in theirs. This gives rise to a strong response to output in our welfare-maximizing rule. Second, in deriving a welfare-maximizing rule, our paper takes into account the financial shock as well as the TFP and government spending shocks, while their papers consider only the latter two shocks. This generates a weak response to inflation in our welfare-maximizing rule.

The paper also demonstrates that the welfare gain from output stabilization is much more substantial than in the model where TFP expands exogenously. In the presence of endogenous TFP growth, it is crucial to take into account a welfare loss from a permanent decline in consumption caused by a slowdown in TFP.[5] Moreover, compared with the welfare-maximizing monetary policy rule, a strict inflation or price-level targeting rule results in a sizable welfare loss due to no response to output. By contrast, a nominal GDP growth or level targeting rule performs well, although it causes relatively high interest-rate volatility.

Related Literature.—The slow recoveries observed in many advanced economies after the global financial crisis of 2007–09 as well as in Japan after the financial crisis of 1997 have stimulated a literature that focuses on endogenous TFP growth as a source of the slowness in the recoveries. This literature covers, for instance, Comin (2011), Queraltó (2013), Anzoategui et al. (2017), Moran and Queraltó (2017), Guerron-Quintana and Jinnai (2018), Benigno and Fornaro (2017), and Bianchi, Kung, and Morales (2017). Our study is closely related to the first five papers in that all of them are based on the expanding-variety framework (i.e., horizontal innovations) following Romer (1990) and Comin and Gertler (2006).[6] However, our study differs from the papers in three respects. First of all, our model assumes that the production sector faces the financial friction, as opposed to the technology adoption sector as in Queraltó or the R&D sector as in Guerron-Quintana and Jinnai. This is a fundamental element to the amplification mechanism of the financial shock from the production sector (the technology demand side) to TFP through the sectors of R&D and technology adoption (the supply side). Second, our model also sheds light on the role of nominal rigidities as a crucially important amplifier of the financial shock along with endogenous TFP growth as well as the financial friction. Last, our analysis examines welfare-maximizing monetary policy rules in the face of financial shocks that can cause a slow recovery, while Moran and Queraltó investigate to what extent monetary policy can

[5] Similarly, Barlevy (2004) argues that business cycle fluctuations can affect welfare by influencing the growth rate of consumption, in contrast to Lucas (1987, 2003). Moreover, against the standard dichotomy in macroeconomics that separates economic growth from business cycle fluctuations, Ramey and Ramey (1995) present the cross-country evidence that countries with larger fluctuations have lower growth.

[6] Benigno and Fornaro (2017) and Bianchi, Kung, and Morales (2017) are based on the Schumpeterian growth framework (i.e., vertical innovations) following Aghion and Howitt (1992) and Grossman and Helpman (1991).

exert influence on TFP, using impulse responses to a monetary policy shock.

Other studies that explain the slow recoveries from a distinct perspective include, for example, Calvo, Coricelli, and Ottonello (2014), who focus on jobless and wageless recoveries and the role of inflation for them; Schmitt-Grohé and Uribe (2017), who emphasize the interaction of the zero lower bound on nominal interest rates and downward nominal wage rigidity in accounting for the joint occurrence of liquidity traps and jobless recoveries; and Eggertson, Mehrotra, and Robbins (2017), who stress a persistently low or negative natural rate of interest that leads to a chronically binding zero lower bound on nominal interest rates in an overlapping generations model.[7]

Regarding the monetary policy implications, Reifschneider, Wascher, and Wilcox (2015) have done a closely related and complementary analysis. These authors conduct optimal-control exercises using a version of the FRB/US model along 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,[8] and that such endogeneity provides a strong motivation for a vigorous policy response to a weakening in aggregate demand—running a "high-pressure economy" in terms of Yellen (2016).[9] 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, the Comin and Gertler (2006) endogenous TFP growth, and nominal rigidities.

The remainder of the paper proceeds as follows. Section I presents a DSGE model of slow post-financial crisis recoveries. Section II confirms that an adverse financial shock can induce a severe recession and a subsequent slow recovery in the model. Section III conducts monetary policy analysis using the model. Section IV concludes.

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[7]See also Ottonello (2017), who takes idle physical capital into consideration.

[8]Summers (2014) argues—in contrast to Say's law—that "Lack of Demand creates Lack of Supply." Yellen (2016) refers to this kind of ideas as the hysteresis effect.

[9]For an early discussion on a high-pressure economy, see Okun (1973).

I A Model of Slow Post-Financial Crisis Recoveries

To describe a slow post-financial crisis recovery as those reported above, this paper introduces a financial friction and endogenous TFP growth in an otherwise canonical DSGE model with nominal rigidities and monetary policy rules.[10] 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.[11] TFP grows endogenously by expanding the variety of intermediate 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). Combining the financial friction, endogenous TFP growth, and nominal rigidities then generates a powerful amplification mechanism of a shock to the borrowing capacity, which is called a "financial shock" as in Jermann and Quadrini. In what follows, the behavior of each economic agent is described.

I.A Final-good firms

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

$$X_{f,t}(h) = X_{f,t}\left(\frac{P^x_{f,t}(h)}{P^x_{f,t}}\right)^{-\eta_x}. \tag{1}$$

[10] Apart from the financial friction and endogenous TFP growth, our model is fairly canonical. Indeed, the model has neither habit formation in consumption preferences, costs of investment adjustment, nor dynamic indexation in price and wage setting. This makes it clear how putting together the financial friction, endogenous TFP growth, and nominal rigidites gives rise to a novel amplification mechanism of financial shocks.

[11] Wholesalers, retailers, and employment agencies are added to the model, only for introducing price and nominal wage rigidities.

Substituting this curve in the aggregator leads to the price of final good $X_{f,t}$, $P^x_{f,t} = [\int_0^1 (P^x_{f,t}(h))^{1-\eta_x} dh]^{1/(1-\eta_x)}$.

I.B 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.

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 (package) $n_{f,t}(h)$ to produce intermediate good $X_{f,t}(h)$ according to the Cobb-Douglas production technology $X_{f,t}(h) = x_t(n_{f,t}(h))^{1-\alpha}(u_t(h)K_{f,t-1}(h))^{\alpha}$ with the capital elasticity of output $\alpha \in (0,1)$ and an economy-wide technology shock x_t, which follows a first-order autoregressive process

$$\log x_t = \rho_x \log x_{t-1} + \epsilon_{x,t}, \tag{2}$$

where $\rho_x \in [0,1)$ and $\epsilon_{x,t} \sim$ i.i.d. $N(0, \sigma_x^2)$. 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 the Cobb-Douglas production technology, along with final-good firms' demand curves (1), yields

$$\int_0^{A_{t-1}(h)} X_{f,t} \left(\frac{P^x_{f,t}(h)}{P^x_{f,t}} \right)^{-\eta_x} df = x_t \left(n_t(h)\right)^{1-\alpha} \left(u_t(h)K_{t-1}(h)\right)^{\alpha}, \tag{3}$$

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

$$K_t(h) = \left(1 - \delta_{k,t}(h)\right) K_{t-1}(h) + I_t(h), \tag{4}$$

$$A_t(h) = \left(1 - \delta_a\right) A_{t-1}(h) + \Delta_{a,t}(h), \tag{5}$$

where $I_t(h)$ is firm h's capital investment, $\Delta_{a,t}(h)$ is the number of newly adopted ideas that 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 is of 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 gross effective 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

$$P_t L_t(h) = P_t W_t n_t(h) + P_t I_t(h) + P_t V_t \Delta_{a,t}(h), \tag{6}$$

where W_t is the real wage rate and V_t is the real value of an adopted idea.[12] 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

$$P_t L_t(h) \leq \xi_t \left(P_t K_t(h) + P_t V_t A_t(h) - \frac{P_t B_t(h)}{r_t} \right). \tag{7}$$

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

[12] Jermann and Quadrini (2012) suppose that firms use an intratemporal loan to finance total payment made in the period, including payments for dividends and intertemporal debt. We choose our specification of the intratemporal loan because the assumption that firms prepay for production factors seems reasonable.

a first-order autoregressive process

$$\log \frac{\xi_t}{\xi} = \rho_\xi \log \frac{\xi_{t-1}}{\xi} + \epsilon_{\xi,t}, \tag{8}$$

where $\rho_\xi \in [0,1)$ and $\epsilon_{\xi,t} \sim$ i.i.d. $N(0,\sigma_\xi^2)$ denotes 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 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

$$\begin{aligned} &P_t W_t n_t(h) + P_t I_t(h) + P_t V_t \Delta_{a,t}(h) + P_t \varphi_t(h) A_{t-1}^* + P_{t-1} B_{t-1}(h) \\ &= \int_0^{A_{t-1}(h)} P_{f,t}^x(h) X_{f,t} \left(\frac{P_{f,t}^x(h)}{P_{f,t}^x} \right)^{-\eta_x} df + \frac{P_t B_t(h)}{r_t^\tau}. \end{aligned} \tag{9}$$

