Central Bank Credibility and Monetary Policy*

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In this paper, a numerical measure of central bank credibility is proposed that can be incorporated into a New Keynesian model under bounded rationality. This measure arises due to the existence of the changes in private beliefs, which are different from those of the central bank. It is shown that central bank credibility matters for macroeconomic stability. Specifically, as credibility increases, macroeconomic variables vary less since private agents' expectations are more anchored. Through this channel, the model generates endogenous volatility changes. Finally, the credibility of the Federal Reserve and the European Central Bank are computed based on the proposed method.

JEL Codes: E3, E52, E58, D8.

1. Introduction

Over the past 20 years, many central banks in advanced countries have introduced inflation targeting as their way of conducting monetary policy. By introducing inflation targeting, the notion of central bank credibility became more important for policymakers. Despite the importance of credibility, there has been little research quantifying time-varying central bank credibility that is determined endogenously by the central bank's actions and economic outcomes in a

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New Keynesian framework, which has been a workhorse for central banking studies in recent decades. In stylized New Keynesian models, it is implicitly assumed that the central bank is fully credible, in the sense that private agents believe that the central bank follows predetermined rules and tries to achieve the policy target, even if the rules and/or target are unknown to the public. Therefore, the results derived from previous studies might be too optimistic and overestimate the efficiency of monetary policy.[1]

In this paper, a numerical measure of central bank credibility is proposed using a version of a New Keynesian model with imperfect knowledge. Then, implications of credibility on macroeconomic stability are analyzed. The proposed credibility measure is defined as the tendency of private agents to rely on the central bank's forecast announcements in forming expectations of future endogenous variables, and is determined by the relative performance of the central bank's forecasts compared with those of private agents. That is, we consider central bank communications, especially announcements of forecasts, as important sources for shaping credibility. As private agents cannot observe internal procedures of the central bank, such as the actual targets and policy rules, the central bank's announcements are the sole sources for measuring its credibility.

The formulation of credibility proposed here reflects the views of policymakers. For instance, Svensson interpreted a large gap between the Riksbank's announced repo rate path and market expectations as being low credibility.[2] Yellen (2006) also described credible monetary policy as a situation in which "market participants correctly anticipate the actions that the Fed will make in response to economic news and shocks." In addition, Blinder (2018) pointed out that ignoring the messages that were sent by the central bank is almost the same thing as not believing the central bank.

In this paper, we find that perpetual assessments of central bank credibility can generate endogenous changes in volatility of endogenous variables, such as inflation and the output gap. Specifically, the baseline model that is estimated based on the U.S. economy

[1]Goodfriend and King (2015) also pointed this out: "Forecasts, and policy, should not be based solely on forecasts from a model that assumes full credibility in the stated policy path." See Goodfriend and King (2015) for details.

[2]See Goodfriend and King (2015).

generates a 33 percent higher standard deviation of inflation compared with the associated rational expectations model. In addition, we also show that volatility of endogenous variables increases as credibility deteriorates. Specifically, comparing volatility of inflation between periods with the credibility level above and below the median, inflation varies 81 percent more when the credibility level is below the median. As the central bank builds a credible reputation, private expectations become more anchored around the zero steady state, which is also the target of the central bank, and this helps to stabilize the economy by preventing vicious feedback cycles produced by the self-referential effects of expectations formation.

This paper contributes to the monetary policy credibility literature. Various researchers have provided different definitions of the credibility of central banks. One of the widely used definitions is related to imperfect information and/or knowledge of private agents regarding monetary policy (Cukierman and Meltzer 1986; Ball 1994, 1995; Erceg and Levin 2003; Schaumburg and Tambalotti 2007). This stream of research describes imperfect credibility as a status wherein private agents cannot directly observe the objectives of the central bank, such as the inflation target, or as the possibility that the central bank may renege on a pre-announced policy path. Our research differs from those, as we allow endogenous changes in the level of central bank credibility evaluated by private agents, based on the central bank's announcements and economic outcomes within a single framework.

On the other hand, many previous studies in the literature have measured the credibility of a central bank and/or analyzed how credibility affects macroeconomic stability. These studies share the same concept of credibility, which is either a deviation of (long-term) inflation expectations from the central bank's target rate or a range between the realized inflation and the target rate (Johnson 1997, 1998; Bomfim and Rudebusch 2000; Demertzis, Marcellino, and Viegi 2010). Ours differs from those in some aspects. First, we explicitly specify the belief structure and build a microfounded model that is consistent with the underlying belief. Second, the credibility measure they suggest is not bounded, so it is difficult to interpret and compare. However, the credibility measure proposed in this paper is bounded to between 0 and 1, so it is easier to interpret and compare across countries and periods.

There have been studies that connect bounded rationality to credibility issues similar to ours. Gibbs and Kulish (2017) study disinflation using a structural model that is close to ours. The credibility measure therein represents the proportion of households that form expectations rationally. Our approach differs from it in some ways. First, the level of credibility is fixed in their model, making it impossible to study the interaction between credibility and macroeconomic outcomes. In addition, they do not specify explicitly the underlying belief structure that can result in the expectation formation used in their study. Hommes and Lustenhouwer (2019) examine the stability of a heterogeneous expectations model under a bounded rationality assumption. Although they incorporate an endogenous credibility measure that is similar to ours, the expectation formations in their model are too restrictive: some stick to policy targets and the others rely on past observations to forecast future variables. Hence, their credibility measure and model cannot account for the forward-looking behavior.

This paper is organized as follows. The microfoundations of the model are explained in Section 2. Belief structures and the credibility measure are proposed in Section 3. Section 4 estimates the model. Section 5 depicts historical credibility of the Federal Reserve and European Central Bank. Section 6 discusses implications of credibility on macroeconomic stability. Finally, Section 7 concludes.

2. Model

This section develops a variant of the canonical New Keynesian model that shares microfoundations with many other models. Details of the microfoundations can be found in Preston (2005). In this model, near rationality is assumed, and households hold subjective beliefs. The formation of expectations will be discussed in detail in the subsequent section.

A continuum of households, i, on the unit interval maximize their lifetime utility

$$\hat{E}_t^i \sum_{T=t}^{\infty} \psi_T \beta^{T-t} \left\{ \frac{c_T(i)^{1-\sigma}}{1-\sigma} - \chi n_T(i) \right\}, \tag{1}$$

where $\beta \in (0,1)$ is the discount factor, $\chi > 0$ measures disutility of labor, and σ is the relative risk aversion parameter, subject to the following budget constraint:

$$c_t(i) + b_t(i) \leq \frac{1+i_{t-1}}{1+\pi_t} b_{t-1}(i) + w_t n_t(i) + \Gamma_t(i) \tag{2}$$

and the no-Ponzi condition

$$\lim_{T\rightarrow\infty} \hat{E}_t^i \left(\Pi_{j=0}^{T-t} \frac{1+i_{t+j}}{1+\pi_{t+j+1}} \right)^{-1} B_t(i) \geq 0. \tag{3}$$

The variables $c_t(i)$, $n_t(i)$, $b_t(i)$, i_t, π_t, w_t, and $\Gamma_t(i)$ denote consumption, labor supply, real bond holdings, nominal interest rate, net inflation rate, real wage, and real dividends from firms. ψ_t is the exogenous preference shifter. The operator $\hat{E}_t^i$ denotes private agents' subjective expectations based on information up to time t.

A continuum of monopolistically competitive firms maximize profits,

$$\hat{E}_t^i \sum_{T=t}^{\infty} \alpha^{T-t} Q_{t,T} \left[p_t(i) y_T(i) - P_T w_T n_T(i) \right], \tag{4}$$

subject to the linear production technology, $y_T(i) = n_T(i)$, and the demand function derived from the households' problem

$$n_T(i) = y_T(i) = \left(\frac{p_t(i)}{P_T} \right)^{-\theta_T} Y_T, \tag{5}$$

where α is the Calvo (1983) parameter and denotes the probability of not being able to reset prices in subsequent periods, and $p_t(i)$ and P_t are the prices charged by firm i and the aggregate price level. In addition, $y_t(i)$ and Y_t present the output produced by firm i and the aggregate output, respectively. $\theta_t > 1$ depicts the elasticity of demand across differentiated goods and follows an exogenous process. The stochastic discount factor $Q_{t,T}$ is given as

$$Q_{t,T} = \beta^{T-t} \frac{P_t Y_t^{\sigma}}{P_T Y_T^{\sigma}}. \tag{6}$$

In a symmetric equilibrium, private agents share the same subjective beliefs; thus, aggregate subjective expectations are the same as individual expectations, although private agents are not aware of this. The log-linear approximation around the zero-inflation steady state gives the following decision rules for consumption and price streams:

$$\hat{c}_t(i) = \hat{E}_t^i \sum_{T=t}^{\infty} \beta^{T-t} \left[(1-\beta)\hat{w}_{T+1} - \frac{1}{\sigma}\left(\hat{\imath}_T - \hat{\pi}_{T+1} - \beta\left(\hat{\psi}_T - \hat{\psi}_{T+1} \right) \right) \right] \tag{7}$$

$$\hat{p}_t(i) = \hat{E}_t^i \sum_{T=t}^{\infty} (\alpha\beta)^{T-t} \left[(1-\alpha\beta)(\hat{w}_T + u_T^*) + \alpha\beta\hat{\pi}_{T+1} \right], \tag{8}$$

where the hatted variables are the log deviations from their steady states, except $\hat{p}_t(i) = \ln(p_t(i)/P_t)$, $\hat{\imath}_t = \ln[(1+i_t)/(1+\bar{\imath})]$, and $u_t^* = \ln(\theta_t/\bar{\theta})$. In the remainder, the hat notations that denote the log deviations from the steady states are dropped for simplicity, as there is no confusion that arises from this notational simplification.

We define the output gap as $x_t = y_t - y_t^n = \sigma^{-1} w_t$. That is, the output gap is the difference between the actual output and the natural output, which is the level of output in a flexible-price environment. Aggregating and imposing market clearing conditions to Equations (7) and (8) yields the following equations, which are counterparts of the dynamic IS and Phillips curve in a canonical New Keynesian model.[3]

$$x_t = \hat{E}_t \sum_{T=t}^{\infty} \beta^{T-t} \left[(1-\beta)x_{T+1} - \frac{1}{\sigma}(i_T - \pi_{T+1} - r_T^n) \right] \tag{9}$$

$$\pi_t = \hat{E}_t \sum_{T=t}^{\infty} (\alpha\beta)^{T-t} \left[\kappa x_T + (1-\alpha)\beta\pi_{T+1} + u_T \right] \tag{10}$$

[3]The decision rules are comparable with the other models with bounded rationality, for instance, Gabaix (2020), which extends a canonical New Keynesian model by incorporating the sparsity-based limited attention suggested in Gabaix (2014, 2016), as the current consumption gap is determined by the streams of future consumption gaps and real interest rates in both models. However, expectation formation differs as Gabaix (2020) assumes a specific term structure of attention allocations while we explicitly specify subjective beliefs held by private agents.

The slope of the Phillips curve is given by $\kappa = (1 - \alpha\beta)(1 - \alpha)/\alpha$. u_t is the autoregressive cost-push shock due to variations in a firm's markup reflecting fluctuations in elasticity of demand θ_t. An exogenous disturbance $r_t^n = \beta(\hat{\psi} - \hat{E}_t\hat{\psi}_{t+1})$ arises due to changes in household preferences, and it can be interpreted as fluctuations in the natural interest rate.[4]

The model is closed with a version of the Taylor rule that describes the behavior of the central bank.

$$i_t = \phi_\pi \pi_t + \phi_x x_t + m_t \tag{11}$$

The central bank reacts to inflation and the output gap. m_t is the monetary policy shock and follows AR(1) process.

3. Beliefs, Forecasts, and Credibility

In this research, we rely on a near-rationality assumption and a learning mechanism, as private agents have imperfect knowledge about how the central bank conducts its policy. In addition, as a byproduct, this assumption sidesteps the technical problem that arises in rational expectations models due to the presence of higher-order beliefs. However, this departure from rational expectations is minimized by assuming that credibility only matters in non-fundamental drift terms in the perceived law of motion (PLM) and that the other parts of the model share the same structure as the rational expectation model without the credibility measure, as shown in detail in the subsequent sections.

3.1 Belief Structures

Private agents have the prediction model expressed below:

$$\begin{aligned} z_t &= H\bar{a}_{t-1} + \Omega s_t + e_t^1 \\ \bar{a}_t &= F\bar{a}_{t-1} + \nu_t, \end{aligned} \tag{12}$$

[4]Equations (9) and (10) can be reduced to the ordinary Euler equation and dynamic Phillips curve if subjective expectations are formed rationally. This can be proven by leading the equation and applying the law of iterated expectations. See Preston (2005) for details.

where $z_t = [x_t\ \pi_t\ i_t]'$ is a vector containing endogenous variables that private agents need to predict and $s_t = [r_t^n\ u_t\ m_t]'$ denotes a vector that observable exogenous disturbances are stacked. e_t^1 is the prediction error of private agents' prediction model. $\bar{a}_t$ indicates a vector of n_a unobserved time-varying terms, possibly random-walk drifts. Following Eusepi, Giannoni, and Preston (2015), it is assumed that the number of the underlying driving forces of drift terms, n_a, is equal to two and denote a^π and a^x, respectively.[5] These terms are labeled as the nominal and real factor. The nominal factor reflects uncertainty about the inflation target of the central bank, and the real factor represents fundamental uncertainty about long-term technological advance.[6] This specification is supported by empirical analysis in Eusepi, Giannoni, and Preston (2015). It is also intuitively plausible based on the Fisher equation. Movements in long-term expectations of the interest rate cannot be decoupled from those of inflation provided that the real interest rate does not deviate substantially from its steady state. Under this assumption, the drift term attached to the interest rate prediction equation can be expressed as $\lambda_1 a^x + \lambda_2 a^\pi$. Following Eusepi, Giannoni, and Preston (2015), we assume $\lambda_2 = 1$ and interpret λ_1 as the relative contribution of the real factor to the nominal interest rate.

