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Imperfect credibility and inflation persistence ☆

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Abstract

In this paper, we formulate a dynamic general equilibrium model with staggered nominal contracts, in which households and firms use optimal filtering to disentangle persistent and transitory shifts in the monetary policy rule. The calibrated model accounts quite well for the dynamics of output and inflation during the Volcker disinflation, and implies a sacrifice ratio very close to the estimated value. Our approach indicates that inflation persistence and substantial costs of disinflation can be generated in an optimizing-agent framework, without relaxing the assumption of rational expectations or relying on arbitrary modifications to the aggregate supply relation.

JEL classification: E31; E32; E52

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1. Introduction

Since the pioneering work of Taylor (1980) and Calvo (1983), business cycle dynamics and the role of monetary policy have been analyzed in models with

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staggered nominal contracts. In recent years, such contracts have been incorporated into dynamic general equilibrium (DGE) models derived from microeconomic foundations.[1] Nevertheless, models with staggered contracts have been criticized for failing to generate a sufficient degree of inflation persistence and for implying unrealistically low costs of disinflation (Ball, 1994a; Fuhrer and Moore, 1995).[2]

In this paper, we formulate a DGE model with optimizing agents and staggered nominal contracts, and we show that this model can generate inflation persistence and substantial output costs of disinflation when private agents have limited information about the central bank's objectives.[3] In particular, households and firms use optimal filtering to disentangle persistent shifts in the inflation target from transitory disturbances to the monetary policy rule. Under these assumptions, the speed at which private agents recognize a new inflation target depends on the transparency and credibility of the central bank. Thus, the signal-to-noise ratio is the key parameter determining the persistence of inflation forecast errors, and hence influencing the persistence of actual inflation and output.

We show that this model can account quite well for the dynamics of output and inflation during the Volcker disinflation. Using data from the Survey of Professional Forecasters, we calibrate the signal-to-noise ratio to match the observed evolution of 1-year-ahead inflation forecasts over the period 1980:4–1985:4. With four-quarter wage and price contracts and an empirically reasonable calibration of capital adjustment costs, the model implies output costs of about 1.7 percentage points for each percentage point reduction in the inflation rate; this sacrifice ratio is remarkably close to the estimated value for the Volcker disinflation.

Our analysis contrasts sharply with existing approaches for generating inflation persistence and substantial costs of disinflation. First, we avoid arbitrary departures from the optimizing-agent framework, such as adding lagged inflation terms to the aggregate supply relation or imposing adaptive rather than rational expectations. Our assumption that agents process information efficiently is consistent with the findings of Evans and Wachtel (1993), who analyzed survey data on inflation expectations and demonstrated that persistent ex post forecast errors during the period 1968–1985 should not be viewed as "irrational" but rather as reflecting the degree of uncertainty about the underlying inflation regime.

Second, our analysis implies that inflation persistence is *not* an inherent characteristic of the economy but rather varies with the stability and transparency of the monetary policy regime. As discussed below, this perspective is consistent with

[1] Lucas (1985) analyzed a DGE model with staggered price contracts of fixed duration, while Levin (1989) analyzed a DGE model with staggered wage contracts of this type. For recent examples, see Rotemberg and Woodford (1997), King and Wolman (1999), and Erceg et al. (2000).

[2] The same criticism applies to models with quadratic costs of price adjustment (cf. Rotemberg, 1996; Kim, 2000), which have similar first-order dynamic properties to models with staggered nominal contracts.

[3] Our approach is similar in spirit to that of Ball (1995a), who used a small structural model to show that imperfect credibility can raise the output costs of disinflation, and to that of Ireland (1995, 1997), who analyzed optimal disinflation paths using a highly stylized DGE framework but did not focus on the quantitative implications. More recently, Kozicki and Tinsley (2001) examined the financial market implications of shifts in the inflation target, using a time-series model of the term structure.

empirical evidence indicating very high U.S. inflation persistence (close to that of a random walk) during the period 1965–1984 and much lower persistence during the remainder of the postwar period. In contrast, the empirical evidence appears to be inconsistent with models that incorporate inherent inflation persistence due to contract structure or adaptive expectations.

Finally, in our model, the costs of disinflation are radically diminished if agents quickly recognize the shift in the inflation target, whereas the learning rate is of relatively minor importance in models with inherent inflation persistence.[4] More generally, our approach suggests that efforts to enhance transparency and credibility can facilitate the effectiveness of monetary stablilization policy.

The remainder of this paper is organized as follows. Section 2 reviews several important stylized facts, and highlights the credibility problems faced by the Federal Reserve during the Volcker disinflation. Section 3 presents our model, while Section 4 describes the calibration and solution methods. Section 5 investigates the model's simulated responses to a disinflation shock. Section 6 compares our approach to accounting for inflation persistence to the previous literature. Section 7 provides conclusions and suggests directions for future research.

2. Key stylized facts

In this section, we briefly characterize the persistence properties of postwar U.S. inflation, and then we highlight several key aspects of the Volcker disinflation. We interpret large and persistent inflation forecast errors as largely attributable to the Federal Reserve's lack of credibility following the unstable policies of the 1970s and the early abandonment of the initial monetary tightening of October 1979.

2.1. The dynamic properties of U.S. inflation

Fig. 1 depicts the postwar evolution of the U.S. GDP price inflation rate (that is, the annualized one-quarter inflation rate of the chain-weighted GDP price deflator). From this figure, it is apparent that inflation exhibited relatively high persistence between the mid-1960s and mid-1980s: annual average inflation rose progressively from 2% to around 10% in 1980, and then fell to about 4% by the end of the Volcker disinflation. Our analysis focuses on explaining the dynamics of inflation during the latter period, while leaving an explanation of the 1965–1979 period to future research.[5]

Interestingly, while U.S. inflation appears to have followed a random walk over roughly the 1965–1984 period, the inflation rate exhibits much less persistence prior to 1965 and after about 1984. These shifts in inflation persistence have been

[4] In models with intrinsic inflation persistence, Bomfim et al. (1997) and Huh and Lansing (2000) find that the credibility of the central bank has relatively small effects on the costs of disinflation.

[5] Christiano and Gust (2000), Clarida et al. (2000), and Orphanides (2000) present alternative interpretations for the rise in inflation during the late 1960s and 1970s; see also Goodfriend (1997).

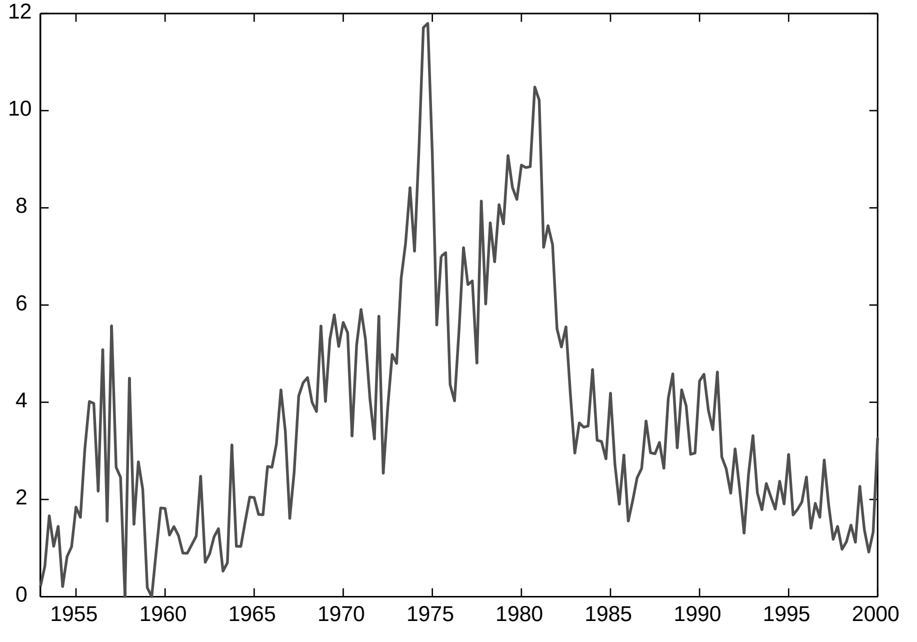

Fig. 1. U.S. GDP price inflation (annualized one-quarter rate).

documented using several different econometric approaches. For example, Taylor (2000) found that the largest autoregressive root of inflation has a 95% confidence interval of {0.94, 1.05} for the years 1960–1979, compared with a confidence interval of {0.50, 0.86} for the years 1982–1999.[6] Similar conclusions have been reached by Evans and Wachtel (1993), who estimated a Markov regime-switching model of inflation, and by Cogley and Sargent (2001), who analyzed a vector autoregression with time-varying parameters. Thus, a high degree of inflation persistence does not seem to be an inherent characteristic of the U.S. economy. As we will see below, our approach is consistent with this evidence, because our model exhibits moderate persistence when monetary policy is transparent and credible, and much higher persistence when agents must use signal extraction to make inferences about the central bank's inflation target.

2.2. A brief chronology of the Volcker disinflation

In October 1979, newly appointed Federal Reserve Chairman Paul Volcker announced a major shift in policy aimed at reducing the inflation rate. Volcker

[6] Even stronger evidence for this result is obtained when one allows for a post-1991 shift in the mean of the inflation process; for example, we found in this case that the largest autoregressive root of inflation is only 0.55 over the 1983–2000 period.