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 $A_t(h)$ so as to maximize the expected present discounted value of the current and future dividends $E_0[\sum_{t=0}^\infty m_{0,t} D_t(h)]$ subject to (3)–(9), 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 the maximization problem. Then, substituting the first-order condition for dividends in those for capital and intertemporal debt yields

$$1 = E_t \left[m_{t,t+1} \frac{\alpha S_{t+1} x_{t+1} u_{t+1}^\alpha n_{t+1}^{1-\alpha} / K_t^{1-\alpha} + (1-\delta_{k,t+1})\big(1/\varphi_{t+1}' + \mu_{t+1}\big)}{1/\varphi_t' + \mu_t (1-\xi_t)} \right], \tag{10}$$

$$1 = E_t \left[m_{t,t+1} \frac{r_t^\tau}{\pi_{t+1}} \frac{\varphi_t'}{\varphi_{t+1}'} \right] + \mu_t \xi_t \varphi_t' \frac{r_t^\tau}{r_t}, \tag{11}$$

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 technology (3) and the borrowing constraint (7), 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

$$\frac{1-\alpha}{\alpha} = \frac{W_t n_t}{\delta'_{k,t} u_t K_{t-1}}, \tag{12}$$

$$S_t = \frac{1/\varphi'_t + \mu_t}{x_t}\left(\frac{W_t}{1-\alpha}\right)^{1-\alpha}\left(\frac{\delta'_{k,t}}{\alpha}\right)^{\alpha}, \tag{13}$$

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

$$P^x_{f,t} = P_t \theta_x S_t \varphi'_t, \tag{14}$$

where $\theta_x = \eta_x/(\eta_x - 1)$.[13] Moreover, the aggregate production technology (3), the budget constraint (9), and the first-order condition for adopted ideas can be rewritten as

$$\int_0^{A_{t-1}} X_{f,t} df = x_t n_t^{1-\alpha}(u_t K_{t-1})^{\alpha}, \tag{15}$$

$$W_t n_t + I_t + V_t\Delta_{a,t} + \varphi_t A^*_{t-1} + \frac{B_{t-1}}{\pi_t} = \theta_x S_t \varphi'_t x_t n_t^{1-\alpha}(u_t K_{t-1})^{\alpha} + \frac{B_t}{r^\tau_t}, \tag{16}$$

$$V_t = E_t\left[m_{t,t+1}\frac{(\theta_x - 1)S_{t+1}X_{f,t+1} + (1-\delta_a)V_{t+1}(1/\varphi'_{t+1} + \mu_{t+1})}{1/\varphi'_t + \mu_t(1-\xi_t)}\right]. \tag{17}$$

In the amplification mechanism of the financial shock, intermediate-good firms' demand curve for adopted ideas (17) plays an important role. Through this curve, an adverse financial shock decreases the value of adopted ideas V_t, because it does not only lower the foreclosure probability ξ_t but also tightens the borrowing constraint (7) and thus increases the associated Lagrange multiplier μ_t. As shown later, such a decrease in the value of adopted ideas 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 (5). Therefore, the adverse financial shock can cause a permanent decline in output relative to a pre-shock growth path through the persistent decline in adopted ideas (or equivalently TFP). This mechanism is strengthened when the financial shock is persistent.

[13] The symmetry among intermediate-good firms implies an identical price for each intermediate good, and thus it follows that $P^x_{f,t} = [\int_0^1 (P^x_{f,t}(h))^{1-\eta_x} dh]^{1/(1-\eta_x)} = P^x_{f,t}(h)$ for all $h \in [0,1]$.

I.C Retailers

There is a representative retailer. It produces retail goods Y_t by combining wholesale goods $\{Y_{h,t}\}_{h\in[0,1]}$ using the CES aggregator $Y_t = (\int_0^1 Y_{h,t}^{(\eta_y-1)/\eta_y} dh)^{\eta_y/(\eta_y-1)}$ 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 retail goods' price 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

$$Y_{h,t} = Y_t \left(\frac{P_{h,t}}{P_t} \right)^{-\eta_y}. \tag{18}$$

Substituting this curve in the aggregator leads to retail goods' price

$$P_t = \left(\int_0^1 P_{h,t}^{1-\eta_y} dh \right)^{\frac{1}{1-\eta_y}}. \tag{19}$$

I.D Wholesalers

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

$$X_{f,t} = Y_{h,t} \left(\frac{P_{f,t}^x}{MC_{h,t}} \right)^{-\eta_a}, \tag{20}$$

where $MC_{h,t}$ is the Lagrange multiplier on the aggregator and represents its marginal cost. Substituting this curve in the aggregator leads to $MC_{h,t} = [\int_0^{A_{t-1}} (P_{f,t}^x)^{1-\eta_a} df]^{1/(1-\eta_a)}$. This shows that the marginal cost is identical among wholesalers. Using the price equations (14), the marginal cost can be rewritten as

$$MC_t = P_t \theta_x S_t \varphi_t' A_t^{1-\theta_a}, \tag{21}$$

where $\theta_a = \eta_a/(\eta_a - 1)$. Then, from this equation and equations (14), (15), and (20), the output of wholesale good $Y_{h,t}$ is given by

$$Y_{h,t} = A_{t-1}^{\theta_a-1} x_t n_t^{1-\alpha} (u_t K_{t-1})^{\alpha}. \tag{22}$$

Using this equation, two more key equations can be derived. First, substituting equations (14), (21), and (22) in wholesalers' demand curve (20) leads to $X_{f,t} = x_t n_t^{1-\alpha} (u_t K_{t-1})^{\alpha} / A_{t-1}$. Combining this equation and intermediate-good firms' demand curve for adopted ideas (17) yields

$$V_t = E_t \left[m_{t,t+1} \frac{(\theta_x - 1) S_{t+1} x_{t+1} n_{t+1}^{1-\alpha} (u_{t+1} K_t)^{\alpha} / A_t + (1 - \delta_a) V_{t+1} (1/\varphi'_{t+1} + \mu_{t+1})}{1/\varphi'_t + \mu_t (1 - \xi_t)} \right]. \tag{23}$$

Second, aggregating wholesale goods' output equations (22), along with retailers' demand curves (18), leads to

$$Y_t = \frac{A_{t-1}^{\theta_a - 1}}{\zeta_{p,t}} x_t n_t^{1-\alpha} (u_t K_{t-1})^{\alpha} = \frac{\left(A_{t-1}^*\right)^{1-\alpha}}{\zeta_{p,t}} x_t n_t^{1-\alpha} (u_t K_{t-1})^{\alpha}, \tag{24}$$

where

$$\zeta_{p,t} = \int_0^1 \left(\frac{P_{h,t}}{P_t} \right)^{-\eta_y} dh \tag{25}$$

represents dispersion of wholesale goods' prices and where

$$A_t^* = A_t^{\frac{\theta_a - 1}{1-\alpha}} \tag{26}$$

represents the level of technology in the whole economy and its growth rate $\gamma_t^* = A_t^* / A_{t-1}^*$ denotes the gross rate of technological change. Equation (24) presents a standard Cobb-Douglas production technology, except that TFP is determined by

$$TFP_t = \frac{\left(A_{t-1}^*\right)^{1-\alpha}}{\zeta_{p,t}} x_t, \tag{27}$$

where $(A_{t-1}^*)^{1-\alpha} / \zeta_{p,t}$ is the endogenous component of TFP and x_t represents a TFP shock.

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 by indexing to the gross steady-state inflation rate π (i.e., $P_{h,t} = \pi P_{h,t-1}$), where π is the steady-state value of the gross inflation rate π_t, while the remaining fraction $1 - \xi_p$ chooses the price $\tilde{P}_{h,t}$ that maximizes the associated profit $E_t[\sum_{f=0}^{\infty} \xi_p^f M_{t,t+f} (\pi^f \tilde{P}_{h,t} - MC_{t+f}) Y_{h,t+f|t}]$ subject to 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

$$\frac{\tilde{P}_{h,t}}{P_t} = \theta_y \frac{\upsilon_{p1,t}}{\upsilon_{p2,t}}, \tag{28}$$

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

$$\upsilon_{p1,t} = \frac{MC_t}{P_t}\frac{Y_t}{C_t} + \beta\xi_p\, E_t\left[\left(\frac{\pi}{\pi_{t+1}}\right)^{-\eta_y} \upsilon_{p1,t+1}\right], \tag{29}$$

$$\upsilon_{p2,t} = \frac{Y_t}{C_t} + \beta\xi_p\, E_t\left[\left(\frac{\pi}{\pi_{t+1}}\right)^{1-\eta_y} \upsilon_{p2,t+1}\right], \tag{30}$$

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 (19) and the price dispersion equation (25) can be reduced respectively to

$$1 = (1-\xi_p)\left(\frac{\tilde{P}_{h,t}}{P_t}\right)^{1-\eta_y} + \xi_p\left(\frac{\pi}{\pi_t}\right)^{1-\eta_y}, \tag{31}$$

$$\zeta_{p,t} = (1-\xi_p)\left(\frac{\tilde{P}_{h,t}}{P_t}\right)^{-\eta_y} + \xi_p\left(\frac{\pi}{\pi_t}\right)^{-\eta_y} \zeta_{p,t-1}. \tag{32}$$

I.E Technology adopters

There is a continuum of technology adopters. Each adopter owns a developed but not yet adopted idea that lies in the interval between A_{t-1} and Z_{t-1}. This adopter makes an investment $I_{a,t}$ for technology adoption using retail goods. The adopter successfully adopts the idea with probability $\lambda_t \in (0,1)$. This probability is of the form

$$\lambda_t = \lambda_0\left(\frac{A_{t-1}}{A^*_{t-1}} I_{a,t}\right)^{\omega}, \tag{33}$$

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

$$\Delta_{a,t} = (1 - \delta_a)\,\lambda_t\,(Z_{t-1} - A_{t-1})\,. \tag{34}$$

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

$$J_t = \max_{\tilde{I}_{a,t}} \left(-\tilde{I}_{a,t} + (1 - \delta_a)\,\{\lambda_t V_t + (1 - \lambda_t)\,E_t[m_{t,t+1} J_{t+1}]\} \right). \tag{35}$$

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 present discounted value $E_t[m_{t,t+1} J_{t+1}]$.