Exogenous disturbances follow the stationary AR(1) process

$$s_t = \Phi s_{t-1} + \varepsilon_t, \tag{13}$$

where ε_t are i.i.d. shocks. It is also assumed that parameters that govern reactions to fundamental disturbances, Ω, are known to private agents and coincide with their rational expectation counterparts.[7] This assumption simplifies analysis and helps place greater focus on the dynamics of long-term expectations, whereas it minimizes deviation from the rational expectations model. Hence, private agents only need to learn about the unobserved drift terms.

[5] a denotes the estimate of $\bar{a}$, which is unobservable to private agents.

[6] The real factor can be also interpreted as a shock to the higher-order belief, or to private agent sentiments, à la Angeletos and La'O (2013). For example, persistent positive waves of the real factor can be considered as strong optimism for the real activities in the economy, as perceived by private agents.

[7] This assumption does not change the qualitative results of this paper, since learning procedures for constants and coefficients attached to structural disturbances are totally separated.

Based on the estimated time-varying drift terms a_{t-1} up to time $t-1$ and the beliefs given above, private agents compute their own forecasts as

$$\hat{E}_t^P[z_T] = HF^{T-t}a_{t-1} + \Omega\Phi^{T-t}s_t, \tag{14}$$

where $\hat{E}_t^P$ denotes the private forecast based on the information up to time t. If time-varying drift terms $\bar{a}$ are more persistent than structural disturbances s_t, long-term forecasts are driven more by time-varying drift terms than by disturbances. For example, if $\bar{a}$ have unit roots, then infinite-horizon long-term forecasts are simply given by the current time-varying drift terms.

$$\lim_{T\to\infty} \hat{E}_t^P[z_T] = Ha_{t-1} \tag{15}$$

Following Eusepi, Giannoni, and Preston (2015), a_t is updated using the steady-state Kalman filter recursion

$$a_t = Fa_{t-1} + K(z_t - Ha_{t-1} - \Omega\Phi s_{t-1}), \tag{16}$$

where the time-invariant Kalman gain matrix is

$$K = PH'(HPH' + R)^{-1}. \tag{17}$$

P is given as $E[(\bar{a}_t - a_t)(\bar{a}_t - a_t)']$ and R denotes private agents' prior beliefs about the covariance matrix of the observation error terms e_t^1 in their prediction equation (12).[8]

The central bank is also near rational and has its own PLM, which is used to predict future endogenous variables. The PLM of the central bank is given as follows:

$$z_t = \Omega s_t + e_t^2, \tag{18}$$

which coincides with the rational expectations solution to the model. Here, e_t^2 is the prediction error of the central bank's prediction model. Compared with that of private agents, the PLM of the

[8]Since the Kalman gain is determined by the private agents' prior beliefs and is time invariant, the steady-state Kalman filter can be understood as a version of the constant-gain learning process, which is widely used in the learning literature—for instance, Eusepi and Preston (2011).

central bank clearly shows that the central bank's forecasts are well anchored, as there are no time-varying terms $\bar{a}$. This formulation seems reasonable, as many central banks predict their economy by using country-specific dynamic stochastic general equilibrium (DSGE) models with rational expectations. In addition, Mokhtarzadeh and Petersen (2021) show that central banks interested in maintaining inflation stability should communicate their predictions solely based on rational expectations in their laboratory experiment. On the other side, the actual law of motion nests that of the rational expectations under this assumption, as shown later. This characterization sets a natural comparison of the model, thereby facilitating interpretation of the results.

The central bank announces its own forecasts of endogenous variables after observing the realization of disturbances

$$\hat{E}_t^{CB}[z_T] = \Omega\Phi^{T-t}s_t, \tag{19}$$

where $\hat{E}_t^{CB}$ denotes the forecast of the central bank based on information up to time t.

The belief structure can be justified under the assumption that no commitment device exists. This is a reasonable assumption, as there is no credible commitment device. It is neither allowed nor possible to inform the public credibly of the central bank's internal decisionmaking procedure, including objectives and rules. A notion of credibility arises due to this point. Even if a central bank deliberately conducts monetary policy and follows its target, private expectations can diverge from the target because the central bank cannot commit to the target and communicate its policy credibly. Private agents continuously evaluate the central bank's resolutions and abilities to achieve the target based on the history of outcomes. The formal definition of credibility used in this paper is presented below.

3.2 Credibility Measure

The tendency of private agents to rely on the central bank's announced forecasts in forming expectations of future endogenous variables defines the credibility.

DEFINITION 1 (Credibility). *Central bank credibility ξ_t is the time-varying relative weight attached to the announced forecasts* *made by the central bank, other than private agents' own forecasts, when private agents derive ensemble forecasts and form expectations. Specifically, private agents use the following subjective expectations:*

$$\hat{E}_t z_T = \xi_{t-1} \hat{E}_t^{CB}[z_T] + (1 - \xi_{t-1}) \hat{E}_t^{P}[z_T]. \tag{20}$$

As the proposed measure determines the relative weight among forecasts, it can be determined naturally based on the relative accuracy of two forecasts. To be precise, the credibility measure, ξ_t, is determined by the following dynamic predictor selection problem, modified from that of Brock and Hommes (1997) and a possibly sluggish law of motion.

$$\tilde{\xi}_t = 1 - \left(\frac{\exp\left(\delta_1 U_t^P\right)}{\exp\left(\delta_1 U_t^P\right) + \exp\left(\delta_1 U_t^{CB}\right)} \times \mathcal{D}_t \right), \tag{21}$$

where

$$U_t^k = -\sum_{j=0}^{\infty} \omega^j \left[\left(z_{t-j} - \hat{E}_{t-j-1}^k [z_{t-j}] \right)' W \left(z_{t-j} - \hat{E}_{t-j-1}^k [z_{t-j}] \right) \right] \tag{22}$$

$$\mathcal{D}_t = 1 - \exp\left(-\delta_2 \left(\hat{E}_{t-1}^{CB}[z_t] - \hat{E}_{t-1}^{P}[z_t] \right)' \left(\hat{E}_{t-1}^{CB}[z_t] - \hat{E}_{t-1}^{P}[z_t] \right) \right) \tag{23}$$

for $k \in \{CB, P\}$ and

$$\xi_t = \xi_{t-1} + \eta(\tilde{\xi}_t - \xi_{t-1}). \tag{24}$$

U^k is the fitness measure of central bank ($k = CB$) or private ($k = P$) prediction. The fitness measure is a discounted weighted sum of the negative of the past squared prediction errors. $\omega \in [0, 1]$ is the memory parameter that controls the degree of discounting of past prediction errors in measuring the fitness. The fitness measure becomes more persistent when ω approaches one. $\mathcal{D} \in [0, 1]$ measures the distance between two predictors and approaches zero as two predictors become similar. W is a weighting matrix and δ_1 and δ_2 are the intensity of choice parameters. $\eta \in [0, 1]$ controls inertia of the credibility measure. As it approaches one, inertia does not exist and the law of motion becomes $\xi_t = \tilde{\xi}_t$. This sluggish process allows slow adjustments, rather than drastic changes, in credibility.

The credibility measure is determined by two parts: the distance between private and central bank forecasts ($\mathcal{D}_t$), and the relative accuracy of these forecasts (U^{CB}, U^P). Firstly, if the central bank's forecasts are close to those of private agents ($\hat{E}^{CB}_{t-1}[z_t] - \hat{E}^{P}_{t-1}[z_t] \rightarrow 0, \mathcal{D}_t \rightarrow 0$), there is no reason for private agents to disregard the forecasts announced by the central bank, because they believe that the central bank shares their views on the economy. In that case, private agents will perceive the central bank to be credible and will make use of it ($\tilde{\xi}_t \rightarrow 1$).[9] At the same time, if two predictors differ ($\mathcal{D}_t \rightarrow 1$) and private forecasts are more accurate than those of the central bank ($U^P > U^{CB}$), private agents will doubt the credibility of the announced policy targets and forecasts of the central bank, and will place more reliance on their own forecasts ($\exp\left(\delta_1 U^P_t\right) / \exp\left(\delta_1 U^P_t\right) + \exp\left(\delta_1 U^{CB}_t\right) \rightarrow 1, \tilde{\xi}_t \rightarrow 0$). Therefore, poor central bank forecasts decrease a central bank's credibility.

Kocherlakota (2011) stated the same point:

> I've been emphasizing the importance of communication and communication matters greatly. But, ultimately, the public's beliefs about the FOMC's inflation objective will also depend on inflationary outcomes. If annual inflation averages less than 1.5 percent for more than three or four years, onlookers will begin to suspect that the FOMC's true objective for inflation is lower than its declared "two percent or a bit under." Correspondingly, if inflation is persistently higher than 2 percent, then the public will begin to believe that the FOMC's true objective for inflation is higher than 2 percent. In either case, inflation expectations could become unmoored, and the FOMC could lose control of inflation itself. Communication can only be effective if the FOMC also retains credibility.

[9] Some policymakers acknowledged this point in their speeches. For example, Bernanke (2004) argued that "The . . . way in which clear and open communication enhances the effectiveness of monetary policy. . . is by helping to align financial-market participants' expectations about the future course of monetary policy more closely with the policy committee's own plans and projections."

This is also in line with Plosser (2010)'s prescription of achieving credibility.

One advantage of this formulation is that the aggregate economic outcomes do not necessarily influence credibility directly. That is, higher inflation realizations than the announced target do not necessarily decrease credibility. If the economy is hit by a severe exogenous shock, aggregate variables can deviate from the pre-announced policy targets. Since private agents understand this possibility and make the same mistakes in predicting macro variables, they take a lenient stance in relation to these deviations. Put differently, this case translates into larger losses in both U^P and U^{CB}, and credibility ξ_t does not change much.[10]

Although this formulation seems similar to those of previous studies, such as Bomfim and Rudebusch (2000) and Hommes and Lustenhouwer (2019), it differs from them in several ways. First, our formulation does not employ past realizations as predictors to make expectations behave adaptively. In aforementioned research, the credibility measure is simply the degree of forward-lookingness. On the contrary, both predictors used in this paper are forward looking. Second, it is more plausible to account for the central bank's real-time communications. In Hommes and Lustenhouwer (2019), the credibility measure represents the proportion of households that use policy targets as their future forecasts. However, as the interim

[10]One might raise the question as to whether central bank credibility can be independent of the central bank's ability of keeping inflation stable if the central bank's staff become very good at predicting inflation and gross domestic product (GDP), to a point where the private sector's expectations totally rely on the central bank's forecasts. In this model, central bank credibility is not independent of the central bank's ability to keep inflation stable in the longer-run perspective. Definitely, credibility rises if the central bank's predictions are good enough. However, it is necessary to understand what makes the central bank's predictions better. In general, a central bank's predictions become more accurate when non-fundamental beliefs (a_t) that affect the private predictions are suppressed. These non-fundamental beliefs emerge when inflation and the output gap diverge from the pre-announced targets continuously beyond the private agents' tolerance. While temporary deviations due to large shocks are tolerated, continuing deviations may trigger divergent beliefs and drops in credibility. Therefore, deliberate policymaking for stabilizing inflation and the output gap is required to achieve high credibility and to make private agents rely more on the central bank's predictions. For this reason, the proposed measure is related to a central bank's ability to stabilize the economy in the longer-run horizon.

targets may not coincide with pre-announced policy targets, it is plausible that households would just use the central bank announcements in predictions, as in this paper, rather than rely on the long-run policy targets.

The proposed measure is also close to the one used by Gibbs and Kulish (2017). In their paper, two forecasts formed by rational expectations and adaptive learning are used to derive the ensemble forecast, and credibility is described as the proportion of households that have the rational expectations. Their measure is closely related to ours, as past realizations matter as well through the learning process but the weight placed on adaptive learning is not changing over time endogenously.

Compared with the credibility measures used in the previous research, the proposed measure possesses several advantages. First, our credibility measure is ex ante bounded in the unit interval, making it easier to interpret and compare. Second, what matters in determining credibility is the relative accuracy of forecasts, not the distance between either the actual or the predicted inflation and pre-announced inflation target. Hence, the deviation of inflation from the target, which arises due to large shocks, does not necessarily damage credibility because the public understands that it is inevitable and that their own predictors also perform badly.

3.3 Equilibrium

Combining expectations formation equations (14), (19), and (20) with policy rule equations (9), (10), and (11), the actual laws of motion (ALM) for this economy can be obtained.[11]

$$z_t = C_0 a_{t-1} + \Omega s_t \tag{25}$$

C_0 is the factor loading matrix, and this changes endogenously, as the credibility measure ξ_{t-1} is contained in this. The ALM and Equations (21), (22), and (24) governing the dynamics of the credibility measure fully characterize the model.