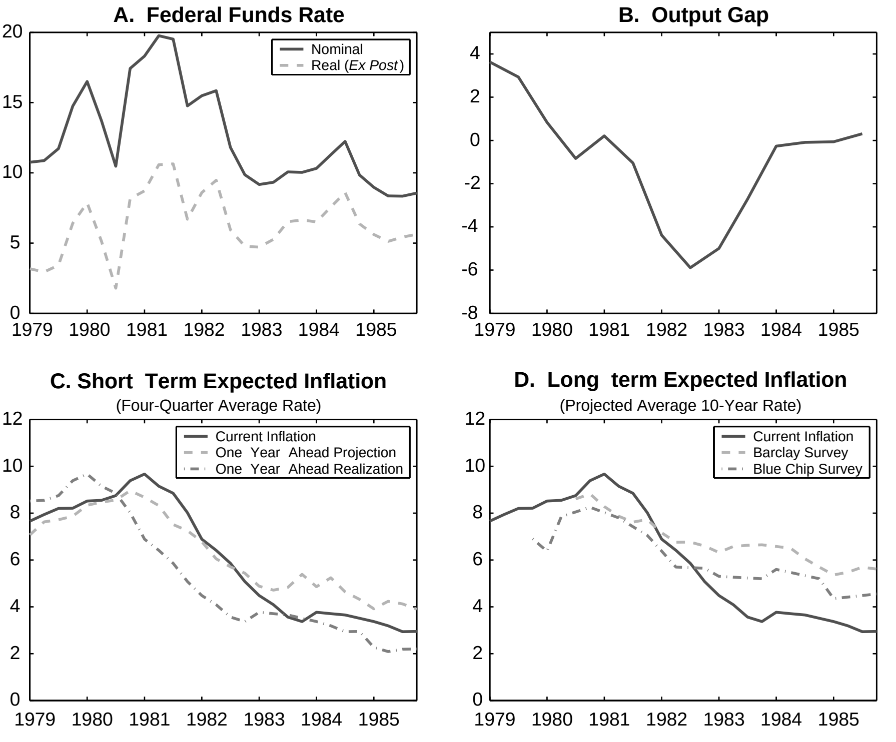

Fig. 2. U.S. macroeconomic indicators, 1979–1985: (A) federal funds rate; (B) output gap; (C) short-term expected inflation (four-quarter average rate); (D) long-term expected inflation rate (projected average 10-year rate).

desired this policy change to be interpreted as a decisive break from past policies that had permitted inflation to rise to double-digit levels; cf. Melton (1985). As shown in Fig. 2A, the federal funds rate increased about 6 percentage points between October 1979 and April 1980, an unprecedented rise over such a short period. Fig. 2A also shows the ex post real interest rate, computed using the four-quarter average GDP price inflation rate. The contractionary effect of high real interest rates was reinforced by the implemention of extensive credit controls in March 1980. In response, GDP contracted at an annual rate of nearly 9% in 1980:2, the steepest one-quarter decline in the postwar period. Alarmed by the apparent free fall in output, the Federal Reserve quickly lowered interest rates: by mid-1980, short-term nominal and real interest rates fell slightly below their values prior to the October 1979 tightening.

In late 1980, the Federal Reserve embarked on a new round of monetary tightening. The federal funds rate rose to 20% by early 1981, implying an ex post real interest rate of about 10%. Real interest rates were maintained near this extraordinarily high level until mid-1982. Volcker's aggressive anti-inflation policy succeeded in reducing the inflation rate from a 10% peak in late 1980 to around 4% by 1983, albeit at the cost of the most severe contraction in post-war U.S. history. Fig. 2B shows the evolution of the output gap as reported in the OECD Economic Outlook. Based on this measure of the output gap, the Volcker disinflation was associated with a sacrifice ratio of 1.7%.[7]

2.3. *Inflation forecast errors and credibility*

Survey-based measures of expected inflation highlight the credibility problems faced by the Federal Reserve in its efforts to reduce inflation. For example, Fig. 2C shows the 1-year-ahead forecast of the four-quarter average GNP price inflation rate, as measured by the median projection from the Survey of Professional Forecasters; very similar patterns can be seen in other measures of short-term expected inflation (such as the Livingston and Michigan surveys).[8] This figure also indicates the current four-quarter average inflation rate and the realized inflation outcome over the next year; note that the inflation forecast error can be inferred from the vertical distance between expected and realized inflation. Evidently, despite the transient policy tightening that began in October 1979, both actual and expected inflation continued to rise over the next 9 months. After renewed Federal Reserve tightening in late 1980, short-term expected inflation finally began to fall, suggesting somewhat greater confidence in the Fed's commitment to this policy stance. Nevertheless, it is apparent that realized inflation fell much more rapidly than was predicted; i.e., short-term inflation forecast errors during the period 1981–1985 were large (averaging over 1.5 percentage points in absolute value) and highly persistent. Fig. 2D shows two survey-based measures of expected average inflation over the subsequent 10 years (from the Blue Chip Economic Indicators and the Barclay Decision-Makers Survey); from this figure, it is apparent that longer-term inflation expectations also adjusted slowly.[9]

In light of these data, it appears that private agents did revise their inflation expectations in response to shifts in monetary policy, rather than simply adapting their forecasts based on current and lagged inflation rates. In particular, expected inflation began to decline in late 1980, whereas actual inflation did not begin to

[7] The sacrifice ratio is estimated by dividing the cumulative undiscounted sum of the annualized output gap between 1980:H2 and 1984:H2 by the change in the inflation rate of the GDP deflator over the same period. For this calculation, we use the output gap series taken from the *OECD Economic Outlook* (various issues). Our estimate is close to the value of 1.8 obtained by Ball (1994b). Nevertheless, it should be recognized that estimated sacrifice ratios are somewhat sensitive to the specific measure of the output gap. For example, Sachs (1985), Blinder (1987), and Mankiw (1991) obtained somewhat higher estimates of the sacrifice ratio for the Volcker disinflation.

[8] During the 1970s and 1980s, the SPF and other inflation expectation surveys were formulated in terms of the GNP price deflator, the "headline" measure of aggregate inflation. Nevertheless, over this period, the one-quarter annualized inflation rate computed using the GNP price deflator never differs more than a few hundredths of a percentage point from the one obtained using the GDP price deflator.

[9] Goodfriend (1993) draws attention to the slow convergence of long-term nominal interest rates. He interprets the temporary spike in nominal interest rates in 1983 as reflecting a continued lack of faith on the part of market participants in the Federal Reserve's willingness to maintain a tight hold on inflation.

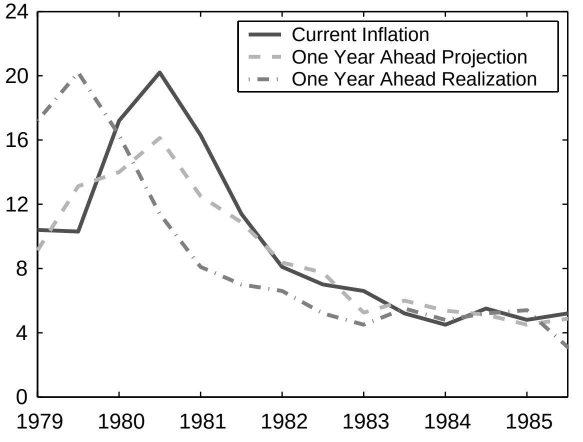

Fig. 3. U.K. short-term expected inflation (four-quarter average rate).

decline until early 1981. In fact, expected inflation remained below the current inflation rate throughout the subsequent year.

Furthermore, we interpret the persistent positive forecast errors as reflecting substantial doubts about whether the Federal Reserve would continue to pursue a disinflationary policy. As Goodfriend (1993) has emphasized, such doubts were reasonably well-founded, given that the Federal Reserve had shown a high degree of tolerance for rising inflation in the 1970s and had aborted the monetary tightening that began in October 1979. A second capitulation became increasingly plausible as the severity of the 1982 recession became more apparent and generated mounting Congressional pressure. The forecasting problem was compounded by the fact that the Federal Reserve did not announce a target path or band for the inflation rate; indeed, as the disinflation progressed, it became increasing difficult to assess how far Volcker intended to push down the inflation rate. Thus, persistent forecast errors seem consistent with rational expectations subject to limited information, and do not necessarily reflect non-rational expectations.

2.4. Evidence from other countries

Although our analysis is primarily devoted to matching the behavior of the U.S. economy during the Volcker disinflation, it is interesting to note that similar patterns appear to be characteristic of the roughly contemporaneous disinflation episodes in the United Kingdom and Canada. As seen in Fig. 3, the United Kingdom's shift towards an aggressive inflation-reduction strategy in 1981 succeeded in reducing the inflation rate from about 17% in late 1980 to around 4% in 1984.[10] Similarly, as shown in Fig. 4, Canada's tightening of monetary policy contributed to a fall in its

[10] See Sargent (1986) for a discussion of the initial stages of the Thatcher disinflation.