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

$$I_{a,t} = \omega\,(1 - \delta_a)\,\lambda_t\,(V_t - E_t[m_{t,t+1} J_{t+1}])\,. \tag{36}$$

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 feedback loop slows the rate of technology adoption and hence the growth rates of A_t and TFP_t. Moreover, substituting equation (36) in equation (35) leads to

$$J_t = (1 - \delta_a)\,\{(1 - \omega)\lambda_t V_t + [1 - (1 - \omega)\lambda_t]\,E_t[m_{t,t+1} J_{t+1}]\}\,, \tag{37}$$

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

I.F 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

$$Z_t = (1 - \delta_a)\,Z_{t-1} + \Phi_t I_{d,t}, \tag{38}$$

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

$$\Phi_t = \chi_z \frac{Z_{t-1}}{\left(A^*_{t-1}\right)^{\rho} I_{d,t}^{1-\rho}}, \tag{39}$$

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

$$1 = \Phi_t \left(1 - \delta_a\right) E_t[m_{t,t+1} J_{t+1}]\,. \tag{40}$$

Combining this condition and the law of motion of developed ideas (38) yields

$$I_{d,t} = \left(1 - \delta_a\right) \left[Z_t - \left(1 - \delta_a\right) Z_{t-1}\right] E_t[m_{t,t+1} J_{t+1}]\,. \tag{41}$$

Thus, a decline in the expected present discounted value of developed but not yet adopted ideas $E_t[m_{t,t+1}J_{t+1}]$—which is led by a decline in the expected present discounted value of adopted ideas $E_t[m_{t,t+1}V_{t+1}]$ because a lower value of V_t decreases J_t as in equation (37)—decreases R&D investment $I_{d,t}$. This then slows the growth rates of Z_t and hence TFP_t.

I.G 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 wage rates for specialized labor, and the rates are set in a staggered manner. A representative employment agency transforms specialized labor into labor package and provides the package 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 first problem, each household chooses consumption C_t and savings B_t to maximize the utility function

$$E_0\left[\sum_{t=0}^{\infty} \beta^t \left(\log C_t - \frac{\chi_n}{1+1/\nu} n_{f,t}^{1+1/\nu}\right)\right], \tag{42}$$

subject to the budget constraint

$$P_t C_t + \frac{P_t B_t}{r_t} = P_t W_{f,t} n_{f,t} + P_{t-1} B_{t-1} + T_{f,t}, \tag{43}$$

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 rate 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

$$1 = E_t\left[\beta \frac{C_t}{C_{t+1}} \frac{r_t}{\pi_{t+1}}\right], \tag{44}$$

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

$$n_{f,t} = n_t \left(\frac{P_t W_{f,t}}{P_t W_t}\right)^{-\eta_n}. \tag{45}$$

Substituting this curve in the aggregator leads to the nominal wage rate

$$P_t W_t = \left[\int_0^1 (P_t W_{f,t})^{1-\eta_n} df\right]^{\frac{1}{1-\eta_n}}. \tag{46}$$

The nominal wage rate 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 wage rates is set by indexing to the gross steady-state wage inflation rate $\pi_w = \pi\gamma^*$ (i.e., $P_t W_{f,t} = \pi_w P_{t-1} W_{f,t-1}$), where γ^* is the steady-state value of the gross rate of technological change γ_t^*, while the remaining fraction $1 - \xi_w$ is chosen at the nominal wage rate $P_t \tilde{W}_{f,t}$ that maximizes

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

subject to 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 (43). The first-order condition for the optimal staggered nominal wage rate $P_t \tilde{W}_{f,t}$ yields

$$\left(\frac{P_t \tilde{W}_{f,t}}{P_t W_t}\right)^{1+\frac{\eta_n}{\nu}} = \theta_n \chi_n \frac{\upsilon_{w1,t}}{\upsilon_{w2,t}}, \tag{47}$$

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

$$\upsilon_{w1,t} = n_t^{1+\frac{1}{\nu}} + \beta \xi_w \, E_t \left[\left(\frac{\pi}{\pi_{t+1}} \frac{\gamma^* W_t}{W_{t+1}} \right)^{-\eta_n \left(1+\frac{1}{\nu}\right)} \upsilon_{w1,t+1} \right], \tag{48}$$

$$\upsilon_{w2,t} = \frac{W_t n_t}{C_t} + \beta \xi_w \, E_t \left[\left(\frac{\pi}{\pi_{t+1}} \frac{\gamma^* W_t}{W_{t+1}} \right)^{1-\eta_n} \upsilon_{w2,t+1} \right]. \tag{49}$$

Under the staggered wage setting, the nominal wage rate equation (46) can be reduced to

$$1 = (1 - \xi_w) \left(\frac{P_t \tilde{W}_{f,t}}{P_t W_t} \right)^{1-\eta_n} + \xi_w \left(\frac{\pi}{\pi_t} \frac{\gamma^* W_{t-1}}{W_t} \right)^{1-\eta_n}. \tag{50}$$

I.H A 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 GDP growth

$$\log r_t = \phi_r \log r_{t-1} + (1 - \phi_r) \left[\log r + \phi_\pi (\log \pi_t - \log \pi) + \phi_{dgdp} \left(\log \frac{GDP_t}{GDP_{t-1}} - \log \gamma^* \right) \right] + \epsilon_{r,t}, \tag{51}$$

where r is the steady-state policy rate, $\phi_r \in [0, 1)$ represents the degree of policy rate smoothing, ϕ_π and ϕ_{dgdp} are the policy responses to inflation and GDP growth, and $\epsilon_{r,t} \sim$ i.i.d. $N(0, \sigma_r^2)$ denotes a monetary policy shock.[14] In the model, GDP is defined as the sum of consumption C_t, capital investment I_t, R&D investment $I_{d,t}$, and government spending G_t,

$$GDP_t = C_t + I_t + I_{d,t} + G_t, \tag{52}$$

[14] No 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 what 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 in models where TFP expands exogenously—seems to be inappropriate, because welfare losses arise not only from nominal rigidities but also from endogenous TFP growth.

while the government spending G_t is given by

$$G_t = \eta_{g,t} GDP_t, \tag{53}$$

where $\eta_{g,t}$ represents the time-varying GDP ratio of government spending and its log-deviation from the steady-state value η_g follows a first-order autoregressive process

$$\log \frac{\eta_{g,t}}{\eta_g} = \rho_g \log \frac{\eta_{g,t-1}}{\eta_g} + \epsilon_{g,t}, \tag{54}$$

where $\rho_g \in [0, 1)$ and $\epsilon_{g,t} \sim$ i.i.d. $N(0, \sigma_g^2)$ denotes a government spending shock. The retail-good market clearing condition is then given by

$$Y_t = GDP_t + \left(\varphi_t A^*_{t-1} - D_t\right) + I_{a,t}\left(Z_{t-1} - A_{t-1}\right). \tag{55}$$

In addition to the GDP components, the demand for retail goods consists of intermediate-good firms' dividend payment costs $(\varphi_t A^*_{t-1} - D_t)$ and technology adopters' investment $I_{a,t}(Z_{t-1} - A_{t-1})$.

The equilibrium conditions consist of equations (4)–(7) (without the index h and with the equality holding in (7)), (10)–(13), (16), (21), (23), (24), (26)–(34), (36)–(40), (44), (47)–(53), and (55), along with the three shock processes (2), (8), and (54).[15]

II A Financial Shock-Induced Slow Recovery

This section confirms that the model presented above possesses the capability to generate a slow recovery induced by an adverse financial shock. To this end, the model is parameterized, linearized around the steady state, and solved for the rational expectations equilibrium. Then, the model's four shocks—the financial shock, the TFP shock, the government spending shock, and the monetary policy shock—are all estimated using U.S. data. Impulse responses to an adverse financial shock show how the shock generates a slow recovery in the model. Next, key elements of the model to generate the slow recovery—endogenous TFP growth and nominal rigidities as well as the financial friction—are explained. Last, impulse responses to other shocks are analyzed to highlight the unique role of the financial shock.