One advantageous feature of the model is that we can recover the ordinary rational expectations model if central bank credibility

[11] See Appendix A for details.

is fixed at the maximum level in any of the cases. That is, when the central bank credibility measure ξ_t is exogenously imposed to be one, the ALM become identical to those in the rational expectations model. Hence, the ordinary rational expectations model can be considered as a special case, in which the central bank is fully credible under any circumstances. The ALM, however, diverge away from that of the rational expectations model, and the effect of the subjective beliefs magnifies as the credibility measure moves away from one.

4. Historical Credibility of Central Banks

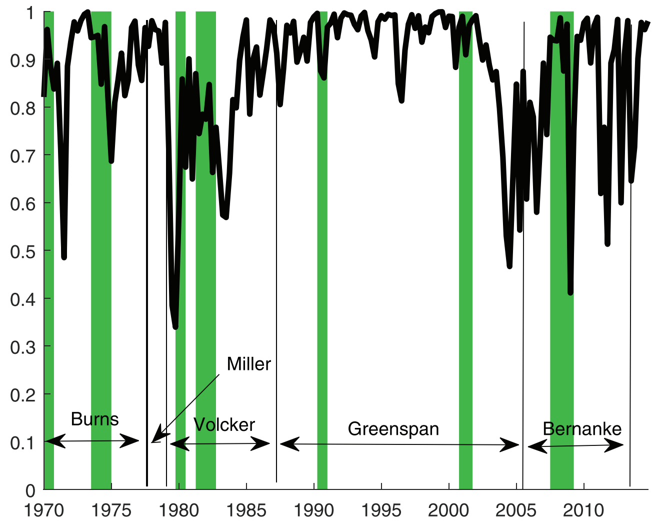
The credibility measure suggested above can be readily computed based on the observed data using Equations (20)–(24) if data exist about the economic forecasts of private agents and the central bank. To understand the credibility measure better, we construct the historical credibility series of the Federal Reserve (the Fed) and the European Central Bank (ECB). In this exercise, we only use the one-quarter-ahead inflation forecasts for data compatibility.[12] For the Fed, we compute credibility for 1968:Q4 to 2014:Q4 using Greenbook and SPF forecasts.[13] Similarly, credibility of the ECB is computed by the European Survey of Professional Forecasters and the ECB's own announcements on economic projections.

Figure 1 shows the historical series of the Federal Reserve's credibility computed by the SPF and Greenbook forecasts and the names of the Fed's chairperson. It shows that the Fed's credibility has fluctuated mostly between 0.3 and 1, but retains relatively high levels. While there have been substantial drops in credibility in 1972, from 1979 to 1980, in the mid-2000s, and during the global financial crisis, mean credibility is higher than 0.85 for the entire period. The shaded

[12]The choice of values of ω, δ_1, and δ_2 are discussed in Section 5. In the estimation, it is shown that considering only inflation forecast errors results in the similar outcomes compared with the case that takes all three variables—output gap, inflation, and interest rate—into account.

[13]There are multiple numbers of Greenbook forecasts in a given quarter. In this procedure, we choose the first Greenbook forecast in the quarter to comply with the assumption that forecasts are announced at the beginning of the period in the model. Lastly, the median forecast from the SPF is used for private forecasts.

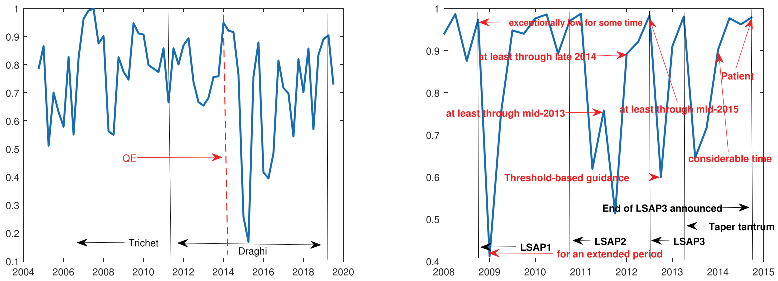
Figure 1. Credibility Measure of the Federal Reserve, 1970:Q1–2014:Q4



areas represent recessions identified by the National Bureau of Economic Research (NBER). This figure shows that shifts in credibility do not show any clear relationship with the business cycle.

Although it is hard to identify one specific factor that determines credibility, since that is determined collectively by various macroeconomic outcomes, the computed credibility of the Fed hints that major changes in the ways of conducting monetary policy are particularly important. In the first few years of the 1970s, frequent modifications in monetary policymaking took place as the techniques required for setting and pursuing money targets were developed. The figure also shows that the Fed's credibility was at a low level at the beginning of Volcker's tenure, but the Fed built credibility slowly over the 1980s. The reason behind this shift might be attributed to a dramatic change in policy course, which attempted to tame persistently high inflation. While credibility remained relatively high until the early 2000s, it shows a persistent drop in the mid-2000s. The Fed's credibility shifts rapidly during the global financial crisis period. Since the Fed introduced new policies sequentially during this period, that might drag credibility downward, as will be

Figure 2. Credibility of the European Central Bank, 2005:Q1–2019:Q3 (left) and Credibility of the Fed during the Global Financial Crisis (right)



presented in details below. Experiencing drops in credibility after introducing new policies seems reasonable. As private beliefs are persistent, realizing the expected effects takes time. Hence, credibility may decrease initially. As the expected effects emerge, the central bank starts to gain credibility.

Lastly, we provide two examples to which our measure of credibility may apply. To do so, we expand the analysis to credibility of the ECB and to the impacts of unconventional monetary policies conducted during the global financial crisis in the United States.

The left panel in Figure 2 depicts the credibility of the ECB. One notable feature is that the ECB's credibility has been persistently lower than that of the Fed. Specifically, the average credibility of the ECB is more than 15 percent lower than that of the Fed. It provides an example of the way in which the proposed measures can be used to compare credibility across economies, and calls for deeper future research on this matter.

The right panel provides the Fed's credibility and major policy events during the global financial crisis. The black and red arrows indicate policy changes regarding quantitative easing and forward guidance, respectively. It is difficult to identify the factors that drive credibility, but we may find some stylized facts regarding the influence of monetary policy on credibility. For instance, as is postulated above, major policy shifts precede drops in credibility. To go into more depth, the figure shows that the Fed's credibility tends to decrease following the announcements regarding quantitative easing.

Interestingly, the impacts of forward guidance seem unclear. This finding is also valid in the case of the ECB. The announcement that the ECB began purchasing government bonds (quantitative easing, or QE) preceded the largest drop in credibility.

If private beliefs are persistent and influential concerning economic outcomes, we can provide an explanation for the above findings. First, policies that only affect private beliefs or expectations, such as forward guidance, may have small impacts in credibility. If credibility is low, forward guidance may not be able to exert meaningful influence, hence it would not be able to enhance credibility. On the other hand, if credibility is high, private agents will change their beliefs immediately following the projections announced by the central bank. Therefore, credibility would not show drastic changes in this case either. Second, it will take a long time to show intended outcomes after major policy changes if economic outcomes are substantially affected by private beliefs, which evolve relatively slowly. This may temporarily damage credibility, as the policy effects come with a delay. We are going to show that these requirements seem to be satisfied in the estimated model.

5. Estimation

As this paper focuses on quantitatively measuring the influence of central bank credibility on the economy, it is necessary to estimate the model to discipline the parameters. As the model is highly nonlinear, we estimate the model by implementing a bootstrap particle filter Metropolis-Hastings algorithm to evaluate the likelihood functions and to derive posterior distributions of parameters.[14]

5.1 Data

We include six observables to estimate the model. For inflation and short-term interest rate measures, the GDP deflator and the federal funds rate (FFR) are used. For the output gap measure, the output gap published by the Congressional Budget Office is used. We also include a private forecasts series on the level of GDP, GDP deflator, and FFR from the Federal Reserve Bank of Philadelphia's Survey

[14]See Herbst and Schorfheide (2015) for theoretical discussion on this method.

of Professional Forecasters (SPF) to match the model-generated private forecasts. The sample period covers 1981:Q3 to 2007:Q4. Since the model lacks the zero lower bound constraint, we only use data from before the financial crisis.[15]

5.2 Calibrated Parameters

We calibrate some parameters before estimating the model. This set of parameters includes the subjective time discount factor, β; two intensity of choice parameters, δ_1 and δ_2; weights on past prediction errors, ω; and the weighting matrix, W. The subjective time discount factor β is set to 0.995. δ_1 and δ_2 are chosen to minimize the distance between the credibility measure estimated in the model and the one calculated directly from the private forecasts and the Fed's forecasts in Figure 1. As a result, $\delta_1 = 1.62$ and $\delta_2 = 23$ are chosen.[16] The parameter that governs weights on past prediction errors, ω, is set to zero for tractability. While there is no memory regarding the past loss due to prediction errors, the persistence of credibility can be still captured by the sluggish evolution of credibility measure which is controlled by η. The weighting matrix W is set as the identity matrix. This means that private agents put the same weight on the prediction errors on the output gap, inflation, and interest rate.[17]

5.3 Method

We estimate the model by constructing a Metropolis-Hastings particle filter (MHPF). The proposal parameters are drawn from a Markov chain repeatedly for 60,000 iterations. We discard the first 10,000 draws to remove any influence from the initial condition.

[15]Extending the sample period beyond 2007 using the shadow rate proposed by Wu and Xia (2016) does not change the estimates substantially.

[16]As long as δ_1 and δ_2 are sufficiently large, the predictor selection problem mimics the classical choice behavior. That is, the agents always choose the predictor that is more accurate, and the weight put on the other predictor becomes negligible. Hence, the quantitative results do not change considerably even if these parameters are changed. See Appendix D.

[17]The case where private agents only consider prediction errors on inflation results in similar outcomes. Specifically, the estimated credibility and private beliefs are almost identical to the one from the baseline case. See Appendix D.

Table 1. Estimated Parameters

Parameters	Distribution	Prior Mean	S.D.	Posterior Mode	[0.05, 0.95]
α	Beta	0.7	0.08	0.73	[0.72,0.73]
σ	Gamma	2	0.5	1.77	[1.76,1.78]
ϕ_x	Gamma	0.12	0.1	0.17	[0.17,0.17]
ϕ_π	Gamma	2	0.15	2.12	[2.12,2.13]
ρ_r	Beta	0.7	0.12	0.73	[0.72,0.73]
ρ_u	Beta	0.7	0.12	0.73	[0.73,0.74]
ρ_m	Beta	0.7	0.12	0.79	[0.78,0.79]
λ_1	Normal	0	0.5	–0.25	[–0.28,–0.25]
f_1	Uniform	0	1	0.74	[0.73,0.75]
f_2	Uniform	0	1	0.99	[0.99,0.99]
σ_{ε^r}	IGamma	0.1	2	0.58	[0.58,0.58]
σ_{ε^u}	IGamma	0.1	2	0.15	[0.14,0.16]
σ_{ε^m}	IGamma	0.1	2	0.50	[0.49,0.51]
K_{11}	Uniform	–1	1	0.34	[0.34,0.36]
K_{12}	Uniform	–1	1	0.12	[0.12,0.12]
K_{13}	Uniform	–1	1	–0.28	[–0.30,–0.28]
K_{21}	Uniform	–1	1	–0.09	[–0.09,–0.08]
K_{22}	Uniform	–1	1	0.30	[0.29,0.31]
K_{23}	Uniform	–1	1	0.14	[0.13,0.15]
η	Beta	0.7	0.12	0.66	[0.64,0.66]
Marginal Log-Likelihood	–1002.9				

Note: The priors and posteriors, Para(1) and Para(2), correspond to the mean and standard deviation of the Normal, Gamma, Inverse Gamma, and Beta distributions and to the lower and upper bounds for the Uniform distribution.

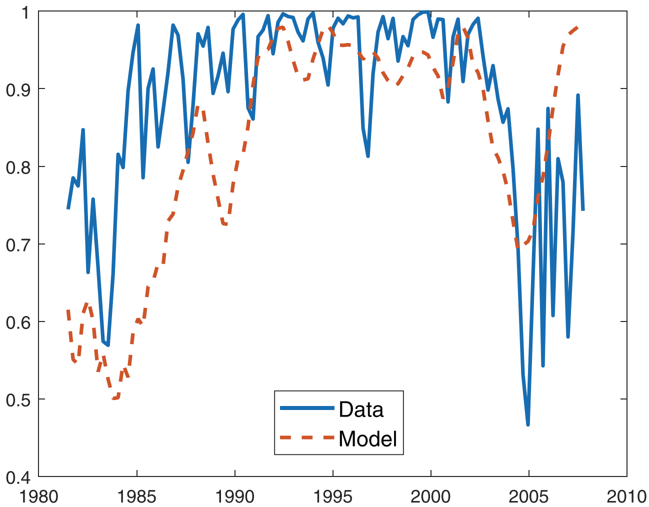
Next, we collect one draw in every five draws to thin out the chain to reduce the autocorrelation of the chain. Then we construct marginal posterior densities from the remaining 10,000 draws. The scaling parameter is set to vary along the iteration so that it guarantees achieving the acceptance rate in between 0.2 and 0.4. The resulting total acceptance rate is around 0.28. Lastly, the number of particles is set to 10,000.[18]

5.4 Estimation Outputs

Table 1 shows the prior and posterior distributions for the model parameters. We choose diffuse priors for f_1, f_2, K, η, and λ_1, as

[18]See Appendix B for details regarding the measurement and transition equations and iteration process.

Figure 3. Comparison between Estimated and Directly Computed Credibility



they are model specific, and so there is no consensus on the choice of these prior distributions. Other priors are quite general in the literature. In the next section, we use the modes of posteriors when simulating the model.