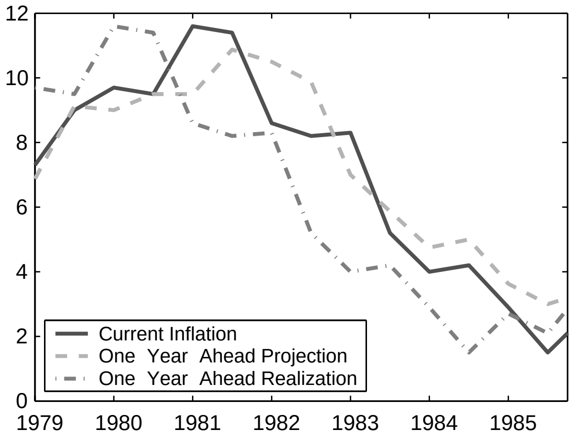

Fig. 4. Canadian short-term expected inflation (four-quarter average rate).

inflation rate from about 10% in mid-1981 to around 3–4% by 1984.[11] As in the Volcker disinflation, both the U.K. and Canadian disinflations were associated with large and highly persistent inflation forecast errors. Moreover, OECD output gap measures imply sacrifice ratios of about 1.3 and 1.8 for the U.K. and Canadian disinflation episodes, respectively; these values are remarkably similar to the estimate of 1.7 for the Volcker disinflation.

3. The model

As in Erceg (1997), we assume that labor and product markets each exhibit monopolistic competition, that wages and prices are determined by staggered four-quarter nominal contracts, and that the capital stock is endogenously determined subject to quadratic adjustment costs.[12] The central bank is assumed to react to the deviation of the output price inflation rate from its target value, and to the growth rate of real output. The key assumption in our analysis is that the central bank's long-run inflation target cannot be directly observed by private agents.

[11] The inflation rate for the United Kingdom is the four-quarter change in the GDP price deflator, while the inflation rate for Canada is the four-quarter change in the GNP price deflator. The survey data on expected inflation are semiannual observations taken from successive issues of the *OECD Economic Outlook*. The inflation forecast reported in the first half of each year is taken from the December survey of the previous year, and represents the inflation rate expected to prevail over the subsequent four quarters; the inflation forecast reported in the second half of each year is taken from the mid-year survey (typically published in June or July).

[12] Under these assumptions, a transitory money growth shock has persistent effects on output and the aggregate price level, but not on the inflation rate; cf. Erceg (1997), and Edge (2000a).

3.1. Firms and price setting

3.1.1. Final goods production

As in Chari et al. (2000), we assume that households use a single final output good Y_t either for consumption or investment. A continuum of differentiated intermediate goods $Y_t(f)$ ($f \in [0,1]$) is transformed into the final output good using a constant returns-to-scale technology of the Dixit–Stiglitz form

$$Y_t = \left[\int_0^1 Y_t(f)^{1/(1+\theta_p)} \mathrm{d}f \right]^{1+\theta_p}, \tag{1}$$

where $\theta_p > 0$.

Firms that produce the final output good are perfectly competitive in both product and factor markets. Thus, final goods producers minimize the cost of producing a given quantity of the output index Y_t, taking as given the price $P_t(f)$ of each intermediate good $Y_t(f)$. Moreover, the final output good is sold at a price P_t that equals the marginal cost of production:

$$P_t = \left[\int_0^1 P_t(f)^{-1/\theta_p} \, \mathrm{d}f \right]^{-\theta_p}. \tag{2}$$

It is natural to interpret P_t as the aggregate price index.

3.1.2. Intermediate goods production

Each intermediate good $Y_t(f)$ is produced by a single monopolistically competitive firm. This firm faces a demand function that varies inversely with its output price $P_t(f)$ and directly with aggregate demand Y_t:

$$Y_t(f) = \left[\frac{P_t(f)}{P_t} \right]^{-(1+\theta_p)/\theta_p} Y_t. \tag{3}$$

Each intermediate goods producer utilizes capital services $K_t(f)$ and a labor index $L_t(f)$ (defined below) to produce its respective output good. The form of the production function is Cobb–Douglas, with the level of total factor productivity X_t identical across firms:

$$Y_t(f) = X_t K_t(f)^{\alpha} L_t(f)^{1-\alpha}. \tag{4}$$

Firms face perfectly competitive factor markets for hiring capital and the labor index. Thus, each firm chooses $K_t(f)$ and $L_t(f)$, taking as given both the rental price of capital R_{Kt} and the aggregate wage index W_t (defined below). Firms can costlessly adjust either factor of production. Thus, the standard static first-order conditions for cost minimization imply that all firms have identical marginal cost per unit of output. By implication, aggregate marginal cost MC_t can be expressed as a function of the wage index W_t, the aggregate labor index L_t, the aggregate capital stock K_t, and total factor productivity X_t, or equivalently, as the ratio of the wage index to the marginal product of labor MPL_t:

$$MC_t = \frac{W_t L_t^{\alpha}}{(1-\alpha)K_t^{\alpha} X_t} = \frac{W_t}{MPL_t}, \tag{5}$$

$$MPL_t = (1-\alpha)K_t^{\alpha} L_t^{-\alpha} X_t. \tag{6}$$

We assume that the prices of the intermediate goods are determined by staggered nominal contracts of fixed duration. For concreteness, we assume that each price contract lasts four quarters, and that one-fourth of the firms reset their prices in a given period. Thus, individual producers may be indexed so that every firm with index $f \in [0, 0.25]$ resets its contract price $P_t(f)$ whenever the date t is evenly divisible by 4; similarly, firms with index $f \in [0.25, 0.5]$ set prices during periods in which $\mathrm{mod}(t, 4) = 1$, and so forth. For a firm which resets its price during period t, $P_{t+j}(f) = P_t(f)$ for $j = 1, 2, 3$. The firm chooses the value of $P_t(f)$ which maximizes the firm's discounted profits over the life of the price contract, subject to its product demand curve (3):

$$\tilde{\mathbb{E}}_t \sum_{j=0}^{3} \psi_{t,t+j}(P_t(f)Y_{t+j}(f) - MC_{t+j}Y_{t+j}(f)). \tag{7}$$

The operator $\tilde{\mathbb{E}}_t$ represents the conditional expectation based on all information available to private agents at period t.[13] Note that the tilde above the expectations operator is meant to indicate that private agents do not have complete information about the central bank's policy rule. The firm discounts profits received at date $t+j$ by the state-contingent discount factor $\psi_{t,t+j}$; for notational simplicity, we have suppressed all of the state indices. Let $\xi_{t,t+j}$ denote the price in period t of a claim that pays one dollar if the specified state occurs in period $t+j$; then the corresponding element of $\psi_{t,t+j}$ equals $\xi_{t,t+j}$ divided by the probability that the specified state will occur.

The first-order condition for a price-setting firm is

$$\tilde{\mathbb{E}}_t \sum_{j=0}^{3} \psi_{t,t+j}\left(\frac{P_t(f)}{(1+\theta_p)} - MC_{t+j}\right)Y_{t+j}(f) = 0. \tag{8}$$

Roughly speaking, the firm sets its contract price so that its expected discounted nominal marginal revenue is equal to its discounted nominal marginal cost.

3.2. Households and wage setting

We assume a continuum of monopolistically competitive households (indexed on the unit interval), each of which supplies a differentiated labor service to the production sector; that is, goods-producing firms regard each household's labor services $N_t(h)$, $h \in [0, 1]$, as an imperfect substitute for the labor services of other households. It is convenient to assume that a representative labor aggregator (or "employment agency") combines households' labor hours in the same proportions

[13] For simplicity, none of the variables is explicitly indexed by the state of nature.

as firms would choose. Thus, the aggregator's demand for each household's labor is equal to the sum of firms' demands. The labor index L_t has the Dixit–Stiglitz form

$$L_t = \left[\int_0^1 N_t(h)^{1/(1+\theta_w)}\,\mathrm{d}h\right]^{1+\theta_w}, \tag{9}$$

where $\theta_w > 0$. The aggregator minimizes the cost of producing a given amount of the aggregate labor index, taking each household's wage rate $W_t(h)$ as given, and then sells units of the labor index to the production sector at their unit cost W_t:

$$W_t = \left[\int_0^1 W_t(h)^{-1/\theta_w}\,\mathrm{d}h\right]^{-\theta_w}. \tag{10}$$

It is natural to interpret W_t as the aggregate wage index. The aggregator's demand for the labor hours of household h—or equivalently, the total demand for this household's labor by all goods-producing firms—is given by

$$N_t(h) = \left[\frac{W_t(h)}{W_t}\right]^{-(1+\theta_w)/\theta_w} L_t. \tag{11}$$

The utility functional of household h is

$$\tilde{\mathbb{E}}_t \sum_{j=0}^{\infty} \beta^j \left\{ \frac{1}{1-\sigma}(C_{t+j}(h))^{1-\sigma} + \frac{\chi_0}{1-\chi}(1 - N_{t+j}(h))^{1-\chi} + \frac{\mu_0}{1-\mu}\left(\frac{M_{t+j}(h)}{P_{t+j}}\right)^{1-\mu} \right\}, \tag{12}$$

where the discount factor β satisfies $0<\beta<1$. The period utility function depends on consumption $C_t(h)$, leisure $1 - N_t(h)$, and real money balances, $M_t(h)/P_t$.