[15] The equilibrium conditions and the steady state in terms of stationary variables are presented in the Online Appendix.

II.A Parameterization of the model

This section begins by parameterizing the model. The model parameters are divided into four sets. The first set contains parameters that are standard in DSGE models. The second is related to the technology innovation and adoption. The third pertains to the financial friction. The fourth includes parameters for the shock processes. Table 1 lists the parameterization of the quarterly model.

Regarding the parameters in the first set, this paper chooses the steady-state gross rate of technological change at $\gamma^* = 1.005$, the steady-state gross inflation rate at $\pi = 1.0062$, and the subjective discount factor at $\beta = 0.9979$ so as to hit the following three target rates that are averages over the pre-crisis period 1984Q1–2007Q3: the per-capita real GDP growth rate of 2 percent annually, the inflation rate of 2.47 percent annually in terms of the GDP implicit price deflator, and the nominal interest rate of 5.32 percent annually in terms of the federal funds rate. Steady-state labor is normalized to unity, i.e., $n = 1$. The paper also sets the steady-state capital utilization rate at $u = 1$, the elasticity of labor supply at $\nu = 1$, the capital elasticity of output at $\alpha = 0.36$, the steady-state capital depreciation rate at $\delta_k = 0.025$ (i.e., 10 percent annually), the steady-state elasticity of capital depreciation at $\delta_2/\delta_1 = 0.3$, the degrees of price and nominal 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 GDP ratio of government spending at $\eta_g = 0.18$, the degree of policy rate smoothing at $\phi_r = 0.7$, and the policy responses to inflation and GDP growth at $\phi_\pi = 1.7$ and $\phi_{dgdp} = 0.25$. These parameter values are more or less within the values calibrated or estimated in previous studies with DSGE models.

The values of the parameters in the second set are based on Comin and Gertler (2006) and Anzoategui et al. (2017). Following them, our paper sets the elasticities 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 $\lambda = 0.0375$ (i.e., an average duration of technology adoption of 15 years), the elasticity of the probability of technology adoption at

Table 1: Parameterization of the quarterly model

Parameter	Description	Value
	Standard parameters in DSGE models	
γ^*	Steady-state gross rate of technological change	1.005
π	Steady-state gross inflation rate	1.0062
β	Subjective discount factor	0.9979
n	Steady-state labor	1
u	Steady-state capital utilization rate	1
ν	Elasticity of labor supply	1
α	Capital elasticity of output	0.36
δ_k	Steady-state capital depreciation rate	0.025
δ_2/δ_1	Steady-state elasticity of capital depreciation	0.3
ξ_p, ξ_w	Degree of price/nominal wage rigidity	0.75
η_y, η_n	Elasticity of substitution among wholesale goods/labor	11
η_g	Steady-state GDP ratio of government spending	0.18
ϕ_r	Policy rate smoothing	0.7
ϕ_π	Policy response to inflation	1.7
ϕ_{dgdp}	Policy response to GDP growth	0.25
	Parameters regarding the technology innovation and adoption	
η_x, η_a	Elasticity of substitution among intermediate/final goods	2.67
λ	Steady-state probability of technology adoption	0.0375
ω	Elasticity of technology adoption probability	0.95
ρ	Elasticity of R&D productivity	0.8
δ_a	Obsolescence rate of ideas	0.02
	Parameters regarding the financial friction	
ξ	Steady-state probability of foreclosure	0.1634
κ_d	Elasticity of dividend payment costs	0.146
τ	Tax benefit	0.35
	Estimated parameters for the shock processes	
ρ_ξ	Financial shock persistence	0.9522
ρ_x	TFP shock persistence	0.4522
ρ_g	Government spending shock persistence	0.6310
σ_ξ	Std. dev. of financial shock	0.0200
σ_x	Std. dev. of TFP shock	0.0177
σ_g	Std. dev. of government spending shock	0.0199
σ_r	Std. dev. of monetary policy shock	0.0024

$\omega = 0.95$, the elasticity of R&D productivity at $\rho = 0.8$, and the obsolescence rate of ideas at $\delta_a = 0.02$ (i.e., 8 percent annually).[16]

As for the parameters in the third set, their values are chosen from Table 2 of Jermann and Quadrini (2012): the steady-state probability of foreclosure is $\xi = 0.1634$, the elasticity of the dividend payment costs is $\kappa_d = 0.146$, and the tax benefit is $\tau = 0.35$.

The values of the parameters in the fourth set are estimated using Bayesian methods, keeping values of the other model parameters fixed at those presented in Table 1. The estimation employs four U.S. quarterly series: real GDP per capita, hours worked, the nominal interest rate, and the debt-repurchase to GDP ratio during the period 1984Q1–2010Q3. The ratio is the same series as in Jermann and Quadrini (2012) and is used to identify the financial shock, following them. The other three series are often employed to identify the other three shocks in empirical literature on DSGE models including Smets and Wouters (2007). The demeaned first log difference is taken for the data on real GDP per capita and hours worked, while the demeaned first difference is applied to the data on the nominal interest rate and the debt-repurchase to GDP ratio. The sample period is chosen to avoid a potential regime shift in monetary policy around the early 1980s and the period of the zero lower bound on nominal interest rates. As for prior distributions, the beta distribution with mean 0.5 and standard deviation 0.1 is selected for the persistence parameters of the financial, TFP, and government spending shocks, while the inverse gamma distribution with mean of 1 (0.1) percent and standard deviation of 0.1 (0.1) percent is chosen for the standard deviations of the three shocks (the monetary policy shock). The posterior mean of these parameters is shown in the bottom part of Table 1.[17]

II.B Impulse responses to an adverse financial shock

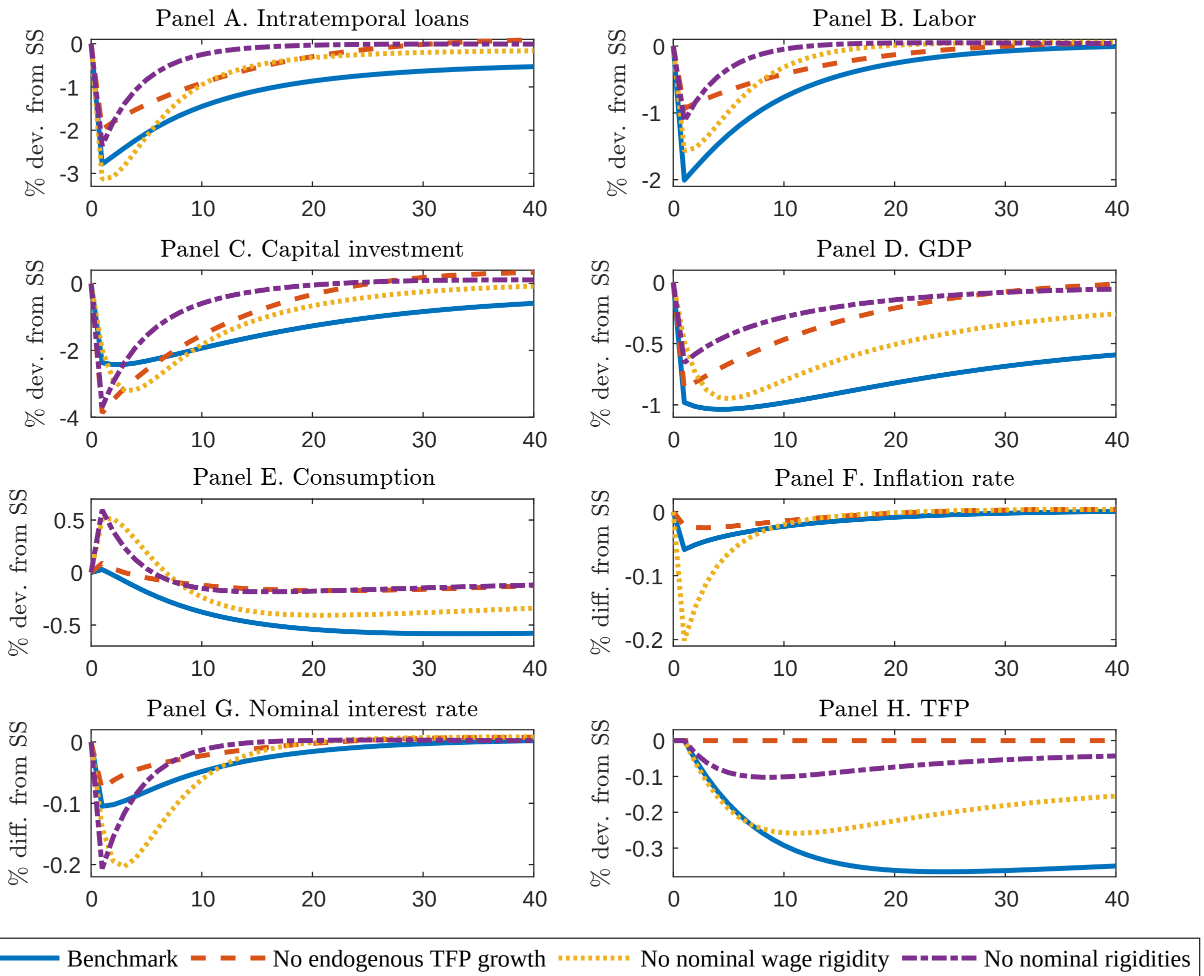
Using the parameter values in Table 1, impulse responses to the financial shock are analyzed.