Some results are worth mentioning. The results for f_1 and f_2 show that the long-term inflation forecasts are highly persistent, and not anchored, but that the perception regarding the long-term business outlook is less persistent. In addition, the estimate of η shows that the credibility measure is moderately persistent.

Next, we compare the estimated credibility and the directly computed credibility derived in the previous section to validate the estimation. Figure 3 presents the credibility series directly computed by the forecast data (blue solid line) and the estimated credibility the non-linear filter (red dashed line). While the estimated credibility shows more sluggish movement, the two series move in a similar manner. Numerically, the correlation coefficient between the two series is 0.48. The correlation reaches 0.57 when the empirical credibility series is smoothed by a moving average with a five-quarter window.

Finally, before analyzing the model, it is necessary to check whether the model results in stable dynamics under the given parameters. Appendix C analyzes the model stability and confirms that the model is stable under the current calibration.

6. Quantitative Results

In this section, we examine the role of central bank credibility on the overall macroeconomic stability by simulating the model. To this end, the model is simulated 50,000 times, for 1,200 periods each, to gauge the effects of endogenously evolving central bank credibility on macroeconomic stability. The initial 1,000 periods are discarded to remove any effects from initial conditions. The model parameters are set to their posterior modes derived from the estimation procedure.

6.1 Endogenous Volatility Changes

First, we compare the macroeconomic volatility obtained in the baseline model to that computed in the rational expectations model to examine whether endogenous central bank credibility can create additional volatility in macroeconomic variables.[19] To this end, standard deviations in the output gap and inflation are computed and compared with those from the rational expectations model.

The results are summarized in Table 2. This table contains the mean standard deviations obtained from the simulations across models and subperiods. In general, introducing the credibility measure in a New Keynesian model raises the volatility of both the output gap and inflation. Specifically, the standard deviation of inflation is 33 percent higher in our model, whereas that of the output gap changes by only 7 percent. We derive two observations from the above results. First, introducing central bank credibility can endogenously generate additional volatility in the economy. Second, shifts in central bank credibility can substantially affect the volatility of inflation, but that of the output gap is affected much less.

Next, the standard deviations of the macro variables are calculated for different levels of credibility to analyze the relationship

[19]The rational expectations model is evaluated at the same parameter values with the exception of the belief structure.

Table 2. Volatility of Macro Variables

	RE	Baseline	$\frac{\text{Baseline}}{\text{RE}}$
$\sigma(x)$	1.37	1.47	1.07
$\sigma(x_h)$	1.36	1.37	1.01
$\sigma(x_l)$	1.37	1.54	1.12
$\sigma(x_l)/\sigma(x_h)$	1.01	1.12	
$\sigma(\pi)$	0.61	0.81	1.33
$\sigma(\pi_h)$	0.54	0.54	1.00
$\sigma(\pi_l)$	0.66	0.98	1.48
$\sigma(\pi_l)/\sigma(\pi_h)$	1.22	1.81	

Note: The average standard deviations are obtained from the simulations. Subscripts h indicate standard deviations computed from periods with credibility higher than the median and l with lower than the median.

between credibility and macroeconomic volatility. To this end, simulated series are divided into two groups of subperiods. One contains variables at periods when credibility is higher than the median, and the other when credibility is lower than the median.[20] For better contrast of the results, we also report standard deviations derived by simulating the same sets of shocks under the rational expectations model since there might be the possibility that higher volatility is caused by larger shocks rather than the endogenous credibility channel.[21]

Table 2 clearly shows that the variations of endogenous variables decrease in credibility. The standard deviations of the output gap and inflation are 12 percent and 81 percent higher in the low-credibility periods. It is appropriate to ask whether this difference is fully caused endogenously by introducing credibility concerns in the model, because some portions of the increments can be caused just by selecting low-volatility realization periods as high-credibility periods. This concern can be resolved by comparing the $\sigma(x_l)/\sigma(x_h)$ and $\sigma(\pi_l)/\sigma(\pi_h)$ ratios between the baseline and rational expectations

[20]The median is around 0.63.

[21]Since there is no change in credibility in the rational expectations (RE) model, we report $\sigma(x_h)$, $\sigma(\pi_h)$, $\sigma(x_h)$, and $\sigma(\pi_h)$ of the RE model based on the credibility level of the baseline model calculated from the same shocks.

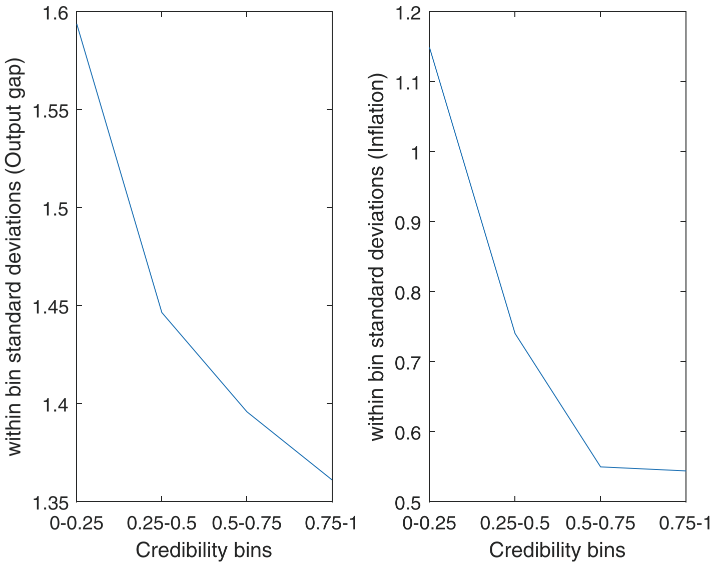
models. As shown in Table 2, accounting for credibility of the central bank significantly increases the ratio for inflation. The endogenous evolution of credibility generates an additional 59 percent increment in the standard deviation of inflation (81 percent minus 22 percent) while that of the output gap shows 11 percent rise in volatility compared with the rational expectations model. Thus, we can conclude that an increase in the standard deviation of inflation and the output gap is largely generated by introducing endogenous credibility into the model. One thing worth noticing is that volatility is almost the same across the models when credibility is in the upper half. This is reasonable, as our model converges on the rational expectations model as credibility enhances.[22]

Next, it is still not clear whether there is a monotonic negative relationship between the credibility and volatility of endogenous variables. To answer this question, we divided the simulated series into finer credibility bins, as in Figure 4. It clearly shows that the standard deviations of the output gap and inflation increase monotonically as credibility decreases. In particular, the variability of inflation increases exponentially as credibility decreases. To be precise, the increments in the volatility of inflation rise from 2 percent to 55 percent as credibility decreases, while the increments in the output gap increase only from 3 percent to 10 percent. This suggests that most of the benefits of higher credibility accrue in the low credibility region. This result is in line with the results discussed in Schaumburg and Tambalotti (2007).

The quantitative results can be connected to the recent experimental studies on central bank credibility (Ahrens, Lustenhouwer, and Tettamanzi 2017; Mokhtarzadeh and Petersen 2021). In these studies, central bank credibility is measured by the fraction of forecasters that have the same (or close) projected value as the one announced by the central bank. As predicted in this paper, it is

[22]It is well known that introducing a learning procedure instead of rational expectations assumption produces an additional layer of interaction between economic outcomes and monetary policy and results in more volatile macroeconomic dynamics compared with rational expectations models as shown above. For instance, Orphanides and Williams (2004) find that policies that fail to maintain control over inflation are vulnerable to episodes in which the public's expectations become decoupled from the policy objectives under imperfect knowledge environment using a perpetual learning model.

Figure 4. Standard Deviations of Output Gap and Inflation across Credibility Quartiles



shown that credibility decreases when the central bank makes larger prediction errors in these experiments. The experimental results can explain the theoretical results provided in this paper reasonably well. First, when credibility is higher, volatility is almost identical to that which arises in the rational expectations model. Second, when credibility is lower, the standard deviations (or similarly, mean square deviations from the targets) of the output and inflation increase. Specially, volatility of the output increases by quantitatively small amounts whereas that of inflation increases substantially. These results are surprisingly in line with the theoretical predictions provided in this model.

Combining the above results with the estimated credibility of the Fed, we can postulate that shifts in the Fed's credibility is one possible explanation for the Great Moderation, referring to the period of low macroeconomic variability between the mid-1980s and the global financial crisis. Since the Fed's credibility during the Great Moderation was higher than during other periods (Table 3), additional volatility injected because of the lower credibility had

Table 3. Average Credibility of the Fed across the Periods

Period	1970–1984	1985–2007	2008–2014
Mean Credibility	0.83	0.91	0.86

been suppressed. This might have contributed to relatively stable macroeconomic developments. For this reason, lower macroeconomic volatility during the Great Moderation might be partially attributed to an increase in the Fed's credibility.

6.2 Underlying Mechanism: Feedback Effect of Private Beliefs

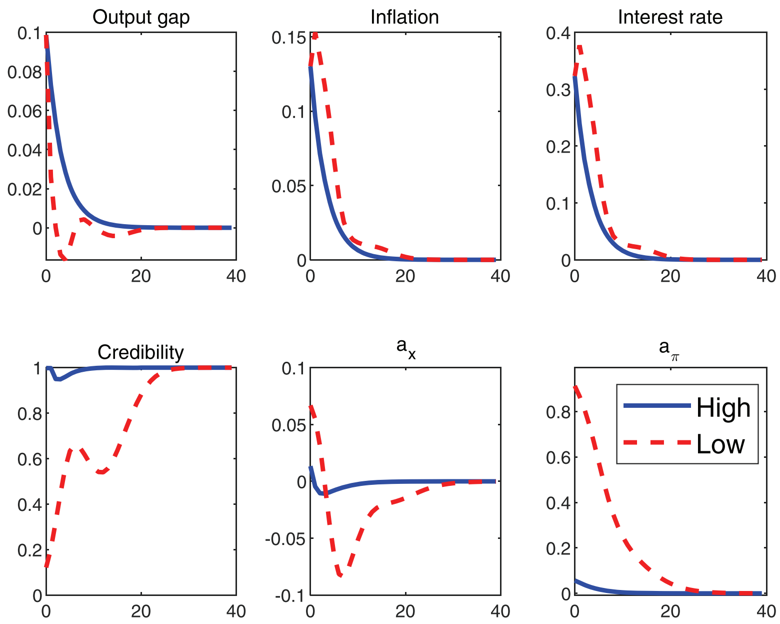
In this subsection, we analyze the underlying mechanism that creates additional volatility in the economy by examining the impulse response of the model. Before proceeding with the results, it is necessary to emphasize that the impulse response is not unique, and depends on a realization of history due to the non-linearity of the model. In particular, the level of credibility and the real and nominal factors that occur when a shock hits the economy are important determinants of the impulse response. For this reason, we derive impulse response functions with different initial conditions for two factors, a^x and a^π, and for credibility ξ.[23] Since two initial values for subjective factors are required to generate impulse response functions, we assume $a_{-1} = a_{-2}$ for simplicity. Finally, it is also noteworthy that impulse response functions obtained in case $a = 0$ and $\xi = 1$ is almost identical to those in the rational expectations model.

Impulse responses are calculated by differencing simulated series with and without a specific temporary shock. Finally, we present impulse responses to the preference shock in the main text, and those to the cost-push and monetary policy shock are delegated to Appendix E, as the underlying mechanism is the same.

In Figure 5, it is assumed that the private agents perceive that the long-term inflation is higher than the zero inflation

[23] Alternatively, we may derive generalized impulse responses as in much of the empirical literature. However, we do not follow this strategy because our method helps to understand better the transmission mechanisms of the model.

Figure 5. Impulse Responses to a One-Standard-Deviation Preference Shock When a_π Is Positive



Note: The blue solid line represents impulse responses from $\xi_{-1} = 1$, $a^{\pi}_{-1} = 0.01$ and the red dashed line represents impulse responses from $\xi_{-1} = 0.4$, $a^{\pi}_{-1} = 0.9$.

target ($a^{\pi}_{-1} > 0$) and the exact values differ across initial credibility. To be exact, a^{π}_{-1} is assumed to be 0.01 and 0.9 for the initial credibility level 1 (high credibility), and 0.4 (low credibility) cases.[24]

When $\xi_{-1} = 1$, subjective factors a^x and a^π do not affect the output gap and inflation, even if these factors have non-zero values. Therefore, their effects on endogenous variables are limited in subsequent periods. For this reason, impulse responses are similar to those of the rational expectations model when initial credibility is equal to one: the output gap, inflation, and interest rate increase and return to the steady state monotonically.

[24] We choose these values for realistic model simulations based on the estimated nominal factor for each credibility level for the U.S. economy.

As credibility deteriorates, however, the model dynamics change considerably. When a^π is positive, a positive preference shock reduces credibility, as a positive a^π makes private forecasts relatively more accurate compared with the central bank's forecasts. Specifically, private forecasts become more accurate as credibility deteriorates since private agents anticipate higher inflation than the central bank at time zero due to the positive perception on the nominal factor. Thus, credibility drops more than 0.2 points immediately in the low credibility case and remains at the lower level for longer periods.

Similarly, the nominal factor is revised upward and returns to zero slowly in all cases, as realized inflation is higher than expected. This shift in the nominal factor again feeds back to even higher inflation and this feedback effect gets larger as credibility decreases since the influence of the nominal factor becomes more substantial. As credibility decreases, private expectations of future inflation increase because of a higher a^π. This increases inflation instantly and feeds into a higher nominal factor. This stimulates inflation again and the self-referential cycle continues. For this reason, inflation even overshoots in the low-credibility case.