Household h's budget constraint in period t states that its expenditure on goods and net purchases of financial assets must equal its disposable income:

$$\begin{aligned} &P_tC_t(h) + P_tI_t(h) \\ &\quad M_{t+1}(h) - M_t(h) + \int \xi_{t+1,t}B_{t+1}(h) - B_t(h) \\ &\qquad = W_t(h)N_t(h) + \Gamma_t(h) + T_t(h) \\ &\qquad\quad + R_{Kt}K_t(h) - 0.5\phi_K P_tK_t(h)\left(\frac{I_t(h)}{K_t(h)} - \delta\right)^2. \end{aligned} \tag{13}$$

The household purchases the final output good (at a price of P_t), which it chooses either to consume $C_t(h)$ or invest $I_t(h)$ in physical capital. Investment in physical capital augments the household's (end-of-period) capital stock $K_{t+1}(h)$ according to a linear transition law of the form

$$K_{t+1}(h) = (1-\delta)K_t(h) + I_t. \tag{14}$$

Financial asset accumulation consists of increases in money holdings and the net acquisition of state-contingent claims. As noted above, $\xi_{t,t+1}$ represents the price of an asset that will pay one unit of currency in a particular state of nature in the subsequent period, while $B_{t+1}(h)$ represents the quantity of such claims purchased by the household at time t. Total expenditure on new state-contingent claims is given by integrating over all states at time $t+1$, while $B_t(h)$ indicates the value of the household's existing claims given the realized state of nature.

Each household h earns labor income $W_t(h)N_t(h)$, and receives gross rental income of $R_{Kt}K_t(h)$ from renting its capital stock to firms. Households incur a cost of adjusting their net stock of physical capital; these adjustment costs are assumed to depend on the square of the deviation of the investment-to-capital ratio from its steady-state level of δ (or equivalently, on the square of the net change in the capital stock). Finally, each household receives an aliquot share $\Gamma_t(h)$ of the profits of all firms and a lump-sum government transfer, $T_t(h)$; we assume that the government's budget is balanced every period, so that total lump-sum transfers are equal to seignorage revenue.

In every period t, each household maximizes the utility functional (12) with respect to its consumption, investment, (end-of-period) capital stock, money balances, and holdings of contingent claims, subject to its labor demand function (11) its budget constraint (13), and the transition equation for capital (14). The first-order conditions for consumption and for holdings of state-contingent claims imply the familiar consumption Euler equation linking the marginal cost of foregoing a unit of consumption in the current period ($\Lambda_t = C_t^{-\sigma}$) to the expected discounted marginal benefit:

$$\tilde{\mathbb{E}}_t\Lambda_t = \beta(1+R_t)\tilde{\mathbb{E}}_t\Lambda_{t+1} = \beta(1+I_t)\tilde{\mathbb{E}}_t\left[\frac{P_t}{P_{t+1}}\Lambda_{t+1}\right] \tag{15}$$

where the risk-free real interest rate R_t is the rate of return on an asset that pays one unit of the output index under every state of nature at time $t+1$, and the nominal interest rate I_t is the rate of return on an asset that pays one unit of currency under every state of nature at time $t+1$. Our assumption of complete contingent claims markets for consumption implies that consumption is identical across households in every period ($C_t(h) = C_t$), and hence that all households have the same marginal value of a unit of the output index. This enables us to omit household-specific subscripts.

The household's Euler condition for investment implies a linear contemporaneous relation between Tobin's q and the investment to capital ratio of the form:

$$q_t = 1 - \phi_K\delta + \phi_K\frac{I_t}{K_t}. \tag{16}$$

Here q_t is the current value to the household of a unit of capital that becomes productive in the following period (measured in units of the final output good). Substituting this relation into the Euler equation for capital yields:

$$\begin{aligned} R_t + \delta + \phi_K(1+R_t)\left(\frac{K_{t+1}-K_t}{K_t}\right) & \\ = \beta(1+R_t)\tilde{\mathbb{E}}_t\frac{\Lambda_{t+1}}{\Lambda_t} & \\ \times\left[\frac{R_{Kt+1}}{P_{t+1}} + \phi_K\left(\frac{K_{t+2}-K_{t+1}}{K_{t+1}}\right) + \frac{1}{2}\phi_K\left(\frac{K_{t+2}-K_{t+1}}{K_{t+1}}\right)^2\right]. & \end{aligned} \tag{17}$$

In the absence of adjustment costs ($\phi_K = 0$) and with no uncertainty, the household would simply accumulate capital to equate the real rental rate $R_{K,t+1}/P_{t+1}$ with the risk-free real interest rate plus depreciation, $R_t + \delta$. Adjustment costs drive a wedge between the expected rental rate and marginal cost; this wedge is increasing in the level of net investment.

Households set nominal wages in staggered contracts that are analogous to the price contracts described above. In particular, we assume that wage contracts last four periods, and that the households are divided into four cohorts of equal size. In each period, the households in one cohort renegotiate their wage contracts, while the nominal wages of all other households remain unchanged. Thus, for a household which resets its contract wage $W_t(h)$ during period t, $W_{t+j}(h) = W_t(h)$ for $j = 1, 2, 3$. The household chooses the value of $W_t(h)$ to maximize its utility functional (12), yielding the following first-order condition:

$$\tilde{\mathbb{E}}_t \sum_{j=0}^{3} \beta^j \left(\frac{1}{(1+\theta_w)} \frac{\Lambda_{t+j}}{P_{t+j}} W_t(h) - \chi_0 (1 - N_{t+j}(h))^{-\chi} \right) N_{t+j}(h) = 0. \tag{18}$$

Roughly speaking, Eq. (18) says that the household chooses its contract wage to equate the present discounted value of working an additional unit of time to the discounted marginal cost.

3.3. Monetary policy

The appropriate characterization of Federal Reserve policy during the Volker disinflation period remains a subject of contention. However, Goodfriend (1991, 1993) argues persuasively that it is reasonable to consider the federal funds rate as the best measure of the stance of U.S. monetary policy even during this period.[14] Based on this perspective, we assume that the central bank adjusts the short-term nominal interest rate so that the ex post real interest rate rises when inflation exceeds its target value of π_t^*, or output growth rises above its trend rate. In addition, as in much of the subsequent literature, we allow for some degree of nominal interest rate smoothing or policy inertia. In particular, monetary policy is described by the following interest rate reaction function:

$$i_t = \gamma_i i_{t-1} + (1 - \gamma_{i)}[\bar{r} + \pi_t^{(4)} + \gamma_\pi(\pi_t^{(4)} - \pi_t^*) + \gamma_y(\ln(y_t/y_{t-4}) - \bar{g}_y)], \tag{19}$$

where the four-quarter average inflation rate $\pi_t^{(4)} = \frac{1}{4}\sum_{j=0}^{3} \pi_{t-j}$, $\bar{r}$ is the steady-state real interest rate, and $\bar{g}_y$ is the steady-state output growth rate. Note that this interest rate reaction function involves the output growth rate and *not* the level of the output

[14] From 1979:4 to 1982:3, the Federal Reserve's stated operational target involved the stock of nonborrowed reserves. Nevertheless, as Cook (1989) and Goodfriend (1991, 1993) have emphasized, the federal funds rate remained the main instrument of monetary policy, because the Federal Reserve made numerous discretionary adjustments to influence the amount of credit extended through the discount window. On this basis, prominent monetarists such as Friedman (1985) and Brunner (1987) criticized the Federal Reserve's failure to adopt a strict monetarist approach.

gap; as discussed below, this specification is consistent with our empirical analysis of interest rate determination from 1980 through 1985.

We assume that the inflation target π_t^* varies over time due to a combination of transitory and highly persistent shocks. Households and firms are assumed to know the form of the central bank's reaction function, including the parameters determining the sensitivity of the nominal interest rate to the inflation rate, the output growth rate, and the lagged interest rate (that is, the parameters γ_π, γ_y, and γ_i, respectively).[15] While agents can infer the current value of the inflation target from knowledge of the central bank's reaction function, they cannot directly observe the underlying components of π_t^*. Thus, agents must solve a signal extraction problem in order to forecast the future path of the inflation target, which in turn influences the outcome of their current decisions (e.g., in setting new wage and price contracts).[16]

In our baseline specification, we formulate the signal extraction problem by assuming that the central bank's inflation target is the sum of a constant steady-state rate of inflation $\bar{\pi}$ and two zero-mean stochastic components. Equivalently,

$$\pi_t^* - \bar{\pi} = (\pi_{pt} - \bar{\pi}) + \pi_{qt} = HZ_t \tag{20}$$

where $H = [1\ 1]$ and $Z_t = [(\pi_{pt} - \bar{\bar{\pi}})\ \pi_{qt}]'$. The time-varying components are determined by the following first-order vector autoregression:

$$\begin{bmatrix} \pi_{pt+1} - \bar{\pi} \\ \pi_{qt+1} \end{bmatrix} = \begin{bmatrix} \rho_p & 0 \\ 0 & \rho_q \end{bmatrix} \begin{bmatrix} \pi_{pt} - \bar{\pi} \\ \pi_{qt} \end{bmatrix} + \begin{bmatrix} \varepsilon_{pt+1} \\ \varepsilon_{qt+1} \end{bmatrix} \tag{21}$$

or

$$Z_{t+1} = FZ_t + \varepsilon_{t+1}.$$

For simplicity, we assume that the highly persistent component $(\pi_{pt} - \bar{\pi})$ has an autoregressive root ρ_p arbitrarily close to unity, while the transitory component π_{qt} has a much smaller autoregressive root ρ_q. Thus, while we assume the central bank's inflation target eventually returns to its steady-state value of $\bar{\pi}$, the shock ε_{pt} drives the inflation target away from steady-state for a very prolonged period. On the other hand, the shock ε_{qt} has only a very transient effect on the target.