[16] The value for the scaling parameter of R&D productivity χ_z is calculated from steady-state conditions, as shown in the Online Appendix

[17] The model with the parameter values in Table 1 indicates that, under the benchmark monetary policy rule (51), the financial, TFP, government spending, and monetary policy shocks account for 20 percent, 23 percent, 54 percent, and 3 percent of the unconditional variance of per-capita real GDP growth, respectively.

Figure 2 illustrates the responses of intratemporal loans, labor, capital investment, GDP, consumption, the inflation rate, the nominal interest rate, and TFP to an adverse financial shock with the size of the estimated one standard deviation presented in Table 1.

Figure 2: Impulse responses to an adverse financial shock



Notes: The figure shows the impulse responses to an adverse financial shock with the size of the estimated one standard deviation reported in Table 1 in the benchmark model and the models with no endogenous TFP growth, with no nominal wage rigidity, and with no nominal rigidities—neither price nor nominal wage rigidity. For the last model, the inflation rate is not shown in panel F and the real interest rate is displayed in panel G. The figure expresses labor in terms of percentage deviations from its steady-state value, the rates of inflation and nominal interest in terms of percentage differences from their respective steady-state values, and the others in terms of percentage deviations from their respective pre-shock steady-state growth paths.

The solid line in the figure—called the "benchmark"—represents the case of the model presented in the preceding section. In this case, when the adverse financial shock hits the economy in period 1, the borrowing constraint (7) is tightened, so that intratemporal loans to intermediate-good firms drop. The firms then reduce labor, capital investment, and purchase of newly adopted ideas. This in turn has a negative impact on the economy as a whole. The reduction of labor and capital investment decrease GDP and consumption as well as the inflation rate, leading to a recession.[18] In reaction to the decreases in inflation and GDP growth, the monetary policy rule (51) lowers the nominal interest rate. On the other hand, the decline in the purchase of newly adopted ideas decreases technology adoption and innovation, so that TFP falls very persistently relative to its steady-state growth path. As noted above, an adverse financial shock lowers the value of adopted ideas V_t through intermediate-good firms' demand curve for the ideas (23). The lower value of V_t decreases technology adopters' investment $I_{a,t}$ through equation (36) and lowers the adoption probability λ_t through equation (33), thereby slowing the growth rates of A_t and TFP_t. Moreover, because the adverse financial shock is persistent, the shock lowers the expected present discounted value of adopted ideas $E_t[m_{t,t+1}V_{t+1}]$ and hence the expected present discounted value of developed but not yet adopted ideas $E_t[m_{t,t+1}J_{t+1}]$ through equation (37). The lower value of $E_t[m_{t,t+1}J_{t+1}]$ decreases R&D investment $I_{d,t}$ through equation (41) and slows the growth rate of Z_t, which constrains TFP growth and causes TFP to fall very persistently relative to the steady-state growth path. Consequently, in response to the adverse financial shock, neither GDP, consumption, nor capital investment returns to the steady-state balanced growth path. Indeed, GDP falls below the path by about 1 percentage point and then recovers by less than half of the fall, remaining below the path by about 0.6 percentage point even after 40 quarters (10 years). From these observations, we confirm that the model possesses the capability to generate a slow recovery induced by an adverse financial shock.

[18] In response to the adverse financial shock, inflation declines because of a decrease in wholesalers' real marginal cost MC_t/P_t. Equation (21) 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 Figure 2, TFP—its endogenous 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' leads to the decline in wholesalers' real marginal cost MC_t/P_t. Such a drop in φ_t' arises because, in response to the shock, intermediate-good firms cut dividends, which reduces their real marginal cost of dividend payments φ_t'.

II.C Key elements to a financial shock-induced slow recovery

The distinguished feature of the model—a financial shock-induced slow recovery—lies in the amplification mechanism of the financial shock, which is generated by combining endogenous TFP growth and nominal rigidities as well as the financial friction. In addition to the benchmark model case, Figure 2 displays the impulse responses in the cases of otherwise identical models but with no endogenous TFP growth (the dashed line), with no nominal wage rigidity (the dotted line), and with no nominal rigidities—neither price nor nominal wage rigidity—(the dot-dashed line). This figure shows that both endogenous TFP growth and nominal rigidities are essential for generating a financial shock-induced slow recovery—no recovery of GDP to the pre-shock steady-state growth path.

To examine in more detail the amplification mechanism of the financial shock, we begin by investigating the role of endogenous TFP growth in the mechanism. In the model with no endogenous TFP growth, TFP expands exogenously at the steady-state rate, as displayed in panel H of Figure 2. Then, as shown in panel D, GDP drops below the steady-state growth path by about 0.8 percentage point on impact of the adverse financial shock, but it recovers to the path thereafter, in sharp contrast with the permanent decline in GDP relative to the path in the benchmark model. Therefore, endogenous TFP growth is a crucially important element of the model to generate a financial shock-induced slow recovery.

Next, turning to the role of nominal rigidities, the model without them also fails to generate a financial shock-induced slow recovery.[19] In response to the adverse financial shock, TFP declines persistently due to endogenous TFP growth, but this decline is small (panel H) and thus leads GDP to dip on impact of the shock and recover to the pre-shock steady-state growth path thereafter (panel D). In the absence of nominal rigidities, the real interest rate falls sharply in response to the shock (panel G). The lower real interest rate supports the expected present discounted values of adopted ideas and developed but not yet adopted ideas, $E_t[m_{t,t+1}V_t]$ and $E_t[m_{t,t+1}J_{t+1}]$, and thus subdues decreases in the technology

[19] Besides, the model with no nominal rigidities causes a rise in consumption in response to an adverse financial shock and hence a co-movement problem between consumption and capital investment.

adoption investment $I_{a,t}$ and R&D investment $I_{d,t}$, which results in the small decline in TFP.

A further investigation shows that both price and nominal wage rigidities are essential for generating a financial shock-induced slow recovery. Indeed, in response to the adverse financial shock, the model with no nominal wage rigidity gives rise to drops in TFP and GDP that are comparable to those in the benchmark model, but causes faster recoveries of both TFP and GDP to the pre-shock steady-state growth paths than in the benchmark model (panals D and H). This is because, in the presence of price rigidity, the real interest rate does not fall very much in response to the shock, which in turn decreases $E_t[m_{t,t+1}V_t]$ and $E_t[m_{t,t+1}J_{t+1}]$, thereby dampening $I_{a,t}$ and $I_{d,t}$. This effect is strengthened by the presence of nominal wage rigidity. In the benchmark model with such rigidity as well, nominal wage rates decline less and labor drops more. This drop in labor directly decreases GDP, which lowers the value of adopted ideas V_t through intermediate-good firms' demand curve for the ideas (23). The lower value of V_t slows down the growth rates of A_t and TFP_t. Consequently, the decline in GDP is larger in the benchmark model.

In addition to endogenous TFP growth and nominal rigidities, the financial friction itself also plays a certain role in the amplification mechanism of the financial shock. In the model, intermediate-good firms (i.e., the production sector) face the financial friction, which is a fundamental element to the amplification mechanism of the financial shock from the production sector to TFP through the sectors of R&D and technology adoption. To see the role of the financial friction in the mechanism, we consider the case in which the financial friction and shock are present in the technology adoption sector as in Queraltó (2013), instead of the production sector.[20] In this case, the amplification of the financial shock due to endogenous TFP growth is much weaker than in our model, and nominal rigidities no longer amplify the shock.[21] This is because the financial shock directly affects technology

[20] In addition, the financial friction and shock of the sort proposed by Gertler and Kiyotaki (2011) are used as in Queraltó (2013), instead of those of Jermann and Quadrini (2012). The financial shock then represents a shock to the moral hazard parameter that governs the fraction of assets banks can divert from creditors. See more details in the Online Appendix.

[21] In the case, there is another drawback: GDP, capital investment, and hours worked do not co-move in response to financial shocks.