Initially, the output gap increases sharply due to the positive preference shock. However, as credibility drops, private agents expect higher nominal interest rates in future periods, and the central bank actually increases the nominal interest rate to stabilize higher inflation. Therefore, the output gap shows a more contracted path compared with the case with a higher credibility.

While the initial real factor is zero, it is revised upward due to the positive reaction of the output gap. Then, as private agents update their perceptions on the real factor, it comes back to zero while the deviation is larger in the low-credibility case.

6.3 Improving Credibility

Finally, in this subsection, we discuss how a central bank can enhance its credibility. There are many things that can affect central bank credibility. For instance, even a single word spoken by policymakers could affect central bank credibility. Hence, it is not an easy task to discuss every possible option for improving credibility. For

Table 4. Monetary Policy Rules and Average Credibility

ϕ_π	**1.12 (–1)**	**1.62 (–0.5)**	**2.12 (Benchmark)**	**2.62 (+0.5)**	**3.12 (+1)**
Mean Credibility	89	95	100	101	102
ϕ_x	**0.07 (–0.1)**	**0.17 (Benchmark)**	**0.27 (+0.1)**	**0.37 (+0.2)**	
Mean Credibility	100	100	101	102	

Note: The average credibility in the benchmark model is normalized to 100. Therefore, the average credibility under different specifications can be interpreted as the percentage changes compared to the benchmark case.

this reason, we only focus on the role of the central bank's systematic reactions to economic developments in shaping credibility. To this end, we analyze how the average credibility changes as we vary the parameters governing the monetary policy rule specified in Equation (11).

Table 4 presents how the average credibility changes as the monetary policy reaction function varies. The upper panel shows the changes in credibility when the central bank's response to inflation changes, while the lower panel presents the changes in credibility as the reaction to the output gap changes. Compared with the benchmark case that represents the current policy practice, stronger reactions to both inflation and the output gap result in a higher mean credibility, though the increments are quite small. This is reasonable since stronger responses to inflation and the output gap make them easier to forecast by pushing them closer to their respective targets.[25]

[25] However, it is uncertain whether stronger responses to inflation and the output gap are welfare improving, since a stronger reaction to inflation results in a more volatile output gap, while a stronger response to the output gap leads to more volatile inflation. This suggests that the optimal monetary policy may depend on central bank credibility. Although we do not analyze the optimal monetary policy under the credibility restriction since that is out of the scope of this paper, we believe that it might be an interesting future research topic.

On the contrary, weaker responses to inflation sharply reduce credibility, while weaker reactions to the output gap do not change credibility substantially. This non-linear relationship between monetary policy reactions and credibility suggests that the Fed is efficiently conducting its policy so that it achieves high credibility without creating excessively volatile macroeconomic responses to monetary policy.

7. Conclusion

In this research, a numerical measure of central bank credibility is proposed and its effects on macroeconomic stability are examined. The main contributions of this paper are to show to what extent accounting for credibility affects macroeconomic stability. Specifically, it is shown that volatility in the output gap and inflation increase as credibility deteriorates due to the self-referential effect of private beliefs. This model can generate endogenous volatility changes based on the shifts in credibility without relying on exogenous volatility regime changes. This result theoretically confirms the idea that maintaining a credible reputation helps to anchor private expectations and to achieve macroeconomic stability. Despite their importance, these results have not yet been fully analyzed in a New Keynesian framework with endogenous central bank credibility concerns, and this paper provides a useful benchmark that can be easily analyzed.

The findings derived in this research have important implications for many issues in monetary policy. For instance, the definition of credibility used in this paper is related to the forward guidance, especially the Delphic effects of forward guidance, as studied in, among others, Campbell et al. (2012, 2017). A central bank's forecasts as described in this model are closely related to forward guidance, as they hint at a future course for the economy and communicate information held by the central bank. Most analyses of forward guidance, however, implicitly assume full credibility so that private agents believe what the central bank says and focus on information flow from the central bank to the public. If the private agents do not think that the central bank is fully credible, the Delphic effects that were described might disappear. Therefore, this research suggests that it is necessary to take the credibility issue into account when the effects of forward guidance are examined.[26]

Although central bank credibility has been considered an important feature that shapes the efficacy of monetary policy, it has not been sufficiently taken into account in quantitative monetary policy studies. Nonetheless, credibility matters in many cases, as documented in this paper, hence more serious research regarding this issue is warranted.

Appendix A. Actual Laws of Motion

First, obtain a minimum state variable (MSV) solution for the rational expectations model below by method of undetermined coefficients.

$$\begin{aligned} x_t &= E_t x_{t+1} - \sigma^{-1}(i_t - E_t\pi_{t+1} - r_t^n) \\ \pi_t &= \kappa x_t + \beta E_t \pi_{t+1} + u_t \\ i_t &= \phi_\pi \pi_t + \phi_x x_t + m_t, \end{aligned} \tag{A.1}$$

A unique and bounded solution exists if $\kappa(\phi_\pi - 1) + (1-\beta)\phi_x > 0$ holds. Note that this condition is satisfied in a current calibration. The MSV solution is given as

$$\begin{aligned} x_t &= a_{11} r_t^n + a_{12} u_t + a_{13} m_t \\ \pi_t &= a_{21} r_t^n + a_{22} u_t + a_{23} m_t \\ i_t &= a_{31} r_t^n + a_{32} u_t + a_{33} m_t, \end{aligned}$$

where

$$\begin{aligned} a_{21} &= \frac{1}{\left(\frac{1-\beta\rho_r}{\kappa}\right)((1-\rho_r)\sigma + \phi_x) - \rho_r + \phi_\pi} \\ a_{11} &= a_{21}\frac{1-\beta\rho_r}{\kappa} \\ a_{31} &= \phi_\pi a_{21} + \phi_x a_{11} \end{aligned}$$

[26]In their experiment paper, Ahrens, Lustenhouwer, and Tettamanzi (2017) emphasize the importance of credibility in shaping the effectiveness of forward guidance.

$$
\begin{aligned}
a_{22} &= \frac{1-\rho_u+\frac{\phi_x}{\sigma}}{\kappa\left[\frac{\phi_\pi-\rho_u}{\sigma}+\frac{1-\beta\rho_u}{\kappa}\left(1-\rho_u+\frac{\phi_x}{\sigma}\right)\right]}\\
a_{12} &= a_{22}\frac{(1-\beta\rho_u)}{\kappa}-\frac{1}{\kappa}\\
a_{32} &= \phi_\pi a_{22}+\phi_x a_{12}\\
a_{23} &= \frac{-1}{\left[\frac{1-\beta\rho_m}{\kappa}(\sigma(1-\rho_m)+\phi_\pi)+\phi_\pi-\rho_m\right]}\\
a_{13} &= a_{23}\frac{1-\beta\rho_m}{\kappa}\\
a_{33} &= \phi_\pi a_{23}+\phi_x a_{13}+1.
\end{aligned}
$$

Combining Equations (14), (19), and (20), obtain future expectations on endogenous variables

$$
\begin{aligned}
\hat{E}_t x_T &= (1-\xi_{t-1})f_1^{T-t}a_{t-1}^x + a_{11}\rho_r^{T-t}r_t^n + a_{12}\rho_u^{T-t}u_t + a_{13}\rho_m^{T-t}m_t\\
\hat{E}_t \pi_T &= (1-\xi_{t-1})f_2^{T-t}a_{t-1}^\pi + a_{21}\rho_r^{T-t}r_t^n + a_{22}\rho_u^{T-t}u_t + a_{23}\rho_m^{T-t}m_t\\
\hat{E}_t i_T &= (1-\xi_{t-1})(\lambda_1 f_1^{T-t}a_{t-1}^x + \lambda_2 f_2^{T-t}a_{t-1}^\pi) + a_{31}\rho_r^{T-t}r_t^n\\
&\quad + a_{32}\rho_u^{T-t}u_t + a_{33}\rho_m^{T-t}m_t.
\end{aligned}
$$

Inserting these expectations into policy rules, Equations (9), (10), and (11), gives the following system of equations:

$$
\begin{aligned}
x_t+\frac{i_t}{\sigma} =& \frac{(1-\xi_{t-1})f_1}{1-\beta f_1}\left(1-\beta-\frac{\lambda_1\beta}{\sigma}\right)a_{t-1}^x\\
&+\frac{(1-\xi_{t-1})f_2}{\sigma(1-\beta f_2)}(1-\lambda_2\beta)a_{t-1}^\pi\\
&+\frac{\sigma(1-\beta)\rho_r a_{11}+\rho_r a_{21}-\beta\rho_r a_{31}+1}{\sigma(1-\beta\rho_r)}r_t^n\\
&+\frac{\sigma(1-\beta)\rho_u a_{12}+\rho_u a_{22}-\beta\rho_u a_{32}}{\sigma(1-\beta\rho_u)}u_t\\
&+\frac{\sigma(1-\beta)\rho_m a_{13}+\rho_m a_{23}-\beta\rho_m a_{33}}{\sigma(1-\beta\rho_m)}m_t
\end{aligned}
$$

$$\pi_t - \kappa x_t = \frac{\kappa(1-\xi_{t-1})\alpha\beta f_1}{1-\alpha\beta f_1} a^x_{t-1} + \frac{(1-\alpha)\beta(1-\xi_{t-1})f_2}{1-\alpha\beta f_2} a^\pi_{t-1}$$
$$+ \frac{\rho_r(\kappa\alpha\beta a_{11} + (1-\alpha)\beta a_{21})}{1-\alpha\beta\rho_r} r^n_t$$
$$+ \frac{\kappa\alpha\beta\rho_u a_{12} + (1-\alpha)\beta\rho_u a_{22} + 1}{1-\alpha\beta\rho_u} u_t$$
$$+ \frac{\rho_m(\kappa\alpha\beta a_{13} + (1-\alpha)\beta a_{23})}{1-\alpha\beta\rho_m} m_t$$
$$i_t - \phi_x x_t - \phi_\pi \pi_t = m_t. \tag{A.2}$$

In matrix form, this system can be expressed as follows:

$$\begin{bmatrix} 1 & 0 & \frac{1}{\sigma} \\ -\kappa & 1 & 0 \\ -\phi_x & -\phi_\pi & 1 \end{bmatrix} \begin{bmatrix} x_t \\ \pi_t \\ i_t \end{bmatrix} = \begin{bmatrix} d_{11} & d_{12} & d_{13} & d_{14} & d_{15} \\ d_{21} & d_{22} & d_{23} & d_{24} & d_{25} \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} a^x_{t-1} \\ a^\pi_{t-1} \\ r^n_t \\ u_t \\ m_t \end{bmatrix}. \tag{A.3}$$

By inverting the leading matrix in the left-hand side, we can obtain the actual laws of motion,

$$\begin{bmatrix} x_t \\ \pi_t \\ i_t \end{bmatrix} =$$
$$\begin{bmatrix} \frac{\sigma d_{11} - \phi_\pi d_{21}}{h} & \frac{\sigma d_{12} - \phi_\pi d_{22}}{h} & a_{11} & a_{12} & a_{13} \\ \frac{\kappa\sigma d_{11} + (\phi_x + \sigma) d_{21}}{h} & \frac{\kappa\sigma d_{12} + (\phi_x + \sigma) d_{22}}{h} & a_{21} & a_{22} & a_{23} \\ \frac{\sigma(\phi_x + \kappa\phi_\pi) d_{11} + \phi_\pi \sigma d_{21}}{h} & \frac{\sigma(\phi_x + \kappa\phi_\pi) d_{12} + \phi_\pi \sigma d_{22}}{h} & a_{31} & a_{32} & a_{33} \end{bmatrix} \begin{bmatrix} a^x_{t-1} \\ a^\pi_{t-1} \\ r^n_t \\ u_t \\ m_t \end{bmatrix}, \tag{A.4}$$

where $h = \phi_x + \kappa\phi_\pi + \sigma$. Note that the actual laws of motion (ALM) and future expectations are identical to those of the rational expectations model without credibility when ξ_{t-1} converges to one. To see this, note that $d_{ij} = 0$ when $\xi_{t-1} = 1$ for all i and j. Therefore, ALM reduces to an MSV solution of underlying rational expectations model as ξ_{t-1} converges to one.

Appendix B. Estimation Procedure

The measurement equation is given as

$$\begin{bmatrix} x_t \\ \pi_t \\ i_t \\ \hat{E}_t^P[x_{t+1}] \\ \hat{E}_t^P[\pi_{t+1}] \\ \hat{E}_t^P[i_{t+1}] \end{bmatrix} = \begin{bmatrix} \mathcal{I}_3 & \mathcal{O}_{3\times 8} \\ \mathcal{O}_{3\times 3} & \mathcal{M}_{3\times 8} \end{bmatrix} \begin{bmatrix} x_t \\ \pi_t \\ i_t \\ a_t^x \\ a_t^\pi \\ \xi_t \\ a_{t-1}^x \\ a_{t-1}^\pi \\ r_t^n \\ u_t \\ m_t \end{bmatrix} + o_t, \tag{B.1}$$

where

$$\mathcal{M}_{3\times 8} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & f_1 & 0 & \rho_r a_{11} & \rho_u a_{12} & \rho_m a_{13} \\ 0 & 0 & 0 & 0 & 0 & 0 & f_2 & \rho_r a_{21} & \rho_u a_{22} & \rho_m a_{23} \\ 0 & 0 & 0 & 0 & 0 & \lambda_1 f_1 & f_2 & \rho_r a_{31} & \rho_u a_{32} & \rho_m a_{33} \end{bmatrix}. \tag{B.2}$$

The transition equations consist of laws of motion which are derived in the main text and deterministic identity equations.