Finally, we assume that the inflation target innovations ε_{pt} and ε_{qt} are mutually uncorrelated with variances v_1 and v_2, respectively, and are not correlated with any other shocks to the model economy. Thus, the Kalman filter can be used to obtain an optimal solution to the signal-extraction problem. In particular, optimal estimates of the unobserved components can be obtained recursively as follows:

$$\tilde{\mathbb{E}}_t Z_t = F\tilde{\mathbb{E}}_{t-1} Z_{t-1} + L_{\text{gain}}(\pi_t^* - HF\tilde{\mathbb{E}}_{t-1} Z_{t-1}) \tag{22}$$

[15] Fuhrer and Hooker (1993) analyzed a structural macroeconometric model in which agents face uncertainty about the coefficients of the monetary policy rule, but not about the inflation target.

[16] Our formulation of the information problem is formally similar to that in Brunner et al. (1980), and in Gertler (1982). The latter showed how imperfect observability of the underlying components of the money supply process could induce "inertial" behavior in the level of the nominal wage.

where the Kalman gain matrix $K_{\text{gain}} = FL_{\text{gain}}$. The term $\pi_t^* - HF\tilde{\mathbb{E}}_{t-1}Z_{t-1}$ is the one-step-ahead forecast error in predicting π_t^* based on its previous values, while the matrix L_{gain} determines how agents respond to a given forecast error by updating their estimates of the underlying components of the inflation target. Finally, given the current estimate $\tilde{\mathbb{E}}_t Z_t$ of these components, the optimal forecast of the inflation target J periods ahead is given by

$$\tilde{\mathbb{E}}_t \pi_{t+J}^* = \bar{\pi} + HF^J \tilde{\mathbb{E}}_t Z_t. \tag{23}$$

4. Solution and calibration

To analyze the behavior of this model, we log-linearize the model's equations around the non-stochastic steady-state associated with a constant inflation rate of $\bar{\pi}$ (that is, the central bank's steady-state inflation target). Nominal variables, such as the contract price and wage, are rendered stationary by suitable transformations. The log-linearized model consists of four key behavioral equations (the Euler equations for consumption (15), the capital stock (17), price-setting (8), and wage-setting (18)), three equations determining actual monetary policy ((19), (20), and (21)), and two equations determining private sector expectations of the inflation target ((22) and (23)). To obtain the reduced-form solution of the model, we use the numerical algorithm of Anderson and Moore (1985), which provides an efficient implementation of the method proposed by Blanchard and Kahn (1980); see also Anderson (1997).

4.1. Parameters of private sector behavioral equations

The model is calibrated at a quarterly frequency. Thus, we assume that the discount factor $\beta = 0.993$, consistent with a steady-state annualized real interest rate $\bar{r}$ of about 3%. The utility function is assumed to be logarithmic in consumption, leisure, and real balances, implying that $\sigma = \chi = \mu = 1$. The Cobb–Douglas capital share parameter $\alpha = 0.3$, and the depreciation rate of capital $\delta = 0.025$ (consistent with an annual depreciation rate of 10%). The price and wage markup parameters $\theta_P = \theta_W = 0.20$, similar to the estimated values obtained by Rotemberg and Woodford (1997) and Amato and Laubach (1999).[17] We set the steady-state inflation rate $\bar{\pi}$ to yield an annual rate of 4%. Finally, the utility parameter χ_0 is set so that employment comprises one-third of the household's time endowment, while the parameter μ_0 is assumed to be arbitrarily small so that real money balances are absent from the log-linearized model.

We draw on the empirical q-theory literature to calibrate a baseline value of the capital adjustment cost parameter ϕ_K. Recent literature estimating a linear

[17] Rotemberg and Woodford (1997) found $\theta_p = 0.15$, while Amato and Laubach (1999) obtained $\theta_p = 0.19$ and $\theta_w = 0.13$.

regression of I_t/K_t on q_t—consistent with Eq. (16) in our model—includes Eberly (1997) and Cummins et al. (1999). Eberly (1997) considered alternative methods of estimating linear models for the investment rate I_t/K_t, and found that the coefficient on q_t ranged from 0.09 to 0.17, implying a value of ϕ_K between 5.6 and 11.1. Cummins et al. (1999) estimated regression coefficients on q_t ranging from 0.08 (ordinary least squares) to 0.11 (instrumental variables), implying values of ϕ_K of 12.5 and 9, respectively. As emphasized by Shapiro (1986), the standard q-theory approach tends to generate upward-biased parameter estimates due to the measurement error in proxies for Tobins's q. Therefore, our baseline calibration utilizes $\phi_K = 5.6$ (that is, the lower bound of the range of estimates in the literature), but we will also consider alternative values for this parameter.

4.2. Monetary policy rule parameters

The parameters of the interest rate reaction function (19) are estimated over the 1980:4–1985:4 period by two-stage least squares. In estimating this equation, we assume that the Federal Reserve maintained a constant value of π_{pt} throughout this period; that is, we identify the error term in the estimated monetary policy reaction function as arising solely from variation in π_{qt} (the transitory component of the inflation target). We use two-stage least squares (with lagged values of inflation, output growth, and the nominal interest rate as instruments) to correct for possible correlation between the error term and the contemporaneous four-quarter inflation rate and output growth rate; in practice, however, OLS and 2SLS give reasonably similar results over the estimation period. We obtain parameter estimates of $\gamma_\pi = 0.64$, $\gamma_y = 0.25$, and $\gamma_i = 0.21$. We also experimented with adding the level of the output gap to the interest rate reaction function, but found that this variable was not statistically significant.

Fig. 5 compares the actual federal funds rate with the fitted values implied by these coefficient estimates. Evidently, this simple specification performs remarkably well in describing monetary policy during the sample period: the estimated residuals are relatively small compared with the movements in the federal funds rate itself, and these residuals exhibit negligible serial correlation.

4.3. Evolution of the inflation target

We set the autoregressive parameter ρ_p on the highly persistent component of the inflation target $(\pi_{pt} - \bar{\pi})$ equal to 0.999, while the autoregressive parameter ρ_q is set equal to zero in our baseline. The latter choice is consistent with our empirical finding that the historical innovations in the monetary policy reaction function over the 1980:4–1985:4 period are close to white noise.

Under these assumptions, the expected future inflation target $\tilde{\mathbb{E}}_t \pi^*_{t+j}$ $(j > 0)$ depends only on a constant $(\bar{\pi})$ and the expectation of the highly persistent component of the target $\tilde{\mathbb{E}}_t\ (\pi_{pt+j})$. In this special case of Eq. (22) with $\rho_q = 0$, the

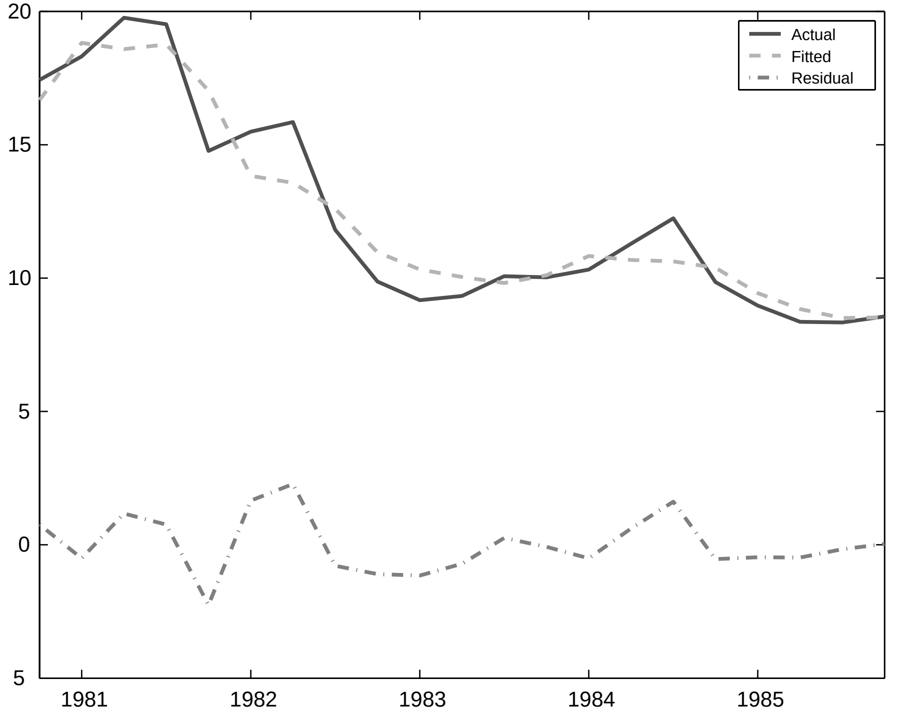

Fig. 5. Actual and fitted federal funds rate.

persistent component of the target evolves according to

$$\tilde{\mathbb{E}}_t(\pi_{pt} - \bar{\pi}) = \rho_p \tilde{\mathbb{E}}_{t-1}(\pi_{pt-1} - \bar{\pi}) + \left[\frac{k_g}{\rho_P}\right](\pi_t^* - \tilde{\mathbb{E}}_{t-1}\pi_t^*). \tag{24}$$

Thus, agents update their assessment of the persistent component of the inflation target by the product of the forecast error innovation and a constant coefficient. This coefficient, which is proportional to the scalar Kalman gain parameter k_g, is an increasing function of the signal-to-noise ratio v_1/v_2 (the ratio of the variances of the persistent and transitory components of the inflation target).