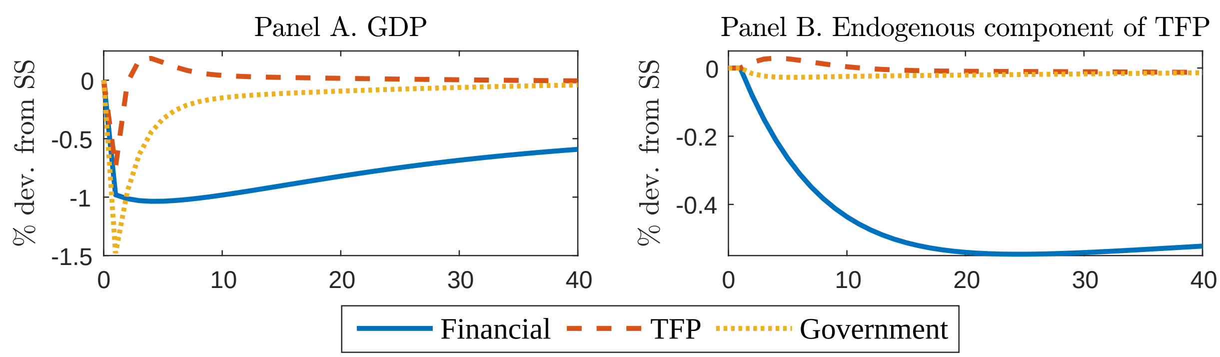
adoption and hence TFP, which implies that there seems to be little difference between the financial shock and a TFP shock for intermediate-good firms.[22] Therefore, in our model the financial friction plays a fundamental role in the mechanism.

II.D Impulse responses to other shocks

The preceding subsection has shown that the estimated adverse financial shock induces a slow recovery. This subsection examines whether the financial shock is unique in causing it.

In addition to those to the financial shock (the solid line), Figure 3 plots the impulse responses of GDP and the endogenous component of TFP (i.e., $(A^*_{t-1})^{1-\alpha}/\zeta_{p,t}$) to adverse shocks to TFP (the dashed line) and government spending (the dotted line) with the size of their respective estimated one standard deviations.[23]

Figure 3: Comparison of impulse responses to adverse shocks



Notes: The figure shows the impulse responses of GDP and the endogenous component of TFP to adverse financial, TFP, and government spending shocks with the size of their respective estimated one standard deviations reported in Table 1. GDP and the TFP component are expressed in terms of percentage deviations from their respective pre-shock steady-state growth paths.

The responses of both GDP and the endogenous component of TFP to the TFP and government spending shocks are much less persistent than those to the financial shock. This indicates that the estimated adverse TFP and government spending shocks do not cause a slow recovery, that is, a significant permanent fall in GDP relative to the pre-shock steady-

[22] Note that TFP shocks are not amplified by nominal rigidities in standard DSGE models.

[23] Regarding the impulse responses to a monetary policy shock, we confirm that they are consistent with those in standard DSGE models with nominal rigidities: in response to a contractionary monetary policy shock, the nominal interest rate rises, while inflation and GDP decline.

state growth path. This finding can be ascribed mainly to the difference in the estimated persistence between the financial shock and the other shocks. The estimated persistence of the financial shock, $\rho_\xi = 0.95$, is higher than that of the TFP and government spending shocks, $\rho_x = 0.45$ and $\rho_g = 0.63$.[24]

III Monetary Policy Analysis

This section examines how monetary policy should react to the financial shock and other shocks. To this end, we begin by deriving a welfare measure from the utility functions of households, and then present a class of monetary policy rules to be analyzed. Using the welfare measure, welfare-maximizing rules are investigated to derive the implications for monetary policy.

III.A Welfare measure

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

$$SW = (1-\beta)E\left[\int_0^1 \sum_{t=0}^{\infty} \beta^t \left(\log C_t - \frac{\chi_n}{1+1/\nu} n_{f,t}^{1+1/\nu}\right) df\right], \tag{56}$$

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 the welfare measure SW for the ease of computation. Let SW^* denote the resulting detrended welfare measure. Still, SW^* is not stationary as it involves a random walk component arising from endogenous

[24] There is an additional reason why the financial shock is unique in causing a slow recovery. Both adverse financial and government spending shocks lead to a decline in inflation and thus lower the real interest rate in the presence of the monetary policy rule (51). This in turn decreases the value of adopted ideas and thus technology adoption investment, which slows down TFP. Yet the impact of the financial shock is much greater than that of the government spending shock. This is because the government spending shock stimulates capital investment, whereas the financial shock leads to a drop in the investment in the initial period and pushes down GDP persistently. This generates an additional decline in the value of adopted ideas and slows down technology adoption investment further. As for the adverse TFP shock, it has a muted impact on the endogenous component of TFP, since it leads to a rise in inflation and thus increases the real interest rate under the rule (51), which in turn raises the value of adopted ideas and thus technology adoption investment.

TFP growth, and thus it cannot be directly approximated. We address this problem by rearranging SW^* and deriving its approximated counterpart, up to the second order, as

$$SW^* \approx -\left[\frac{Var\left(c_t\right)}{2c^2} + \frac{\beta}{1-\beta}\frac{Var\left(\gamma_t^*\right)}{2\left(\gamma^*\right)^2} + \frac{\chi_n}{\nu}\frac{Var\left(n_t\right)}{2}\right] + \frac{\varepsilon_c}{c} + \frac{\beta}{1-\beta}\frac{\varepsilon_{\gamma^*}}{\gamma^*} - \chi_n\varepsilon_n - \frac{\chi_n}{1+1/\nu}\varepsilon_{\zeta_w}, \tag{57}$$

where Var is the unconditional variance operator, $c_t \left(= C_t/A^*_{t-1}\right)$ is detrended consumption, its steady-state value is denoted by c, $\varepsilon_x = E[x_t] - x$ is the "bias" between the unconditional mean and the steady-state value of variable x_t, and $\zeta_{w,t} = \int_0^1 \left(W_{f,t}/W_t\right)^{-\eta_n(1+1/\nu)} df$ denotes wage dispersion arising from the staggered wage setting of households.[25] 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 (57) shows that the stationary welfare measure SW^* is negatively related to the biases 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}, $Var\left(c_t\right)$, $Var\left(\gamma_t^*\right)$, $Var\left(n_t\right)$) and is positively related to the biases in detrended consumption and the rate of technological change (i.e., ε_c, ε_{γ^*}).

A distinctive feature of the welfare measure (57) lies in the presence of the terms related to the rate of technological change γ_t^* (i.e., ε_{γ^*}, $Var\left(\gamma_t^*\right)$). In standard DSGE models where TFP expands exogenously, 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. In addition, because growth affects levels permanently, the weights attached to the γ_t^*-related terms involve $\beta/(1-\beta)$ and thus they are much greater than the other weights.

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 (51) with the benchmark parameterization reported in Table 1) and under an alternative monetary policy rule, and let $\Delta SW = SW_a^* -$

[25] The derivation of (57) is presented in the Online Appendix. The variances in (57) are calculated from the first-order approximation to the equilibrium conditions presented above, while the biases are calculated from the second-order approximation. For the calculations, Dynare is used.

SW_b^*. Then, this difference also equals the corresponding difference in terms of the welfare measure (56); that is, $\Delta SW = SW_a - SW_b$, where SW_b and SW_a denote the values of the welfare measure (56) 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 instead of the benchmark rule. Moreover, $g = \exp(\Delta SW) - 1$ 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 that $SW_b + \Delta SW = SW_a = SW_b + \log(1+g)$.

Using the welfare measure (57) and the welfare gain measure g, a welfare-maximizing monetary policy rule is analyzed in what follows.

III.B A class of monetary policy rules to be analyzed

This paper considers a class of monetary policy rules that adjust the current policy rate in response to the contemporaneous rates of inflation and GDP growth as well as the past policy rate. Specifically, two forms of such rules are analyzed. One form is, of course, the rule (51). This rule is referred to as "flexible inflation targeting." Moreover, in this form, the specification of $\phi_{dgdp} = 0$ is called "strict inflation targeting," while the specification of $\phi_\pi = \phi_{dgdp}$ 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 GDP growth[26]

$$\log r_t - \log r_{t-1} = \phi_r(\log r_{t-1} - \log r_{t-2}) + (1-\phi_r)\left[\phi_\pi(\log \pi_t - \log \pi) + \phi_{dgdp}\left(\log \frac{GDP_t}{GDP_{t-1}} - \log \gamma^*\right)\right]. \tag{58}$$

[26] For first-difference rules, see, e.g., Orphanides (2003).

This rule is referred to as "flexible price-level targeting," and in this form, the specification of $\phi_{dgdp} = 0$ is called "strict price-level targeting" and the specification of $\phi_\pi = \phi_{dgdp}$ is called "nominal GDP level targeting."[27]

In each specification of the monetary policy rules, three requirements are imposed on the values of the coefficients, following Schmitt-Grohé and Uribe (2007b). First, the values guarantee local determinacy of the rational expectations equilibrium. Second, they satisfy $1 \leq \phi_\pi \leq 10$, $0 \leq \phi_{dgdp} \leq 10$, and $0 \leq \phi_r < 1$. Last, they meet the condition on the volatility of the policy rate, $2(Var(r_t))^{0.5} < r - 1$. Then, a combination of the coefficient values that fulfills these three requirements and maximizes the welfare measure (57) is computed using the second-order approximation to the equilibrium conditions of the model around the steady state.