The estimation procedure can be summarized by the following:

(i) Draw $\mathcal{V}$ from the Markov chain (proposal parameter).

(ii) Generate particles of exogenous disturbances z.

(iii) For $t = 1 : T$,
- Propagate state variables x_t given particles z_t and initial states x_{t-1}.
- Evaluate likelihood functions $p(y_t \mid x_t, z_t, \mathcal{V})$.
- Resample the particles weighted by their likelihoods.
- Approximate the time t likelihood $\hat{p}(y_t \mid \mathcal{V})$ weighted by likelihoods of each particle.

(iv) Approximate the likelihood function $\hat{p}(y_{1:T} \mid \mathcal{V})$.

(v) With probability $\alpha(\mathcal{V} \mid \theta^{i-1}) = \min\left\{1, \frac{\hat{p}(y_{1:T}|\mathcal{V})p(\mathcal{V})}{\hat{p}(y_{1:T}|\theta^{i-1})p(\theta^{i-1})}\right\}$, set $\theta^i = \mathcal{V}$ otherwise, $\theta^i = \theta^{i-1}$ where $p(\theta)$ is the prior distribution.

We set the standard deviations of observation errors to 20 percent of the standard deviations of corresponding actual data series following Herbst and Schorfheide (2015).

Appendix C. Model Stability

Combining Equation (16) and Equation (25) gives

$$a_t = (F + KC_0 - KH)a_{t-1} + K\Omega\varepsilon_t. \tag{C.1}$$

As explained in Eusepi, Giannoni, and Preston (2015), the self-referentiality of beliefs can lead to instability. This instability arises if any eigenvalue of the matrix $F+KC_0-KH$ lies outside the unit circle. This approach is, however, not possible in this case, because the model stability depends on the evolution of the credibility measure ξ. Specifically, C_0 contains ξ, so the evolution of credibility affects the dynamics of beliefs. For this reason, we analyze a Jacobian matrix of this non-linear system following Hommes and Lustenhouwer (2019) and Branch and McGough (2010), among many others.

$\tilde{\xi}_t$ is determined by the following:

$$\tilde{\xi}_t = 1 - \frac{\exp\left(\delta_1 U_t^P\right)}{\exp\left(\delta_1 U_t^P\right) + \exp\left(\delta_1 U_t^{CB}\right)} \times \left(1 - \exp\left(-\delta_2\left(\hat{E}_{t-1}^{CB}\pi_t - \hat{E}_{t-1}^{P}\pi_t\right)^2\right)\right). \tag{C.2}$$

We introduce an auxiliary variable q_t which is defined as below.

$$q_t = \frac{1 - \exp(\delta_1 U_t^{CB} - \delta_1 U_t^P)}{1 + \exp(\delta_1 U_t^{CB} - \delta_1 U_t^P)} = \tanh\left(-\frac{\delta_1}{2}(U_t^{CB} - U_t^P)\right) \tag{C.3}$$

Using this auxiliary variable and evaluating the distance between two predictions, $\tilde{\xi}_t$ can be simplified as below.

$$\tilde{\xi}_t = 1 - \frac{q_t + 1}{2}\left(1 - \exp(-\delta_2 f_2^2 (a_{t-2}^{\pi})^2)\right) \tag{C.4}$$

The model can be summarized as a system of non-linear equations.

$$\begin{aligned} z_t &= M_1(a_{t-1}, \xi_{t-1}, s_t) \\ a_t &= M_2(a_{t-1}, z_t, s_{t-1}) \\ \xi_t &= M_3(q_t, a_{t-2}, \xi_{t-1}) \\ q_t &= M_4(a_{t-2}, s_{t-1}, z_t) \\ a_{t-1} &= I(a_{t-1}) \\ s_{t+1} &= M_5(s_t) \\ s_t &= I(s_t) \end{aligned} \tag{C.5}$$

Before analyzing the stability, we show that there is a steady state in this system.

PROPOSITION 1. *A steady state of the model exists and this steady state satisfies* $x = 0$*,* $\pi = 0$*,* $i = 0$*,* $a = 0$*,* $s = 0$*,* $q = 0$*, and* $\xi = 1$*.*

Proof. It is easy to show that $x = 0$, $\pi = 0$, $i = 0$, $a = 0$, $s = 0$, $q = 0$, and $\xi = 1$ solve the system of equations.

As this steady state with $x = 0$, $\pi = 0$, and $i = 0$ coincides with that of a rational expectations model, we label this steady state as the fundamental steady state.

The next proposition provides the global stability result of the model. The main idea behind this result is that, as zero credibility is the most de-stabilizing condition, the system is globally stable if the eigenvalues of the Jacobian are inside the unit circle when the credibility measure ξ is fixed at zero for all t.

PROPOSITION 2. *The fundamental steady state is globally stable under the baseline calibration.*

Proof. If full credibility, $\xi = 1$ for all t, is imposed, the economy has a globally stable steady state, which is the fundamental steady state, as the belief terms a do not affect the dynamics, and the steady state is exactly the same with that of the underlying rational expectations model. As ξ moves away from one to zero, the influence of the belief terms a on the system increases and the economic dynamics become more unstable. Therefore, if the economic system is stable under zero credibility, it is globally stable. Under the assumption that $\xi = 0$ for all t, the system can be written as follows:

$$\begin{aligned} a_t &= M_2(a_{t-1}, M_1(a_{t-1}, s_t), s_{t-1}) \\ s_{t+1} &= M_5(s_t) \\ s_t &= I(s_t). \end{aligned} \tag{C.6}$$

Then, we can obtain the following Jacobian matrix:

$$\begin{bmatrix} f_1 - kf_{11} + \Delta_{11} & -kf_{12} + \Delta_{12} & ka_{11} & ka_{12} & ka_{13} & -ka_{11}\rho_r & -ka_{12}\rho_u & -ka_{13}\rho_m \\ -kf_{21} + \Delta_{21} & f_2 - kf_{22} + \Delta_{22} & ka_{21} & ka_{22} & ka_{23} & -ka_{21}\rho_r & -ka_{22}\rho_u & -ka_{23}\rho_m \\ 0 & 0 & \rho_r & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \rho_u & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \rho_m & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}, \tag{C.7}$$

where

$$\begin{aligned} \Delta_{ij} = K_{i1}\frac{\sigma dk_{1j} - \phi_\pi dk_{2j}}{\phi_x + \kappa\phi_\pi + \sigma} + Ki2\frac{\kappa\sigma dk_{1j} + (\phi_x + \sigma)dk_{2j}}{\phi_x + \kappa\phi_\pi + \sigma} \\ + K_{i3}\frac{\sigma(\phi_x + \kappa\phi_\pi)dk_{1j} + \phi_\pi\sigma dk_{2j}}{\phi_x + \kappa\phi_\pi + \sigma} \end{aligned}$$

$$dk_{11} = \frac{f_1}{1 - \beta f_1}\left(1 - \beta - \frac{\lambda_1\beta}{\sigma}\right), \quad dk_{12} = \frac{f_2}{1 - \beta f_2}\left(\frac{1 - \lambda_2\beta}{\sigma}\right)$$

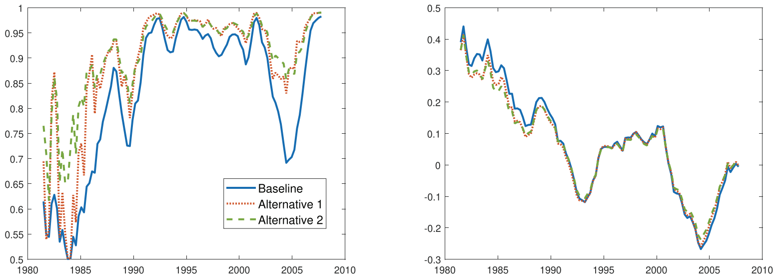
$$dk_{21} = \frac{\kappa\alpha\beta f_1}{1 - \alpha\beta f_1}, \quad dk_{22} = \frac{(1 - \alpha)\beta f_2}{1 - \alpha\beta f_2},$$

where $kf_{ij} = f_j K_{ij} + \lambda_j f_j K_{i3}$, $ka_{ij} = K_{i1}a_{1j} + K_{i2}a_{2j} + K_{i3}a_{3j}$, and K_{ij} denotes (i, j) element of the Kalman gain matrix. It has three zero and five non-zero eigenvalues, which are all inside the unit circle under baseline calibration. Therefore, the fundamental steady state is globally stable.

Appendix D. Alternative Calibration

In this appendix, we provide evidence that using alternative calibrations for δ_1, δ_2, and W does not change the quantitative result considerably. To be precise, we illustrate this robustness by showing

Figure D.1. Estimated Credibility with Different Calibrations (left) and Estimated a^{π} with Different Calibrations (right)



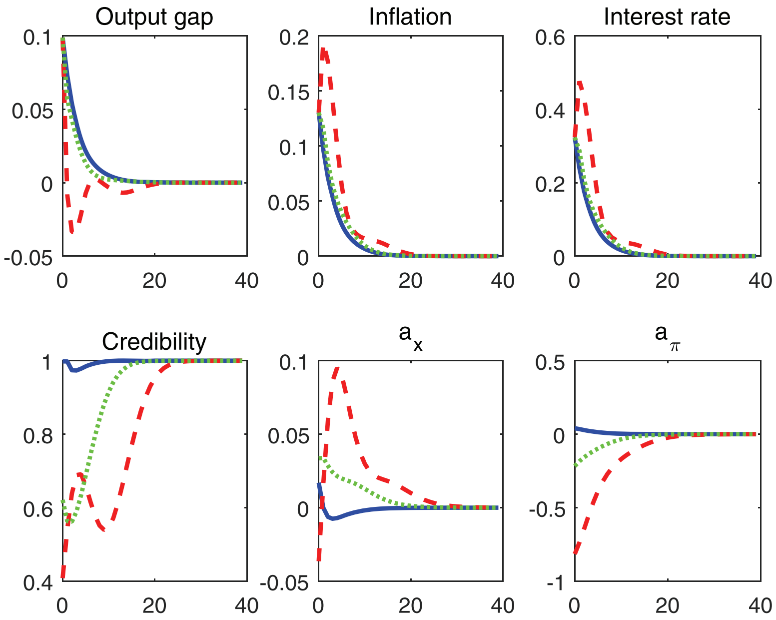
the estimated credibility and private beliefs across different calibrations. Figure D.1 presents the estimated results. The blue solid lines represent the estimated series obtained from the baseline calibration. The red dotted lines and the green dashed lines are estimated results with different calibrations. Specifically, "Alternative 1" shows the case that $\delta_1 = \delta_2 = 15$ while "Alternative 2" stands for the case with different W shown below.

$$W = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

We choose $\delta_1 = \delta_2 = 15$ as an alternative calibration in this exercise, but choosing any values with sufficiently large δ_2, say greater than 2, produces very similar result. Under "Alternative 2" assumption, the private agents only care about the forecast errors associated with inflation. The estimated output shows that the results are quite similar to the baseline case.

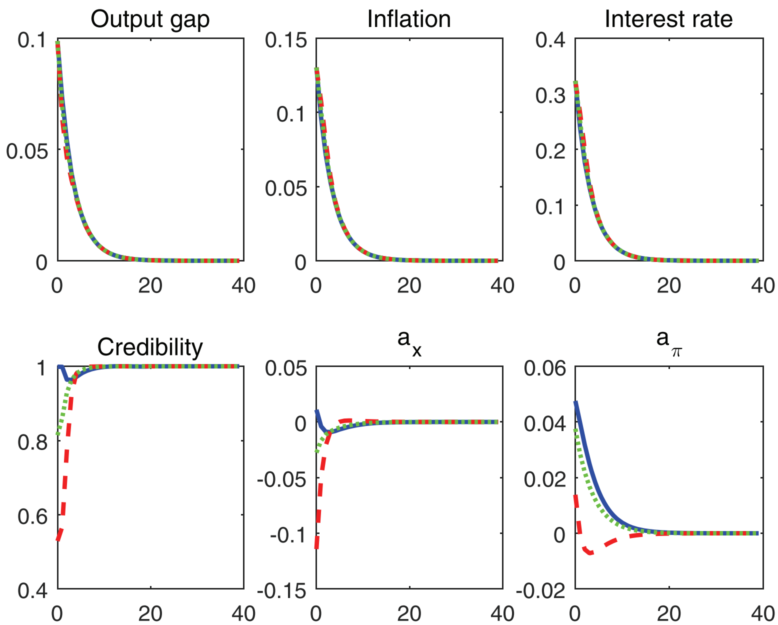
Appendix E. Additional Impulse Responses

Figure E.1. Impulse Responses to One-Standard-Deviation Preference Shock When a_π Is Negative



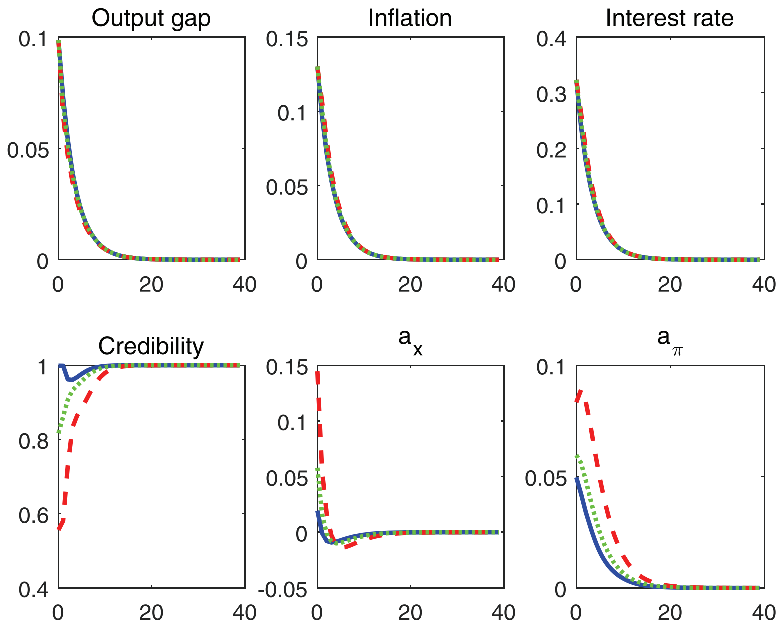
Note: The blue solid line represents impulse responses from $\xi_{-1} = 1$, $a^{\pi}_{-1} = -0.01$ and the red dashed line represents impulse responses from $\xi_{-1} = 0.4$, $a^{\pi}_{-1} = -0.9$. The green dotted line represents impulse responses from $\xi_{-1} = 0.6$, $a^{\pi}_{-1} = -0.3$.