In estimating the signal-to-noise ratio, we utilize the same assumptions described above, namely, that the Federal Reserve maintained a constant value of π_{pt} after 1980:4, so that the path of the transient component π_{qt} can be computed from the residuals in the estimated monetary policy rule. We proceed by minimizing the sum of squared deviations between the observed data on four quarter-ahead expected inflation over the period 1980:4 to 1985:4 (taken from Survey of Professional Forecasters) and the corresponding inflation expectations implied by our model. Our point estimate of v_1/v_2 implies a value of the Kalman gain of 0.13. Thus, using Eq. (24), we find that nearly half of a given change in π_{pt} is incorporated into agents'expectations within a year.

5. Results

In this section, we analyze the behavior of the calibrated model in response to a shock to the highly persistent component π_{pt} of the inflation target. In particular, we assume that π_{pt} falls from an initial value of 10% to its steady-state level of 4% (annual rates); this shock is roughly equal to the decline in the GDP price inflation rate during the Volcker disinflation. The shock is assumed to occur in 1980:4.

5.1. The baseline calibrated model

5.1.1. Full information about the inflation target

The dashed lines in Fig. 6 show the impulse response functions (IRFs) of the model when private agents have full information about the central bank's inflation target (as in Taylor, 1983); that is, agents correctly interpret the reduction in the inflation target as a persistent shock and have perfect foresight about the subsequent path of π_t^*. Inflation falls from 10% to 4% within a year, and exhibits very little persistence beyond the length of the four-quarter nominal contracts. The short-term nominal interest rate falls slightly in the initial period (1980:4) and is close to steady-state within a couple of quarters. Real output initially declines markedly, but rebounds *above* baseline shortly thereafter. The initial output contraction occurs because the estimated monetary policy rule implies a sharp jump in the ex ante real interest rate. However, given that inflation expectations are anchored by the new lower target, progress in reducing inflation allows nominal and real interest rates to fall quickly and thereby causes output to rebound.

These results are qualitatively similar to those obtained by Ball (1994a) and Fuhrer and Moore (1995). Although those authors utilized models with staggered price contracts and flexible wages, it is clear that the inclusion of staggered wage contracts in our model does not generate much additional inflation persistence. Furthermore, while the output costs of disinflation depend on the sensitivity of real marginal cost to output and on the form of the monetary policy reaction function, these factors have minimal effect on the duration of a disinflation episode when agents have full information about the shift in the inflation target.

5.1.2. Imperfect observability of the inflation target

The solid lines in Fig. 6 show the IRFs of the baseline version of the calibrated model; that is, the signal-to-noise ratio is set to its estimated value (implying a Kalman gain of 0.13), and hence private agents gradually learn about the persistent shock to the inflation target. It is evident from Fig. 6 that the signal extraction problem plays a critical role in accounting for the broad features of the Volcker disinflation episode, namely, sluggish inflation adjustment, a persistently negative output gap, and an initial rise in the nominal interest rate. Inflation exhibits much greater persistence in this case: only about half the decline in inflation occurs within a year, and inflation is still only 3/4 of the way toward steady-state after 2 years. Our model's predicted path for inflation in the six quarters following the shock is in fact very close to what was observed in the Volcker disinflation. The slow inflation

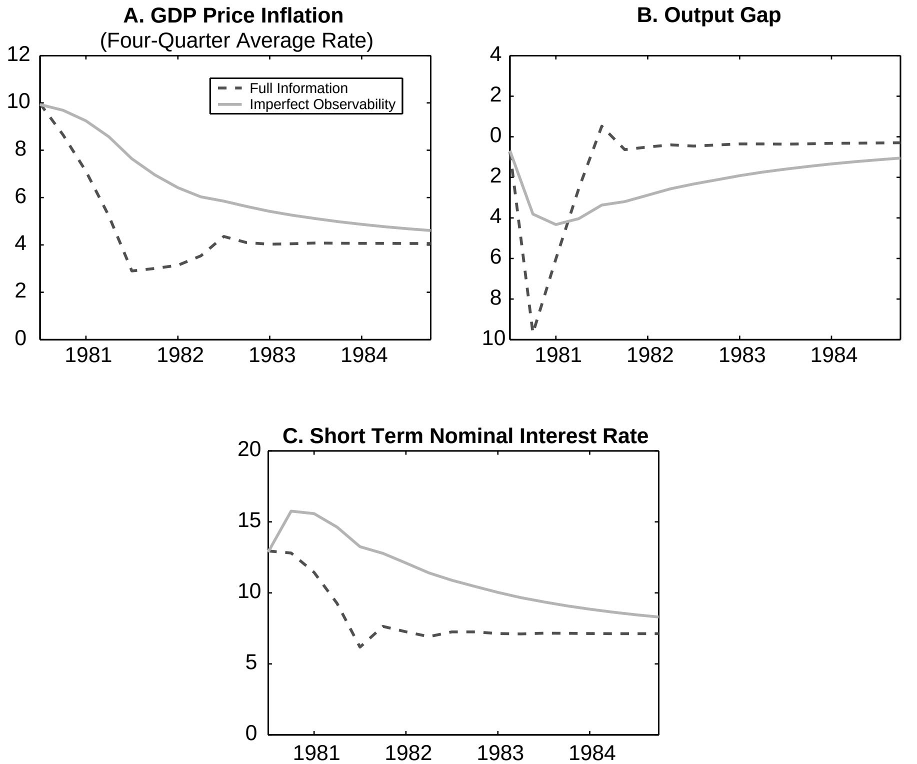

Fig. 6. Disinflation under alternative informational assumptions about the inflation target: (A) GDP price inflation (four-quarter average rate); (B) output gap; (C) short-term nominal interest rate.

decline in our model reflects that current inflation is partly anchored by expectations about the future inflation target.

In this case, the output gap exhibits a substantial and persistent decline, which contrasts strongly with the results for the case in which private agents have complete information about the inflation target. In particular, since current inflation decreases slowly, the policy rule requires high ex ante real interest rates over a sustained period. Output is about 4% below potential during the first year after the disinflation shock, and only recovers gradually as the central bank reduces interest rates in response to falling inflation. Thus, our calibrated model yields a sacrifice ratio of 1.7 during the 5 years after the disinflation shock, a result which is virtually identical to the empirical estimate of 1.7, and broadly in line with the estimates for Canada and the United Kingdom discussed in Section 2.4.

Furthermore, the nominal interest rate rises initially by about 300 basis points, an implication that contrasts sharply with the results obtained under full information (for which the nominal interest rate starts falling immediately at the start of the disinflation). This difference in nominal interest rate behavior results from the

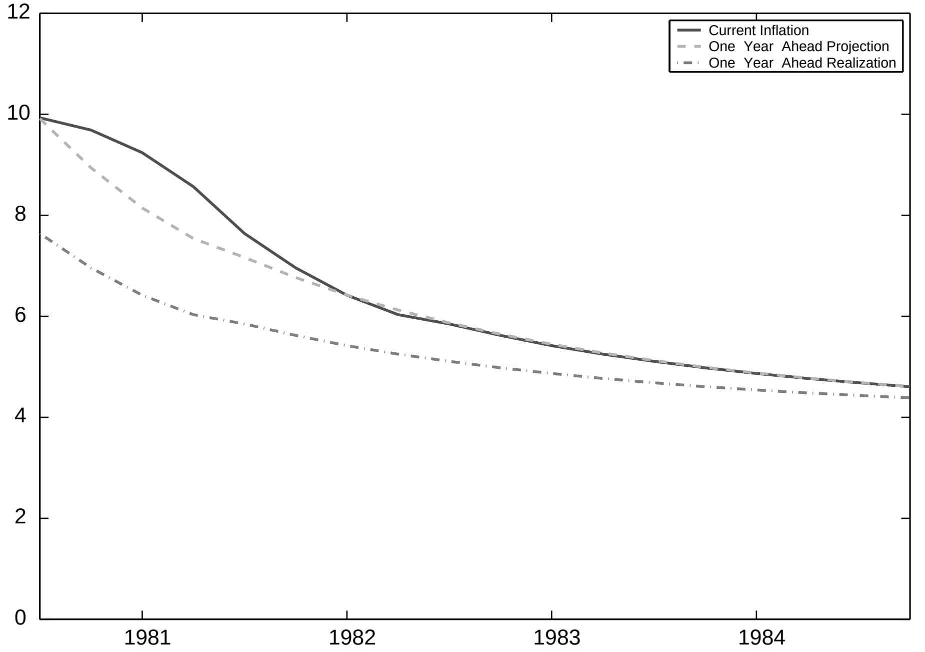

Fig. 7. Short-term expected inflation (four-quarter average rate).

greater sluggishness of inflation and because output exhibits a smaller initial contraction than under complete information.

Finally, as shown in Fig. 7, expected inflation falls sharply below current inflation at the announcement of the disinflation, but then declines somewhat more slowly thereafter. This pattern of comovement between actual and expected inflation is remarkably similar to that observed in the Volcker disinflation and in the roughly contemporaneous disinflation in the United Kingdom (cf. Figs. 2C and 3, respectively). And as emphasized in Section 2, this pattern clearly departs from what one would expect if private agents' expectations evolved in a simple adaptive fashion. In the medium term, inflation expectations move quite closely with actual inflation, demonstrating that persistent positive forecast errors are not inconsistent with the assumption of rational expectations subject to limited information about the central bank's objectives.