III.C Welfare-maximizing monetary policy rules

For each specification of the monetary policy rules, the top part of Table 2 shows a welfare-maximizing combination of its coefficient values in the three cases of the financial shock only, the non-financial shocks only (i.e., the TFP and government spending shocks only), and all the three shocks in the (benchmark) model. In this table, three findings are detected.[28]

First of all, a welfare-maximizing monetary policy rule features a strong response to output and a weak response to inflation in the model. Within the rule specifications and coefficient value requirements, the welfare-maximizing rule in the case of all the three shocks is the flexible inflation targeting rule (51) with $\phi_\pi = 1$, $\phi_{dgdp} = 10$, and $\phi_r = 0.996$.[29] This

[27] For recent discussions on nominal GDP level targeting, see, for example, Woodford (2012) and English, López-Salido, and Tetlow (2015). One point to be 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 respective target paths, because the original specifications grant leeway in the choice of the target paths.

[28] We confirmed that the three findings are robust to values of parameters that pertain to the technology innovation and adoption and the financial friction, such as $\omega = 0.9$, which is the calibrated value in Comin, Gertler, and Santacreu (2009); $\rho = 0.6$ and 0.99, which are respectively the lower bound and nearly the upper bound reported in Comin and Gertler (2006); and $\xi = 0.199$ and $\kappa_d = 0.426$, which are the values used and estimated respectively by Jermann and Quadrini (2012) for their extended model.

[29] The policy response to output hits its upper bound, while that to inflation hits its lower bound. The rule remains welfare-maximizing even when introducing the policy response to nominal wage inflation,

Table 2: Welfare-maximizing monetary policy rules

No.	Policy rule	ϕ_π	ϕ_{dgdp}	ϕ_r	$(Var(r_t))^{0.5}$	Welfare gain g	$\Delta\varepsilon_{\gamma^*}$
			Benchmark model: all three shocks				
1	F-IT	1.00	10.00	0.996	0.13%	20.23%	0.16%
2	S-IT	10.00	—	0.853	0.33%	15.37%	0.13%
3	NGDP-GT	10.00	10.00	0.982	0.45%	19.90%	0.16%
4	F-PLT	1.00	1.82	0.962	0.48%	19.81%	0.16%
5	S-PLT	1.00	—	0.000	0.23%	15.50%	0.13%
6	NGDP-LT	1.00	1.00	0.929	0.43%	19.79%	0.16%
			Benchmark model: financial shock only				
7	F-IT	1.00	10.00	0.992	0.14%	17.70%	0.14%
8	S-IT	10.00	—	0.000	0.13%	14.42%	0.12%
9	NGDP-GT	10.00	10.00	0.970	0.37%	17.54%	0.14%
10	F-PLT	1.00	0.53	0.634	0.34%	17.50%	0.14%
11	S-PLT	10.00	—	0.000	0.10%	14.67%	0.12%
12	NGDP-LT	1.00	1.00	0.830	0.40%	17.48%	0.14%
			Benchmark model: non-financial shocks only				
13	F-IT	10.00	10.00	0.987	0.28%	2.06%	0.02%
14	S-IT	5.47	—	0.874	0.18%	1.86%	0.02%
15	NGDP-GT	10.00	10.00	0.987	0.28%	2.06%	0.02%
16	F-PLT	1.00	0.19	0.894	0.12%	1.99%	0.02%
17	S-PLT	1.00	—	0.958	0.05%	1.78%	0.02%
18	NGDP-LT	1.00	1.00	0.955	0.25%	2.01%	0.02%
			No endogenous TFP growth: all three shocks				
19	F-IT	1.93	0.06	0.999	0.00%	0.13%	0.00%
			No endogenous TFP growth: financial shock only				
20	F-IT	1.95	0.07	0.999	0.00%	0.10%	0.00%
			No endogenous TFP growth: non-financial shocks only				
21	F-IT	10.00	1.31	0.465	0.93%	0.12%	0.00%

Notes: The case of "non-financial shocks" considers only the TFP and government spending shocks, while these two shocks and the financial shock are considered in the "all three shocks" case. For each policy rule ("F-IT": flexible inflation targeting, "S-IT": strict inflation targeting, "NGDP-GT": nominal GDP growth targeting, "F-PLT": flexible price-level targeting, "S-PLT": strict price-level targeting, and "NGDP-LT": nominal GDP level targeting), the welfare gain g denotes the one from adopting this rule instead of the benchmark rule (i.e., the rule (51) with $\phi_\pi = 1.7$, $\phi_{dgdp} = 0.25$, and $\phi_r = 0.7$) in terms of a permanent increase in consumption, and $\Delta\varepsilon_{\gamma^*}$ represents the difference in the bias of the rate of technological change in the annual percentage rate when adopting the rule instead of the benchmark rule.

rule achieves a higher value of the welfare gain measure g—which represents the welfare gain from adopting the rule instead of the benchmark rule (i.e., the rule (51) with $\phi_\pi = 1.7$, $\phi_{dgdp} = 0.25$, and $\phi_r = 0.7$) in terms of permanent increase in consumption—than the other rules considered, as shown in No. 1–6 in Table 2. The feature of the welfare-maximizing rule is inherited from that in the case of the financial shock only. In this case, the welfare-maximizing rule is almost the same: the flexible inflation targeting rule (51) with $\phi_\pi = 1$, $\phi_{dgdp} = 10$, and $\phi_r = 0.992$, as can be seen in No. 7–16 in the table.

Our finding contrasts sharply with the result of Schmitt-Grohé and Uribe (2006, 2007a, b) that a welfare-maximizing monetary policy rule features a muted response to output and focuses on inflation stabilization in their models. There are two reasons for the contrast. First, TFP grows endogenously in our model, whereas it expands exogenously in theirs. This gives rise to a strong response to output in our welfare-maximizing rule. In fact, if endogenous TFP growth is abstracted from our model, the welfare-maximizing flexible inflation targeting rule (51) responds much more weakly to output ($\phi_{dgdp} = 0.06$) and more strongly to inflation ($\phi_\pi = 1.93$), as demonstrated in No. 19 in Table 2.[30] Second, the type of shocks considered in deriving a welfare-maximizing rule is different. Their papers employ only TFP and government spending shocks, while our paper exploits not only the two shocks but also the financial shock. This generates a weak response to inflation in our welfare-maximizing rule. Indeed, in the case of the non-financial shocks only (reported in No. 13–18 in the table), the welfare-maximizing rule is flexible inflation targeting and has strong responses to both inflation and output ($\phi_\pi = \phi_{dgdp} = 10$) in the presence of endogenous TFP growth. Moreover, in its absence, the rule keeps a strong response to inflation ($\phi_\pi = 10$) but has a weak response to output ($\phi_{dgdp} = 1.31$), as displayed in the last row.[31]

$\phi_{\pi_w}[\log(\pi_t W_t/W_{t-1}) - \log \pi_w]$, along with the requirement $0 \leq \phi_{\pi_w} \leq 10$, as in Schmitt-Grohé and Uribe (2006, 2007a): the welfare-maximizing coefficient values are $\phi_\pi = 1$, $\phi_{dgdp} = 10$, $\phi_r = 0.996$, and $\phi_{\pi_w} = 0$.

[30] As emphasized in the preceding section, nominal wage rigidity is another key element of the model to generate a financial shock-induced slow recovery. However, even if this rigidity is abstracted from the model as in Schmitt-Grohé and Uribe (2007b), the welfare-maximizing flexible inflation targeting rule still features a stronger response to output ($\phi_{dgdp} = 9.99$) relative to that to inflation ($\phi_\pi = 2.38$).