Figure E.2. Impulse Responses to One-Standard-Deviation Preference Shock When a_x Is Negative



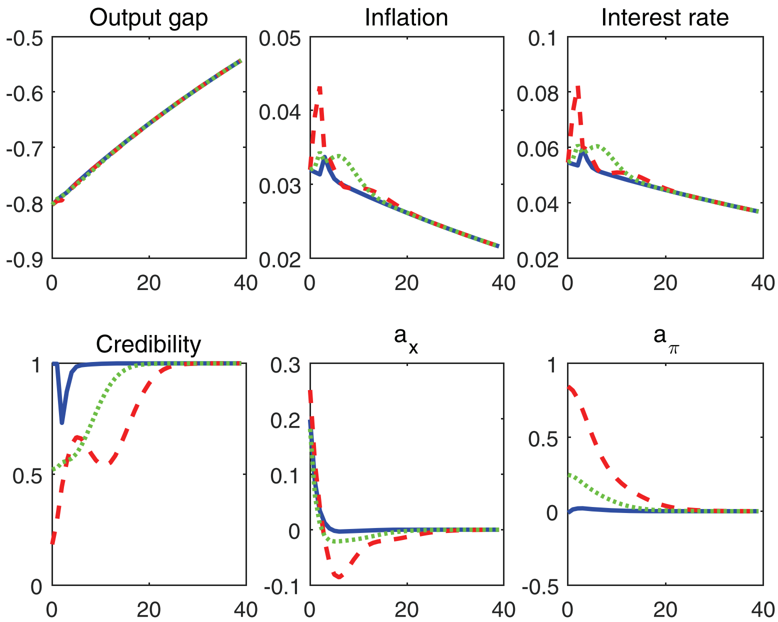
Note: The blue solid line represents impulse responses from $\xi_{-1} = 1$, $a^x_{-1} = -0.01$ and the red dashed line represents impulse responses from $\xi_{-1} = 0.4$, $a^x_{-1} = -0.9$. The green dotted line represents impulse responses from $\xi_{-1} = 0.6$, $a^x_{-1} = -0.3$.

Figure E.3. Impulse Responses to One-Standard-Deviation Preference Shock When a_x Is Positive



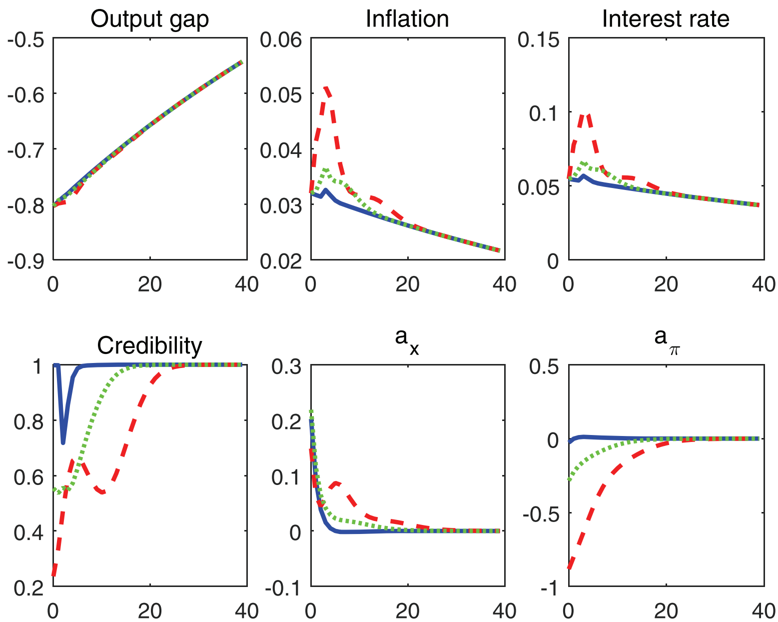
Note: The blue solid line represents impulse responses from $\xi_{-1} = 1$, $a^x_{-1} = 0.01$ and the red dashed line represents impulse responses from $\xi_{-1} = 0.4$, $a^x_{-1} = 0.9$. The green dotted line represents impulse responses from $\xi_{-1} = 0.6$, $a^x_{-1} = 0.3$.

Figure E.4. Impulse Responses to One-Standard-Deviation Cost-Push Shock When a_π Is Positive



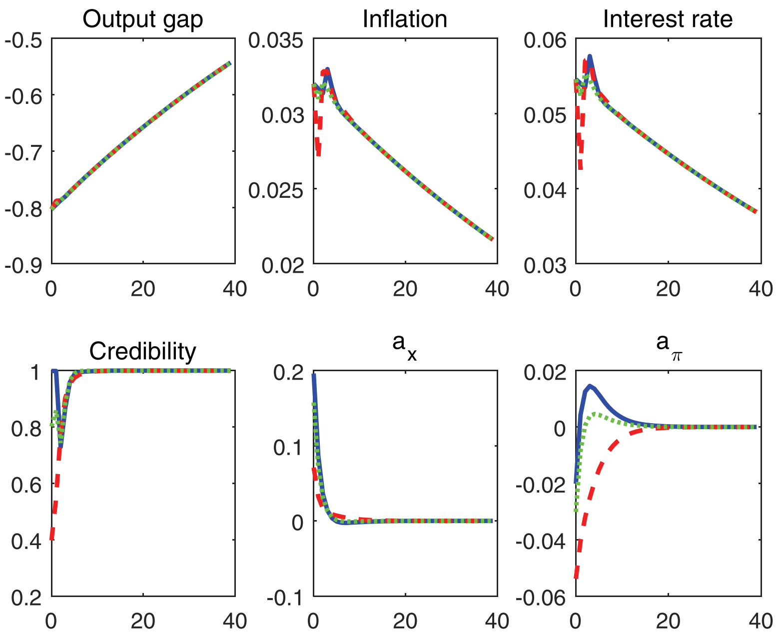
Note: The blue solid line represents impulse responses from $\xi_{-1} = 1$, $a^{\pi}_{-1} = 0.01$ and the red dashed line represents impulse responses from $\xi_{-1} = 0.4$, $a^{\pi}_{-1} = 0.9$. The green dotted line represents impulse responses from $\xi_{-1} = 0.6$, $a^{\pi}_{-1} = 0.3$.

Figure E.5. Impulse Responses to One-Standard-Deviation Cost-Push Shock When a_π Is Negative



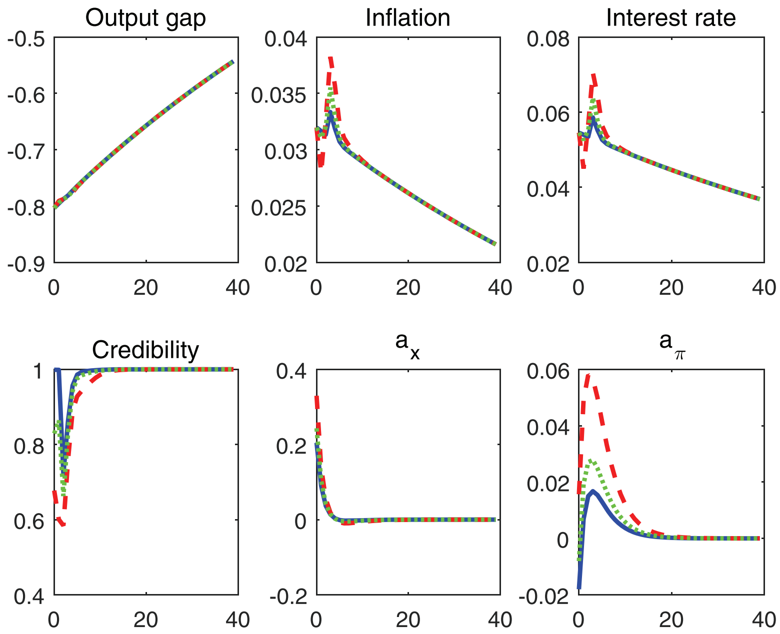
Note: The blue solid line represents impulse responses from $\xi_{-1} = 1$, $a^{\pi}_{-1} = -0.01$ and the red dashed line represents impulse responses from $\xi_{-1} = 0.4$, $a^{\pi}_{-1} = -0.9$. The green dotted line represents impulse responses from $\xi_{-1} = 0.6$, $a^{\pi}_{-1} = -0.3$.

Figure E.6. Impulse Responses to One-Standard-Deviation Cost-Push Shock When a_x Is Negative



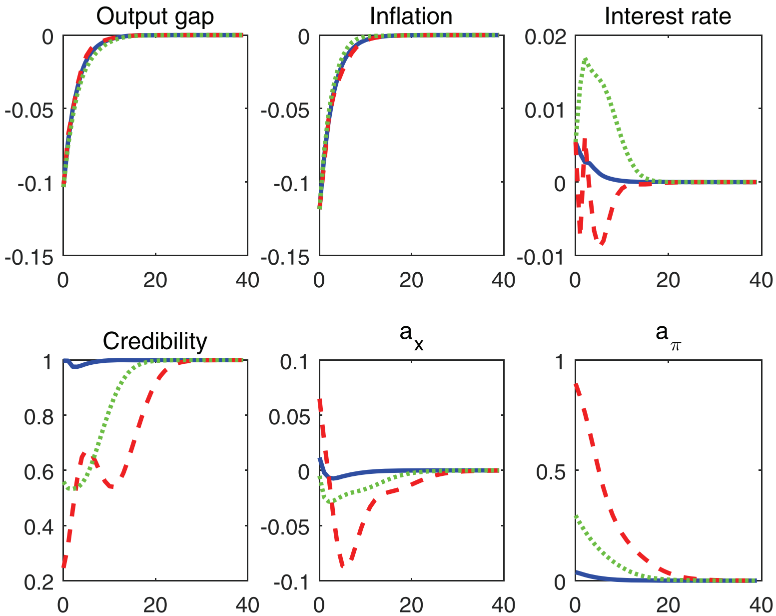
Note: The blue solid line represents impulse responses from $\xi_{-1} = 1$, $a^x_{-1} = -0.01$ and the red dashed line represents impulse responses from $\xi_{-1} = 0.4$, $a^x_{-1} = -0.9$. The green dotted line represents impulse responses from $\xi_{-1} = 0.6$, $a^x_{-1} = -0.3$.

Figure E.7. Impulse Responses to One-Standard-Deviation Cost-Push Shock When a_x Is Positive



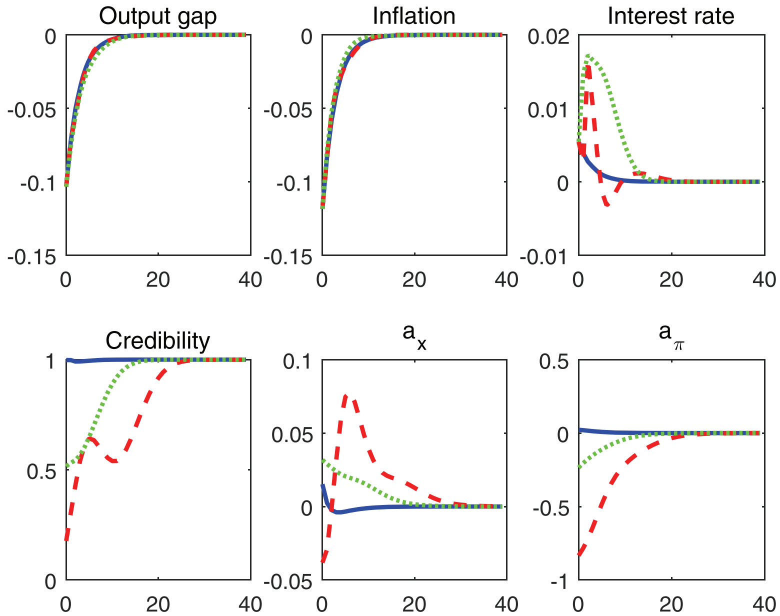
Note: The blue solid line represents impulse responses from $\xi_{-1} = 1$, $a^x_{-1} = 0.01$ and the red dashed line represents impulse responses from $\xi_{-1} = 0.4$, $a^x_{-1} = 0.9$. The green dotted line represents impulse responses from $\xi_{-1} = 0.6$, $a^x_{-1} = 0.3$.