5.2. *Sensitivity analysis*

Now we consider the degree to which these results depend on particular aspects of our model specification. First, it is evident that endogenous capital accumulation plays a crucial role. Fig. 8 shows the responses of consumption and investment to the disinflation shock; while investment only accounts for about 20% of aggregate output, the sharp drop in investment accounts for nearly half of the peak decline in

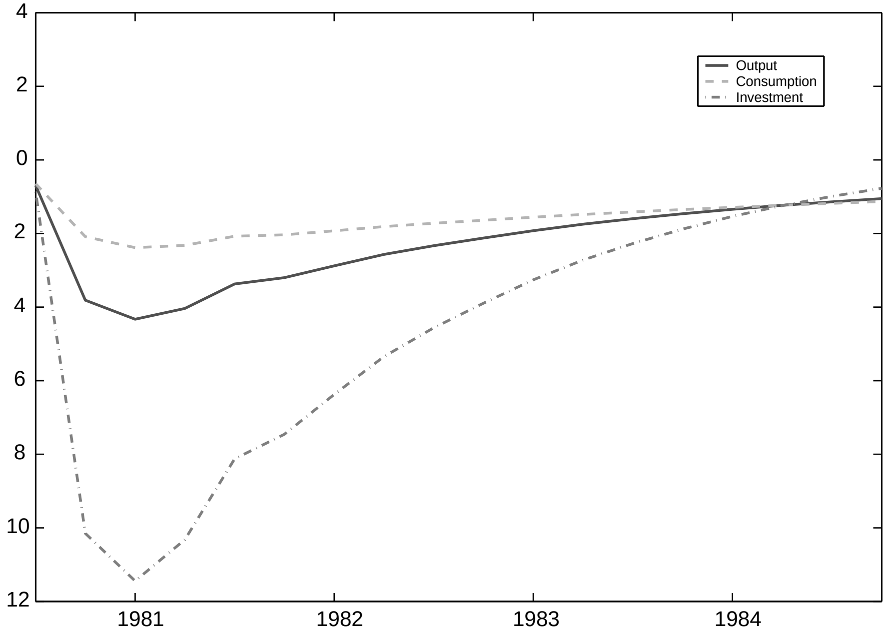

Fig. 8. Expenditure components of real GDP.

output in early 1981. To evaluate the quantitative implications in the absence of investment fluctuations, we can simply make capital adjustment costs extremely high (namely, $\phi_K = 100$). As shown in Fig. 9A, the output response is much smaller in this case, and the sacrifice ratio is only 0.8 (less than half its baseline value).

It is also useful to analyze the extent to which our results are sensitive to empirically plausible variations in the adjustment cost parameter ϕ_K. With perfect foresight and a fixed level of aggregate labor hours, our baseline calibration ($\phi_K = 5.6$) implies a half-life of about 10 quarters for the response of the aggregate capital stock to a 1% permanent rise in the real interest rate. Using a reasonable upper bound on the magnitude of adjustment costs estimated in the q-theory literature (namely, $\phi_K = 12$), this half-life increases to about 15 quarters.[18] As shown in Fig. 9A, the output response is somewhat lower in this case compared with the baseline calibration, and the sacrifice ratio is about 1.3. Finally, in the case of relatively low adjustment costs ($\phi_K = 2$, implying a half-life of only 5 quarters), the output response is somewhat larger and we obtain a sacrifice ratio of 2.6.

As seen in Fig. 9B, nominal wage inertia also plays a significant role in determining the magnitude of the output response to the disinflation shock. With completely flexible wages, the model yields a sacrifice ratio of only 0.9, compared with a sacrifice ratio of 1.7 for the baseline model. Intuitively, nominal wage rigidity

[18] Given the probable upward bias of adjustment cost estimates in the empirical q-theory literature, it seems very unlikely that the true adjustment cost parameter would be any larger than $\varphi = 12$.

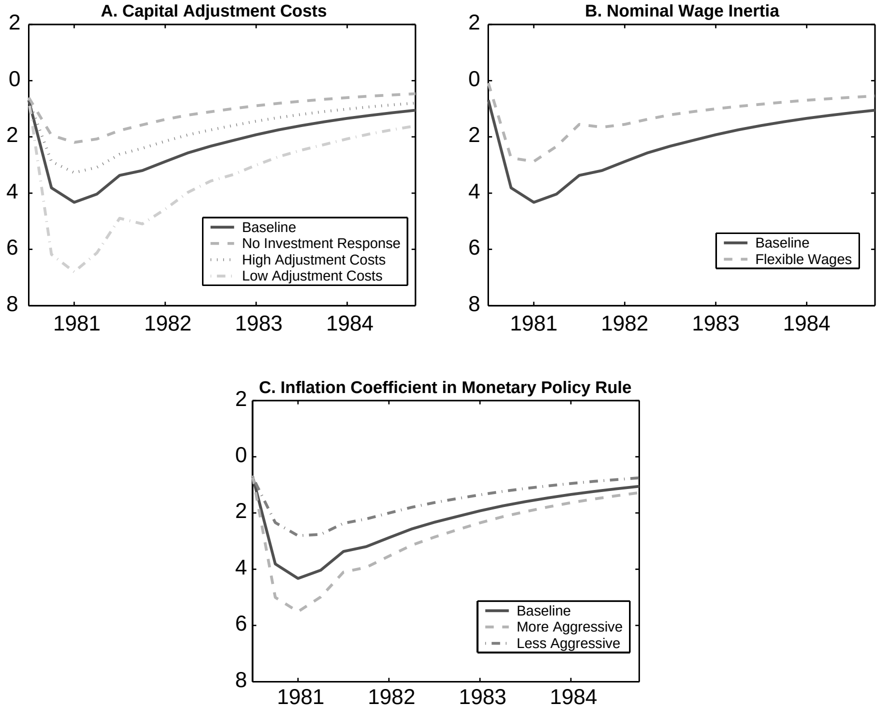

Fig. 9. Output response under alternative specifications: (A) Capital adjustment costs; (B) Nominal wage inertia; (C) Inflation coefficient in monetary policy rule.

reduces the sensitivity of real marginal cost to the output gap. Because price inflation depends on current and expected future real marginal costs, price inflation falls less in response to a given output gap as wages become less flexible. Thus, in the context of a disinflation shock, nominal wage inertia implies that the real interest rate rises by a larger amount under the monetary policy rule (because price inflation remains further above target), and hence output declines more sharply relative to the case of completely flexible wages.[19]

Finally, the output response is somewhat sensitive to the degree of aggressiveness of the policy response to deviations of inflation from target. As noted in Section 4.2, regression analysis was used to determine the baseline value of this coefficient ($\gamma_\pi = 0.64$). To gauge the implications of estimation uncertainty, we now consider setting this coefficient at either edge of the 95% confidence interval (namely, $\gamma_\pi = 1.05$ and $\gamma_\pi = 0.23$). The results shown in Fig. 9C indicate that the magnitude of the output contraction is an increasing function of the inflation coefficient in the policy

[19] Although not shown here, the results of this experiment are not sensitive to changes in the value of θ_p or to increasing the value of θ_w. For values of θ_w below the baseline value of 0.2, the model implies unreasonably large output costs of steady-state inflation, but the dynamic response to a disinflation is quite similar to that shown in the figures.

rule, while the timing of the output trough is not sensitive to the value of this coefficient.

5.3. Inflation forecast errors

Our model's ability to generate inflation persistence clearly depends on highly autocorrelated expectational errors in forecasting the central bank's inflation target, and correspondingly in forecasting inflation itself. For our interpretation to be empirically plausible, it is essential that the magnitude of the forecast errors implied by our model should not markedly exceed the observed pattern during the Volcker disinflation. In fact, Fig. 10A shows that the inflation forecast errors implied by our model tend to be considerably *smaller* than those implied by the data. The dotted line indicates the forecast errors implied by our model in response to a fall in the persistent component of the inflation target alone, while the dash-dotted line indicates the pattern of forecast errors if the historical monetary policy innovations are also included. In either case, the forecast errors implied by the model are bounded by the historical forecast errors throughout the Volcker disinflation (except in 1980:4, the initial period of the shock). Thus, our model does not require implausibly large forecast errors in order to explain a high degree of inflation persistence.

Interestingly, the historical data exhibit a considerably *higher* degree of persistence in inflation forecast errors compared with those implied by our model. In particular, while our simple specification of the inflation target process implies a geometric pattern of convergence in the inflation forecast errors, the observed forecast errors show little tendency to decline, even several years after the initiation of the disinflation. For example, short-run inflation expectations in early 1984 remained in the range of 5%, nearly 2 percentage points higher than the realized inflation rate. Moreover, survey data on long-term expected inflation show a considerably more sluggish decline than is implied by our calibrated model.