[31] Our first finding implies that the allocation achieved by the welfare-maximizing rule differs from the one that would be obtained if prices and wages were all flexible. This contrasts sharply with the result

The second finding detected in Table 2 is that the welfare gain from output stabilization is much more substantial than in the model where TFP expands exogenously. The welfare gain from adopting the welfare-maximizing monetary policy rule instead of the benchmark rule is huge. It is indeed a permanent increase in consumption of 20.23 percentage points. This gain is about two orders of magnitude greater than that attained under the welfare-maximizing flexible inflation targeting rule in the model with no endogenous TFP growth ($\phi_\pi = 1.93$, $\phi_{dgdp} = 0.06$, and $\phi_r = 0.999$), i.e., $g = 0.13$ percentage point.[32,33] This huge welfare gain arises mostly from an improvement in the bias of the rate of technological change $\Delta\varepsilon_{\gamma^*}$, which is a 0.16 annual percentage point. A simple calculation indicates that, with other things being equal, the improvement generates a 19.3 percentage point welfare gain, which accounts for most of the total welfare gain of 20.23 percentage points.[34]

How does the welfare-maximizing monetary policy rule improve the bias ε_{γ^*} through output stabilization? In particular, does the strong policy response to output improve it not only for negative shocks that deteriorate output growth but also for positive shocks that enhance the growth? As noted above, the strong response to output is inherited from the welfare-maximizing rule in the case of the financial shock only. Thus we examine the relationship between the financial shock and output growth in the model. Positive and negative financial shocks with the same magnitude have symmetric effects on output growth in the first-order approximation to equilibrium conditions of the model. Yet in the second-order approximation, they have asymmetric effects on it, that is, negative financial shocks have a stronger impact on output growth than positive ones, due to the presence of the

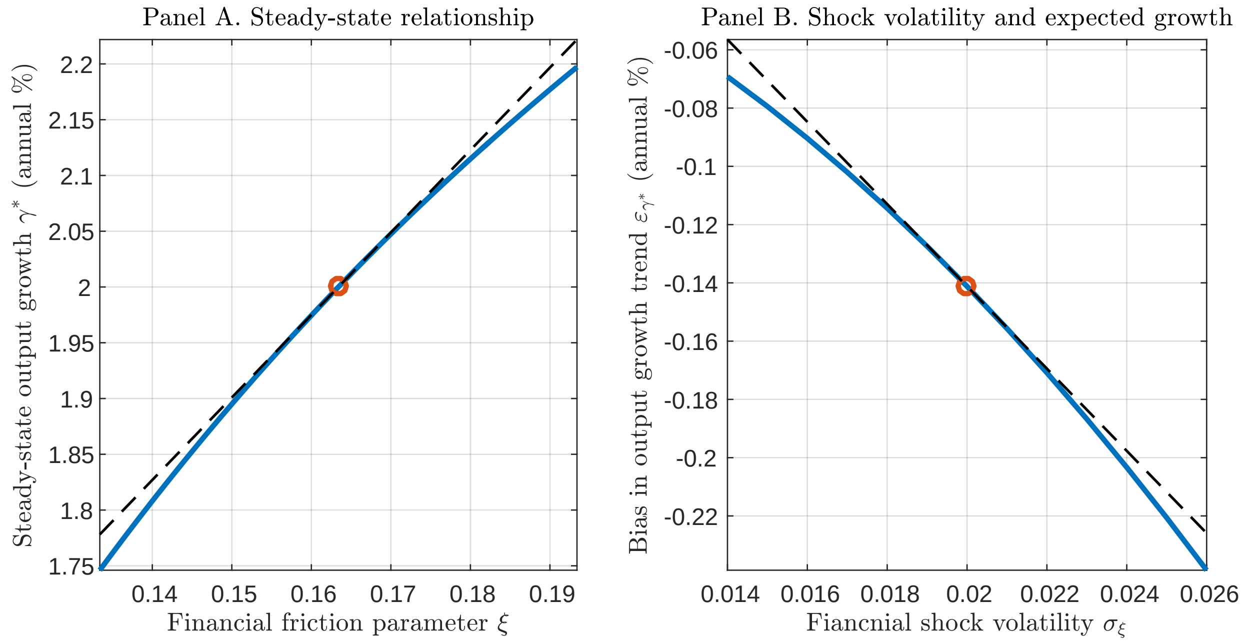
of standard DSGE models (with neither endogenous TFP growth nor financial friction) that a welfare-maximizing monetary policy rule accomplishes the allocation obtained under flexible prices and wages.

[32] By taking into account the influence of business cycle fluctuations on the growth rate of consumption, Barlevy (2004) demonstrates that welfare costs of the fluctuations are about two orders of magnitude greater than those computed originally by Lucas (1987).

[33] Notice that, in the model with no endogenous TFP growth, output stabilization is not welfare-maximizing, so that there is a welfare loss from it compared with the welfare-maximizing flexible inflation targeting rule.

[34] In the simple calculation, the welfare gain g_{γ^*} from the improvement in the bias $\Delta\varepsilon_{\gamma^*}$ is computed by solving $\sum_{t=0}^{\infty} \beta^t \log(1+g_{\gamma^*}) = \sum_{t=0}^{\infty} \beta^t \log(1+\Delta\varepsilon_{\gamma^*})^t$. Approximately, $g_{\gamma^*} = \beta/(1-\beta)\Delta\varepsilon_{\gamma^*} = 0.9979/(1-0.9979) \times 0.16/4 = 19.3$ percent.

Figure 4: Relationship between financial shock and output growth



Note: In each panel of the figure, the dashed line is a tangent line to the curve at the circled point that corresponds to the benchmark values reported in Table 1.

binding borrowing constraint.[35] Indeed, we can see the asymmetric effects through the relationship between the financial friction parameter ξ and steady-state output growth γ^*. This relationship is plotted in panel A of Figure 4, where γ^* is an increasing and concave function of ξ. For example, a drop in ξ by 3 percentage points from the benchmark value of $\xi = 0.1634$ decreases the growth rate γ^* by 25 basis points, while a rise in ξ by the same size increases the rate γ^* only by 20 basis points. Therefore, a tightening in the borrowing constraint has a more effect on output growth than a loosening with the same magnitude. We can also see the asymmetric effects through the relationship between the financial shock volatility σ_ξ and the bias in output growth trend ε_{γ^*} under the benchmark monetary policy rule. Panel B of the figure displays the relationship and indicates that ε_{γ^*} is a decreasing and concave function of σ_ξ. This implies that a negative financial shock—which tightens the borrowing constraint—have a greater impact on output growth trend than a positive one

[35] This paper assumes that the borrowing constraint is always binding. In a more general case in which whether the constraint is binding or not depends on the current state of the economy, positive and negative financial shocks with the same size would have asymmetric effects even in the first-order approximation.

with the same size—which loosens the constraint.[36] These results suggest that the strong policy response to output in the welfare-maximizing rule can ameliorate social welfare by mitigating the deteriorating effect of negative financial shocks on output growth that is greater than the enhancing effect of positive ones.

The third finding in Table 2 is that 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 coefficient values of $\phi_\pi = 10$ and $\phi_r = 0.853$ and the strict price-level targeting rule with those of $\phi_\pi = 1$ and $\phi_r = 0$ generate lower welfare by 4.86 percentage point and 4.73 percentage point permanent declines in consumption relative to the welfare-maximizing rule, respectively. This is because these rules have no policy response to output and thus cannot directly mitigate slowdowns in TFP growth caused by adverse financial shocks. On the other hand, the nominal GDP growth or level targeting rule performs well, even compared with the welfare-maximizing rule. Indeed, the welfare gains from adopting the welfare-maximizing rule instead of the nominal GDP growth targeting rule with its welfare-maximizing coefficient values of $\phi_\pi = \phi_{dgdp} = 10$ and $\phi_r = 0.982$ and the nominal GDP level targeting rule with those of $\phi_\pi = \phi_{dgdp} = 1$ and $\phi_r = 0.929$ are permanent increases in consumption of only 0.33 percentage point and 0.45 percentage point, respectively. The welfare-maximizing rule contains a much weaker response to inflation than the two nominal GDP targeting rules: $\phi_\pi(1 - \phi_r) = 0.00$, 0.18, and 0.07 in the welfare-maximizing rule and the nominal GDP growth and level targeting rules, respectively. This implies that the size of the policy response to inflation has a minor welfare effect. One point to be emphasized here is that both nominal GDP targeting rules cause higher interest-rate volatility than the welfare-maximizing rule. This higher volatility arises from the stronger response to inflation and the lower policy rate smoothing under the nominal GDP targeting rules.[37]

[36] This finding is consistent with the cross-country evidence provided by Ramey and Ramey (1995) that countries with larger business cycle fluctuations have lower economic growth.

[37] In the Online Appendix, we conduct financial crisis scenario simulations, using the estimated adverse financial shocks for the U.S. during the Great Recession period 2008Q4–2009Q3. The simulations highlight the effectiveness of the welfare-maximizing rule over other selected rules and the higher interest-rate volatility

IV Concluding Remarks

This paper has developed a model in which an adverse financial shock can induce a severe recession and a subsequent slow recovery, such as those observed in many economies after the global financial crisis of 2007–08. Specifically, the Jermann and Quadrini (2012) financial friction and shock and the Comin and Gertler (2006) endogenous TFP growth have been introduced into an otherwise canonical DSGE model with nominal rigidities. With this model, the paper has examined a welfare-maximizing monetary policy rule. It has been shown that the welfare-maximizing rule features a strong response to output and a weak response to inflation, in stark contrast with the result of previous monetary policy literature including Schmitt-Grohé and Uribe (2006, 2007a, b), and that the welfare gain from output stabilization is much more substantial than in the model where TFP expands exogenously. In the presence of endogenous TFP growth, it is crucial to take into account a welfare loss from a permanent decline in consumption caused by a slowdown in TFP. Moreover, compared with the welfare-maximizing rule, a strict inflation or price-level targeting rule results in a sizable welfare loss, whereas a nominal GDP growth or level targeting rule performs well, although it causes relatively high interest-rate volatility.

This paper has studied interest rate policy only. After lowering the policy rate to an effective lower bound, central banks in advanced economies have been underpinning economic recovery in the wake of the 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.

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generated by the nominal GDP growth targeting rule.

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