Figure E.8. Impulse Responses to One-Standard-Deviation Monetary Policy Shock When a_π Is Positive



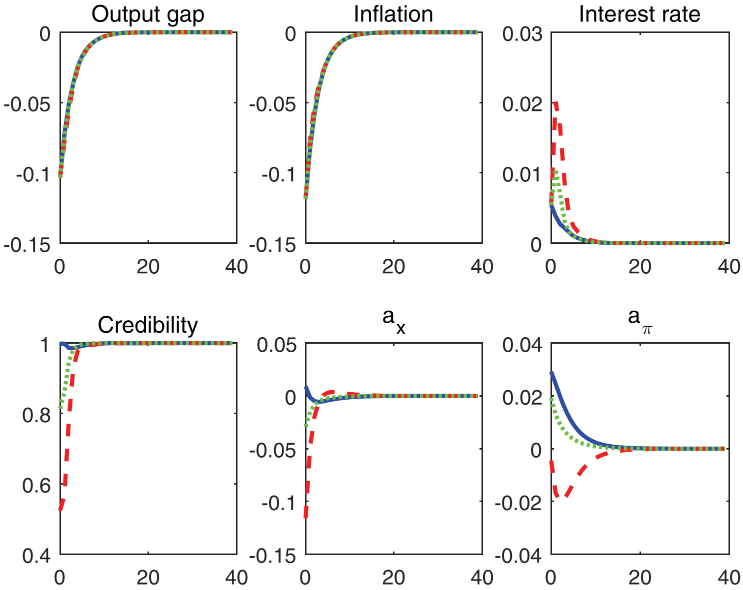
Note: The blue solid line represents impulse responses from $\xi_{-1} = 1$, $a^{\pi}_{-1} = 0.01$ and the red dashed line represents impulse responses from $\xi_{-1} = 0.4$, $a^{\pi}_{-1} = 0.9$. The green dotted line represents impulse responses from $\xi_{-1} = 0.6$, $a^{\pi}_{-1} = 0.3$.

Figure E.9. Impulse Responses to One-Standard-Deviation Monetary Policy Shock When a_π Is Negative



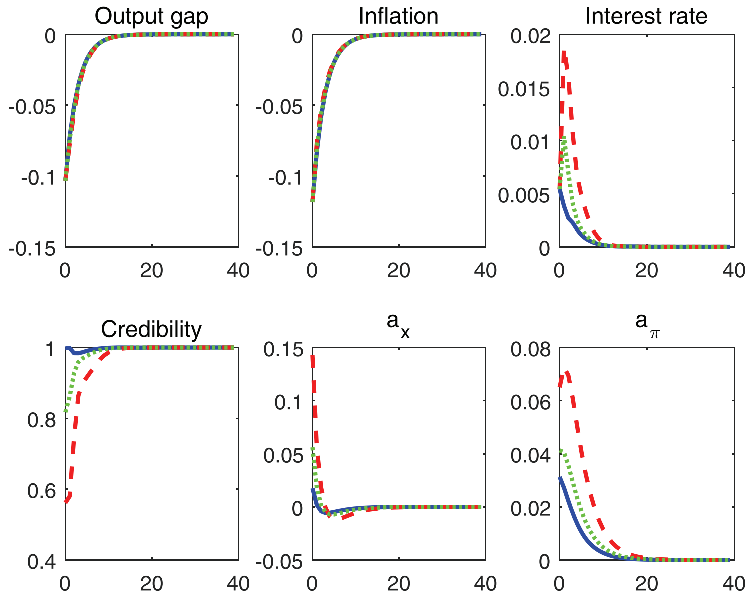
Note: The blue solid line represents impulse responses from $\xi_{-1} = 1$, $a^{\pi}_{-1} = -0.01$ and the red dashed line represents impulse responses from $\xi_{-1} = 0.4$, $a^{\pi}_{-1} = -0.9$. The green dotted line represents impulse responses from $\xi_{-1} = 0.6$, $a^{\pi}_{-1} = -0.3$.

Figure E.10. Impulse Responses to One-Standard-Deviation Monetary Policy Shock When a_x Is Negative



Note: The blue solid line represents impulse responses from $\xi_{-1} = 1$, $a^x_{-1} = -0.01$ and the red dashed line represents impulse responses from $\xi_{-1} = 0.4$, $a^x_{-1} = -0.9$. The green dotted line represents impulse responses from $\xi_{-1} = 0.6$, $a^x_{-1} = -0.3$.

Figure E.11. Impulse Responses to One-Standard-Deviation Monetary Policy Shock When a_x Is Positive

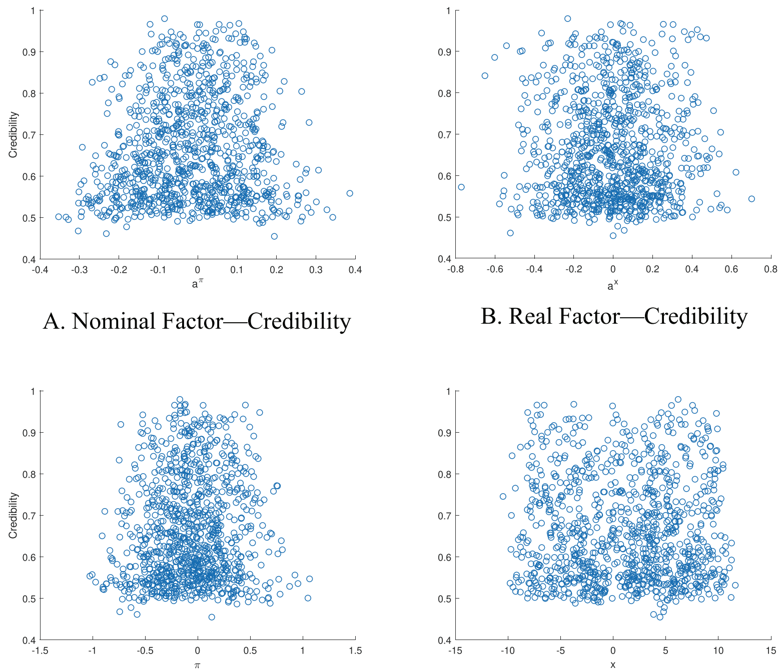


Note: The blue solid line represents impulse responses from $\xi_{-1} = 1$, $a^x_{-1} = 0.01$ and the red dashed line represents impulse responses from $\xi_{-1} = 0.4$, $a^x_{-1} = 0.9$. The green dotted line represents impulse responses from $\xi_{-1} = 0.6$, $a^x_{-1} = 0.3$.

Appendix F. Scatter Plots of Simulated Series

We provide additional evidence that a combination of lower credibility and shifting private beliefs undermines macroeconomic stability based on the simulated time series. Figure F.1 shows the relationship between credibility and economic outcomes. The upper panels present the relationship between private beliefs and credibility while the bottom panels illustrate the co-movements of macro variables and credibility. The nominal factor spreads out as credibility deteriorates. This leads to more volatile realizations of inflation that is caused by a self-referential effect examined above. The real factor shows the same pattern as in the nominal factor. It suggests that the private beliefs are closely related to central bank credibility as asserted. However, the output gap does not show any distinctive pattern across the different levels of credibility. This is in line with the above result that the volatility of the output gap is not significantly affected by credibility.

Figure F.1. Scatter Plots of Simulated Series



A. Nominal Factor—Credibility

B. Real Factor—Credibility

C. Inflation—Credibility

D. Output—Credibility

References

Ahrens, S., J. Lustenhouwer, and M. Tettamanzi. 2017. "The Stabilizing Role of Forward Guidance: A Macro Experiment." Working Paper.

Angeletos, G.-M., and J. La'O. 2013. "Sentiments." *Econometrica* 81 (2): 739–79.

Ball, L. 1994. "Credible Disinflation with Staggered Price-Setting." *American Economic Review* 84 (1): 282–89.

———. 1995. "Disinflation with Imperfect Credibility." *Journal of Monetary Economics* 35 (1): 5–23.

Bernanke, B. S. 2004. "Central Bank Talk and Monetary Policy." Speech to the Japan Society, New York, October 7.

Blinder, A. S. 2018. "Through a Crystal Ball Darkly: The Future of Monetary Policy Communication." *American Economic Review: Papers and Proceedings* 108 (5): 567–71.

Bomfim, A., and G. Rudebusch. 2000. "Opportunistic and Deliberate Disinflation under Imperfect Credibility." *Journal of Money, Credit and Banking* 32 (November): 707–21.

Branch, W., and B. McGough. 2010. "Dynamic Predictor Selection in a New Keynesian Model with Heterogeneous Expectations." *Journal of Economic Dynamics and Control* 34 (8): 1492–1508.

Brock, W. A., and C. H. Hommes. 1997. "A Rational Route to Randomness." *Econometrica* 65 (5): 1059–95.

Calvo, G. A. 1983. "Staggered Prices in a Utility-Maximizing Framework." *Journal of Monetary Economics* 12 (3): 383–98.

Campbell, J. R., C. L. Evans, J. D. M. Fisher, and A. Justiniano. 2012. "Macroeconomic Effects of Federal Reserve Forward Guidance." *Brookings Papers on Economic Activity* (1, Spring): 1–80.

Campbell, J. R., J. D. M. Fisher, A. Justiniano, and L. Melosi. 2017. "Forward Guidance and Macroeconomic Outcomes Since the Financial Crisis." *NBER Macroeconomics Annual 2016*, Vol. 31, ed. M. Eichenbaum, E. Hurst, and J. A. Parker, 283–357. Chicago: University of Chicago Press.

Cukierman, A., and A. Meltzer. 1986. "A Theory of Ambiguity, Credibility, and Inflation under Discretion and Asymmetric Information." *Econometrica* 54 (5): 1099–1128.

Demertzis, M., M. Marcellino, and N. Viegi. 2010. "Anchors for Inflation Expectations." Working Paper.

Erceg, C., and A. Levin. 2003. "Imperfect Credibility and Inflation Persistence." *Journal of Monetary Economics* 50 (4): 915–44.

Eusepi, S., M. Giannoni, and B. Preston. 2015. "The Limits of Monetary Policy with Long-term Drift in Expectations." Working Paper.

Eusepi, S., and B. Preston. 2011. "Expectations, Learning, and Business Cycle Fluctuations." *American Economic Review* 101 (6): 2844–72.

Gabaix, X. 2014. "A Sparsity-based Model of Bounded Rationality." *Quarterly Journal of Economics* 129 (4): 1661–1710.

———. 2016. "Behavioral Macroeconomics via Sparse Dynamic Programming." Working Paper.

———. 2020. "A Behavioral New Keynesian Model." *American Economic Review* 110 (8): 2271–2327.

Gibbs, C. G., and M. Kulish. 2017. "Disinflations in a Model of Imperfectly Anchored Expectations." *European Economic Review* 100 (November): 157–74.

Goodfriend, M., and M. King. 2015. "Review of the Riksbank's Monetary Policy 2010-2015."

Herbst, E. P., and F. Schorfheide. 2015. *Bayesian Estimation of DSGE Models.* Princeton University Press.

Hommes, C., and J. Lustenhouwer. 2019. "Inflation Targeting and Liquidity Traps under Endogenous Credibility." *Journal of Monetary Economics* 107 (November): 48–62.

Johnson, D. 1997. "Expected Inflation in Canada 1988-1995: An Evaluation of Bank of Canada Credibility and the Effect of Inflation Targets." *Canadian Public Policy* 23 (3): 233–58.

———. 1998. "The Credibility of Monetary Policy: International Evidence Based on Surveys of Expected Inflation." In *Price Stability, Inflation Targets and Monetary Policy,* 361–95. Proceedings of a conference held by the Bank of Canada, May 1997.

Kocherlakota, N. 2011. "Communication, Credibility and Implementation: Some Thoughts on Past, Current and Future Monetary Policy." Speech in Carlson School of Management, University of Minnesota, September 6.

Mokhtarzadeh, F., and L. Petersen. 2021. "Coordinating Expectations through Central Bank Projections." *Experimental Economics* 24 (3): 883–918.

Orphanides, A., and J. Williams. 2004. "Imperfect Knowledge, Inflation Expectations, and Monetary Policy." In *The Inflation-Targeting Debate,* ed. B. S. Bernanke and M. Woodford, 201–46. University of Chicago Press.

Plosser, C. I. 2010. "Credible Commitments and Monetary Policy After the Crisis." Speech to the Swiss National Bank Monetary Policy Conference, Zurich, Switzerland, September 24.

Preston, B. 2005. "Learning about Monetary Policy Rules when Long-Horizon Expectations Matter." *International Journal of Central Banking* 1 (2, September): 81–126.

Schaumburg, E., and A. Tambalotti. 2007. "An Investigation of the Gains from Commitment in Monetary Policy." *Journal of Monetary Economics* 54 (2): 302–24.

Wu, J. C., and F. D. Xia. 2016. "Measuring the Macroeconomic Impact of Monetary Policy at the Zero Lower Bound." *Journal of Money, Credit and Banking* 48 (2–3): 253–91.

Yellen, J. L. 2006. "Enhancing Fed Credibility." Speech to the Annual Washington Policy Conference, sponsored by the National Association for Business Economics (NABE), Washington, DC, March 13.