5.4. Output persistence

We have shown that our model can account for a highly persistent downturn in the level of output in response to a disinflation, implying an empirically plausible sacrifice ratio. However, even under imperfect observability, a disinflation has a highly front-loaded effect on the level of output, with the output trough occuring only two to three quarters after the shock. The path of output implied by our model in response to a disinflation shock is shown by the dotted line in Fig. 10B (with the dash-dot line showing the model output path when the historical monetary policy innovation is also included). It is clear that the model implies a much more rapid downturn than actually occurred in the Volcker disinflation; in the historical episode, output reached a trough only in mid-1982, more than a year-and-a-half later than the monetary policy tightening. The rapid output response reflects that the expenditure components of output in our model show very little persistence in growth rate terms. As we have seen in Fig. 9A, increasing the cost of adjusting the

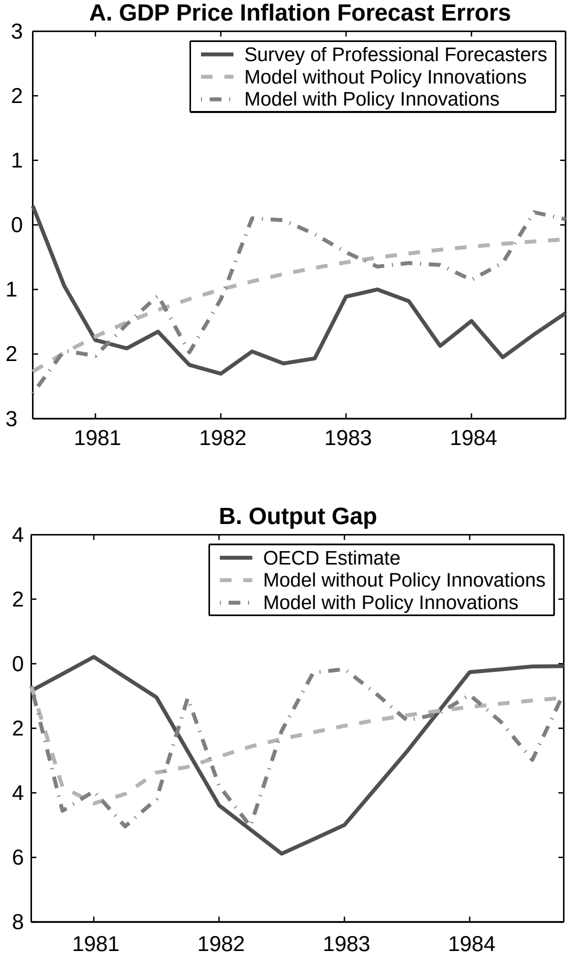

Fig. 10. Comparing the model results with U.S. data: (A) GDP price inflation forecast errors; (B) Output gap.

capital stock does not delay the timing of the investment trough, but simply dampens the response of investment expenditures.

Accounting for persistent effects of shocks on the growth rate of output is a challenge to a broad class of models with optimizing agents, and in our model, greater output persistence would certainly enhance its ability to account for the behavior of other endogenous variables. For example, with a sharp initial downturn in output, the nominal interest rate in our model does not peak as sharply as in the data. Although not shown here, we have found that output persistence is not substantially affected by incorporating habit persistence in consumption into the baseline model. In future research, it will be useful to consider these issues in models with timing lags in investment decisions (cf. Edge, 2000b), which may be somewhat more successful in accounting for the delayed output downturns that seem to have characterized historical disinflation episodes.

6. Comparison with existing literature

As shown above, our formulation of staggered four-quarter wage and price contracts is useful in accounting for empirically reasonable costs of disinflation. In contrasting our approach with the existing literature, however, it is useful to consider the following stylized representation of the aggregate supply relation:

$$\pi_t = \beta\hat{\pi}_{t+1} + \lambda x_t, \tag{25}$$

where π_t is the one-quarter annualized inflation rate (as a deviation from its steady-state value), x_t is the deviation of output from its flexible-price level, and $\hat{\pi}_{t+1}$ is the one-step-ahead inflation forecast; in this specification, the parameters satisfy $0<\beta\leqslant 1$ and $\lambda>0$.

Eq. (25) is immediately recognizable as the workhouse New Keynesian Phillips Curve under the assumption that agents make rational inflation forecasts using *all* information at time t; that is, $\hat{\pi}_{t+1} = \mathbb{E}_t\pi_{t+1}$, where we use the operator $\mathbb{E}_t$ (without a tilde) to indicate that private agents have full information about monetary policy (including the central bank's inflation target). In particular, as shown by Yun (1996) and others, this equation can be derived from microeconomic foundations when prices are determined by Calvo-style contracts and wages are completely flexible. This formulation exhibits no intrinsic inflation persistence and implies that disinflations can be conducted without any output costs.

One approach to accounting for inflation persistence has been to incorporate lagged inflation terms into Eq. (25) while maintaining the assumption that agents make rational forecasts (cf. Clarida et al., 1999):

$$\pi_t = \theta\pi_{t-1} + (1-\theta)\beta\tilde{\mathbb{E}}_t\pi_{t+1} + \lambda x_t. \tag{26}$$

When $\theta = 1/2$ and $\beta = 1$, Eq. (26) can be viewed as representing overlapping two-period *relative* real wage contracts (Buiter and Jewett, 1989); similar implications can be obtained under other assumptions about the indexation of nominal contracts (Christiano et al., 2001; Calvo et al., 2001). As shown by Fuhrer and Moore (1995), such a specification can account for very high inflation persistence and substantial costs of disinflation.

An alternative approach has been to assume that some or all agents have adaptive expectations. For example, Roberts (1998) considers a specification in which a fraction θ of private agents make one-step-ahead inflation forecasts based on past inflation, while the remaining agents have rational expectations; evidently, this specification can be represented exactly as in Eq. (26), but with a different structural interpretation than that of Fuhrer and Moore (1995).[20] Of course, this approach

[20] Alternative specifications of adaptive expectations have been considered by Ball (2000) and Ireland (2000).

departs from the optimizing-agent framework, in which agents use information efficiently in making their forecasts.[21] Furthermore, as noted above, survey data on inflation expectations clearly incorporate additional information beyond that contained in lagged inflation data.

In contrast, our approach assumes that private agents have rational expectations but must use signal extraction to make inferences about the central bank's inflation target; that is, we assume that $\hat{\pi}_{t+1} = \tilde{\mathbb{E}}_t \pi_{t+1}$, where $\tilde{\mathbb{E}}_t$ indicates the rational forecast given all information available *to private agents* at time t. By defining $u_t = \beta(\tilde{\mathbb{E}}_t \pi_{t+1} - \mathbb{E}_t \pi_{t+1})$, we obtain the following aggregate supply relation:

$$\pi_t = \beta \mathbb{E}_t \pi_{t+1} + \lambda x_t + u_t. \tag{27}$$

Evidently, $u_t \equiv 0$ in the New Keynesian model described above, whereas u_t will contribute to inflation persistence in the case where private agents do not have full information about the central bank's inflation target.

We can obtain an analytic expression for the behavior of u_t when aggregate demand is determined by the New Keynesian IS curve, the central bank follows a simplified interest rate reaction function (involving only the current one quarter inflation rate and the current output gap), and the inflation target π_t^* is the sum of a random walk component π_{pt} and a white noise component π_{qt}.[22] In this case, we find that u_t follows the process:

$$u_t = (1 - \kappa_g) u_{t-1} + (1 - \kappa_g) \phi \varepsilon_{pt}, \tag{28}$$

where $\phi < 0$, κ_g is the Kalman gain coefficient in the updating Eq. (24) for $\tilde{\mathbb{E}}_t \pi_{pt}$ that applies when $\rho_p = 1$, and recalling that ε_{pt} is the innovation in the persistent component of the inflation target. In the case of full information about the inflation target, the Kalman gain $\kappa_g = 1$, and hence $u_t = 0$ as in the New Keynesian model; in this case, inflation exhibits no persistence, and disinflation does not involve any output costs. In contrast, a lower signal-to-noise ratio regarding the inflation target (and hence lower κ_g) is associated with higher volatility and persistence of u_t, and this persistence passes through into the actual inflation process.

7. Conclusions

In this paper, we have formulated a DGE model with optimizing agents and staggered nominal contracts, in which private agents use optimal filtering to make inferences about the central bank's inflation target. We have shown that this model accounts quite well for several important features of the Volcker disinflation episode: a pronounced initial rise in the nominal interest rate, a sluggish decline in the inflation rate, a persistently negative output gap, and persistent inflation forecast errors. In this framework, inflation persistence is not an inherent characteristic of the

[21] Recently, several authors have studied models in which optimizing agents have a finite information-processing capacity; see Sims (2001), Woodford (2001), and Orphanides and Williams (2001).

[22] That is, $x_t = \tilde{\mathbb{E}}_t x_{t+1} - (1/\sigma)(i_t - \tilde{\mathbb{E}}_t \pi_{t+1} - r_t^*)$ and $i_t = \bar{r} + \pi_t + \gamma_\pi(\pi_t - \pi_t^*) + \gamma_x x_t$, where x_t denotes the output gap.

model economy, but rather arises whenever agents must learn about shifts in the monetary policy regime.

To avoid a non-linear signal extraction problem, we have assumed that private agents have complete information about the specification and coefficients of the monetary policy rule, and that the inflation target itself is the only aspect of monetary policy that is not fully observed. As noted above, however, the appropriate characterization of Federal Reserve policy during the Volcker disinflation period continues to be somewhat contentious even after two decades, and hence was almost certainly not as transparent to market participants at the time. In future research, it would be interesting to allow for time variation in the policy rule coefficients and for a discrete probability of policy reversals. More generally, our analysis emphasizes the benefits of explicitly considering informational constraints faced by private agents as well as by the central bank, and we believe that such an approach may be fruitful in explaining inflation and output persistence in other periods.

Finally, we have proceeded under the assumption that private agents behave optimally, but have not directly considered the optimization problem of the central bank itself. In future research, it will be useful to give explicit consideration to the incentives and commitment mechanisms of the central bank, and to investigate various approaches for enhancing the credibility and transparency of the monetary policy regime.[23]

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[23] For analysis of the time-consistency issue as well as incentive and commitment mechanisms for monetary policy, see Ball (1995b) and Svensson and Woodford (1999). For discussion of practical issues related to credibility and transparency of inflation targeting regimes, see Taylor (1982), McCallum (1995), and Bernanke et al. (1999).

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